Techno-Economics of Residential Broadband Deployment

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Summary

Residential broadband is increasingly being seen as a catapult for a more general economic growth. Deployment of advanced broadband access networks is a prerequisite for the continuous development and success of broadband. This thesis investigates available deployment strategies for broadband access networks required to support the near-future transmission requirements of converged voice, video, and data services. The approach of telecoms using Digital Subscriber Line technology is compared to entry strategies based on Fibre-to-the-Home to evaluate the financial feasibility of residential broadband deployment in different geographical areas.

A fundamental assumption in residential broadband deployment is that the required investments are based on financially feasible premises. Investment appraisal of deployment scenarios is therefore of interest to operators and regulators alike, but is not trivial and relies on knowledge of the technological, economic, and regulatory parameters that affect the foreseen cost and revenue of networks and services. In contrast to existing static methods of evaluating financial feasibility this thesis argues that properties of the networks and services need to be related to competitive interactions between infrastructures when evaluating financial feasibility.

To accomplish this, this thesis is divided into three main parts, where the first part analyses properties of packet-based multimedia services and performs quantitative forecasting of near-future transmission requirements. The second part analyses residential broadband deployment based on Digital Subscriber Line technology in comparison to Fibre-to-the-Home, describes the parameters that shape deployment, and identifies plausible deployment strategies capable of meeting the identified transmission requirements. The last part develops a quantitative simulation model based on existing techno-

economic (engineering) cost models that additionally calculates revenues and estimates financial feasibility. To study competitive interactions the thesis supplements the framework with elements of game theory, using the von Stackelberg model.

The framework is applied to the case of Denmark, using a dataset from the Danish LRAIC model, motivated by the foreseen wide-scale FTTH deployment by the energy utility sector in Denmark. The results show that the future of residential broadband networks is based on converged voice, video, and data services that pose stringent quality of service requirements on transmission. While these services, and especially IPTV, can be expected to raise transmission requirements from 20 Mb/s to 50-100 Mb/s in the course of the next five years, this thesis concludes that there are no strong demand sided requirements that call for FTTH rather than DSL, given that the DSL infrastructure is upgraded to meet these requirements.

The study shows that DSL deployment is highly reliant upon the existing copper infrastructure. Copper loop lengths determine maximum transmission throughput and can limit service selection and thereby revenues. Upgrade strategies are based on co-locating DSL equipment in existing copper aggregation nodes. In the case of Denmark, there are two levels of aggregation points. The first is on average located 0.7 -1.6 km from customer premises, enabling on average 7-16 Mb/s in transmission throughput, while the second is on average 70 – 210 m from customer premises, enabling transmission throughput of 52-90 Mb/s. While the short distance to secondary nodes enables high transmission throughput, the number of nodes (and thereby the cost) increases by a factor of 10 for each level.

By applying game theory the thesis shows that telecom operators are forced to embark on residential broadband deployment as a defensive move. This is especially true in densely populated cities where VDSL/VDSL2 deployment from secondary distribution points can offer competitive transmission throughput to that of FTTH, thereby functioning as a barrier to entry. For other geographical areas than cities, deployment of DSL from primary distribution points captures the majority of potential revenue stream, while minimising deployment cost. In addition to selecting the right location of equipment, timing of deployment is a key-variable for telecoms, as price of equipment can change significantly depending on global deployment trends.

The study of FTTH deployment highlights the effect of long expected lifetime of ducts and trenches. While access trenches account for 61% of

the € 2,019 capital expenditure of FTTH per subscriber in cities at 50% broadband market share, that ratio is reduced to 35% of the annualised € 228 cost. The study concludes that FTTH deployment in Denmark can be financially feasible in cities if take-up rate is above 25% (translates to 40% of the foreseen residential broadband market) but not in other regions of the country. However, by considering economics of scope from other operations, e.g. shared digging cost, the Danish energy utility sector can deploy financially feasible FTTH in all geographic areas in Denmark.

Keywords

Access Networks, Broadband, Multimedia Services, DSL, FTTH.

Resumé (in Danish)

Udbredelsen af bredbåndsforbindelser til private husstande betragtes som et vigtigt element i kampen for øget velstand og beskæftigelse. Udrulning af nye accessnet er forudsætningen for en vedvarende udvikling og udbredelse af bredbånd. Denne afhandling undersøger mulige udrulningsstrategier, der kan imødekomme fremtidens mediekonvergens. Projektet er baseret på en komparativ analyse mellem den strategi teleoperatørerne fremmer, hvor Digital Subscriber Line teknologien anvendes på den eksisterende kobber infrastruktur, og en strategi baseret på udrulning af ny optisk fiberinfrastruktur, som elselskaberne foretrækker. Løsningerne er analyseret udfra teknologiske egenskaber og vurderet på baggrund af finansielle fordelagtighed.

I nutidens liberaliserede telemarked er det en grundlæggende forudsætning at investeringer i accessnet skal være finansielt fordelagtige. Investeringskalkuler kan kaste lys over forskellige investeringsalternativer og hjælpe operatører og tilsynsmyndigheder med at vælge den rigtige fremgangsmåde. Denne værdiansættelse kræver kendskab til adskillige teknologiske, økonomiske og regulatoriske forudsætninger som påvirker investering, drift, og ydelse. Der findes tekno-økonomiske metoder til at gennemgå disse beregninger, men deres problem er, at de bygger på et statisk grundlag og dermed ikke tager højde for de dynamiske ændringer, der sker på markedet bla. som følge af konkurrencen. Et af formålene med denne afhandling er at fremme forståelsen af samspillet mellem netværk, tjenester og udrulning af accessnet i et konkurrerende marked.

Afhandlingen er delt op i tre overordnede dele. Den første analyserer fremtidens multimedietjenester og beregner kvantitative estimater af de transmissionskrav, som disse tjenester stiller. I anden del analyseres de tekniske faktorer der gælder ved udrulning af accessnet baseret på DSL og

FTTH. Derved identificeres mulige udrulningsstrategier for teleselskaber og energiselskaber, der imødekommer de krav, som fremtidens tjenester stiller. Den sidste del af afhandlingen udvikler en tekno-økonomisk omkostningsmodel, der simulerer kapitaludgifter og ydelser for de identificerede udrulningsstrategier. Ydermere suppleres investeringskalkulerne med spilteori, ved brug af von Stackelberg metoden.

Modellen bruger det empiriske datasæt, som Telestyrelsen har udviklet for den danske LRAIC model for at analysere udrulning af accessnet i fire geografiske områder i Danmark. Analysen tager højde for den forudsete konkurrence mellem teleoperatører og energiselskaber og konkluderer, at selvom fremtidens multimedietjenester vil kræve en stigning i transmissionshastighederne fra de nuværende 20 Mb/s til 50 – 100 Mb/s i løbet af de næste fem år, så findes der ikke et velbegrundet efterspørgselsorienteret behov for at anvende optisk fiber fremfor andre transmissionsmedier, som kan tilbyde samme hastighed.

Analysen af DSL viser, hvor afhængige teleoperatørerne er af den eksisterende kobber infrastruktur i deres tjenesteudvalg. Transmissionshastigheden afhænger af kabellængden fra central til husstand, som i mange tilfælde er for lang til at understøtte fremtidens hastighedskrav. For at øge indtægtsmuligheder kan teleoperatørerne flytte DSL-udstyr ud i knudepunkter tættere på kunderne. I Danmark findes der to knudepunkter på hver kobberlinje. Ved at placere DSL-ustyr i det første knudepunkt som er gennemsnitligt placeret 0,7 – 1,6 km fra den enkelte husstand muliggøres en transmissionshastighed på 7-16 Mb/s. Det andet knudepunkt er placeret 70 – 210 m fra den enkelte husstand og ved at placere udstyret der, muliggøres en transmissionshastighed på 52 – 90 Mb/s. Antallet af knudepunkter stiger dog med en faktor 10 når man går tættere mod kunden, og investeringen forhøjes fra € 379 til € 1.806 for hver bruger i storbyer.

Ved brug af spilteori viser afhandlingen, at teleoperatører er tvunget til investering i DSL udstyr placeret i et af knudepunkterne, som forsvarsstrategi. Dette gælder især i storbyer, hvor udrulningen tættere ved brugeren muliggør transmissionshastigheder svarende til FTTH, men sænker overskuddet. I byer og landområder er udrulningen til det første knudepunkt den dominerende strategi, idet den muliggør hovedparten af fremtidens tjenester, mens investeringsomkostningerne er begrænsede. Teleoperatører skal, udover at finde den optimale placering af DSL-udstyr,

vælge det rigtige tidspunkt for udrulningen, vidende at pris og kapacitet kan ændre sig markant, afhængigt af udvikling og globale tendenser.

Analysen af FTTH udrulning i Danmark viser, at investeringsomkostningerne er domineret af gravearbejde, som i storbyer tegner sig for 61% af den samlede investering. Når dette beløb er omdannet til årlige omkostninger, som tager hensyn til den lange levetid på fiber, så reduceres andelen af gravearbejde til 35% af det årlige beløb. Hovedparten af investeringen i FTTH udrulning er ikke relateret til antallet af brugere. Omkostningen ved at passere alle husstande i storbyerne, uden at tilslutte kunder, er således € 502 per husstand. Denne udgift vokser til € 4.777 i landområderne.

Afhandlingen konkluderer, at FTTH udrulning i Danmark kun vil være fordelagtig i storbyer, såfremt over 25% af samtlige husstande (40% af den forudsete bredbånds-marked) abonnerer på tjenesten. Derimod vil FTTH udrulning i andre områder i Danmark ikke være fordelagtige under de samme forudsætninger. Det er dog muligt at udrulle FTTH fordelagtig i alle geografiske områder i Danmark hvis det er muligt at dele graveomkostningerne med andre, f.eks. i forbindelse med nedgravning af elkabler.

Preface

This thesis is a result of a three year period and the final step in obtaining a Ph.D. degree at the Centre for Information and Communications Technologies (CICT) within the Technical University of Denmark. While the dissertation describes a core subset of my work, it only partially represents what I have been doing during the period and mostly neglects the personal development that was the goal of the whole exercise and my reason for taking the journey in the first place.

The work has mostly been carried out in Denmark but I have been fortunate enough to get the chance of working as a guest researcher at the University of Oslo, the University of Cambridge and Microsoft Research Asia. In addition to adding substance to the thesis, these periods have broadened my horizon and strengthened the multidisciplinary dimensions of my work. This could not have been done without financial support and I would especially like to thank TDC, Nordforsk, Iceland Telecom, Reykjavik Energy, and the Otto Mønsteds Fond for their contributions. Despite this support, the opinions and conclusions of this report only represent my views and findings and do not imply any endorsements by any of the sponsors.

During the course of the project many good people have assisted me and contributed to this final result. In addition to my supervisors, I would first and foremost like to thank Sæmundur E. Þorsteinsson, director of Iceland Telecom R&D, for extending his mentorship, Rajen Akalu for lively discussion and Morten Falch for collaboration and guidance. Additionally there are various industry and academic contacts that deserve thanks, of which I would especially like to mention Esben Dahl-Nielsen from Alcatel Denmark.

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Last but not least, I would like to thank my loving wife, Beinta Fossádal, who unselfishly tolerated me during a period of intense writing but also tenderly took care of our son, Helgi Jakob, during my absence.

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Copenhagen, 9th of February 2007

Halldór Matthías Sigurðsson

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Chapter 1

General Introduction

This chapter introduces the open issues of deployment of residential broadband networks and services. The focus is then sharpened on the technological alternatives and financial viability of upgrade strategies for telecoms using Digital Subscriber Line technology in comparison to entrant strategies based on Fibre-to-the-Home deployment through a case study of Denmark. The aim is to highlight technological, economic, and regulatory factors that drive infrastructure development, control financial feasibility, shape infrastructure competition, and affect policy goals aimed at promoting broadband deployment.

1.1.   Motivation

In 2003 the International Telecommunications Union described the prominent "birth of broadband" (ITU 2003). Less than three years later, the Organisation for Economic Co-operation and Development (OECD) describes a shift in the most developed broadband markets that are "advancing to the next stage of development" (OECD 2005). This stepwise development of infrastructure evolution had already been identified and predicted in literature, e.g. by Maxwell (1999) and Alcatel (2004) and is characterised by media convergence[1] and the coexistence of commercial

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[1]   In this thesis the term media convergence is used in a broad form to represent the disappearing boundaries between traditional types of

voice, video, and data services (hereafter called multimedia services) over a single converged access network.

There is a general consensus that the long-term future of access networks is based on optical fibre (Ims 1998; Bates 2002; Green 2006), but less unity surrounds the path to that goal. Two main strategies exist [2] (see Figure 1) where traditional telecommunications operators (telecoms)[3] unsurprisingly lead a phalanx of those advocating for stepwise introduction of fibre, using Digital Subscriber Line (DSL) variants over decreasing copper distances. Entrants on the other hand, lead by financially strong electric utility companies (EUC)[4] that additionally see potentials for economics of scope from their existing operations, are free of path dependency from existing infrastructures and promote immediate wide-scale Fibre-to-the-Home (FTTH)[5].

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services, and the specific networks designed to carry them. This tentative definition neglects many of the important dimensions that other sources have broken media convergence into, such as service convergence, network convergence, terminal convergence etc. For more information see e.g. Øst (2003) and BREAD D2.2-3.2.

[2]   Despite the promise of new future competitive technologies, such as wireless and Power Line communications (PLC) this thesis accepts the view and arguments of other research projects such as IST-Broadwan (2006) that these technologies are unlikely to become significant in terms of wide-scale residential broadband adoption. Coaxial cable / Hybrid Fibre Coaxial (HFC) networks can provide the third main strategy but as they are not widely deployed in Europe (and that is not expected to change, according to Oslen et al. 2006), in addition to often being owned by incumbent telecom operators, resulting in reduced competitiveness.

[3]   The terms telecommunication, telecommunications, telecom and telecoms tend to be used indiscriminately and interchangeably in literature (Melody, 1997). Throughout this thesis the term 'telecom' will be used unless otherwise needed or stated.

[4]   This type of often semi-public broadband initiatives are in literature also referred to as Municipal broadband (Sutherland 2006), Municipal Electric Utility (Osorio 2004), and Local Government Broadband Initiatives (Gillett 2003)

[5]   Literature uses the terms fibre-to-the-home (FTTH), fibre-to-the-premises (FTTP), and fibre-to-the-user (FTTU) indiscriminately. This
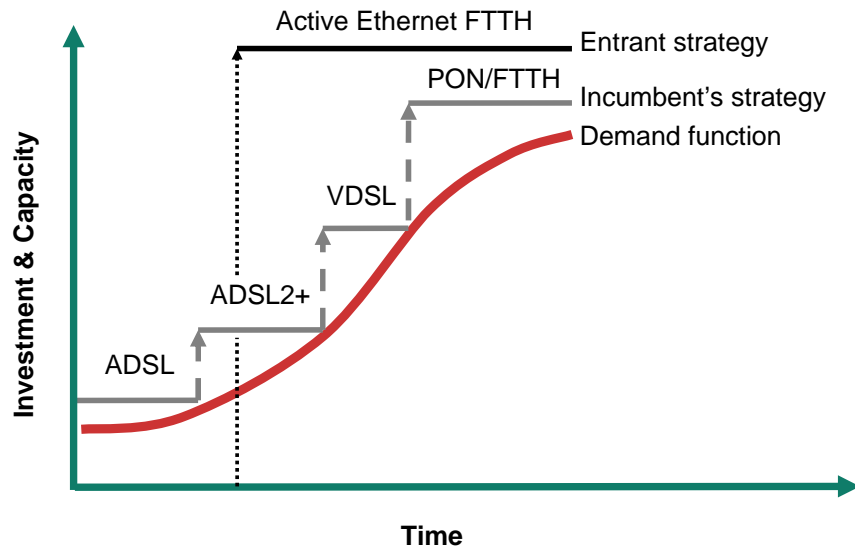
Figure 1, Alternative investment strategies for broadband access networks

Both approaches require substantial investment (although of different magnitudes) which should be balanced by expected long term revenues. The accumulated margin of this balance between cost and revenues determines profit of deployment and is in economic theory denoted by $\prod^i(n)^6$, where i is the firm undertaking the infrastructure investment and n is the total number of competing infrastructures. Under the postulate that firms maximise profits, the dominant deployment strategy of i can be predicted by solving $\text{Max}[\prod^i(n)]$. A fundamental assumption in today's liberalised and competitive telecommunications markets is that infrastructure investment by all n firms is based on financially feasible premises. Assuming that total profitability of all deployments decreases

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thesis will use FTTH as an acronym for all types of access networks where the optical fibre runs inside subscribers home/premises.

[6]   In reality the profit $\prod$ is a function individual to each firm, the technology it applies, and various exogenous and endogenous parameters of the production. This reasoning and terminology stems from the theory of industrial economics and is extensively used throughout the thesis. For further reading of industrial economics see Tirole (2003).

with the number of competing infrastructures[7], this requirement sets an upper bound $\bar{n}$ on the viable level of infrastructure competition[8] in a given area, limited by $\sum_{i=1}^{n} \Pi^i(n) \geq 0$. This provides a taxonomy for sustainable residential broadband deployment:

$\prod(1) < 0$	The market is not profitable for private sector deployment
$\prod(1) > 0 > \prod(2)$	The market is a natural monopoly[9], where only one firm is viable, but not two or more
$\prod(2) > 0$	The market sustains infrastructure competition between at least two firms

[7] In a recent study, Höffler (2005) concludes based on empirical data that infrastructure competition between DSL and cable has a significant and positive effect on broadband penetration. Using inductive reasoning this would lead to increased revenues and thus might falsify the otherwise grounded assumption of decreasing profits. However, for clarity this possibility is disregarded.

[8] A tentative definition of infrastructure competition is competition where "an alternative provider has complete control of all aspects of its network and the services it delivers". Among interchangeable terms in literature are "platform competition" (DotEcon 2003), "intermodal competition" (Newman 2003), and "facilities based competition" (Laffont and Tirole 2001). This is in contrast to service competition where an entrant makes use of various wholesale services available from the incumbent operator.

[9] Several definitions have been given of a natural monopoly in literature. The traditional view of economics was that economies of scale could justify natural monopolies or to put it in a normative context, market situations where a monopoly exists were seen as socially desirable. More recently literature has moved to a technical definition of natural monopoly in relation to the cost function, defining a natural monopoly if "over the relevant range of outputs, the cost function is subadditive" (Baumol et al. 1982). Importantly for this study also, Newbery (2001) adds that it is "possible that a network utility has a local natural monopoly but not a national natural monopoly". For a thorough discussion of natural monopolies see also Sharkey (1982).

While this simple taxonomy disregards the technological, economic, and political parameters that influence the profit function, which are the subject of the rest of the thesis, it demonstrates a simple way of analysing appraised level of infrastructure competition. This thesis is motivated by the desire to investigate the questionable financial viability of coexisting but competitive wide-scale DSL and FTTH deployment and aims at contributing the to ongoing literature debate of residential broadband development.

1.2.   Background Information

From the introduction of telephony in the late 19th century, telecommunications infrastructures have been developing through a combination of public and private ownership and interventions. Throughout the 20th century, most countries used the argumentation of lower social cost to justify the creation of statutory monopoly operators and their exclusive responsibility for deploying networks and providing services equitably to all members of society (Olsen, 1993). An ideological shift was implemented in the US and Europe during the 1980s and 1990s with the liberalisation of the telecommunications market, privatisation of incumbents and introduction of regulated competition.

In addition to legislative reforms, the last two decades of the 20th century also witnessed the emergence of new technologies, such as optical transmission, digital switching, and mobile telephony that transformed the telecommunications industry from within. However, the resulting infrastructure upgrades and investment in new equipment were mostly limited to backbone networks where cost could be shared among a large number of users. Access networks, on the other hand, connect each household with an individual connection to an aggregation point and represent the largest share of the physical telecommunications infrastructure, as well as the largest investment.

While the existing copper access network provided adequate data transmission properties in the 1980s through the use of analogue modems, the requirements and popularity of dial-up connections to the Internet in the late 1990s quickly outgrew the potentials of analogue transmission. By the turn of the century, operators started offering high-speed Internet connectivity as an overlay service over the existing copper infrastructure using Digital Subscriber Line (DSL) technology. Despite inherent limitations in speed and range of the DSL technology, urban adaptation took-off, marking the "birth of broadband" (ITU 2003).

Since the introduction of broadband the availability of digital content and development of broadband applications has flourished. At the same time transmission capacity in broadband access networks has been increasing exponentially, resulting in an ongoing cycle of increase in supply and demand (MIT 2005). Combined with media convergence and a paradigm shift[10] towards IP transmission, operators capable of providing "triple-play" services (voice, video and data) are now expected to dominate the future residential broadband market.

To this date, broadband access networks, as well as the general Internet, have been designed to offer a single "best effort" transport service class over a competitively neutral service delivery platform. With the foreseen addition of voice and video services, access networks need to support considerably higher transmission capacity and more stringent Quality of Service (QoS) requirements. To facilitate this, legacy access networks need to be upgraded or new networks to be established (National Research Council 2002).

The concept of augmenting the service offering of telecom operators through deployment of new access networks is not new. Marvin Sirbu's opening sentence in his IEEE Communications Magazine article from 1988 is a testimony of that: "Much attention has been focused recently on the prospects for optical fibre-based services to the home". This came following a strong belief during the late 1980 and early 1990 that telecoms would take over video distribution facilitated by a policy change by the US regulator, the Federal Communications Commission (FCC)[11].

Although describing events that took place over two decades ago they represent the same attempts as seen today and therefore provide a starting

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[10] The term paradigm shift was originally used by Thomas Kuhn in his 1962 book "The Structure of Scientific Revolutions" to describe a change in basic assumptions within the ruling theory of science. More recently the term has been adopted to technology as explained by Dosi (1982): "The procedures and the nature of 'technologies' are suggested to be broadly similar to those which characterize 'science' ". This thesis uses the term informally to indicate change in basic assumptions or methods of doing things.

[11] In the early 1990s the FCC removed earlier prohibitatooions on diversification between the cable and telecom industry. According to Chen et al. (1994), the so-called 'Video Dial Tone' ruling in 1991 paved the way for telecom plans of video distribution.

point in understanding the dynamics of current residential broadband deployment. Literature primarily accredits the telecom diversification attempts of the 1990s to the threat of infrastructure competition from cable operators threatening to implement telephone and interactive broadband services over the existing CATV networks[12].

Despite the ambitious telecom driven FTTH plans of the 1990s, neither the telecom nor the cable operators successfully diversified and the world has not witnessed any wide-scale upgrades to the existing copper access network *yet*. While literature disagrees to exactly which reasons led to their failure, most sources agree that the outcome was determined by lacking financial feasibility or, as Maxwell puts it, "the fundamental reason was money" (Maxwell 1999).

1.3.   Residential Broadband Deployment

Today, in 2006, literature, broadband statistics, and industry feedback seem coherent; wide-scale upgrades to the existing copper based access networks are underway, aimed at facilitating advanced multimedia services over converged high speed data transmission networks[13]. Literature generally attributes these plans to the desire to increase average revenue per user (ARPU), mainly through the introduction of Internet Protocol Television (IPTV) (Maxwell 1999; Heavy Reading 2004).

Additionally, EUC based Fibre-to-the-Home (FTTH) deployment is emerging as a recognised trend in telecommunications (Gillett 2004). However, fibre technology is rapidly evolving and although all

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[12] For a more detailed discussion see e.g. Green and Dutta-Roy (2001) and Maxwell (1999).

[13] As an example of this the major incumbents in Europe (T-Systems in Germany and BT in Great Britain), America (AT&T and Bell Canada), and Asia (NTT in Japan) have all started upgrading their access networks to support higher broadband speeds. For an overview see e.g. Lin (2006) and industry reports from Point Topic (www.point-topic.com) and Light Reading (www.lightreading.com). Additionally, the above mentioned as well as all major incumbents in Europe have started or at least initiated plans of offering IPTV services over their DSL infrastructure. An example is the Danish incumbent, TDC, who according to TVinternational (2006) 'is embarking on a major network upgrade to enable most of its system to support a triple play of video, broadband and telephony'.

deployments share similar principles of laying optical fibre all the way to the customer, implementations vary. A common feature tends to be the choice of Active Ethernet and industry collaboration, often based on emerging "open access"[14] business models (Larsen et al. 2006).

In contrast to deploying fibre all the way to the customer, telecom operators predominantly chose gradual Fibre-to-the-Node (FTTN) in combination with DSL technology over diminishing copper loops. With transmission capacity over copper loops inherently limited by attenuation, the location of the Node controls the services offering as well as the required infrastructure investment. The main design problem of telecom operators is thus to decide if and then when to move active equipment out of the local exchange and then how far towards the customer. The technological solution of EUC-based FTTH is also in contrast to reported greenfield deployments of most incumbent telecoms that choose Passive Optical Networks (PON) and maintain vertical integration (Edmon et al. 2006, p. 17).

Given the evolving state of broadband technology, variety in implementations and resulting risk of failure, the question arises of why EUCs embark on a new market where they in many cases lack strategic competences. Gillett et al. (2004a) describe EUCs activities through their role as early adopters of technology that recognise the social benefits of broadband and have a tradition of supporting and being involved in local economic development. Furthermore, as experienced infrastructure operators, research indicates that EUCs enjoy economies of scope by utilising synergies with other activates (see eg. Urzúa 2004). Recognising that around 70% of FTTH deployment cost comes from groundwork, advocates of EUC involvement have gone as far as insisting that it would be "foolish not to deploy fibre when doing other required ground work" (Gorm 2005).

Opponents of EUC involvement on the other hand point out that if there was a viable business case in FTTH, it should be left to the liberalized and

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[14]   In the US this term is often used to describe regulatory requirements on network access providers to grant competitors access to their infrastructure, i.e. unbundling of the local loop. However, here the term refers to network access providers that voluntarily do not offer any value added services themselves other than bit transmission and rely on agreements with external service providers to offer services and content over their access networks.

highly competitive telecommunications market. While evidence shows that incumbent operators are flocking over to FTTH in Greenfield scenarios, research indicates that the financial viability of almost all upgrade FTTH deployment scenarios is highly risky (Monath 2003; Olsen 2006). Furthermore, there has been criticism from the telecommunications industry that EUCs are operating outside of their competence area, misjudging the competitive strengths of more economical alternatives such as DSL, and subsidising their telecommunications activities through monopolised core electricity activities.

Regulators, striving for economic development and advanced telecommunications infrastructures serving the population equitably, see EUC involvement as a double-edged sword. On the positive side, FTTH deployment speeds up development, raises service level significantly and leads to desired infrastructure competition. On the negative side, EUCs can skew competition and drive the telecommunications market back into de facto public monopoly. Theoretically and empirically there is a lack of evidence to support either case.

While the previous description is very far from exhaustive, it highlights the disagreement surrounding entry, competition, and implication of residential broadband deployment. While a great number of literature and general research has been focused on the technological, economic, and political challenges associated with deployment and operation of residential broadband, many open questions remain. This problem is particularly pressing in the Nordic countries, where the public debate is centered around the financial viability of imminent wide-scale FTTH deployment by the EUC sector in competition with alternative DSL roll-out strategies of the incumbent.

1.4.   Telecommunications in the Nordic countries

The Nordic countries[15] were early adopters of both Internet and broadband access. All five rank among the top 10 countries in the world with the highest number of broadband subscribers in OECD statistics (OECD 2006). Although liberalised and privatised, each market is still dominated by a strong national incumbent operator that maintains and operates a ubiquitous legacy copper infrastructure. With little tradition of coaxial

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[15]   The Nordic countries comprise a region in Northern Europe consisting of Denmark, Finland, Iceland, Norway and Sweden.

cable networks (apart from Denmark, where the incumbent own much of the cable TV infrastructure) copper lines from the only existing access network in most areas.
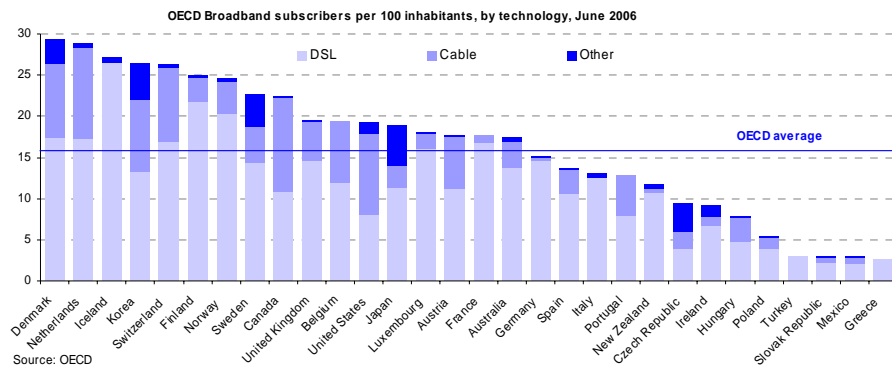
Figure 2, OECD Broadband subscribers per 100 inhabitants, by technology, December 2005.
Source: OECD (2006)

This strong governance of incumbent operators has shaped the infrastructure development, resulting in deployment of DSL technology, and manifesting itself in high DSL subscription rates (see Figure 2). In line with European Union (EU) legislation, which all countries have adopted[16], the incumbents are required to allow competitors access to their access network through three types of local loop unbundling: Full unbundling (or access to "raw copper"), Line sharing (also called shared access), and Bit stream access. While this legally ensures service competition, in practice incumbents have kept their dominance in PSTN services and have even been gaining foothold on the residential broadband market[17].

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[16] Denmark, Sweden and Finland are members of the European Union, while Norway and Iceland are members of the European Economic Area. All countries are however subject to EU legislation in telecommunications.

[17] In Denmark, the incumbent TDC holds 80,2% of the PSTN market and the broadband market share has increased steadily from 37% in ultimo 2000 to 53,5% in 2005 (Telestyrelsen, 2006).

Despite wide adaptation and mature markets, international comparison reveals relatively high prices and low transmission rates (Internetnz 2006). Additionally, a study into competition in the Nordic telecommunications sector found the market to be internally heterogeneous and "with room for further price reductions" (Nordisk Ministerråd 2004, p. 5). This seems to indicate that the incumbents enjoy monopolistic "market power"[18] and that there is room for competition on the market.

The most realistic competitive threat in the Nordic countries stems from EUC. While there is evidence of FTTH based EUC involvement in all the Nordic countries, there are differences in the paths and strategies of each country. Initially Sweden led the development as an early adopter of FTTH and as a result now has the highest share of optical broadband connections in the world (Larsen 2006). Norway on the other hand is the country with the least EUC activity followed by Finland. The remaining two countries, Denmark and Iceland, have a low number of connected households but both stand at the brim of ambitious but distinct EUC involvement plans. If these plans will be realised, they mark the turning point of dominant EUC involvement in telecommunications, resulting in currently unforeseeable changes to the telecommunications market, as well as policy and regulation, in both countries.

1.4.1. The Danish case of EUC based infrastructure deployment

Electric Utility Companies in Denmark were early adopters of FTTH, with trials dating back to 2002. To date deployment has been limited and mainly restricted to areas with existing ground work, resulting in 11.971 connected households at the end of 2005 or only 0,89 pct. of private customers (Telestyrelsen 2005). According to a recent report from the Danish Competition Authority (Konkurrencestyrelsen 2005), 43 of 131 EUCs have either already deployed, or are planning to deploy FTTH. Moreover these 43 utilities represent roughly 75% of the residential electricity market share and are planning to extend their networks to half a million households by the end of 2007 and 1.2 million households by the end of 2016.

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[18] Intven and Tétrault (2000) defined market power as "the ability of a firm to independently raise prices above market levels for a non-transitory period without loosing sales to such a degree as to make this behaviour unprofitable".

EUC based FTTH	Ultimo 2004	Planned
Connected households [Km]	10 600	958 000
Km. of fibre [Km]	6 500	66 700
Investment [million. €]	88	1 253
Deployment cost pr. km fibre [€]	7 915	17 150

Table 1, Danish FTTH based EUC deployment plans.
Based on: Lorenzen (2006)

In comparison to the 2.4 million residential electricity customers, these plans will result in 20% FTTH availability by year-end 2007 and 50% by 2016. Furthermore, given the 1.3 million current broadband subscribers, Denmark can be expected to rank high in international comparison of FTTH deployment. However, success is far from guaranteed as the number of EUC representing these plans is high and their choices of technological solutions and business models vary. The competitive authorities analysed the magnitude of the foreseen investment, which was estimated to be € 1.3 billion, but concluded that they do not have the means to measure or predict the financial viability of the planned investment (Konkurrencestyrelsen 2005).
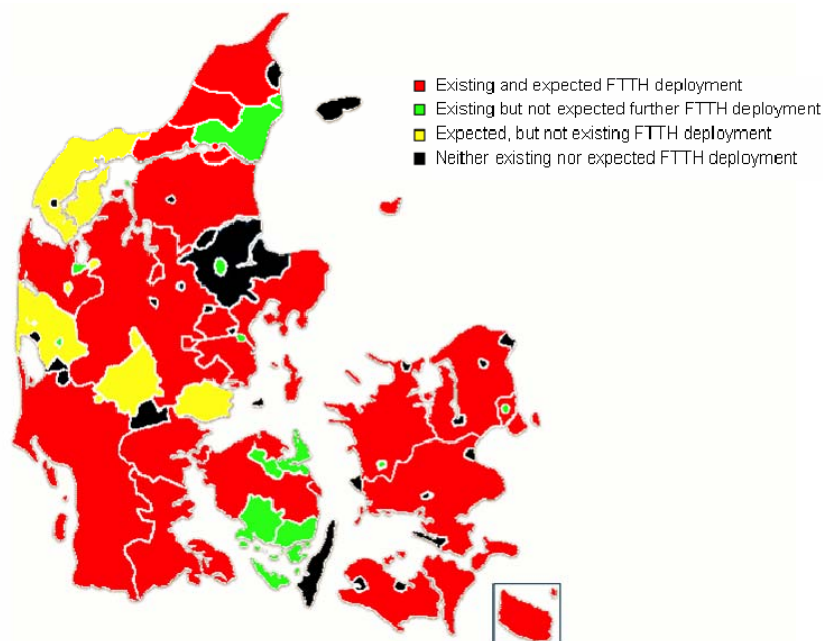

Figure 3, Map over planned EUC based FTTH deployment in Denmark
Source: Konkurrencestyrelsen (2005)

The problem of evaluating telecommunication infrastructure appraisal is not new and several methodologies have been proposed (Sugden and Williams 1978; Ims et al. 1998; Frigo 2003; Weldon and Zane 2003). Regardless of methodology applied, academic literature that has analysed the financial feasibility of FTTH deployment seems unanimous, (Monath 2003; Tuerck and Barrett 2004), drawing similar conclusions as Olsen et al. 2006 that "fibre to the home is viable only in dense urban areas". Comparing these results to the map of planned EUC deployment in Denmark (of Figure 3) reveals an inconsistancy with EUCs planning FTTH deployment in all geographic areas.

1.5.   Problem Definition

This thesis investigates available deployment[19] strategies for broadband access networks capable of meeting the near-future[20] transmission requirements of converged voice, video, and data services. The approach of telecoms using Digital Subscriber Line technology over decreasing copper distances is compared to entry strategies based on Fibre-to-the-Home to identify dominant strategies. A fundamental assumption, and in most cases a regulatory requirement, is that the investment is based on financially feasible premises. Estimating the profit function is not trivial and relies on knowledge of the technological, economic, and regulatory parameters that characterise the networks and services offered. The aim of this thesis is to identify and analyse under which preconditions dominant deployment strategies by telecoms and entrants can be financially feasible.

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[19]   In the thesis, the term deployment is used to indicate infrastructure development as a result of investment, both for new networks as well as upgrades of existing networks. This definition highlights the supply sided approach of the thesis but should not to be understood such that neither technological determinism nor technology push is advocated.

[20]   Although not specifically defined the term near-future is used to indicate time span of approximately five years. This timeframe is used as an indicator of the lifespan of existing technologies, such as first generation ADSL and cable modems. A large share of the required investment in access networks has a lifespan greatly exceeding this time limit (such as the 20-40 year estimated lifespan of optical fibre, trenches and ducts etc.) and that is considered when depreciating the cost. The limitation of near-future is therefore more used to limit the uncertainties related to technological development of the end equipment and services.

To evaluate financial feasibility[21] the thesis develops a quantitative simulation model based on existing techno-economic (engineering) cost models supplemented with concepts of non-cooperative game theory. The model is applied to the case of Denmark to answer the question whether and then in which geographical areas Electric Utility Company based FTTH deployment can be financially feasible. Additionally the thesis considers the result of FTTH based infrastructure completion on the current copper infrastructure, the future prospects of DSL technology, and the prospects of coexisting and competing DSL and FTTH infrastructures.

The empirical study follows the general principles of the Danish Long Run Average Incremental Cost (LRAIC) model, using an empirical dataset of 20 test areas as basis for calculations of available upgrade alternatives of the existing copper infrastructure. This will be compared to the cost of a new FTTH network using the scorched node principle, i.e. calculating the cost of building a new and optimised network based only on the structural location of the existing copper network. The results will be evaluated against two key parameters, i) the take-up rate, i.e. the ratio of households that subscribe to the network, and ii) amount of shared trench costs within the EUC.

Finally the conclusions of the financial feasibility study will be used to reflect upon the regulatory implications on policy goals aimed at promoting broadband deployment. More specifically the thesis will use the taxonomy introduced at the beginning of the chapter to evaluate the level of sustainable infrastructure competition in different geographical scenarios.

The challenges that the thesis aims at addressing, and contributing to the solution of, can be seen through the following two quotes from Professor David Newbery of Cambridge University who summarises ongoing literature quests:

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[21] Lynggaard (1996) defines financial feasibility as an appraisal project that results in positive net present value.

"The practical question is what fraction of the existing network needs to be upgraded (in terms of bandwidth and services provided) or extended, and what is the cost penalty, if any, in allowing new entrants to provide this upgrading or expansion rather than incumbents?"

(Newbery, 1999; p. 315)

"The regulatory issues are primarily those of ensuring that where competition is efficient or desirable, that it can happen, and where not, the natural monopoly facilities are properly regulated."

(Newbery, 1999; p. 315)

1.5.1.   Conceptual framework

For the purpose of this thesis, technology, economics, and regulation will be used to span the dimensions of the desired analysis space, i.e. to represent the parameters affecting the financial feasibility of residential broadband deployment. While this is far from being an exhaustive list it represents the core elements extracted from previous techno-economic studies conducted within the field of Information and Communications Technologies (ICT), such as Tadoyani (2000), Skouby (1997) Melody (1997), and Commons (1932), to name a few.

Additionally the development of residential broadband is divided into three chronologic phases where the factors leading towards a deployment are called *drivers,* the control parameters of the transitional phase and success factors of arising competition are called *dynamics,* and the results of the changes that emerge once the competition/development has stabilised *implications*. Together these elements define a conceptual framework of understanding as visually represented in Figure 4.

Imminent Residential Broadband Deployment
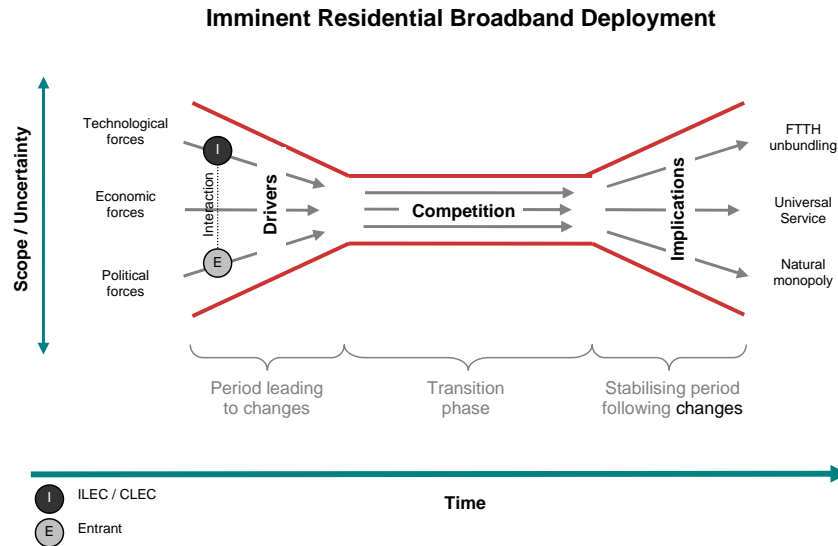
Figure 4, Conceptual framework of the study

1.6.   Theoretical Framework

Residential broadband development occurs within the context of several interrelated theoretical fields, of which technology, economics, and regulation determine the focus of this study. Instead of viewing the subject through the lens of each theory, this project uses financial feasibility as a common objective by which the effect of various parameters falling within the otherwise separated theoretical fields can be weighted. The conventional approach to doing this is called project appraisal. Sugden and Williams (1978) define project appraisal as:

> *"A project, broadly defined, is a way of using resources; a decision between undertaking and not undertaking a project is a choice between alternative ways of using resources. Project appraisal is a process of investigation and reasoning designed to assist a decision-maker to reach an informed and rational choice."*
>
> *(Sugden and Williams 1978)*

The methodology used for solving appraisal problems is to construct a mathematical model that represents the essence of the problem. Literature

provides several alternatives for performing telecommunications modelling and simulation of which the following types described in Table 2 were considered for this project. The list is not exhaustive but provides the boundaries of the core element of this study, i.e. analysis of individual deployments of access networks and services, as well as the interaction between market players.

Type of model:	Descriptive feature:	Examples of studies:
Economic models	Economic models are used for analysing dynamics within the telecommunications market. When mathematical relationships have been described, the models can be solved analytically or simulated in programming languages. The models are simplified generalisations and provide high level guidance about market dynamics.	Competition in telecommunications by Jean-Jacques Laffont and Jean Tirole (2000)
Econometric models	Econometric models use statistical methods to formulate and test hypotheses about significance of parameters. They require databases with historical data and are therefore most useful in explanatory studies of past events. In telecommunications they are e.g. used on macro level to identify important factors affecting broadband diffusion (GAO 2006).	Bits of Power: The Involvement of Municipal Electric Utilities in Broadband Services by Carlos A. Osorio Urzúa (2001)
Engineering Cost Models / Cost Proxy Models	Cost Proxy Models are button-up models used to sum up the Capital and Operational Expenditure for each network element. They have e.g. been used in policy and regulation to fix interconnection prices. An example is the Long Run Incremental Cost (LRIC) model used in the US and most EU countries, and the Long Run Average Incremental Cost (LRAIC) model used in Denmark.	Cost Proxy Models and Telecommunications Policy: A New Empirical Approach to Regulation by Farid Gasmi (2002). Local loop unbundling: Flaws of the cost proxy model by Christian M. Dippon (2001).
Techno-Economic models	Techno-Economic models were designed to evaluate deployment scenarios, and to aid in the selection of optimal technology and deployment time. They are implemented in spreadsheets such as Excel, and are	Broadband Access Networks – Introduction to strategies and techno-economic evaluation by Leif A. Ims et al. (1998)

	useful e.g. for comparing the Capital Expenditure of FTTH and DSL.	
System dynamics models	System dynamics models explain the interaction between the many forces and players involved in telecommunications. They are useful in evaluating "what if" scenarios and capturing key behaviours that are observed in real-world systems such as the introduction of a "killer application"	Networking Technology Adoption: System Dynamics Modeling of Fiber-to-the-Home by Andjelka Kelic (2005)
Case studies / business plans	Business plans are used by industry for evaluating financial viability of individual deployment projects. Their strength stem from "accurate" representation of circumstances and more tailor-made solutions. Their weakness is the rigid form of study they provide and lack of dynamics.	Bredbåndsnet i et landområde ved Jels by Steffensen and Andersen (2005)
Game-theoretic models	Game-theoretic models in telecommunications can capture non-cooperative interactions between operators, e.g. for exploring entry strategies, and how market outcomes are affected by competition or regulation.	Regulation and Entry into Telecommunications Markets by Bijl and Peitz (2002)

Table 2, Available theoretical models for telecommunications analysis

In a broad sense all of the simulation models of Table 2 can be divided into two categories based on whether they focus on individual implementations (micro-level), or dynamics of the market as a whole (macro-level). On the macro-level economic models focus on market dynamics, while econometric models use historic data to analyse influential parameters (proxies) and describe cost structures. Most of these models stem from analysis of the Public Switched Telecommunications Networks (PSTN) and are based on a homogeneous set of services (i.e. voice services). These models are widely used in academia and by regulators as tools to describe and adjust the fundamental principles governing telecommunication markets.

Micro models, on the other hand, are more industry inclined where they aid in predicting financial viability of individual deployment scenarios. Ims et al. (1998) describe a widely used theoretical and methodological framework for techno-economic studies stems from several pan European

research projects initiated in the 1980s to increase European competitiveness and induce infrastructure development within member states. In comparison with economic models, techno-economic models are static, simulating cost and revenue from a given set of input parameters, but have been extended to perform risk and sensitivity analysis (Ims, Stordahl, and Olsen 1997).

At the time of development, techno-economic models were designed to aid equipment vendors and incumbent operators in the selection of optimal technology and deployment time, given a relatively long-term and fixed operational environment. For this purpose, techno-economic models are still under development in several research projects[22] (Olsen 2006) as well as being applied at industry level for decision support on infrastructure development[23]. Given the tight integration of techno-economic studies into the telecom industry, they often rely on confidential information about cost and marketing.

Despite proven benefits of techno-economic models and other simulation approaches there is a fundamental lack of models that encapsulate the broader dynamics and development within the ever-changing residential broadband market. This problem can be broken down into two levels: the first is due to the complexity on micro-level, i.e. analysing and comparing the broad spectrum of alternative networks and services competing in different geographic areas. The second is on the macro-level where the problem becomes that of interrelating deployment scenarios, given influences from extrinsic factors such as competition and policy and regulation.

An interesting alternative approach to analysing the financial viability of FTTH deployment is provided by Weldon (2003), and Frigo et al. (2004). Both are based on similar methodologies of calculating deployment cost as the techno-economic models but use simpler assumptions about operational cost and revenue. For illustration the approaches use take-up

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[22] See e.g. CELTIC-ECOSYS (http://optcomm.di.uoa.gr/ecosys/index.html) and IST-BROADWAN (http://www.telenor.no/broadwan/)

[23] The Norwegian incumbent Telenor reports the use of Techno-Economic models for planning and implementing strategic decisions, and additionally Nokia, T-Systems and France Telecom have participated in development of these models.

rate as a fundamental parameter to estimate financial viability of FTTH deployment (see Figure 5). The advantage of this approach is that it is straightforward and requires less operator specific information than the techno-economic models. The downside is that it neglects depreciation of the infrastructure considered, i.e., it calculates possible investment based on positive cash balance rather than investment feasibility. Furthermore, much like the techno-economic models, the approach does not consider competition or other sorts of market dynamics.
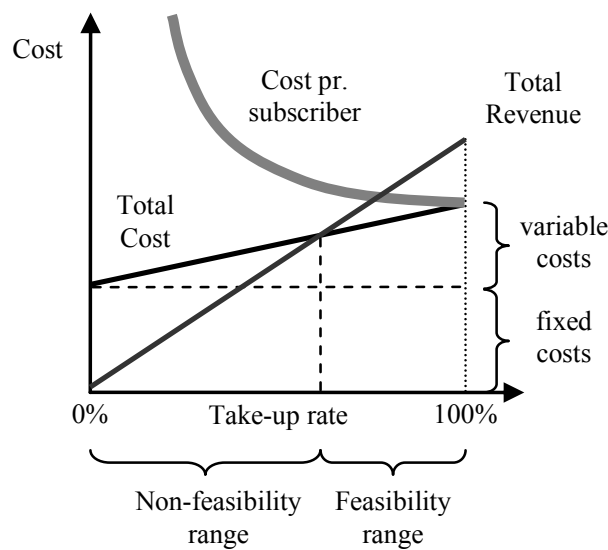
Figure 5, Feasibility of residential deployment as a function of take-up rate

Contrary to cost models, game theory has successfully been used to analyse market dynamics in telecommunications (Newbery, 1999; Faulhaber and Hogendorn 2000, Bijl, and Peitz 2000,2002; Woroch 2004; Bourreau and Dogan 2005). In general, game theory can be used in analysing competition between firms to find a dominant strategy for each player, or an equilibrium that all players are content with (Kreps 1990; Fudenberg and Tirole 1991). The prospect of augmenting techno-economic models by game theory to analyse FTTH deployment offers insight into the foreseen competitive interactions and counteractions from already established residential broadband networks.

1.6.1. Game Theory

As mentioned above, game theory has been proposed as a tool for analysing infrastructure competition. Game theory is the branch of microeconomics concerned with the analysis of optimal decision making in competitive situations, but it is important to note that, as such, game theory does not foretell the outcome of competition. It is rather a set of mathematical expressions used as a language for logical behaviour. Given presumptions about the conducts of players, game theory maps the available strategies[24] of each player in the game. To find the likely outcome, game theory uses the concept of Nash equilibrium[25].

Microeconomic theory has two main models of conduct under oligopolic competition: the Bertrand model, and the Cournot model (Basanko and Braeutigam 2005). Each is based on a different set of preconditions, but both represent games where the strategies of the players are determined by their choices of outputs or prices. To analyse infrastructure competition in telecommunications, Kreps (1990) suggests that a third option, the von Stackelberg model is better suited. According to this approach a monopolist first decides its actions, followed sequentially by the actions of new entrants. Fudenberg and Tirole (1991) list constraints for the sustainability of a Stackelberg equilibrium, but the model nevertheless, offers insight into expected interactions under infrastructure competition.

1.6.2. Telecommunications Regulation

Regulation of telecommunications networks and services is in most countries seen as a necessary requirement to meet government objectives and to ensure public interest (Melody 1997). The form and nature of these interventions may vary but are generally justified in economic theory by the presence of some sort of market failure (Olsen 1993). In the case of access networks the two main economic reasons that have been used to justify interventions are (i) the belief that access

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[24] Besanko and Braeutigam (2005) define strategy as "A plan for the actions that a player in a game will take under every conceivable circumstance that the player might face".

[25] Fundenberg and Tirole (1991) define a Nash equilibrium as "a profile of strategies such that each player's strategy is an optimal response to the other player' strategies".

networks constitute a *natural monopoly* for which competition is in principle not feasible, and regulation is therefore necessary to control monopoly power, and (ii) to achieve *universal service*, in which all (or most) users have the opportunity of affordable access to the services of the network (Faulhaber and Hogendorn 2000).

While individual studies on universal service have been performed by the author in relation to this project, the main effect of telecom regulation on the subject of this thesis occurs within the context of competition. In Europe, competition is ensured through a combination of service and infrastructure competition (Intven and Tétrault 2000). Where and how the line between service and infrastructure competition should be drawn and how it should be implemented, has been disputed in theory and practice (Henten and Skouby 2005). Advocates view service competition as a step in a "ladder of investment" (CPTA 2001, Cave 2004), while opponents argue that it acts as investment reticence (Wieland 2006). In general infrastructure competition is favoured by regulators, since it is expected to induce long-term economic efficiency and relax regulation requirements in the industry (Bourreau and Dogan 2003).

1.7. Proposed Solution Approach

Having defined the problem and the objectives of the study, the next step is to break the problem down into practical solvable parts. This is a problem solving procedure consisting of three self-contained parts as illustrated in Figure 6. Each part includes a literature study of its own, followed by a set of research questions outlined in Section 1.7.1
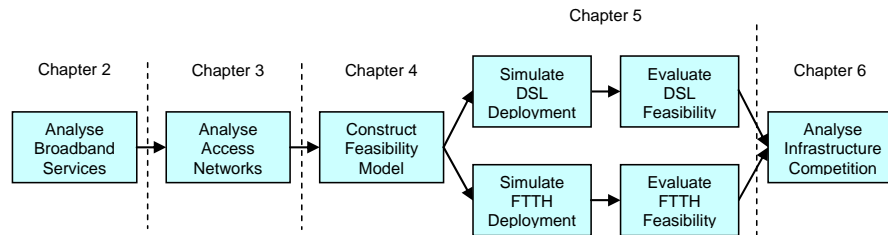

Figure 6, Proposed Problem Solving Procedure

The thesis proposes a two-tier modelling approach to analyse the financial viability of access network deployment in a competitive environment. The first tier is based on a simulation model for deployment cost, initially developed and implemented by the author for the IST-BREAD project as

described in Sigurdsson (2005; 2006). The model follows the general structure of existing techno-economic models reported e.g. by Ims (1998), Tonic Deliverable 7 (2002), Broadwan Deliverable 15 (2004), and Ecosys Deliverable 8 (2005). Results from this model feed results to a second tier, based on an economic duopoly model inspired by the game theoretic approach of Bijl and Peitz (2002) and the von Stackelberg game of (Kreps 1990).

In its generic form the cost model from Sigurdsson (2006) can simulate the Capital and Operational Expenditure (CAPEX and OPEX) of both wired and wireless access, but in this thesis it has been modified with the more specific goal of performing a case study of DSL and FTTH deployment in Denmark. For that purpose the model is tailored to fit the principles of network structure and dimensioning, as well as cost figures defined for the Danish Long-Run Average Incremental Cost (LRAIC) model as described in ITST (2001) and implemented in ITST (2006b). Additionally the model has been augmented to simulate revenues based on the requirements defined in the service profiles of Section 4.5.9.

Building on the outcome of the cost/revenue model a feasibility model has been developed to estimate pre-tax profit. The method is based on subtracting an estimated general operational cost from the revenue base as described in Ecosys D6. An illustration of the proposed framework for modelling financial feasibility is provided in Figure 7. In contrast to most other techno-economic models this proposes using the tilted annuity, proposed by the Danish National Regulator (ITST 2001) to estimate the cost component of the feasibility calculations. The argument for using this particular approach rather than the conventional Net Present Value (NPV), Internal Rate of Return (IRR), or Cash flow approaches is that it alleviates the issue of a specific time horizon for the study and simplifies the comparison with actual revenues.

Regardless of the approach taken, these models are at best indicators of likely outcome or, as Hillier (1995) notes "a model is an abstract idealisation of the problem, where approximations and simplifying assumptions generally are required". The proposed model is no exception to this rule, resulting in limitations of the general applicability as described in Section 1.7.2. The goal is never-the-less to develop a methodology with a general approach, allowing for future modifications and ultimately a better model.
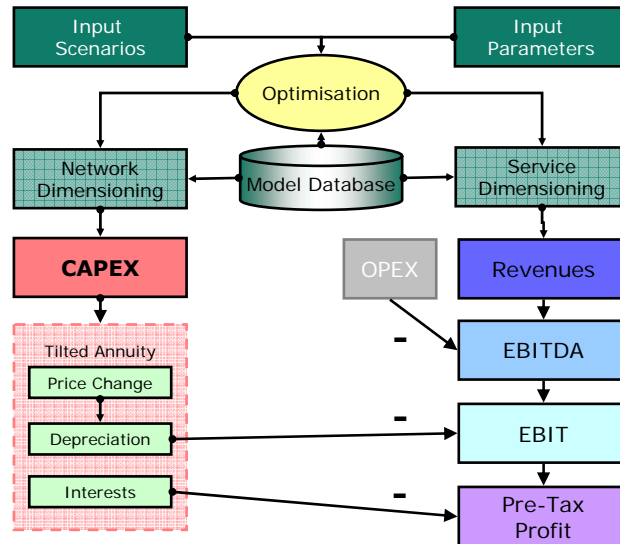
Figure 7, Proposed framework estimation of financial feasibility
Inspired by: Ecosys (D6;p. 32)

The last step in modelling is to consider the dynamics of infrastructure competition. However, competition in telecommunications is more complex than in many other industries because of the nature of communications networks (Laffont and Tirole 2000). In situations where a relatively small number of firms compete, game theory has been shown to yield a sensible analysis of firm's behaviour and market structure (Bijl and Peitz 2002). The proposed solution is to use game-theory, inspired by the von Stackelberg game adapted from Kreps (1990).
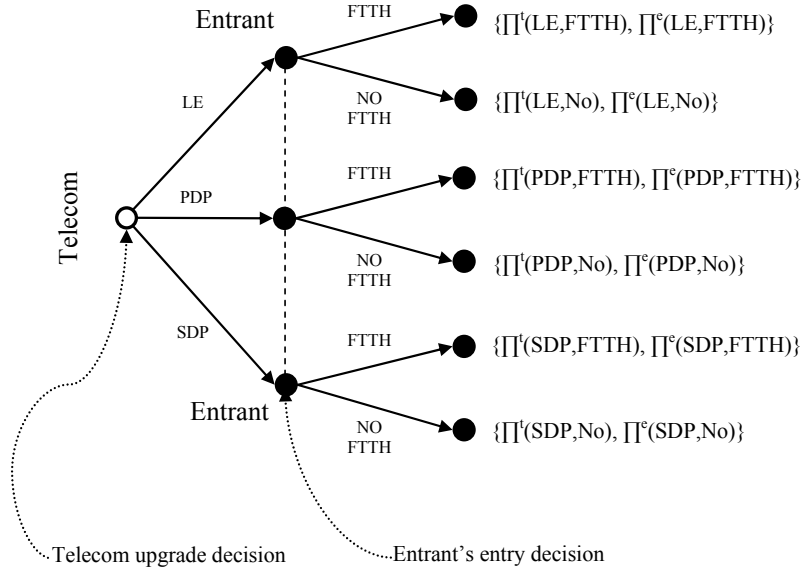
Figure 8, The von Stackelberg game
Adapted from: Kreps (1990, p. 46)

The von Stackelberg game assumes that players move sequentially. When adapted to the telecom and entrant case of this thesis, the telecom operator is the first mover, selecting between three deployment strategies {deployment from: Local Exchange (LE), Primary Distribution Point (PDP), or Secondary Distribution Point (SDP)}. The entrant then makes a decision {FTTH, or No FTTH}, well knowing what the telecom operator has selected. Assuming that both players make rational decisions, the game can then be solved through backwards reasoning. The telecom knows that the entrant chooses a response to its action that maximises its pay-off, denoted $\prod^e$. The telecom therefore finds the response by the entrant for each of its alternatives and from that subset selects the action that grants the highest payoff, denoted $\prod^t$.

1.7.1.   Summary of Research Questions

In addition to this introductory chapter the thesis is composed of four main chapters that each provides a self-contained research question:

Chapter 2 uses mixed qualitative and quantitative analysis to answer the underlying research question of which transmission requirements near-

future services will pose and how emerging technologies and services deviate from currently considered triple-play services. The aim is to provide an up-to-date definition of the service profiles that the access networks considered later the in the thesis need to fulfil, and to evaluate the correctness of the technological premises of currently planed deployments.

Chapter 3 uses qualitative analysis to analyse which alternatives broadband access network deployment strategies exist for telecoms using DSL technology over legacy copper networks, in comparison to entry strategies based on Fibre-to-the-Home deployment. The purpose is to identify a set of plausible strategies that local exchange carriers and entrants have for fulfilling the transmission requirements of the near-future residential broadband services defined in Chapter 2.

Chapter 4 describes a quantitative simulation model developed for this thesis, based on existing techno-economic (engineering) cost models and economic models of game theory to estimate the financial profitability of competing DSL and FTTH infrastructures in various geographic scenarios. The model is applied to the Danish telecommunications market to answer the question of financial feasibility, competitive abilities, and dominant strategies for both players.

Chapter 5 summarises the results of the simulation to analyse regulatory implications of policy goals for promoting broadband deployment. The aim is to classify market segments based on the sustainable level of infrastructure competition required to answer the question of deployment probability.

1.7.2.   Delimitation

This study is supply-oriented, focusing on the effect of technological, economic, and political factors on residential broadband deployment, and ultimately on the financial feasibility of infrastructure investment.

This focus is not to be understood such that the existence of other forces that may influence the outcome of residential broadband deployment are left aside, but merely that the intention is to analyse these factors in a cost-related manner. Below is a list of some of the most evident issues that would be relevant in a broader study, but fall outside the scope of this specific thesis.

Demand vs. supply centric focus

Knowledge of which services users prefer, how they perceive and use them in comparison to other alternatives, price elasticity, and how willing users are to subscribe and pay for these new services, is of vital importance when evaluating the future success and financial feasibility of networks and services. While this work did not include any empirical study of broadband demand, and does in general shares the inherent limitations of other supply-sided techno-economic studies, it seeks to accommodate criticism in two ways: i) the characteristics of broadband services are analysed in depth in Chapter 2 and, based on that, foreseen broadband demand is forecasted, ii) the simulation model uses customer take-up as one of the main parameters for evaluating which circumstances are required for a deployment to be feasible. This facilitates further studies that could take these results and analyse if this take-up rate is realistic, given the nature of demand in specified areas. Readers interested in demand-side analysis of residential broadband and models of technology diffusion are referred to Geroski (2000), Fildes and Kumar (2002), Teletronikk (2004), and Savage and Waldman (2005).

Operational environment of residential broadband

For comparing different deployment approaches for offering networks and services, especially between industry sectors, several operational characteristics are important, yet not covered in this thesis. Knowledge of operational efficiency and cost structures between the operators analysed would also be useful, but is not available. For this reason the thesis assumes the same operational environment for classical telecoms and new entrants. This assumption can influence the outcome, as becomes evident when comparing the cost structures of DSL in comparison to cable modems. Newman (2003; 2005) builds on a McKinsey and JPM study when he estimates that marketing, acquisition, and provisioning account for around 33% and that customer service and billing account for 27%. The severe limitations of this study become evident when comparing the difference of these two components for the two industries to the mere 23% that

depreciation accounts for, which none the less is of main importance in this thesis.

AND THE ECONOMICS WILL BE EVEN MORE CHALLENGING IN 2005
Average BB costs per subscriber* – $ per month in 2005

DSL (ILEC)	
Total costs	$30
Network transport	3.0
ISP costs	2.0
Marketing, acquisition, and provisioning	10.0
Maintenance	2.0
Installation	2.0
Customer service/billing	8.0
Depreciation**	7.0
	2005E

Cable	
Total costs	$24
Network transport	3.0
ISP costs	2.0
Marketing, acquisition, and provisioning	6.0
Maintenance	1.0
Installation	5.0
Customer service/billing	4.0
Depreciation**	3.0
	2005E

Figure 9, Cost structures of DSL and Cable Modem
Source: Newman (2003)

Another important difference between these two industries has to do with the effect of vertically integrated business models, compared to open access. This gap is characteristic for the comparison of incumbent operators and the energy utility sector, but is not fully analysed in this thesis. Readers interested in the debate on open access versus vertical integration are referred to Lehr, Sirbu, and Gillett (2004), PacketFront (2005), Farrell, and Weiser (2003).

Technological solutions considered in the thesis

The thesis only considers deployment of broadband access networks based on DSL and FTTH technologies. Despite the promise of new future competitive technologies, such as wireless, mobile, satellite, and power-line communications (PLC) this thesis accepts the view and arguments in other research projects such as IST-Broadwan (2006) that these technologies are unlikely to become significant competitors to wire-line technologies. This view is supported e.g. in Rodini et al. (2003), who address the question to which degree broadband access and mobile services are complements or substitutes, and more recently in Frederiksen (2006), who concludes that since the unit cost per MB for mobile access

(3G) is 200-500 times as high as for wire-line broadband access, they must be considered complementary. Coaxial cable / Hybrid Fibre Coaxial (HFC) networks can provide a real alternative and competitor to the two technologies considered, but as they are not widely deployed in Europe (and that is not expected to change according to Oslen et al. 2006), and often owned by incumbent telecom operators, their competitiveness is reduced. Readers interested in the techno-economics of cable and HFC access networks are referred to Newman (2003; 2005), Cave, Majumdar, and Vogelsang (2002), and BREAD D 2.1-3.1.

General applicability of the study

As Sugden and Williams (1978) describe, the quantitative results of appraisal projects are at best indicators, and their accuracy is determined by the model used and the precise input parameters fed into it. The implication for this study is that the financial conclusions can not be taken as an expected outcome of a business proposition but rather as inputs for further analysis. Additionally, while the conclusions allow for a relative comparison of feasibility between the scenarios selected in this study, they do not necessarily applicable for a generalized comparison with other technologies, as the outcome of a comparison highly depends on the many modelling assumptions taken. This does not imply that the results can not be applied outside the framework of this study, but is rather as a cautionary advice that care must be taken.

Impact of broadband

The increasing level of interest in broadband among nations world-wide is presumably due to an understanding that broadband brings social and economic benefits. The question whether broadband actually does deliver these benefits or in general which exogenous impact broadband has on society and how desirable it is, will not be addressed. Readers interested in the economic impact of broadband are referred to Gillett, Lehr, and Osorio (2006), and Lee, Oh, and Shim (2005), while those seeking more critical review of the socio-economic effect should refer to Firth and Mellor (2005).

1.8.   Contributions

The main contributions of this thesis are considered to include:

- Analysis of the transmission requirements of near-future multimedia services
- An up-to-date definition of service profiles capable of fulfilling the transmission requirements of near-future converged multimedia services.
- A comparative analysis of plausible broadband access network deployment strategies for telecoms using DSL technology over legacy copper networks in comparison to entry strategies based on Fibre-to-the-Home deployment.
- A techno-economic framework for evaluating the financial feasibility of residential broadband deployment
- Simulation study of the financial feasibility of FTTH and DSL deployment in Denmark
- Taxonomy for sustainable competition in residential broadband.

1.9.   Structure of the Thesis

Chapter 1: General Introduction

Chapter 2: Residential Broadband Services

Traditional Services	**Emerging Technologies**	**Case Studies**	**Demand Forecasting**
Voice	Peer-to-Peer	Skype	Capacity
Video	Inst. Messag.	TVAvisen	QoS
Data	Games …		Revenues

Chapter 3: Residential Broadband Networks

Access Technologies	**Deployment Strategies**
DSL	**Telecom**
FTTH	**Entrant**

Chapter 4: Modelling Framework

Techno-Economic Model

Modelling Cost-Benefit

Modelling Financial Feasibility

Modelling Competition

Chapter 5: Simulation Results

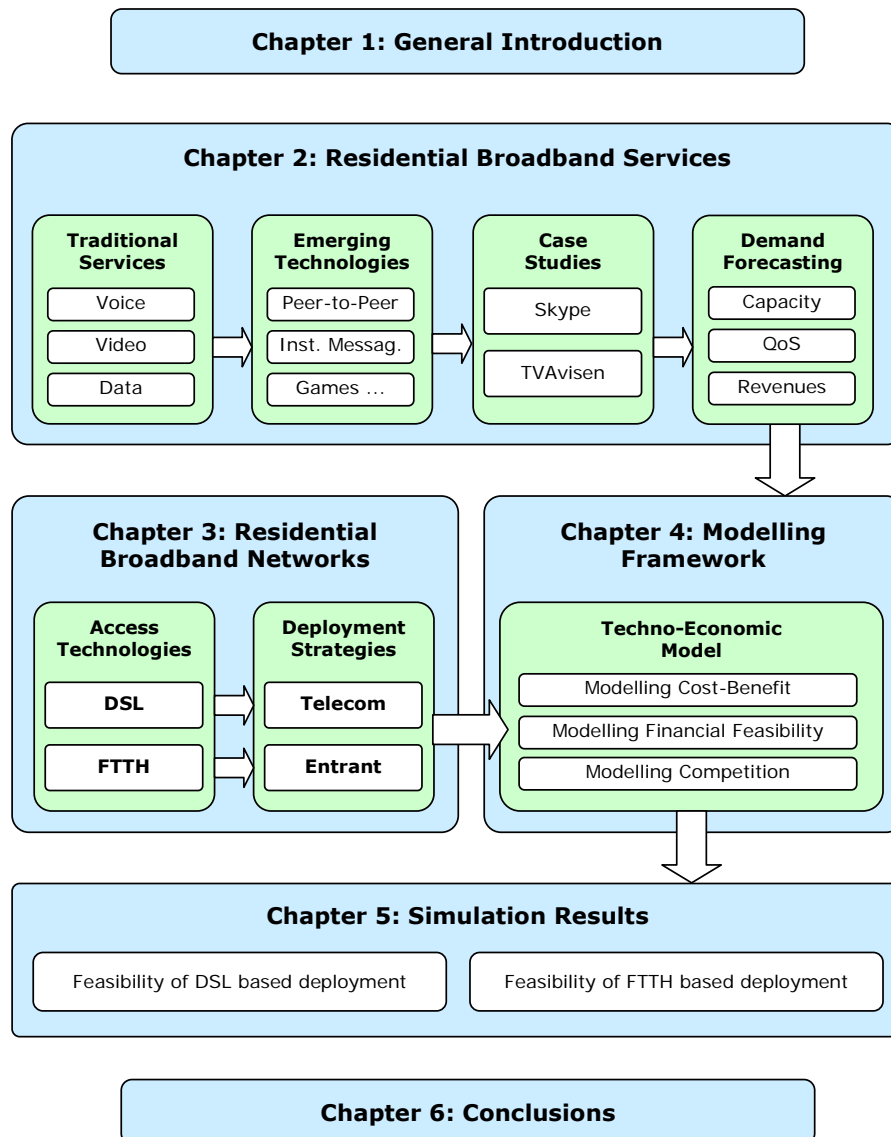| Feasibility of DSL based deployment	Feasibility of FTTH based deployment

Chapter 6: Conclusions

Figure 10, Report Structure

Chapter 2

Residential Broadband Services

This chapter describes the transformation from data-centric to multimedia broadband services, characterised by coexisting provision of voice, video, and data over a common IP platform. The chapter analyses the challenges involved in introducing voice, and video services into the broadband service portfolio, additional transmission and Quality of Service (QoS) requirements posed by real-time services, previously provided analysis of service development, empirical evidence of deviations from these predictions, and concludes by forecasting near future transmission requirements.

2.1.   Introduction

This chapter analyses the observed changes in residential broadband services, characterised by media convergence (see Figure 11). This trend goes hand in hand with a recognized goal in networking to realise the convergence of all categories of communications services, voice, video, and data, onto a common IP platform (ITU 2003; Analysys 2004). In comparison to existing Web-based services, voice and video services require considerably more transmission capacity as well as posing new Quality of Service (QoS) requirements.

To this date, broadband access networks, as well as the general Internet, have been designed to offer a single "best effort" transport service class

over a competitively neutral service delivery platform. To cope with the foreseen increase and diversity in demand, network access providers are upgrading their broadband access networks (or building new) to support higher throughput but also advanced transmission functionality (such as multicast etc.). However, control of these features is local and only available within the boundary of the respective networks. This can provide a competitive edge to service providers favoured by the network access provider, in comparison to those services providers offering the same services over the general Internet.
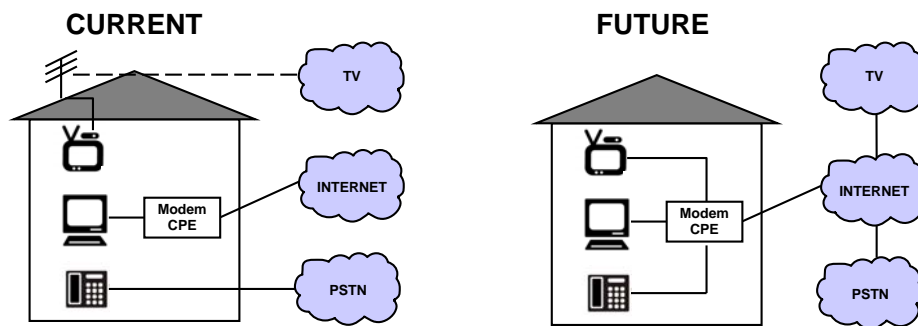

Figure 11, Witnessed media convergence

However, transmission properties are far from being the only parameters that affect service provision. The nature of the services offered as well as the provisional environment can have great influence on deployment and success of multimedia services. Whit this in mind, this chapter will provide a fundamental understanding of requirements and deployment of residential broadband services. The first part of the chapter brushes up the nature of packet-based networks and especially the means of fulfilling Quality of Service requirements of real-time services. The middle section identifies and analyses characteristics, deployment, and success of prominent voice, video, and data services. The selection criterion is subjective but aims at augmenting earlier studies (such as Maxwell 1999 and Chlamtac et al. 2005) by looking at where service development has deviated from earlier predictions. This is highlighted through two case studies of Skype and TV Avisen. Skype is a well known Voice over IP services provider that uses peer-to-peer technology to reach world wide dominance without traditional switching infrastructure, while TV Avisen is the most popular web-casting service in Denmark. The last section sums up the analysis by estimating the transmission properties required to fulfil near-future demand.

2.1.1.   Methodology and research objectives

The first part of the chapter uses qualitative analysis to answer the underlying research question foreseen transmission requirements of near-future services , and whether and if so how emerging technologies and services deviate from currently considered triple-play services included in the business models of most network access providers.

2.2.   Literature study

Literature provides an abundance of work related to multimedia services. The literature study performed for this part of the project was mainly performed in the year 2003-2004 and was highly influenced by the following Ph.D. courses taken bu the author:

1) INF-5080: Multimedia - Coding and Transmission
   University of Oslo, spring semester 2004, 5 ECTS

2) INF-5070: Media Servers and Distribution systems
   University of Oslo, spring semester 2004, 10 ECTS

3) Practical Voice Over IP: SIP and related protocols
   KTH – Royal Institute of Technology,
   1-2 April 2004, 7.5 ECTS

4) Pricing of Communications Networks
   KTH – Royal Institute of Technology,
   8-12 Mars 2004, 7.5 ECTS

All of the above mentioned courses are highly recommended and provide a thorough coverage of development and deployment of multimedia services in broadband access networks. A problem of this literature study was that no "grand theory" of multimedia services exists, so it would be wrong to maintain that the literature study provides a complete account of all relevant literature. In the same way it is not even possible to provide an adequate review of the subset considered. However, using a broad stencil, the following literature review provides an honest attempt of capturing the most important themes.

2.2.1.   List of contributions

Several studies of selected topics within the scope of this chapter have been carried out and published during the course of the project. The

largest share of these studies deals with the subgroup of peer-to-peer technology. There are two reasons for this, the first being the increasing importance and impact that P2P technology is having on almost all types of broadband services, as reflected in the remainder of the chapter. The second reason is experience from an external stay at Microsoft Research Asia, in Beijing, China, during the period March to June 2005. Below is an overview of the main contributions of the papers.

- *Sigurdsson, H.M., Halldorsson, U.R. and Hasslinger, G. (2006). Potentials and Challenges of Peer-to-Peer Based Content Distribution, Accepted for publication in Telematics and Informatics, Elsevier, Netherlands.*
  This paper was originally presented as a contribution to CICT's 2nd International conference on "Next Generation Broadband: Content and user perspectives" in Copenhagen, Denmark 2005. In the paper the authors examine the potentials and challenges of peer-to-peer technology in content distribution, and analysed how, and in which circumstances, peer-to-peer technology can be used to increase the efficiency of multimedia services. The paper provides an up-to-date overview of the development of peer-to-peer networks as well as describing the economics laws governing their use.

- *Sigurdsson H.M. (2006). Streaming com P2P (Portuguese translation of "Peer-to-Peer Aided Streaming in a Future Multimedia Framework"), RTI – Redes, Telecomm E Installacoes, No: 76, September, pages: 104-117, Brazil.*
  In this paper, which was also published as a CTI working paper under the name "Peer-to-Peer Aided Streaming in a Future Multimedia Framework", the author proposes a novel conceptual model called Server Initiated Peer-to-Peer (SIP2P), which combines the client/server and peer-to-peer paradigms into a hybrid distribution system suited for a future multimedia framework. Instead of deploying expensive high capacity servers as in traditional streaming services, SIP2P uses low capacity servers to disseminate a few copies of legal content into a P2P network. Peers are then motivated with monetary rewards to share their, often underutilised, resources to distribute the content.

The paper presents a hypothesis that states the conditions for SIP2P to prevail in such a future framework. To prove the hypothesis, economic methods of calculating utility are presented both for peers and operators. Based on calculations of utility, the economic efficiency of SIP2P over traditional streaming is examined and guidelines for adjusting peer reward are presented.

- *Tadayoni R., Sigurdsson, H.M., 2006. IPTV Market Development and Regulatory Aspects, Proceedings for the International Telecommunications Society Conference (ITS2006), Beijing, China.*
  This paper analyses the development of IPTV technology, provision and marketing aspects of IPTV, and discusses major regulatory implications of the foreseen shift from traditional TV broadcasting to IPTV. A general overview of architectures and the technologies used in IPTV services is given, and the main stake holders in the value-chain are identified, along with the current service architecture, the available content in IPTV platforms, and the current business models. Furthermore the regulatory framework of traditional TV broadcasting in Europe is analysed and recommendations given for adapting the legislation to the new requirements of IPTV.

- *Sigurdsson, H.M. (2005) The Cost of Universal Service Obligations in PSTN and VoIP, In proceedings of the BBEurope 2005 Conference, Bordeaux, France.*
  Universal Service Obligations are a set of requirements that are imposed to ensure widespread access to telecommunication services in areas that otherwise might not be sufficiently profitable in a purely commercial environment. Disagreement surrounds the current discussion on which approaches should be used to ensure universal access during the foreseen transitional period of competing PSTN and VoIP services. Although providing basically the same perceptional functionality to end users, VoIP and PSTN services differ greatly in the technical scope of the services they provide. PSTN includes costly data transmission within its system, while VoIP is essentially an overlay service requiring the existence of a separate data connection. These inherent properties greatly affect the implementation and cost of offering universal service in PSTN and VoIP.

In this paper the technical and economic aspects of providing universal service obligations in PSTN and VoIP are examined. A cost model for the public telecommunications system in Iceland is developed which serves as the basis of an empirical study of the cost of universal service obligations in rural areas. The study reveals different cost structure of VoIP and PSTN systems, as well as additional cost of offering services in rural and remote areas. The paper concludes with a case study for Iceland, proposing a framework for calculating the number of commercially unprofitable areas and customers.

- *Sigurdsson, H.M. (2005). PeerPush: A Peer-to-Peer Based Multimedia Content Syndication System, Technical Paper, Microsoft Research Asia, Beijing, China.*
This paper introduces PeerPush, a novel content distribution architecture for all types of multimedia content using a hybrid of syndication and peer-to-peer networks. The architecture makes use of inherent characteristics of multimedia consumption on the Internet to leverage delivery delay with delivery quality and overall efficiency of the system. The paper uses simulation of empirically inspired scenarios to demonstrate average download duration time improvements of 20-30% with syndication-aided peer-to-peer networks, compared to randomized joining. Moreover, the study shows that network syndication improves the throughput of P2P system 2-3 times and induces a fair distribution where contributing peers are ensured lower distribution delay than free riding peers.

- *Hasslinger, G., Sigurdsson, H.M., Halldorsson, U.R. (2007). Efficiency of peer-to-peer overlays as compared to alternatives for content distribution on the Internet, Seventh IEEE International Symposium on Cluster Computing and the Grid — CCGrid 2007, Rio de Janeiro, Brazil.*
P2P establishes routing on the application layer causes unnecessary backbone and peering traffic. Transmission paths from source to destination often depend on activity in communities separated by language, social factors or local preferences supported by specific application protocols. This paper investigates the efficiency of P2P data transfers with regard to quality of service and provides empirical measurements of the generated traffic in comparison to alternative content distribution schemes.

- *Sigurdsson, H.M. (2004). Streaming video using real-time transport protocol over IEEE 802.11b wireless networks, Course paper for INF-5070, University of Oslo*
  This paper analyses streaming of real-time video over wireless 802.11b networks using the Real-time Transport Protocol (RTP). The paper presents the results of Quality of Service measurements and discusses the implications of wireless transmission on high bit-rate video streaming.

- *Sigurdsson, H.M. (2004). Measuring QoS parameters in real-time transport protocol transmissions, Course paper for 2G5564, Royal Institute of Technology, Stockholm.*
  This paper gives an introduction to the RTP/RTCP protocols and presents the standard methods used to calculate QoS. The paper proposes a simple 1-5 scale to classify expected speech quality in a simple manner to customers of a wireless VoIP service.

2.2.2. Literature review

A starting point for all studies of multimedia networks and services is Tanenbaum's renowned 'Computer Networks' (1996). This textbook provides the required introduction to all aspects of packet-based networks, protocols and applications, as well as the general properties of multimedia services. Among other things, Tanenbaum explains the startling fact (to young engineering students like the author at least) that concepts of advanced packet-based multimedia are not products of the Internet age, but rather that incumbent operators designed Broadband Integrated Services Digital Network (B-ISDN) two decades ago and have, since then, been experimenting and preparing for the emergence of residential broadband services like Video-on-Demand (VoD).

This was confirmed when reviewing operator-driven multimedia field trials in the 1990s in Europe (AMUSE 1996), Asia (Song and Lee 2006) and the US (Lin 2006). Conccetto et al. (1999) describe the findings of the Amuse project where in 1996 residential users were provided with interactive multimedia services, including VOD, News on Demand, etc. While the Amuse project demonstrated the functionality and availability of technological solutions capable of providing advanced multimedia services, Conccetto et al. found that high cost of equipment, limitations of services delivery platforms, lack of standardisation, and immature user interfaces result in damaging effects on customers, who were technology disenchanted at the time.

Rahman (2001) continues with a collection of research papers on multimedia networking from the late 1990s. He builds on "the witnessed and explosive growth in use of multiple media forms (voice, data, images and video etc.)" and the "number of technology, management and design issues … we need to address .. in the process of realizing our technological ambitions". Although outdated in terms of transmission technology (i.e. it focuses on the ATM based ISDN-B), the book provides an overview of research approaches used to provide real-time transmission and handle QoS requirements of multimedia services, regardless of the technological platform.

What the approaches mentioned above have in common is that they stem from what Denton (2003) describes as "Bellheads"[26], i.e. those that endorse circuit-switching or in general the technological solutions of the "telecom world". The opposite, "Netheads", adhere to the packet-switched networks, or the technological solutions of the "IP world". This clash of cultures raised heavy disputes around the turn of the century, about which transmission protocol should prevail over broadband networks, the Internet Protocol (IP) or Asynchronous Transmission Protocol (ATM) (see e.g. (Sexton and Reid 1997; Maxwell 1999; Faynberg et al. 2000; Garcia 2000).

To cut a long story short, the IP protocol won the fight and has since become dominant in all areas of transmission networking. Jensen (2003) studies why this happens and finds that "IP represents a shift in the philosophy of telecom business besides being a fairly easy and widespread protocol". Regardless of the protocol, the key issue of the Netheads versus Bellheads discussion remains unanswered, i.e. how the current telecommunications infrastructures can cope with increasing data transmission. Faynberg et al. (2000) discuss the problems that modem based data traffic was causing in the PSTN and methods of interconnecting IP and the PSTN.

Using an engineer's perspective, Maxwell (1999) neutrally compares and analyses the strengths of both worlds in an attempt to predict the future of residential broadband. He works his way up from the physical layer and provides an excellent analysis of the available technologies,

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[26] The term Bellhead refers to the regional Bell operators, more often called Incumbent Local Exchange Carriers (ILEC) in the aftermath of the US Telecommunications Act of 1996.

services, as well as market and business aspects of residential broadband. In forecasting the future of broadband he predicts a stepwise evolution, with each step characterised by providing different transmission speeds and services.

Recognising the problems involved in realising the future broadband society, the US National Research Council put together a "committee on broadband last mile technology". In (NRC 2002) the committee reviews technologies, strategies, and policies for fostering broadband deployment. Among the contributions of the NRC study is a dynamic definition of broadband, relating the term to services, rather than to transmission bit rate like in earlier studies.

Chlamtac et al. (2005) provide a broad analysis of the challenges faced by municipal driven FTTH broadband deployment. While Chlamtac et al (2005) only touch upon regulatory issues, Nuechterlein and Weiser (2005) focus exclusively on implication of residential broadband deployment on policy and regulation, grounded in the US telecom regulation. Austin and Bradley (2005) focus more on implementation of broadband, both services and networks and which potentials and challenges future broadband has. Together with NRC (2002), these three can be recommended for encircling most of the necessary issues of residential broadband deployment.

In "requirements of triple play services towards broadband access networks" the B@Home project analyses how the requirements of multimedia services towards broadband infrastructures evolve over time. The project uses several dimensions to span the requirements space, where the most important ones are: service type and quality, usage scenarios, number and type of terminals. The deliverable compares service development to evolution of network characteristics to see "how the different types of broadband networks (telephony, cable, wireless and fibre) are able to support the growing network requirements of triple play services" (B@Home WP0, D0.5.2., 2005).

Going over to the services themselves, the literature study was divided between i) individual studies of voice, video, and emerging data services, and ii) general technological aspects (e.g. coding and transmission, Quality of Service, etc.) of providing multimedia services over converged IP networks. Starting with voice in the first category, Dang et al. (2002), and James et al. (2004) provide detailed but good technical accounts of VoIP technology, Analysys (2003) describes the provisional aspects, and finally Frederiksen (2006) looks at

implementing them. What all the sources highlight, although from different perspectives, is the different characteristics of voice services based on the nature of the service provided.

In comparison to voice services, provision of commercial video services is less mature and faces more challenges. Despite the promises of Simpson (2006) and Dashti (2003) who provide an extensive general theoretical overview of IPTV and Cooper et al. (2001) who describe how the Bellheads elegantly can provide video over ATM, Fleury (2005) describes the problems of implementing IPTV, due to lack of standards, and (ITU-T 2006) due to lack of middleware. As seen below, industry feedback also indicates that vendors as well as operators are having troubles entering this otherwise promised "holy grail of operators" (HeavyReading 2004).

The focus of the literature study within the last category, data services, was on the emerging but already extremely popular instant messaging (IM) and peer-to-peer (P2P) services. Both technologies are innovative products of the 'Nethead' world that defy the transmission characteristics of all existing services and pose new technological as well as business oriented challenges to the rest of the telecom and media world. However, if viewed as surmountable challenges in an evolutionary path, both technologies have the potential of severely affecting the development path of residential broadband.

Moving to the technological aspects of IP services, the Norwegian Teletronikk recently devoted a special issue to 'Real-time communication over IP' (Teletronikk 2006). There Perkis et al. (2006) point out the immature state of service delivery platforms as "no satisfactory automated configurable way of delivering and consuming content exists that scales automatically to different terminal and network characteristics, device profiles or QoS". In general the papers indicate that standardisation problems within audio visual coding have to the most degree been solved, but that challenges of providing provisional support functions, such as transcoding and guaranteeing maximums latency remain.

The open issues of service delivery platforms are addressed by Rao, Bojkovic, and Milovanovic (2006) who relate service development to the convergence of communications and computing, and study how proposed multimedia standardisation frameworks, such as ISO/IEC MPEG-21, are easing service deployment for operators. This is supplemented by Feng, Siu, and Zhang (2003) who describe the

integration of meta data in service development using the MPEG-7 standard.

Telecommunications forecasting is an integral part of planning and deploying networks and services. Literature provides an abundance of traditional telecommunications demand forecasting models, of whom Fildes et al. (2002) provide a good overview, before concluding that providing "successful modelling of new markets has been limited" (Fildes 2002). The techno-economic research projects IST-2000-25172 TONIC and more recently FP6-IST-BROADWAN and CP1-021-ECOSYS, all have deliverables on broadband demand forecasting. A summary of some of their work as well as a broad overview of current research topics in telecommunications forecasting are provided in a dedicated issue in Teletronikk 4.2004 on the subject.

The literature review confirms that, after decades of active research and development, converged IP based multimedia services have only recently become ready for wide-scale commercial deployment. Industry feedback indicates that both existing and emerging operators are aggressively investing in network infrastructure and service delivery platforms. Despite this, there are reports of deployment problems, and for that reason services need to be analysed individually due to individual real-time requirements, and in context of individual provisional challenges. Additionally, common general issues such as: standardisation, security, and service development platforms need to be addressed.

The remainder of the chapter broadly describes the characteristics and deployment of multimedia services in residential broadband networks based on the parameters identified in the literature study. The goal is to specify the technical requirements of multimedia services as a prerequisite for the next chapter where they will be put into context with possible implementation scenarios.

2.3. *Defining Broadband*

In literature the term broadband originally denoted Internet connectivity with higher transmission speeds than capable with PSTN based dial-up technologies (56 kb/s[27]), without referring to any certain speed or specific

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[27] 56 kb/s in the US and Canada and 64 kb/s elsewhere

service. Throughout the past few years several quantitative definitions of the lower bound of transmission speed have appeared. The International Telecommunication Union Standardization Sector (ITU-T) recommendation I.113 defines broadband as everything faster than primary rate ISDN (1.5 to 2 Mb/s) (ITU 2003). The FCC definition of broadband is 200 kb/s in one direction, and advanced broadband is at least 200 kb/s in both directions (FCC 2006). Similarly the Organization for Economic Co-operation and Development (OECD) defines broadband as 256 kb/s in at least one direction.

While 256 kb/s seems to be the most widely used definition of broadband transmission speed, recent media convergence and especially the required transmission speeds of packet-based video have resulted in higher transmission rates, up to several Mb/s. This has fuelled criticism on literature that only states maximum transmission speeds when a range of different characteristics would be better suited to determine the appropriateness of a particular broadband platform for specific applications. As an example Crull (2006) uses the following metaphor: "Its like selling a car based on how high the speedometer goes". This has motivated more general definitions of broadband that also consider the services offered by broadband. This is illustrated by the following definition of Maxwell (1999):

> *Residential broadband is the market for interactive switched transmission services to homes and apartments with data rates in excess of one megabit per second. Residential broadband networks will provide greater speed, interactivity, and mixed services, from data communications to interactive video.*
>
> *(Maxwell 1999; p. 4)*

Despite a more general approach, this definition still defines a fixed lower bound on transmission rates that might change with time. A common problem with all these definitions therefore seems to be that it is inevitable that the as technology improves that the definitions have to be changed. With unsolved issues on how the definition of broadband can or should evolve over time, many sources have avoided using qualitative definitions of transmission speeds and instead focus on the services that broadband should support. This is evident in the following definition of broadband provided by the US National Research Council:

> ***Broadband Definition 1:*** *Local access link performance should not be the limiting factor in a user's capability for running today's applications.*
>
> ***Broadband Definition 2:*** *Broadband services should provide sufficient performance – and wide enough penetration of services reaching that performance level – to encourage the development of new applications.*
>
> *(National Research Council 2002; p. 11)*

This definition highlights the dynamic nature of broadband and indicates that a prerequisite to discussing broadband is an understanding of the services that broadband is to provide. Regardless of the definition and transmission speeds, the availability of broadband and its ability to support services is ultimately determined by the infrastructure over which it is carried. It has long been realised that in its current form, copper cannot suffice to bridge the enormous and growing gap between the consumed multimedia content and the equally enormous and growing content that is generated. The bottleneck between the two has in literature been called the "last-mile bottleneck" (Maxwell 1999; NRC 2002; Green 2006).

It is also important to bear in mind that broadband speeds are only as fast as the slowest portion of the network that the information traverses, and that the speeds referred to are usually maximum speeds of nominal values that can vary greatly. This emphasises the need for analysis and understanding of various other properties than just transmission speeds when comparing the viability of access networks to fulfil the requirements of residential broadband.

2.4.   Packet-based Networks

In packet-based networks information is split up into packets. Each packet contains a part of the information in addition to a header with support information, such as where the packet comes from and where it is going. The packet-based network then forwards each packet from node to node through the network until it reaches the destination. In literature the network architecture of packet-based networks is frequently divided into seven layers based on the Open Systems Interconnection (OSI) reference model. Functionality of each layer is governed by a protocol that ideally operates independently of the layers above and below.

With the advent of the Internet and its predecessor, the ARPANET[28], the ability and need to connect multiple networks together in a seamless way led to the design of the more widely used TCP/IP reference model. The third important reference model, but different from the two previous ones, is the ATM (and B-ISDN ATM). Unfortunately, all models have their shortcoming and none of them can describe the disparity of technologies and protocols used in residential broadband today.

For the purpose of this study, the specifics of the models are less important than the possibility of separating and identifying network functionalities. This is especially important later in the thesis when analysing how the control of infrastructure at different layers can affect service provision. For that purpose a slightly modified version of the hybrid reference model of Tanenbaum (1996, p. 44) will be used, as illustrated in Figure 12.
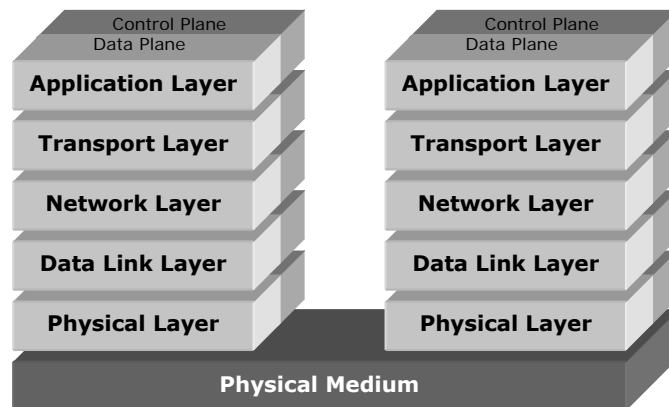

Figure 12, Network architecture reference model

At the bottom of this model is the *physical layer* that is concerned with transmitting raw bits over a physical medium, which in this thesis is exclusively copper or fibre.

The *data link* layer takes care of transferring data frames between adjacent network nodes. Examples of data link layer protocols discussed later in

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[28] The ARPANET was a research network sponsored by the US Department of Defence.

this thesis are Ethernet, Asynchronous Transfer Mode (ATM)[29], and Point-to-Point Protocol (PPP). If several links interconnect at a single node, that link can use addresses in the data frames to redirect (switch) frames between links. In computer networks this is referred to as layer 2 switching. In Ethernet, switching can be based on Media Access Control (MAC) address, or Virtual Local Area Network (VLAN) tags. Prioritising or expediting transmission of certain frames based on VLAN tags (or other data frame identifiers) is one way of providing quality management in IP networks.

In contrast to the data link layer that only knows network nodes in its proximity (i.e. takes care of node-to-node transmission), the *network layer* is responsible for end to end (source to destination) packet delivery. The Internet Protocol (IP) is the most widely used network layer protocol. IP adds a header to all packages that includes unique global addresses of sender and receiver, used to route packets by intermediary nodes. Among other fields, the currently deployed IP version 4 header includes a type of service field. This field can be used to tell routers which kind of service a packet should get or, in other words, prioritise the packet by indicating how important it is compared to other packages. This kind of service differentiation is one way of providing quality management in IP networks but not widely implemented.

The *transport layer* accepts information from applications and ensures transmission with varying level of reliability depending on the protocol stacks used. When using the IP suite, one of two major transport layer protocols is used, Transmission Control Protocol (TCP) or User Datagram Protocol (UDP)[30]. TCP is connection-oriented where receiving nodes ensure correctness and send confirmation upon receipt of packages. While this functionality is useful in most web-based services, the delay and inefficiency from functions such as error detection and retransmission make TCP unsuited for real-time transmission. UDP provides an unreliable connectionless datagram service, and is more robust for real-time transmission.

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[29] As mentioned before, Asynchronous Transfer Mode uses a different reference model. ATM therefore also takes care of functions that are outside the scope of the data link layer.

[30] Other less used transport layer protocol exist such as the Stream Control Transmission Protocol (STCP) and Datagram Congestion Control Protocol (DCCP)

In ATM, the ATM Adaptation Layer (AAL) provides network and transport layer services. AAL specifies five types of connections, each with different QoS parameters appropriate for different types of services. This service classification remains the most appropriate mapping between service requirements and transmission properties, and is described in further detail in section 2.5.3.

2.4.1.   Categories of packet-based networks

Regardless of the reference model, layers as well as networks in general can offer reliable or non-reliable services of two types: connection-oriented or connectionless[31]. In connection-oriented networks a channel is set-up between respective layers of the originating and destination nodes prior to transmission. ATM is a connection-oriented virtual-channel based protocol that additionally can provide guaranteed transmission properties. This is accomplished by having "intelligence" in each network node (maintaining state) and informing it (reserving resources) along the entire end-to-end path, prior to transmission.

This differs from the method used in pure IP networks where each packet is sent from the originating node without checking if or how the network can get it to the destination node. The edge of the IP networks thereby possesses the intelligence, leaving the IP routers in the core of the network "dumb", with the simple task of checking the destination IP address against a forwarding table to determine the "next hop". If the queue for the next hop is long, the datagram may be delayed. If the queue is full or unavailable, an IP router is allowed to drop a datagram. The result is that IP provides a "best effort" service that is subject to unpredictable delays and data loss.

2.4.2.   Quality of Service in packet-based networks

As the transmission delay (known as latency), the transmission delay variance (known as jitter), and the loss of packets increase, the perceived quality of the communication deteriorates. Quantitative measurements of these values are called Quality of Service (QoS) parameters. While advanced coding schemes, such as Forward Error Correction (FEC), can reduce perceived quality decay, successful real-

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[31] For simplicity, Tanenbaum (1996; p. 23) uses the telephone system to describe connection oriented service and the postal system to represent a connectionless service.

time multimedia systems are always contingent upon loss and timing constraints with respect to end-to-end QoS requirements.

2.4.3. Managed Networks

The general Internet is segregated into a collection of autonomous systems. An autonomous system is a self-contained set of networks under the same administrative control. It is usually managed by a single corporate entity and therefore also often referred to as a "managed network". Although connecting to the Internet, the networks are heterogeneous by nature and can build on different underlying technologies and protocols. For this reason different autonomous systems may offer different transmission services such as multicasting, priority treatment to different classes of traffic etc.

In the early days of the Internet it was common for large operators to use their core ATM networks for the underlying transport of IP traffic. Today, most operators have upgraded or are in the process of upgrading, their core networks based on concepts of Next Generation Networks (NGN) (Traupman et al. 1999). Multi-protocol label switching (MPLS) is a key technology in this process, solving many of the inherent problems of pure IP networks by offering traffic engineering, based on label switched paths (LSP) in a similar manner to virtual channels in ATM (Awduche 1999; Li 1999).

2.4.4. The Internet

The Internet is often referred to as a 'network of networks'. It consists of numerous autonomous systems (often referred to as managed networks) that interconnect through trunking and peering agreements and obey the same Internet Protocol. Each network node has a unique IP address with which the rest of the nodes can communicate[32]. If two (or more) communicating nodes belong to the same autonomous system, the transmission may be subject to traffic management policies that guarantee a specific set of QoS parameters. However, the general

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[32] In reality network nodes can also have private addresses which are not directly accessible through the Internet, using Network Address Translation (NAT) to relay packages through. For simplicity however, I only treat public addresses.

Internet only defines a single transport service class, so when packets transcend autonomous systems they generally lose all QoS guarantees[33].

The impact of this gap between traffic capabilities and quality guarantees within and between autonomous systems severely affects the competitive situation of service providers on the Internet. Operators of managed networks are increasingly offering advanced multimedia services within their boundaries, using the competitive advantage that their control of local resources offers. However, these upgrades are local to the respective managed network and can therefore provide the operator (and those service providers that are granted access to these features) with a competitive edge in provision of services compared to those offering the same service over the general Internet. However, the effect varies greatly between individual multimedia services. Therefore the next section analyses the nature of different multimedia services and especially their transmission and QoS requirements.

2.5.   *Multimedia Services*

The formal definition of multimedia is "a service in which the interchanged information consists of more than one type, such as text, graphics, sound, image and video" (ITU, 1997). In this thesis the term is used to indicate services that rely on different media types (not necessarily a combination). However, there is a fundamental difference between different types of content and services and the requirements they pose on different layers of the underlying network. Below is a list of the most important transmission properties that have been identified and will be used in the remainder of the study to classify multimedia services:

▪ *Which transmission rate (bandwidth) a service requires[34]*

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[33] The Border Gateway Protocol (BGP) which is the de facto interdomain routing protocol for the Internet includes a policy mechanism, allowing interdomain policy information to be expressed directly within the protocol. However, this functionality requires agreements between the respective domains, as well as all the domains that a packet passes through on its way, and is not in wide use.

[34] In its original form, the term "bandwidth" is a measure of frequency range and is typically measured in hertz. Bandwidth is a central concept in many fields, including information theory, radio communications, signal processing, and spectroscopy. In recent years bandwidth has been adopted for data transmission rates. Despite this

This property is measured in bits per second (b/s) and varies greatly between voice, video, and data. For example a webpage can be transmitted swiftly over only a few kb/s link, audio can require around hundred kb/s, and video several Mb/s.

- *Which rate type the services fall under*
  This property is measured in bits per second (b/s) and can be either a stream or burst. For example, audio and video data streams require a relatively predicable constant bit rate (CBR) and have a quantifiable upper bound, even through their rates often fluctuate. In contrast variable bit rate (VBR) transmission is compromised of unpredictable delivery of "blocks" of data. Applications like file transfer move data in bulks that can increase data rate to use all available throughput (no upper bound).

- *How tolerant the service is towards transmission delay/jitter*
  This property is measured in milliseconds and can vary greatly in or between IP networks. Of multimedia services, real-time applications are said to have the most stringent delay requirements. For example ITU recommends less than 170 ms delay for toll quality voice transmission.

- *How tolerant the service is towards packet loss*
  This property is measured in percent dropped packages (or more commonly packet loss rate (PLR)). With increased congestion in IP networks, packet loss can soar. The perceptual effect of packet loss on multimedia services varies and for example research shows (Dashti 2003) that packet loss of voice has severely more negative effect on video-conferencing than equal effect on video.

- *Is the service one-way, one-to-many, two-way, or many-to-many*
  This property is measured by the number of senders and receivers and their level of interactivity. If a node only receives information the transmission is called one-way, whereas if the

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partly incorrect usage of the term, it has become common and is widely used (Maxwell 1999; NRC 2002; Austin and Bradley 2005). This thesis will therefore use the term bandwidth in wired networks in a relaxed manner to represent data transmission rates.

node also sends information the connection is two-way. If there is only one receiver the connection will be performed point-to-point (sometimes also called unicast), otherwise as broadcast (sometimes also called multicast). For example in radio distribution to several (possible thousands) of receivers are one-way broadcasts, while a regular phone conversation is based on two-way communications.

Delay Tolerance	Delivery Type	Description
High	Asynchronous	No constraints on delivery time.
	Synchronous	Data is time-sensitive but flexible.
	Interactive	Delays may be noticeable to users/applications, but don't adversely affect usability or functionality.
	Isochronous	Time-sensitive to an extent that adversely affects usability.
Low	Mission-critical	Data delivery delays disable functionality.

Table 3 Categorisation of delay tolerance (Source: QoS Forum 1999)

2.5.1. Real-Time Services

An important subgroup of multimedia services can be categorised as real-time. The most common form of real-time services are based on audio and video streams at constant rates and are characterised by limits on delay, jitter, and packet loss they can withstand. Among these, those real-time services that offer two-way isochronous communication (e.g. interactive voice) are most sensitive, while e.g. one-to-many broadcasting of video can be displayed with a delay (buffer) at the customer side without affecting perceptual quality.

Internet applications that require transport functions suitable for real-time data use the Real-time Transport Protocol (RTP). RTP was developed to support real-time transmission of audio and video over User Datagram Protocol (UDP) and support IP multicast (Schulzrinne 2006). For IP networks, the problem with UDP based RTP traffic is that there are no limits to the amount of traffic it can generate, and it does not respond to network congestion as TCP based applications. As a result, streaming media UDP traffic can cause two major problems on the Internet: congestion, and unfair allocations of resources among competing traffic flows (Hong et al. 2001).

RTP consists of a data and a control part. The data part of RTP provides network transport functions, such as time based reconstruction. The control part is called Real-time Transmission Control Protocol (RTCP) and allows monitoring of the data delivery and provides simple error control and identification functionality (Sigurdsson 2004b). However, RTP is an application protocol; designed to be independent of the underlying transport network and implemented by each application using it. This means that although most real-time applications use RTP, the extent and functions implemented can vary greatly.

RTP does not address the issue of resource reservation or quality of service control. RTP can therefore only help to make use of the available resources. In addition, RTCP can be used to share information between participants about the experienced QoS parameters, and thereby allowing dynamic adaptation to available resources. Knowledge of QoS parameters can, for example, be used to tune session parameters, such as codec used, prior to a new session or during an active session. QoS monitoring in RTP/RTCP can thereby result in an increase in users' perceived quality and usability of available resources. The flow of packets in an RTP session is illustrated in Figure 13.
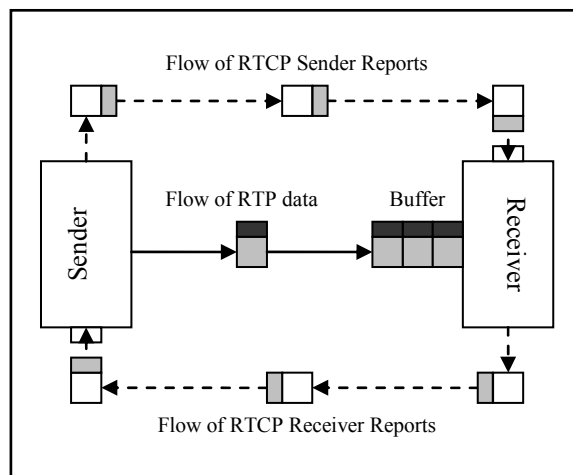

Figure 13, Flow of packets in an RTP session

Due to the lack of end-to-end guaranties of UDP and inherent problems on the Internet such as Network Address Translation (NAT) and firewalls, some of today's real-time traffic in residential broadband

networks is transported using the Transmission Control Protocol (TCP) instead of UDP[35]. TCP flow control mechanisms assure the correctness of TCP streams, but the delay introduced by the retransmission of lost packets creates a bigger problem than the loss itself, if the rate of loss is reasonably small[36].

Another approach used in many real-time applications on the Internet to solve problems of quality deterioration associated with packet loss is to use error correction schemes. Among these, Forward Error Correction (FEC) is the most widely used[37]. In FEC the sender adds redundant data to its messages, which allows the receiver to detect and correct errors. The advantage of FEC is that retransmission can be avoided, or e.g. in the case of VoIP perceived voice quality does not necessarily deteriorate even though packets are lost in transmission. However, the downside is wastage associated with transmission of redundant information.

2.5.2.   *Supporting real-time services in future networks*

RTP does not address resource reservation nor does it guarantee quality-of-service for real-time services (Schulzrinne et al. 2003). It does, however, belong to an enhanced Internet service model put forth by the Internet Engineering Task Force (IETF) to support both best-effort and real-time service. In that framework, RTP and RTCP, together with The Resource Reservation Protocol (RSVP) and Real-Time Streaming Protocol (RTSP), provide a comprehensive solution that facilitates advanced multimedia services over IP networks (Sigurdsson 2004b).

RSVP resembles a connection-oriented protocol, with a negotiation phase to establish a path within certain parameters, a transmission phase, and a disconnect phase that returns network resources to the common pool (Maxwell 2004). RSVP resembles ATM as both establish virtual paths, and then each network node must remember what to do

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[35]   Although proprietary and not published, there are indications that the successful voice provider Skype uses TCP for transmissions in some cases. (Baset and Schulzrinne, 2004)

[36]   Su (1999) estimates this value to be below 10%.

[37]   A subset of FEC, but the most important by far is Reed-Solomon coding because of its widespread use in CDs, DVDs, and hard drives.

with specific packets, a substantial deviation from the IP philosophy of a single common transport service. However, RSVP, like ATM, was not implemented nor supported in broadband access networks.

While the initial plans for RSVP deployment on the Internet were not successful, there is an increasing tendency for implementing traffic management[38] in managed networks today (Traupman 1999; Awduche 1999). The direction of this development can be divided into two: backbone and access networks. The battle for the future of access networks is still under way and will be dealt with in the next chapter of the thesis.

The fight for dominant transmission technology in backbone networks is partly over. After a hefty debate, ATM that was called the "darling of the telephone industry" (Startdust, 1999) and had been widely implemented in backbone networks, lost. During its prime time, ATM was seen as an integrated replacement for the entire telephone system and all existing networks and services, capable of offering and supporting all kinds of information transfer. Despite advanced QoS support and technological supremacies of ATM, IP now undisputedly dominates in all areas of transmission network (Jensen 2003).

However, the legacy of ATM still remains. Multi-Protocol Label Switching (MPLS), which now has emerged as a new de facto standard in backbone networks, was developed as an overlay service for backbone networks to extend many of the virtues of ATM to IP, e.g. by enabling layer 2 circuit-switching over a layer 3 network. It allows virtual circuits (also called tunnels) to be created over an IP backbone so that, once set up, data can be switched simply and quickly across the tunnel without the need for analysing individual packets or the need to make complicated routing decisions at each network node.

In this way, network access providers can create efficient virtual channels within their backbone networks. This is useful when aggregating traffic with similar characteristics at the edge and expediting it to relevant nodes in the network. An example of usage is transmitting real-time voice and video over separate, but dedicated virtual channels to the appropriate service provider. MPLS thereby

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[38] Also called traffic engineering

combines the QoS, traffic engineering and availability characteristics of ATM, with the scalability, efficiency and multi-point nature of IP.

2.5.3. *Traffic contracts and Quality of Service*

Despite widespread deployment, there is still no universal definition of traffic types and transmission characteristics in IP networks. The ATM Forum solved this by defining the following five types of connections, each with different QoS parameters appropriate for different types of services:

- *Constant bit rate (CBR)*
  Ideal for real-time traffic requiring guaranteed constant rate, such as high quality audio, video.

- *Variable bit rate – real-time (rt-VBR)*
  Ideal for real-time and non-real-time traffic at variable bit rate.

- *Variable bit rate – non real-time (VBR)*
  Ideal for resource demanding non-real-time multimedia services that demand average rate guarantees.

- *Available bit rate (ABR)*
  Primarily for data services that have no rate guarantees but require priority over best-effort traffic.

- *Unspecified bit rate (UBR)*
  Services without any transmission requirements, i.e. pure best-effort with no guarantees.

While the above classes are from ATM, a technology that undeniably has lost to IP in terms of wide-spread adoption, it represents a prediction of the upcoming classification of IP traffic. Furthermore, as discussed in Chapter 3, ATM is used for underlying transmission in Digital Subscriber Line (DSL) and a subgroup of the passive optical network broadband access networks. Lastly, classification of transmission types fits well with economic theories of pricing for communications networks (Courcoubetis and Weber 2003).

2.6. *Voice Services*

Since the introduction of telephony in 1876 the basic concept of setting up a dedicated switched tunnel capable of transmitting the human voice in a

more or less recognisable form between two end users has not changed in the Public Switched Telecommunications Network (PSTN). Originally, connections were established manually through switching offices, and transmission throughout the telephone network was analogue, with the actual voice signal being transmitted as a variable electrical voltage from source to destination.

With the advent of digital electronics and computers, digital transmission became possible. Since the 1970s telecommunications networks have evolved towards digital circuit-switched networks where each connection is transmitted as a statically reserved 64 kb/s stream. With the increasing importance and widespread use of packet-based networks, the traditional voice service stands at the brim of a new evolution, the transformation towards packet-based Voice over IP.

Despite a great deal of focus and predictions of a swift and drastic transformation[39], the implementation and adoption of VoIP has been limited. The ITU estimates that VoIP's share of commercial phone subscriptions[40] was below 2% of the 1.29 billion fixed lines in 2005 (combination of data from Bueti and Obiso (2006) and Biggs (2006)). More positively, VoIP has been increasing its share of the international voice traffic, growing steadily from 0.2% in 1998 over 4.8% in 2000, to 15.5 % in 2004 (Biggs 2006).

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[39] The expectations of VoIP can e.g. be seen through the following quote by FCC commissioner Powell: "It's probably the most significant paradigm shift in the entire history of modern communications, since the invention of the telephone" (Gaever, 2004).

[40] Also referred to by some sources as: mainline, Primary Line Subscriptions, or Public Available Telephone Service.
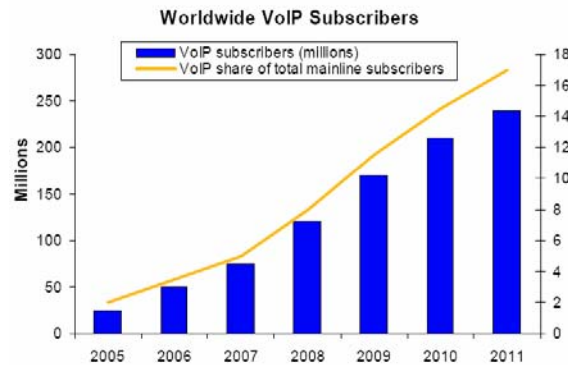
Figure 14, Projections of worldwide VoIP Subscribers
Source: Biggs (2006) based on IDATE (2006)

2.6.1.   *Voice over IP (VoIP)*

Voice over IP (VoIP) is a term used for a range of protocols used to transport real-time voice and the necessary associated signalling over IP networks. Being a synonym means that several types of VoIP solutions with different properties often get mixed together, disregarding often fundamental differences. Analysis (2004, p. 19) proposes a taxonomy based on a provisional model. With this method, the following three categories of residential VoIP can be identified:

▪   Self-provided consumer

   This provisional model is user driven and does not require an service provider since corresponding users connect directly to each other, either by means of IP addresses or through an address server. Users run a piece of software on their computers or use an analogue terminal adapter (ATA) to establish a connection over a "best effort" Internet connection.
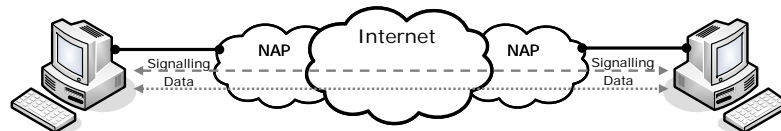

Figure 15, Provisional model for "self provided" VoIP

▪   Independent of Internet access

In this provisional model customers buy phone service from a service provider on the Internet. Users run a piece of software on their computers or more commonly uas a plain old telephone attached through an analogue terminal adapter (ATA) to establish a connection over a "best effort" Internet connection. The operator uses a gateway to map the customer's connection over to a telephone number that can be used to receive and forward calls from the PSTN.
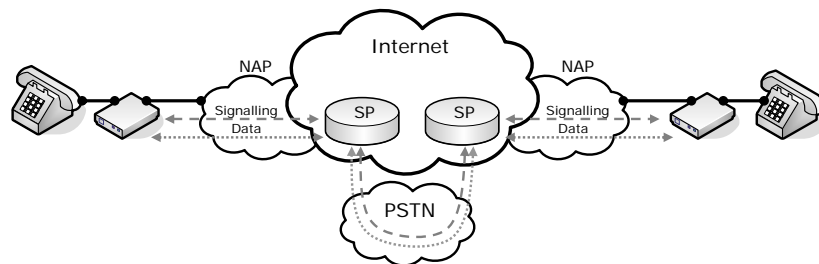

Figure 16, Provisional model for "Independent of Internet access" VoIP

▪   Provided by broadband access service provider

This solution is similar to the previous model but here the service provider operates from within a managed network. Transmission is therefore tightly integrated with the underlying transmission network and the voice service identical to that of PSTN and users are in many cases oblivious or ignorant of the VoIP nature of the service.
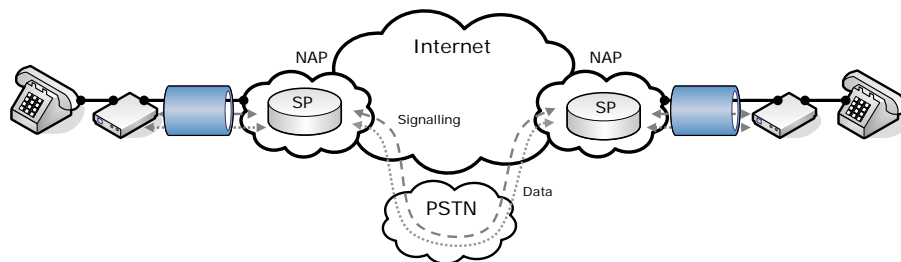

Figure 17, Provisional model for "Provided by broadband access service provider" VoIP

In addition to the above mentioned difference in provisional models, there is a fundamental difference in the VoIP business models that

service providers use as compared to the PSTN, in particular related to peering and interconnect termination. The biggest difference is that VoIP service providers use the general Internet to carry long distance and international traffic all the way to the terminating PSTN operator. This enables VoIP service providers to offer close to "local" tariffs all around the world. Despite this, Davidsen and Johansen (2006, p. 27) argue that "the overall cost picture is not fundamentally changed when moving from PSTN to VoIP" since the service provisioning related costs like customer acquisition, billing and customer service dominate the infrastructure-related cost. What they neglect is that emerging VoIP service providers often use web-based customer support and prepaid billing, reducing service provisioning cost considerably. When combined with peer-to-peer technology that eliminates the need for central infrastructure, VoIP truly is disruptive[41].

VoIP Standards

Several open and proprietary VoIP protocols are available, of whom three are in most widespread use. ITU's H.323 was the original breakthrough but more recently then IETF's Session Initiation Protocol (SIP) is becoming the most widely used. Both SIP and H.323 are peer based, meaning that they reside within hardware or software terminals at the user side (terminals), where the content is coded and prepared for transmission using the RTP protocol. The third main protocol is Media Gateway Control Protocol (MGCP) which was designed to facilitate wide-scale public telecom networks by providing centralised control of the media gateways.

Coding and transmission

"One of the key requirements for the widespread deployment of VoIP is the ability to offer toll-quality service equivalent to the existing PSTN" (Johnson 2004). The onus to fulfil this requirement is on coding and conditions of transmission. The PSTN ensures this by using a fixed

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[41] Davidsen and Johansen (2006) evaluate the disruptive nature of VoIP using Clayton Christensen's disruptive theory. They conclude that 'there is little doubt that VoIP has a disruptive potential' but argue that we are just not there yet. This thesis argues that with web based provisioning, billing, and support, as well as P2P infrastructures we are at least much closer.

sampling rate and coding[42] over a guaranteed circuit switched transmission path. By contrast, VoIP is not limited to any specific coding and can have higher or lower data rates depending on the codec used, the available transmission capacity between the end points, and the user's preferences. James et al. (2004) study how VoIP affects voice quality, and confirm the negative effect of packet loss, which they conclude must be "below 1 percent in order to deliver a level of voice quality that is PSTN equivalent". However, with the use of Forward Error Correction this limit can be raised and in addition their work also shows that despite packet loss of up to 5 percent, perceived quality level is above that delivered in traditional GSM. In a study of international transmission properties on the Internet, Marsh and Li (2004) found that "most of the connections have very low loss rates (less than 1%)[43]" indicating that the Internet can sustain high quality VoIP transmissions. However, this study was conducted on cross country basis, thus only indicating long distance transmission, neglecting transmission properties of the access network.

Providing VoIP services

The study so far indicates that the Internet can facilitate high-quality long-distance VoIP calls but that limitations of "best-effort" transmission in local access can skew competitiveness of local VoIP service providers. This can again be seen as a competitive edge for network access providers that have the possibility of implementing service differentiation in their networks and thereby guarantee service level of VoIP services offered. Alternatives for implementing service differentiation in residential broadband networks, the role of network access providers, and the resulting competitive edge were studied by the author in (Sigurdsson 2004).

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[42] In the PSTN the local loop terminates in a Line Interface Card (LIC) where the voice signal is converted to digital form using Pulse Code Modulation (PCM). In PCM, a device called codec (coder-decoder), produces 8000 8-bit samples per second (125 μsec/sample) yielding a 64 kb/s data stream (Sigurdsson, 2003).

[43] Those that did not have adequate transmission properties all used satellite connectivity or were countries with undeveloped telecommunications infrastructure.

For attracting customers, Moortgat and Conings (2003) suggest that VoIP providers need to differentiate themselves from PSTN competition by providing attractive additional services. They argue that "enhancing the communications experience from just talking to talking plus chat, possibly in combination with video and/or multiparty conferences" (Moortgat and Conings 2003) is key to success. However, currently there has been no evidence of successful commercial video based VoIP service[44].

On the contrary to both Johnson's (2004) call for toll quality, and Moortgat and Coning's (2003) call for additional features, the most successful voice service provider so far, Skype (2006), has attracted over 50 million registered users world wide by offering often low quality, and limited features. However, Skype's service is free, indicating the price reductions provide the strongest attraction to customers. Additionally, Skype uses peer-to-peer technology (see Section 2.7.1) to reduce (or more correctly abolish) infrastructure and transmission requirements/costs.

But how can traditional operators compete against innovative and economical service providers? Frederiksen (2006) looks at why and when operators should move over to VoIP. He argues that due to the already established production facilities of PSTN telephony, both incumbent operators and well established competitors (which are frequently subsidiaries of incumbents in other countries) face substantial transition costs when moving over to VoIP and thus "it only makes sense for small entrants with emphasis on Internet access to act as quickly as possible in relation to VoIP".

Subscription statistics

It is difficult to measure the use of residential VoIP, among other things due to the different definitions of what constitutes a residential VoIP services. Limiting the number to paying customers, IDATE (2006) estimated the total number to be 25 million in 2005, (see Figure 14). Market research from analyst firm Point Topic estimated that the "number of phone-to-phone VoIP subscribers soared from 10.3 million

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[44] Whereas there seems to be a tendency of increased video telephony and usage of web cameras in Internet Messaging.

at the start of 2005 to more than 18,7 million by the end of the year" and the "PC-to-phone market at over 4,7 million" (PointTopic 2006).

Using data from the same Point Topic report, LightReading (2005b) classifies phone-to-phone VoIP service providers based on their customer base (see Table 4). An interesting fact when looking at the list is the mixed presence of 'Bellheads' and 'Netheads', contradicting Frederiksen's predictions.

Service Provider	Number of paying customers
Skype Technologies SA	1.000.000
Vonage Holdings Corp.	500.000[45]
France Telecom SA	330.000
FastWeb SpA	300.000
Cablevision Systems Corp.	189.000
AT&T Corp.	53.000

Table 4, Leading VoIP service providers categorised by user base in Q1 2005
Source: LightReading (2005b)

When looking at the Danish market, Frederiksen's argumentation seems to hold better. The number of phone-to-phone VoIP subscribers has soared from 60 thousand in 2005, to 155 thousand in mid 2006 (Telestyrelsen 2006, p. 40)[46]. This growth stems almost exclusively from smaller competitive network access providers, with the incumbent holding mere 5,6 percent in contrast to 80,3 percent in PSTN. Despite this, industry reports show that the incumbent is mounting for a fight, investing in VoIP infrastructure from Cisco for the residential market (LightReading 2006a) and from Alcatel for the enterprise market (LightReading 2006b).

How the 'Nethead' vs. 'Bellheads' fight for the VoIP market will progress can not be predicted yet, but Analysys (2003, p. iv) predicts competition on the VoIP market as "very few providers, possibly none in the short to medium term, of these IP voice and associated convergent services will have significant market power".

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[45] Telecommunications International reports 1.6 million subscribers as of 1 April 2006

[46] These figures only account for registered VoIP subscriptions that fulfil the requirements of a Public Available Telephone Service (PATS), i.e. not computer based VoIP such as Skype.

Recent industry research indicates that the telecoms are relatively quick to gain strong market power once they launch new services. Telcoms (2007) reports that the retail unit of the UK incumbent BT had notched up more than 1 million subscribers to its VoIP services, representing more than a third of BT's consumer broadband base. These figures represent two products: BT Broadband Talk that enables customers to use their broadband connections as an extra line with a VoIP-enabled phone, and BT Softphone, which is a downloadable PC-to-PC VoIP chat application. Like Telecoms.com (2007b) points out, success of these telecom provided services may be contributed to them being offered for "free" as part of bundled broadband packages, thus limiting the revenues to begin with at least.

2.6.2. Instant Messaging

Instant Messaging (IM) is becoming one of the fastest growing broadband services, estimated to have over one billion registered users[47] and a total of 378 million active users of which 224 million users belong to the single most popular service QQ[48] (See Table 5). IM is a form of interactive real-time application between two or more people. Traditionally the messages were text-based but new applications additionally offer voice and video services with varying levels of delay tolerance[49]. Additionally, most IM services offer contact and presence management, broadcasting the status of users to a group of users defined as friends.

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[47] These figures refer to registered "usernames" and since a single user can have had multiple usernames it does not indicate a user base. Also note that although active users represent usernames that have been used (logged on) recently, some users might be using a multitude of usernames.

[48] QQ is the most popular free instant messaging computer program in Mainland China. However, there is considerable controversy surrounding the correctness of the 224 million active users.

[49] Interactivity ranges from real-time voice and video to "push to talk", Pod-casting etc.

Service Name	Service Provider	Total number of registered users [million]	Number of active users [million]
QQ	Tencent Holdings Limited	549	224[50]
AIM	AOL	195	53
Windows Live Messenger	Microsoft	240	45
Yahoo!Messenger	Yahoo	60 [51]	21
ICQ	AOL	180[52]	20
Skype	Skype Technologies SA	136 [53]	15

Table 5, IM service worldwide user based on
Based on: Wikipedia(2006)

Coding and transmission

The protocols used by the majority of IM service providers today are proprietary (Analysis 2003, p. 116). There have been signs of consolidation, where e.g. in 2005 Windows Live Messenger and AIM became interoperable but otherwise providers seem to aim for building exclusive customer bases through "lock-in". For interoperability and future development, the Session Initiation Protocol (SIP) is the most promising candidate. It already provides session-oriented application initiation and certain presence management facilities and aided by extensions proposed by IETF, SIP can facilitate IM functionality.

Providing IM services

IM services run as software applications at the client side, connecting to a server (service platform). In most cases the service platform only receives control messages from users, while communication between users takes place directly between peers over RTP. Like in VoIP the service platform can either run on dedicated servers or be floating in peer-to-peer based overlay networks. However, an interesting difference between IM services and VoIP is that while operators have been trying to apply VoIP using PSTN business models, IM services

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[50]   According to www.tencent.com.hk/ir/pdf/fs_20060825a_e.pdf

[51]   According to http://developer.yahoo.com/messenger/ as of October 2006

[52] According to http://www.icq.com/products/whatisicq.html

[53] According to:
http://www.skypejournal.com/blog/archives/2006/10/skype_starts_to_build_us_traction.php#more as of October 2006.

have mainly been run by 'Netheads', using untraditional technical approaches and business models.
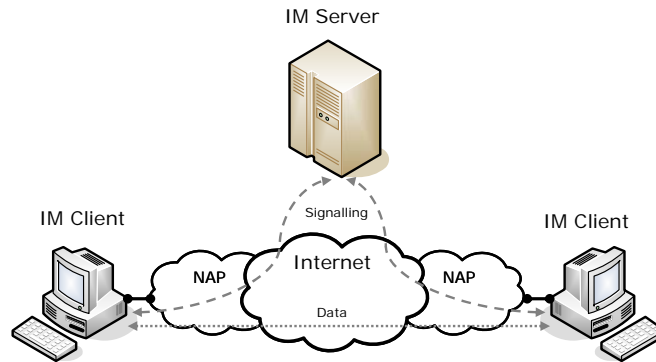

Figure 18, Network architecture of Instant Messaging

None of the 'Bellheads' are or have seriously attempted to compete as IM service providers. However, most of them are hoping to drive mobile data transmissions through mobile IM. On the fixed side, 'Bellheads' can expect serious PSTN competition as IM matures as a voice provider. An example of this trend, AOL has recently unveiled a new PSTN compatible IM addition that grants all AIM users a local phone number for free. Skype runs a similar PSTN gateway service, where users can get local numbers in different countries for around 4€ per month. However, most sources agree that "this transition will inevitably take several years" (Analysis 2004).

2.6.3.   *Future perspectives of voice services*

Despite growth in volume and service selection, emerging VoIP services have not been as successful in attracting customers from the existing PSTN. Research on consumer preferences and behaviour indicate that customers are tenacious (Figure 19) and refrain from switching between platforms. In economics this effect is called switching cost and is often included in cost modelling (Bijl og Peitz 2002).
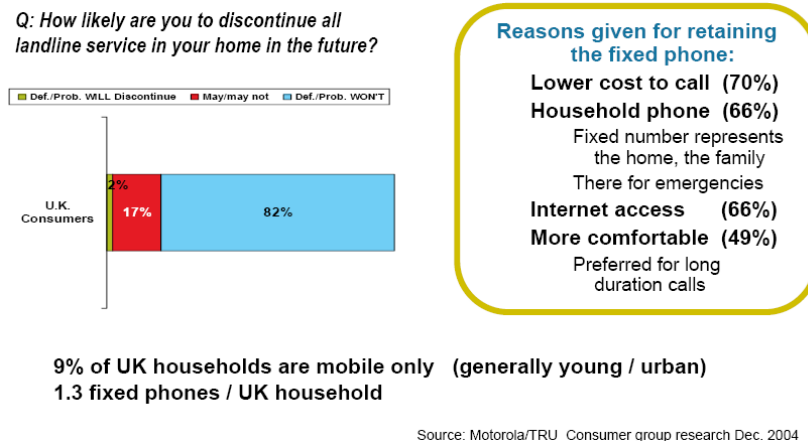
Figure 19, Service preferences in PSTN
Source: Latham (2005)

This reluctance to adopt new technologies is confirmed by BT, which reports that the success of its VoIP solution is largely due to developments in technology allowing users to make calls on phones rather than using software clients on the PC. "Around 60 per cent of our new subscribers take the higher value deals which include the BT wireless hub and handset" (Telcoms.com 2007).

Despite the slow changes, most sources agree that in the long term both services and user behaviour will move from voice services as we currently know them, towards new converged platforms that integrate functionality such as voice, instant messaging, presence, mobile. Daviden and Johansen (2006) put this transformation on a ten year horizon (see Figure 20) where a new type of fixed mobile platform dominates other alternatives.
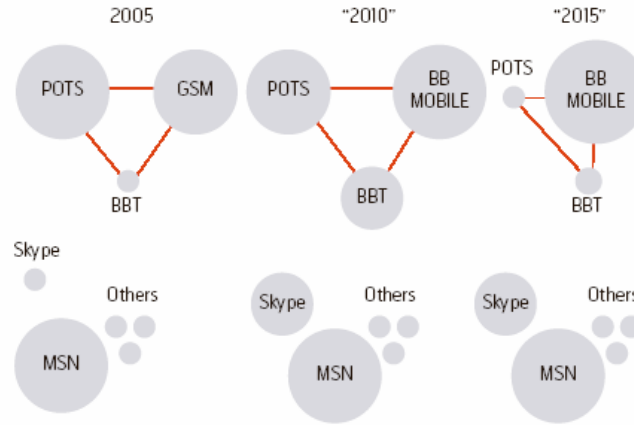
Figure 20, Foreseen development of PSTN, Mobile, and VoIP
Source: Davidsen and Johansen (2006)

2.7.   Data Based Services

Data services provide the basis for all broadband connections. While
loosing some of their earlier significance both in terms of relative
transmission volume and revenue, e-mail and web-based service still
represent the most widely used services on the Internet. This becomes
evident when comparing the nearly 84 billion e-mails sent daily worldwide
in 2006 to the 7 billion IM messages (IDC 2005) and a few million VoIP
calls.

Most data services are not real-time and thus suffice with available bit rate
(ABR) or unspecified bit rate (UBR) as classified in Section 2.5.3. There
are exceptions such as virtual private networks (VPN) and terminal
services that are more resource demanding. However, all these service
types have been studied extensively in literature (Tanenbaum 1996; Sexton
and Reid 1997; Maxwell 1999; Chlamtac et al. 2005); having not deviated
greatly from the predicted development paths, they will therefore not be
analysed further.

An exception to the general rule of foreseeable development is Peer-to-
Peer (P2P) technology. P2P utilises the abundance of underutilised end-
equipment and broadband transmission capabilities by efficiently building
overlay networks with built-in scalability and redundancy. To begin with,
they were used for file-sharing but through active research in the past five
years they have evolved into "infrastructures" capable of providing

advanced functions such as telephone switching, contributing to the search for extra-terrestrial life[54] etc.

2.7.1.   *Peer-to-Peer Networks (P2P)*

Content providers and market supply has traditionally been lagging market demand, mostly due to content owners' fear of copyright violations. While waiting impatiently, users have built up communities of their own based on the peer-to-peer (P2P) technology. These networks take advantage of the immense number of often underutilised end systems by storing increasing amount of content locally. This shift from expensive centralised hardware, operated and controlled by operators and service providers, to perceivably free decentralised user driven systems has resulted in network communities of unprecedented scales.

After a growth period, dominated by the use of file-sharing applications and motivated to a large degree by access to copyright protected material, peer-to-peer networks are now being adapted into a wide spectrum of mainstream applications. Today, the potentials of peer-to-peer networks are reflected through hugely successful file sharing and VoIP applications, which through active research and development in the past few years can offer stability, redundancy, and scalability at a fraction of the cost of traditional server based services.
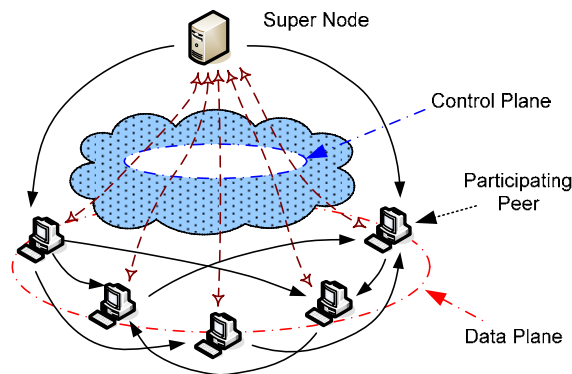

Figure 21, Network architecture of peer-to-peer overlay networks

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[54] See the Home@Seti project (http://setiathome.ssl.berkeley.edu/)

Despite success in some areas, the Achilles heel of peer-to-peer technology has been its inability to represent a complete revenue model accounting for all players involved in the value chain of content distribution. This is largely due to legal uncertainty surrounding the use and conflict of interests, e.g. where users regard traffic and content as free commodities while Internet Service Providers (ISPs) bear increasing cost of transmission and the music industry reports decreasing record sales due to file-sharing.

	1st Era	2nd Era	3rd Era	4th Era
Period	1999 – 2001	2000 – 2002	2002 – 2004	Recent trends
Architecture	Centralised search, P2P data transfers	Decentralised, partly hierarchical	Hybrid	Hybrid
Applications	Mainly file-sharing	Mainly file-sharing	File-sharing, Software distribution, Instant messaging (IM)	File-sharing, IM, Streaming, VoIP, Gaming, Cooperative working
New Functions	Sharing of data and resources	Distributed search and data transfer	Scalable, resilient structure, parallel multi source up- and download	Integrating P2P functions in special purpose solutions
Popular networks	Napster	Gnutella, Freenet	FastTrack, eDonkey, BitTorrent, MSN Messanger	Skype, PodCasting, networks for smaller communities

Table 6, Development of peer-to-peer applications

Today, there is an increasing tendency to use peer-to-peer applications for real time communications and for streaming video (Chou et al. 2003; Li 2004). In less than two years after its foundation, the Skype peer-to-peer solution for voice over IP (VoIP) reached global market leadership in VoIP. Peer-to-Peer technology will then not only be used for file sharing but will seamlessly integrate into advanced multimedia services. Among the most likely application types are:

- Conversational services
- Collaborative tools
- Multi user games and e-learning
- Manifold types of content distribution

Content distribution networks (CDNs) were introduced to improve the performance of static or transaction-based Web content. In recent time streaming media, radio, Internet TV etc. have become an increasing portion of their content. Starting from a client-server based architecture, popular servers are supported by surrogate or cache servers. In this way an overlay network is established often based on

the infrastructure of a content distribution network to avoid bottlenecks at servers and to reduce the access time to content by shortening transmission paths to clients (Popesccu et al. 2006). Using a rigid infrastructure enables better utilisation of resources and full control over content and its distribution.

One of the main issues of CDNs is where to place the caches or surrogate servers. This is a trade-off between the costs of resources (hardware, provisioning, and transmission resources) and transmission distance to the consumer. Main challenges lie in efficient content management and routing of content to satisfy the user demand, as well as measurement to confirm a sufficient level of the perceived QoS.

Content distribution via peer-to-peer networks goes a step beyond towards a completely distributed structure involving the resources of the peers interested in the content. P2P content distribution allows for more flexibility in the overlay network, which may be structured according to different content e.g. by trackers for each item in the BitTorrent network or according to other criteria. The size of the overlay can automatically adjust to the population of peers and thus user demand with a replication strategy for the data being set up by the P2P protocol.

On the other hand, there are still open issues on control of usage and delivery which are of great concern to content owners and providers. In addition, no guarantee for perceived QoS can be assured in current global P2P overlays, where each peer may enter or leave the network at any time. While ongoing research is addressing QoS in P2P networks (Heckmann 2006), incentives for peer participation are essential to ensure sufficiency of resources. This can be accomplished e.g. through admission control or by inducing peers to contribute resources through some form of incentives.

One of the key issues that can facilitate evolution of future applications is the adoption of Digital Rights Management (or at least avoidance of conflicts with IPR). In contrast to earlier file sharing applications that violate Intellectual Property Rights (IPR) of audio, video, software etc., future applications will take advantage of the technical benefits of peer-to-peer networks, without exploiting intellectual property rights. Nevertheless, resource and file sharing will prevail, since the volume of interesting unlicensed multimedia content provided by single users and communities on the Internet is increasing.

2.7.2.   Multiplayer Games

Home (console) gaming has throughout the past decade become increasingly popular. Today, the tendency is for more and more of these games to connect to the Internet to provide a richer experience. There are three types of multiplayer games, network based games, massive multiplayer on-line games (MMOG), and Gaming-on-Demand.

Network based games are similar in structure to instant messaging where users connect to other users through signalling with a game server, after which users communicate directly in a peer-to-peer fashion. MMOG, on the other hand use client/server architecture where all traffic passes through a common network server (or a cluster of servers) that maintains state of all players. Despite a common source all transmissions from the server are mostly unicast.

The third category, Gaming-on-Demand, decrease the processing power and storage capacity requirements of computer and video games by executing the game at a server and streaming the game experience to the user. The client device only decodes and presents the received streams, and transmits the user commands back to the server. In this way resource limited devices such as IPTV set-top-boxes can be used to play advanced games. Due to its mission critical transmission requirements, this kind of service sets strict requirements on the transmission network in terms of throughput and round trip time (RTT), or around 100 ms according to Laulajainen et al. (2006).

It is a widely-held industry view that network based games and MMOG will not be a major generator of revenues for broadband access providers Chlamtac et al. (2005). With revenues increasing in service provision that passes over the network, network access providers are likely to have a stronger bargaining power when selling advanced transmission functionality to customers.

2.7.3.   Future perspectives of data services

Data services are and will be an integral part of future residential broadband services. However, the distinction between data services and other types of services is likely to disappear as applications and services using converged multimedia features increases. Measures by operators to fully capture the value and service delivery of all of these applications are not likely to work and therefore operators have to

embrace Internet services and rather focus on being prepared to offer a variety of transmission services that can meet specific needs.

In the short run the use and consequently the amount of traffic generated by p2p overlay networks is going to cause worries to operators, concerned about the volume and inefficiency of content distribution. Additionally P2P technology poses challenges to content owner since, as the author has shown in Sigurdsson et al. (2006) one of the main drivers for use of current file sharing P2P networks is illegal content. However, when integrated into future services P2P has e.g. the potentials of reducing cost and increasing redundancy and is likely to be incorporated into an increasing number of applications.

2.8.   *Audio / Video Services*

Streamed television services have been around for some time, but only in the past year have dedicated sets of live channels been offered as a package to consumers. While the services to a large extent still are in an embryonic stage, several sources, e.g. Juniper Research (2005) suggest that "these services could well become a significant source of income for operators, aggregators, and application/content providers (p.1)". Many analysts are more sceptical, questioning whether IPTV will actually become a significant incremental profit stream in the foreseeable future (LightReading 2006d; Telecoms.com 2007b). Although IPTV holds the potentials of increased average revenue per user (ARPU), the margin of offering the service is low[55] since much of the income goes directly back to the content owners. This is in contrast to voice and data services where much of the income remains within the operator. However, in the increasing competition for customers, if adding low-margin IPTV to service bundle enable the telecoms to reduce customer churn, and thereby keep them paying for voice and data services, then it might be a viable strategy none the less. There is also room for new and innovative services within video that may change TV in the same way as new features in VoIP and IM services are revolutionising voice. Just like with VoIP, operators

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[55] LightReading (2006d) and Telecoms.com (2007b) question whether IPTV will become a significant incremental profit stream for telecoms in the foreseeable future. While this scepticism may prove well founded, both point out that if offering IPTV as a part of a broadband service bundle can keep subscribers (i.e. reduce churn) then it may still be worthwhile.

will in this process face competition from traditional video and TV distributors they are trying to steal customers from, but also from "nimble media companies, such as the peer-to-peer driven Venice Project (see below) that may try to "disintermediate" the telecoms by providing their own video services via the open Internet, rather than over the managed networks of the telecom operators" (LightReading 2006d). This section will analyse the technical characteristics of audio / video services with the aim of identifying distinctive features in comparison to more traditional provision of audio, video and TV.

2.8.1. Coding

The most widely used audio standard today is the Compact Disk (CD), which uses 16 bit pulse code modulation at 44.1 KHz with two stereo channels. This gives a transmission rate of 1.35 Mb/s and a storage requirement of 607.50 MB for one hour of audio. Video in the European Phase Alternating Line (PAL) standard uses 24 bits per pixel and 25 frames per second. Assuming no compression and a resolution of 640 x 480 pixels, result is a stream of 175.78 Mb/s and a storage requirement of 77.25 GB for one hour of video. For high-definition television this requirement must be increased by a factor 5.33 (Halvorsen 2001). However, most playback applications use a compression codec like moving picture expert group (MPEG). MPEG-1 strives for a data rate of about 1.2 Mbps whereas MPEG-2 is targeted for bit streams up to 40 Mbps. The current DVD standard uses MPEG-2 and has an average video bit rate of 3.5 Mbps and a maximum bit rate of 9.8 Mbps. Including system overhead, the maximum rate of combined elementary streams (audio + video + sub-picture) is 10.08 Mbps (Halvorsen 2001).

2.8.2. Compression

Compression technology is an integral component of digital audio / video transmission as well as an active field of research, where the goal is to reduce the number of bits that are required to represent the original content. There are several compression standards to choose from, of which standards from the Moving Expert Group (MPEG), International Telecommunication Unions Telecommunications Standardization Sector (ITU-T), and Microsoft Windows Media are most widely used.

The required bandwidth for encoded content has been constantly dropping in the past decade. In fact, over the past ten years, the bandwidth required for video has been halved every three years

(Karyabwite 2004). Although improving fast, there has been an inherent lag in market adaptation of advanced coding in wide-scale TV services, as compared on the Internet, due to non-upgradeable hardware decoders in set-top boxes, which mainly have been MPEG-2 to this day.

None the less, MPEG-2 encoded broadcast TV in standard definition has dropped to around 3 Mbit/s and MPEG-4 / H.264 are expected to provide similar quality at 1,5 Mbit/s (Alcatel 2004). High definition TV in MPEG-2 requires roughly 15 Mbps while MPEG-4 is down to roughly 8 Mbit/s, and is expected to drop further (Simpson 2006). With bandwidth requirements going down and access network transmission rates increasing, the previous delivery gap has been bridged, enabling IPTV.

Advancements in coding have not only resulted in lower bandwidth but also more advanced functionality. New codecs such as MPEG-4 include functions such as media objects, where parts of content displayed simultaneously on the screen can be changed, allowing everything from simple subtitle functions to changing background or textures. However, the ability of an IPTV service to offer advanced functionality is not only determined by the coding standard used but rather by combined support for functionality at all levels of the value chain, from set-top box, auxiliary systems (middleware), servers, to the content production.

2.8.3.   TV Broadcasting

The main functionality of most current IPTV systems is providing customers with traditional broadcast TV. TV Broadcast Servers are real-time servers of linear content, which take TV channels as input and stream them out to a transmission network. There is no fixed limit to the number of channels which a server can transmit but both hardware and transmission networks have upper limits. The source of the input signal to the broadcast server limits the complexity of the IPTV broadcast services, e.g. if input signals are from satellite and do not provide selection of subtitles.

An important issue in broadcasting is sharing of server resources. If the system supports multicasting the broadcasting server only has to output one video stream pr. broadcast channel and the transmission equipment generates extra copies at the edge of the network. Alternatively, if the system only supports unicasting, the server has to output one stream pr. viewer and transmit them individually through the transmission

network. If we consider the case of a broadcasting server with 100.000 concurrent viewers of 30 channels, unicasting would require at least 100 – 200 Gb/s in throughput while multicasting would only require 30 - 60 Mb/s (0,03-0,06 Gb/s). Currently multicasting support is only supported within managed IP networks and not on the public Internet[56].

2.8.4.   *Video-on-Demand*

Increasingly, IPTV service providers are offering content on demand (non-linear). In contrast to broadcasting, the content is stored in encoded form on a storage server, from where users can find and select the content they want. VoD requires extensive storage capacity and higher throughput from the server and the transmission networks since all content is sent individually through unicast.

As a service enabler, VoD can be used to make additional content available (such as renting movies), providing existing content after initial broadcasting (e.g. watching content at a more convenient time), or to combine it with broadcasting to offer additional functionality (e.g. time-shifting and personal-video recoding). The additional functionality of VoD incurs higher requirements on content protection than broadcasting does and therefore VoD needs to operate within a digital rights managements system that guarantees rightful content usage.

2.8.5.   *Webcasting*

Webcasting servers are small brothers to commercial broadcasting/VoD servers. They stream video content, most often in low quality, over the public Internet for viewing on a computer screen. These servers are most often operated without any auxiliary systems such as DRM and can not be said to offer substitute or competitive services to commercial IPTV. However, if combined with P2P technology it is possible to offer commercial VoD/broadcasts over the public Internet to a limited extent, but then they are not considered as webcasting.

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[56] A research initiative called MBone or Multicast Backbone (Macedonia Brutzman 1994) tried to establish multicasting on the Internet through virtual multicast network based on multicast islands connected by multicast tunnels. While the project raised interest it did not become widely adopted.

2.8.6.   User Generated Content (YouTube)

YouTube is a popular free video sharing Web site which lets users upload, view, and share video clips. Technologically the concept is simple; a client/server architecture that utilizes Adobe Flash technology to eliminate the need for separate add-on codecs or third-party video players when viewing clips. Founded in February 2005 the company was named "invention of the year" in 2006 by Time Magazine and acquired by Google in October 2006 for $ 1.65 billion. According to a July 16, 2006 survey, 100 million clips are viewed daily on YouTube, with an additional 65,000 new videos uploaded each day. The site has almost 20 million visitors each month[57].

Despite this enormous success, Gartner (2006) predicts a peak in user generated content in 2007 and then a slight decline. While this will mostly affect the number of active blogging sites, which the company estimates to be around 100 million at the end of 2006, the fall of the "hype" is likely to reduce the amount, and nature of current user generated video sites. One of the reasons for the foreseen changes to the current user driven pages is the lack of viably implemented business models, i.e. revenue streams that can match the incurred cost. In this respect Forbes (2006) estimates that YouTube, which is streaming 40 million videos and 200 terabytes of data per day, may be paying as much as $1 million a month for transmission but did prior to March 2006, not have any revenue streams.

2.8.7.   VodCasting / PodCasting

Vodcast is a term used for the online delivery of VOD content via syndication[58]. The term stems from audio-based podcast and refers to content distribution of subscription content through a Really Simple Syndication (RSS) feed. This method of aggregating content e.g. on IPods for later consumption has become popular on the web and lately video blogging has been moving in this direction. The concept has also

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[57] See http://en.wikipedia.org/wiki/YouTube

[58] Web syndication (also called publish/subscribe service) is a method of pushing and filtering content notifications. The major difference between the web syndication and the traditional web access is that users subscribe to the content they are interested in advance and get it pushed to them upon availability. An example of syndication standards is Really Simple Syndication (RSS).

been taken a step further by using peer-to-peer networks to take care of the content distribution.

2.8.8. Peer-to-Peer TV / Joost

After tremendous success with Kaaza and Skype, entrepreneurs Janus Friis and Niklas Zennstrom have started a new project aimed at distributing legal TV content with the help of peer-to-peer networks. After being launched as the "The Venice Project" the name has been changed over to Joost. The application is currently in beta-testing but a screen shot of the latest stable version, from February 2007, is depicted in Figure 22.

Figure 22, Screenshot of Joost / P2P streaming TV

The aim of Joost is to develop "secure P2P streaming technology that allows content owners to bring TV-quality video and ease of use to a TV-sized audience mixed with all the wonders of the internet." All the content on The Venice platform is to be provided by content owners directly and will be protected by commercial level encryption, compliant with the Digital Millennium Copyright Act (DMCA) framework. The service will be supported by advertising and may even include a pay per view element.

2.8.9. Auxiliary Systems

In a commercial environment, several auxiliary systems run in parallel to coding and transmission within an IPTV service. Among these are subscription management, billing, digital rights management (DRM),

metadata etc. In contrast to traditional broadcasting, where all these functions were designed as pre-processed passive information within the data, all of the auxiliary systems in IPTV can be interactive. This allows customers to change subscription, perform instant purchases (micro payments), interact through searching, voting etc.

In general, the more advanced features an IPTV system is designed to offer, the more complicated the auxiliary system becomes. This is one competence area where telecommunication operators usually have more experience than traditional broadcasting operators, e.g. in designing and deploying new communication services and operating interactive distributed subscription and billing databases. An example could be implementing betting during a sports event.

2.8.10. Set-top boxes

In its most simple form, a set-top box is a decoder, a piece of hardware that takes in IP packets with encoded video, decodes the content and then displays it on a television. However, most set-top boxes today are mini computers running embedded software that also facilitates user interaction through a graphical user interface. In addition to user interactivity and representation, a set-top box communicates with auxiliary systems and may include some local recoding functionality.

In modern households, several other devices than set-top boxes (such as computers and PDAs) are capable of decoding and displaying video content. IPTV has the potential of moving over to these devices but only if the content is adapted to the characteristics of individual devices. This requires advanced DRM features, and support for transcoding or scalable video codecs.

2.8.11. Current deployment status

Despite positive reports of technological progress through research initiatives, industry feedback is more double-edged. Early reports from major operators were that "despite various attempts to enter the video business and complete the triple play, [they] have so far found success frustratingly elusive" (HeavyReading 2004). Equipment vendors also faces problems, especially with video. Oracle dropped out of the video server market and Alcatel was forced to change strategies after facing problems with its Alcatel 5959 Open Video Server. In response Alcatel initiated collaboration with software developer Microsoft to develop and integrate an IPTV solution into its infrastructure (LightReading

2005a). This strategy seems to be a success and recently the duo has been landing deals across the world, most recently with the Danish incumbent TDC that committed itself to Alcatel's 7302 Integrated Services Access Manager (ISAM) along with middleware from Microsoft (LightReading 2006c). TDC is not the first European carrier to choose Microsoft's IPTV platform. Deutsche Telecom, Telecom Italia, Swisscom, and BT Group have all committed to the same solution. Despite this high profile collaboration between the two absolute world leaders in infrastructure and software, it seems that the two are still 'ironing out problems' (LightReading 2006). In addition to incumbent-driven triple-play, FTTH entrants all around the world are deploying multimedia services on new infrastructures.

Analysis from Point Topic (2006b) show that the commercial IPTV customer base has doubled in the year to June 2006, from under 1.5 million to almost 3 million. Europe is the most important region for IPTV, with the strongest growth in subscriber numbers during the period. There have been a large number of service launches but the most successful in terms of paying customers are France Telecom with over 600,000 subscribers at the end of 2006 (LightReading 2007b), and Telefonica with over 300,000 (Point Topic (2006b). According to Seamundur E. Thorsteinsson, director of Iceland Telecom Research, the Icelandic incumbent leads in international comparison of IPTV adaptation, with almost half of all DSL customers also subscribing to IPTV. However, as pointed out by Telecoms.com (2007b) in their article "IPTV to be big but free" much of the uptake can be attributed to telecoms offering the service for "free" in a broadband service bundle.

Region	Number of IPTV subscribers ('000s)		
	H1 2006	H1 2005	H2 2004
Asia Pac sub total	987	612	408
Europe sub total	1505	521	436
Americas sub total	409	267	161
Other regions...............................	50	70	50
Total worldwide	2.950	1.470	1.055

Table 7, IPTV worldwide subscriber by region (Source: Point Topic 2006b)

2.8.12. *Future perspectives of audio / video services*

Much like VoIP, the consumption of digital audio and video content is soaring, but apparently without affecting the traditional audio / video services much. Computer based consumption of multimedia content

thereby seems to supplement rather than substitute broadcast TV (see Figure 23). However, as operators gear up to offer substitute services such as IPTV this is bound to change, although partly without users knowing that the transmission of the content is over broadband access networks. What viewers will be able to mark are the potentials of the back-channel that IPTV / broadband has in comparison to traditional one-way broadcasting. Development of interactive audio / video services that utilise two-way transmission and user profiling is in its infancy but according to Bill Gates, the founder of Microsoft, IPTV will dramatically change the appearance, consumption, and experience of TV or as he says "in five years from now, people will laugh at what we have now"[59].

ALL THOSE WHO WATCH ONLINE/ MOBILE VIDEO ONCE A WEEK OR MORE

None 1%
3%
20%
54%
23%

- I watch a lot less normal TV as a result of my online/mobile viewing
- I watch a bit less normal TV as a result
- I watch about the same amount of TV - my online viewing is extra
- I watch more TV because of my online/mobile viewing
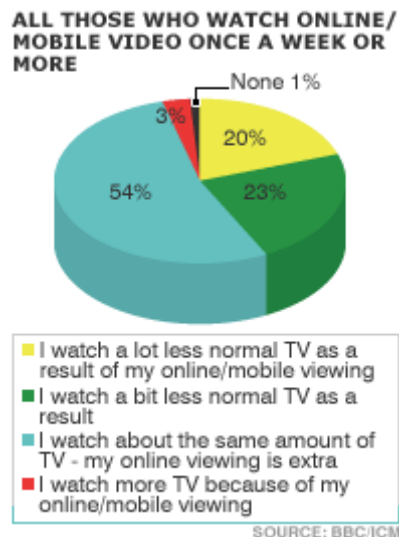
SOURCE: BBC/ICM

Figure 23, Effect of on-line viewing on traditional services (Source: BBC 2006)

Industry researchers are more sceptical about the potentials of IPTV as a "killer application" for broadband. Forrester Research has warned of low consumer interest and only moderate revenue potential for the technology in Europe, and predicts only one in four European xDSL/fibre broadband subscribers will have IPTV by 2016. Lars

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[59] Quote taken from Bill Gates at a panel discussion at the World Economic Forum 2007 in Davos. For more information see http://www.weforum.org/en/index.htm

Godell, principal analyst at Forrester Research backs this by claming that "Europeans are generally unwilling to pay much for TV content - and a discount scheme is needed to entice them to buy triple play. In a mature TV market, this means incumbents will need to price IPTV below competing cable and satellite TV services." This critical view on IPTV economics is supported by LighReading (2006d) and Telecoms (2007b) that rather foresee IPTV as a means of reducing churn rather than increasing profits.

Despite pessimistic forecasts, most European incumbents have committed themselves to IPTV. Among the most prominent are: Deutsche Telekom, France Telecom, Telecom Italia, Telefonica, BT, TDC, Swisscom, Iceland Telecom. While implementations vary, most incumbents used service delivery platforms[60] from Microsoft / Alcatel or France Telecom / Thomson. Allegedly, the Microsoft solutions uses a Windows Media codec, while the France Telecom solution uses MPEG-2. To persuade customers, most of these offering the set-top boxes required, as well as trial subscriptions, for free.

2.9.   *Deploying Multimedia Services*

Deployment of packet-based multimedia services is governed by the underlying transmission infrastructure. In the case of deployment over the general Internet there is no communication between delivery and transmission, while the two can be tightly bound when services are delivered within managed networks. This section will describe some of the properties of service delivery platforms.

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[60]   The term "service delivery platform" is not rigidly defined in literature but is used in this thesis to describe the software / hardware needed on top of transmission networks to offer multimedia services.
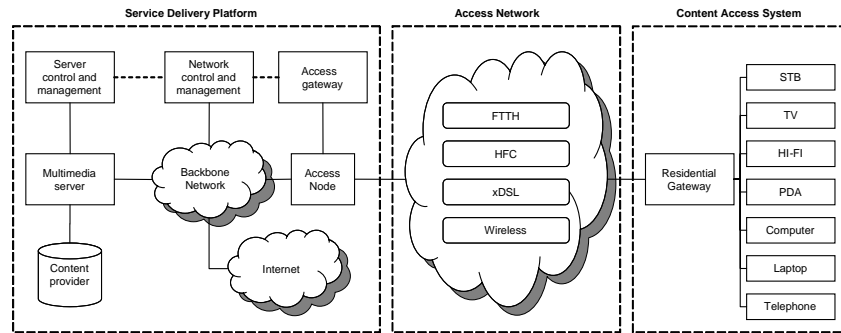
Figure 24, Overview of provisional components of multimedia services

2.9.1. *Service Development Platforms*

Service development platforms (often also called middleware)[61] constitute the software environment necessary for the creation of services for given infrastructure platforms. Service development platforms are either open / infrastructure independent or tightly tied to specific infrastructures. This interrelationship between service development platforms and infrastructure platforms is one of the important parameters when it comes to development of broadband services.

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[61] Rao et al. (2006, p.24) describe middleware as 'a horizontal layer residing on top of a set of networked computers, providing a set of distributed services with standard programming interfaces and communications protocols, even though the modelling host and OS may be heterogeneous'.

```
  ┌──────────────┐       ┌──────────────┐
  │ Application  │       │ Application  │
  └──────┬───────┘       └──────┬───────┘
  ┌──────┴──────────────────────┴───────┐
  │                 API                  │
  ├──────────────────────────────────────┤
  │            Middleware                 │
  │    (Distributed System Services)      │
  └──────┬──────────────────────┬────────┘
```

Platform Interface   Platform Interface

```
  ┌──────────────┐       ┌──────────────┐
  │ Infrastructure│      │ Infrastructure│
  │ Platform      │      │ Platform      │
  │ - OS          │      │ - OS          │
  └──────────────┘       └──────────────┘
```
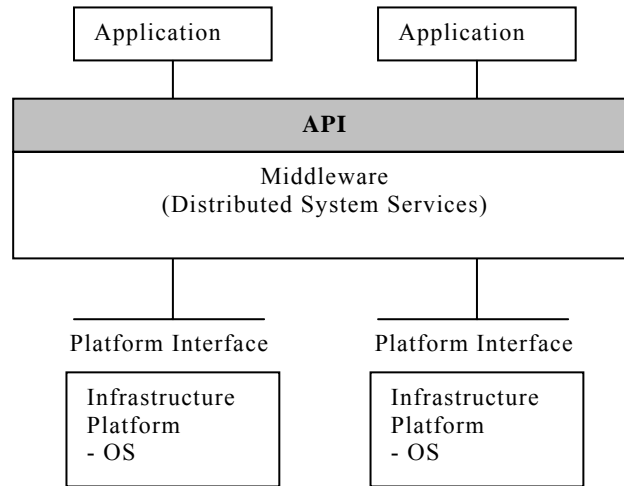
Figure 25, Use of Middleware
Source: Bernstein 1996

To this day, most residential broadband networks have been designed to
offer simple IP based transmission services. Applications have resided
at the edge of the network and have not required support from the
network infrastructure. However, emerging residential broadband
networks are increasingly offering QoS guarantees. In contrast to early
multimedia implementations where Applications Programming
Interfaces were specific to each vendor equipment and specific
implementations, SDP provides heterogeneous API that ease
development and porting of services between infrastructures. The
Parlay and Parley X are examples of SDP for telecommunications.
Currently there is no single SDP for all multimedia services but ITU-T
(2006) is working on a SDP for IPTV. The aim is to provide broader
interoperability between IPTV terminal and IPTV system. This is
accomplished by specifying a set of APIs that application vendors can
conveniently use to develop new services and applications without
paying attention to specific details of the underlying platforms (ITU-T
2006).

2.9.2. *Standardisation*

In contrast to the strictly defined format and characteristics of
traditional services (i.e. PSTN and broadcast TV) multimedia services
lack an overall standardized framework for end-to-end delivery. Only a
few aspects of such a system have been deeply studied and

standardized, and a lot of issues, new to both the broadcasters who produce the content and to the operators ensuring its delivery, have yet to be addressed (Fleury 2005). The result is a broad diversity in implementation where most deployments are based on proprietary solutions. This has been identified as a major incubator to adoption and development of IPTV (Tadayoni and Sigurdsson 2006; 2007).

Realising the negative effects of market fragmentation and lack of interoperability, large players from different areas in the value chain have teamed up to produce a holistic solution. One of the most promising platforms is Microsoft IPTV, where Microsoft as a server and middleware provider has teamed up with Alcatel, a dominant infrastructure provider. Repeated delays and implementation problems within the Microsoft IPTV platform alone serve as a reminder of the colossal task of standardising IPTV.

Standardisation projects are further from materialising but important pieces of the puzzle are on their way e.g. through MPEG-21, which defines a framework for the creation, delivery and management of multimedia content, Multimedia Home Platform (MHP) which standardises middleware and representation of content. Traditional standardisation bodies such as ITU and IETF are also turning their attention towards IPTV as mentioned before. On EU level there is however not a general consensus around public involvement, as a recent EU Communication concludes "that mandating EU-wide standards [...] would not contribute significantly to the growth of interactive digital television in Europe, and could have significant negative effects" (EU 2006).

When evaluating the potentials of standards for multimedia services, David Clark of MIT has developed a theory that he calls "the apocalypse of the two elephants", as illustrated in Figure 26. This figure shows the amount of activity surrounding a new subject. When the subject is first discovered, there is a burst of research activity in the form of discussions, papers, and meetings. After a while this subsides, corporations discover the subject, and the billion-dollar wave of investment hits (Tanenbaum 1996).

According to the theory it is essential that a standard is written in the trough between the two "elephants". If they are written too early, before the research is finished, the subject may still be poorly understood, which leads to bad standards. If they are written too late, so

many companies may have already made major investments in different ways of doing things that the standards are effectively ignored.
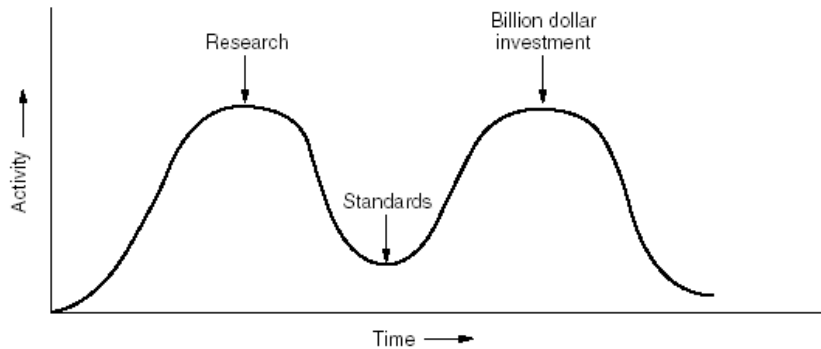

Figure 26, The apocalypse of the two elephants
Source: Tanenbaum 1996

When applying the theory to current multimedia service deployment it highlights a pressing need for standardisation in IPTV prior to imminent investment. While most provisional issues of VoIP have been addressed, e.g. with SIP (See Section 2.6), there a lack of holistic standardisation framework for IPTV is likely to become a roadblock in development.

2.9.3. Interactivity

Interactivity has been hailed as one of the major strengths of IPTV, where the return channel of the infrastructure platforms on which it is deployed allow the customer to communicate with the service provider. Interactivity can be divided in levels based on how deep into the system it goes. The simplest level is "basic interactivity" that e.g. allows users to select and change channels in IPTV. In some of the infrastructure platforms such as DSL, there is only a limited amount of network bandwidth and therefore basic interactivity goes back to the DSLAM where it gets processed. Although limiting as such, this (as well as intelligence in set-top boxes) can be used to report viewing habits and conduct popularity measurements in IPTV. The next level of interactivity is "VCR-like" where viewers can break free from linear viewing by pause, rewind, and fast-forward. Implementing these functions puts a much heavier burden on the video delivery system and network transmission since the nature of the viewing goes from

broadcasting to VoD. The last level of interactivity is "Content-oriented interactivity" where users are given the ability to respond directly to the content itself. This can be everything from responding to an advertisement to controlling the outcome of a program.

Despite being a gateway to new and advanced services, interactivity in IPTV represents possibility rather than a built-in feature. To offer advanced functionality, all the equipment from the user to the production studio has to support the same features. This will require a tighter interaction and cooperation between different actors of the value chain. Until IPTV grows in market share, content providers are not likely to put a lot of efforts into supporting interactivity, creating a hen-and-egg problem. In the meantime, telecom operators are more likely to use their core competences in ICT to focus on interactive set-top box functionality where games, betting etc. can be conducted without integration with content.

2.9.4.   DRM and Conditional Access (CA)

Digital Rights Management (DRM) systems include a number of technologies, which are used to protect the copyright of digital content. For example, the Open Mobile Alliance (OMA) defines the scope of their implementation of DRM "to enable the controlled consumption of digital media objects by allowing content providers to express usage rights, e.g., the ability to preview DRM content, to prevent downloaded DRM content from being illegally forwarded (copied) to other users, and to enable new business models with super distribution of DRM content".

In the broadcast world the protection of content rights is ensured using Conditional Access (CA) systems. CA systems were first implemented for analogue satellite and cable networks. The aim was to establish a business model for the provision of Direct To Home (DTH) satellite services and to be able to offer premium pay TV, by excluding the non-payers. CA systems have developed further in the digital broadcasting and are also used for digital terrestrial broadcasts.

2.10. *Demand Forecasting*

While literature provides an abundance of traditional telecommunications demand forecasting models[62], providing "successful modelling of new markets has been limited" (Fildes 2002). Maxell (1999) calls broadband market analysis "structured guessing" and blames the lack of success on the state of flux that technological development is in and the "random walk technology often takes on its way to mature markets". He argues that the "Internet as an enormous commercial network clearly is an accident.. and that the voice network was not intended as a data network" to stress his point of uncertainty in long-term planning (Maxwell, 1999, p. 263).

Despite Maxwell's self critique, his analysis and resulting projections describe the evolution of the residential broadband market reasonably well. He foresaw a stepwise development of three phases where the first phase would provide web based services over up to 7 Mbps ADSL. The second phase would be characterised by introduction of Video on Demand over up to 26 Mbps extend DSL (using Fiber-to-the-Node). The final step would bring Fibre-to-the-Home (FTTH), justified by the demand for High Definition TV (HDTV).

Using a historical approach, Eldering et al. (1999) showed that the speed at which data can be transmitted over twisted wire pairs, using analogue modems, has doubled every 1.9 years. Since then, his predictions have also held for DSL technology and according to an updated regression by Myken (2006), predicted transmission rates at the end of 2006 are around 20 Mbps. Given demographic disparity, the points around the trend-line of Figure 27 can be seen as averages on a curve that describes demand levels for a broad range of possible subscription packages. Individual demand is again function of exogenous parameters such as family size, age, etc.

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[62] In 'Telecommunications demand forecasting – a review' Fildes et al. (2002) provide a good overview of academic methods, while Stordahl (2003a) and more generally a special issue on 'Telecommunications Forecasting' in Teletronikk (2004) provide a more industry oriented overview.
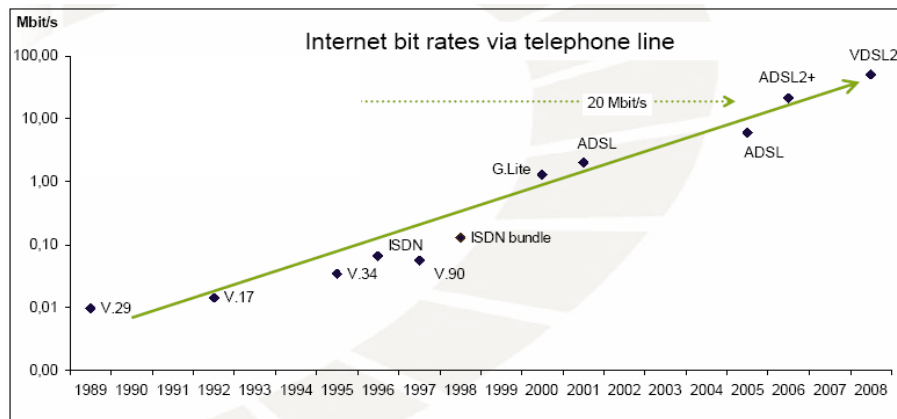
Figure 27, Historical transmission capacity over twisted copper pairs
Source: Myken (2006)

Alcatel, a leading DSL and FTTH equipment provider, builds on Maxwell's concept of a stepwise evolution but defines four tiers, each defined by aggregating requirements of services demanded by typical households. According to this approach, tier 4, which is the near-future situation, requires one HDTV, 1-4 standard definition TV streams, 1-2 VoIP streams, in addition to data services. These service requirements results in an aggregated household demand of 20 Mbps. That estimate is confirmed through industry research, by Scott Clavenna, Chief Analyst at Heavy Reading (Heavy Reading 2004), who calls "twenty the magic number". According to him, "operators worldwide are finding that a minimum of 20 Mbits/s is required to enable a compelling triple-play offer over DSL."

Tier	Service Description	Bandwidth (BW)	Technology	Reach
Tier 1		512 kb/s	ADSL2, READSL2	6 km
Tier 2		3-6 Mb/s	ADSL2	3 km
Tier 3		10 Mb/s	ADSL2+ MPEG-2	2 km
Tier 4		20 Mb/s	ADSL2+ MPEG-4	2 km

Figure 28, Evolution of aggregated services demand
Source: Alcate (2004b)

When using the method of aggregating service demand, two contrasting development trends have to be considered, i) increase in number and usage of multimedia services demanding increased transmission capacity, ii) advances in coding and transmission reducing the required transmission capacity and relaxing QoS requirements. This development is depicted in Figure 29 which, in addition to illustrating the contrasting trends, aggregates estimated bandwidth requirement per household. The Danish incumbent uses this method and estimates a near-future plans of 21 Mbps in 2008 (Nielsen 2005).
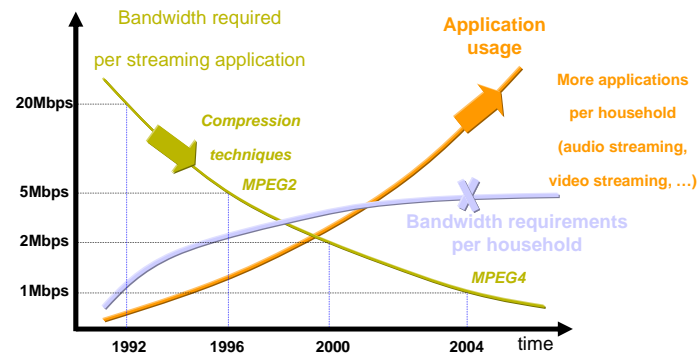
Figure 29, Main trends in bandwidth provision and utilisation
Source: Karyabwite (2004)

For the purpose of the techno-economic model developed in Chapter 4 this thesis defines four service profiles that span the expected subscription packages for near-future broadband connectivity.

2.10.1. Quality of Service Requirements

Table 8 provides an overview of the QoS requirements of the multimedia services considered in the project.

Category	Service	Download	Upload	Rate	Delay	PLR	Flow	Type
Voice	PATS	64	64	CBR	150	1%	two-way	unicast
	ECS	30	30	rt-VBR	400	3%	two-way	unicast
Audio	Audio-conferencing	128		rt-VBR			two-way	multicast
	Audio-on-Demand	256		rt-VBR			one-way	unicast
	Broadcast Audio	128		rt-VBR			one-way	multicast
Video	Broadcast SDTV @ MPEG-2	4.000		CBR			one-way	multicast
	Broadcast HDTV @ MPEG-2	15.000		CBR			one-way	multicast
	Broadcast SDTV @ MPEG-4	2.000		CBR			one-way	multicast
	Broadcast HDTV @ MPEG-4	8.000		CBR			one-way	multicast
	Video-on-Demand SDTV	2.000		CBR			one-way	unicast
	Video-on-Demand HDTV	8.000		rt-VBR			one-way	unicast
	Video-telepony	384	384	rt-VBR			two-way	unicast
	Video-conferencing	384	384	rt-VBR			two-way	multicast
Data	File Transfer	1.000-5.000		UBR			one-way	unicast
	WWW	256-1.000		ABR			one-way	unicast
	E-mail	1.000		UBR			one-way	unicast
	Peer-to-peer	5.000		UBR			two-way	unicast
	Instant Messaging	10		ABR			two-way	unicast
	Gaming-on-Demand	1.500		CBR	100		two-way	unicast

Table 8, Types and QoS requirements of multimedia services

2.11. Case study: Skype

This section provides a case study of Skype, a well known telecommunications services that uses peer-to-peer technology to provide Voice over IP (VoIP) in an efficient manner. The goal of the study is to demonstrate the disruptive benefits of peer-to-peer based content distribution using empirical data and to highlight how new and emerging types of multimedia services have the possibility of impacting residential broadband.

2.11.1. Overview

In August 2003, Skype (Skype 2006) launched a peer-to-peer network to offer a voice over IP service. The service runs as a software application, downloadable for free after registration. Initially the service provided free voice calls to other registered Skype users but since March 2005, SkypeOut and SkpyeIn functions have been added to receive and/or make calls to regular phone subscribers in the Public Switched Telecommunications Network (PSTN). Both features are sold at a charge as well as a voicemail service, forming a basis for revenue.

In contrast to the hardware infrastructure demanding PSTN, Skype uses peer-to-peer technology to build up a global service delivery platform.

Skype has local PSTN termination agreements in most countries but uses the general Internet to carry traffic to local/nearest Points of Presence. For the operator the main competitive strengths of Skype in comparison to the PSTN are low infrastructure costs and low or non-existing transmission tariffs. While there are several drawbacks for customers to use Skype in comparison to PSTN[63], free computer-to-computer tariffs and considerably lower international tariffs apply[64].

The fast paced growth of Skype provides an impressive example of how innovative technologies such as P2P can change the foundation of a whole industry. Moreover, combined with the nature and properties of the Internet, Skype has managed to spread beyond national boundaries to form a truly global service. In September 2005, Skype was acquired by Ebay in a several billion deal. Although no official statistics exist, estimates suggest that the business scope of Skype was in 2005 roughly:

- more than 50 million registered users
- more than 3 million users being online with Skype at the same time at daily peak busy periods
- 42% European users, around 12% in North America and more than 20% in Asia
- 40 million voice call minutes being served via Skype per day, which corresponds to approximately 30 000 calls in parallel in the mean over a day.

<div align="right">(Based on Sigurdsson et al. (2007))</div>

Although merely serving as rough estimates, and only partly confirmed by other sources (Vollenweider et al. 2005; Sullivan 2005), these figures illustrate that Skype has undoubtedly established itself as one of the most popular VoIP services in the World.

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[63] These e.g. include fluctuating QoS, no location information, restricted Intelligent Networks services.

[64] Comparison of international tariffs between the Danish incumbent TDC and Skype in April 2007 revealed an average 560% higher tariff for calls originating in Denmark destined to the Nordic countries. Calls to the United States were 1260% more expensive and calls to Germany 327%.

2.11.2. Peer-to-peer network structure and technical aspects

Skype uses a two-level decentralised peer-to-peer overlay network for searching the user directory and call setup. The details of the peer-to-peer protocol are not public but according to a study by Baset and Schulzrinne (2004) some of the main properties are:

- Skype uses a wideband codec covering a frequency range from 50 – 8 000 Hz. This may go well beyond the sound quality of the standard PSTN, which is restricted to a 300 – 3400 Hz band. The voice codec usually generates an IP data flow of 30 – 40kbit/s, which may be increased up to 130 kbit/s for improved quality, when the access rate and capacities on the transmission path allow for a higher rate.

- Skype uses 256-bit symmetric end-to-end encryption based on AES (Advanced encryption standard). Encryption keys are negotiated under a public key encryption based on 1536 or 2048 bit RSA. This also goes beyond usual regular phone calls, although a comprehensive assessment of the security level is difficult for a proprietary protocol.

- Firewall and NAT traversal is achieved, which makes Skype available even through protected enterprise networks. Skype seems to use a variant of the STUN protocol (Rosenberg et al. 2003) to determine, whether a user is located behind a firewall and then tries to use open TCP ports via a relay station for connections over a firewall. An arbitrary peer from the network pool is chosen as an intermediate relay station.

- Skype supports instant messaging and conferencing. In addition, video conferencing can be offered.

2.12. Case study: TVAvisen

This section analyse the potentials of emerging video distribution service utilising peer-to-peer overlay networks using empirical data gathered at the Danish National Broadcaster (DR). The traces used were collected from the web-based news on demand service "TV Avisen" throughout April 2005[65], which according to The Danish Media Organisation is the

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[65] The author would like to thank Johan Winbladh from the Danish Broadcasting Corporation DR.dk for his assistance in gather the empirical data for the study.

most popular web service in Denmark. These traces represent roughly half a million successful requests and incurred transmission of 4.7 TB of data, see Table 9.

Table 9, Broadcasting statistics

Log period	1 April 2005 - 30 April 2005
No. of successful requests	476.295 requests
Total no. of bytes sent	4,70 TB

2.12.1. The Challenge

Even with significant technological advances, a common phenomenon of streaming video applications nowadays is repeated freezing, buffering and defects (Sripanidkulchai et al. 2004a, 2004b). As a result, streaming applications are limited, mostly to live broadcasting where the users are willing to sacrifice the quality in order to get timely information. Even in cases when high quality distribution is technically available, the investment and the transmission cost of offering large scale high-quality video content render them unfeasible.

2.12.2. Motivation

This study is motivated by the desire to develop a content distribution system where users can subscribe to content and the quality they desire (i.e. uses syndication). The content gets delivered through a peer-to-peer network and the user gets a notification as soon as he/she can consume the content in a problem-free fashion. If the user does not wish to consume the content immediately upon notification, the content gets stored locally for later consumption. In the TV Avisen example this would mean that the Danish Broadcasting Corporation could offer high quality to new subscribers as soon as it becomes available, for a fraction of the cost of traditional server-based streaming.

2.12.3. The Basic Concept

The concept builds on Sigurdsson (2005) where the author proposed Server Initiated Peer-to-Peer (SIP). The basic idea of SIP2P is to build a peer-to-peer overlay network capable of distributing high quality multimedia content that end users have subscribed to in advance. The concept is based on changing the role of the streaming server in the current service to a seeding server, which transmits a few copies of the content to a subset of supernodes and then only communicates control

messages between participating peers that take care of transmitting the actual content among themselves. Instead of deploying expensive high capacity servers as in traditional streaming services, SIP2P suffices with low capacity seeding servers to disseminate a few copies of legal content into a P2P network. Peers can then be motivated with monetary rewards for sharing their, often underutilised, resources to distribute the content.
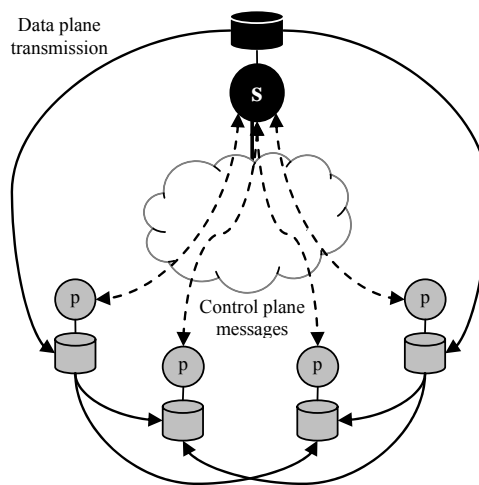

Figure 30, Conceptual Model of Server Initiated Peer-to-Peer (SIP2P)

2.12.4. *Experimental Results*

The author has already in (Sigurdsson 2005) shown in an experimental study that in a VoD service, assuming a $5 rental price, that the possible discount/profit per rental of SIP2P over traditional streaming services is 15-18% (Sigurdsson 2005). However, the assumption was that content is free to the consumers and the goal to examine cost saving/increase in quality for the service provider. Under these assumptions DR is subject to capital expenditure for new hardware and the operational expenditure related to transmission cost, both linearly related to maximum capacity and called Total Cost of Ownership (TCO).
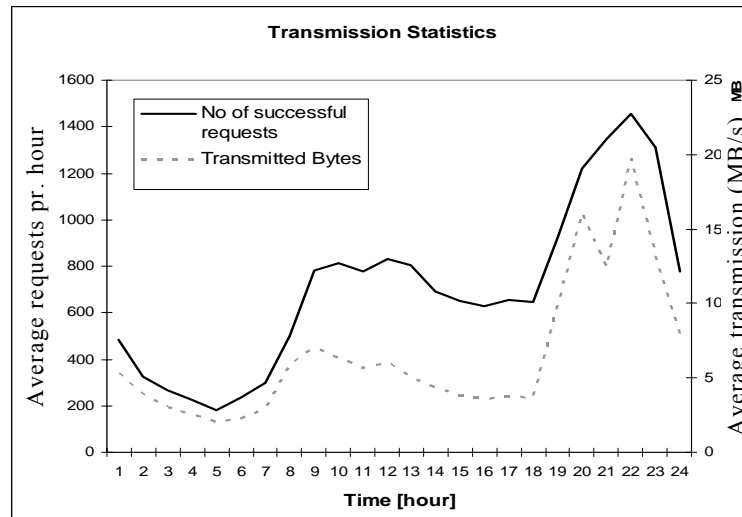
Figure 31, Transmission Statistics for "TV Avisen " a popular news on demand service in Denmark
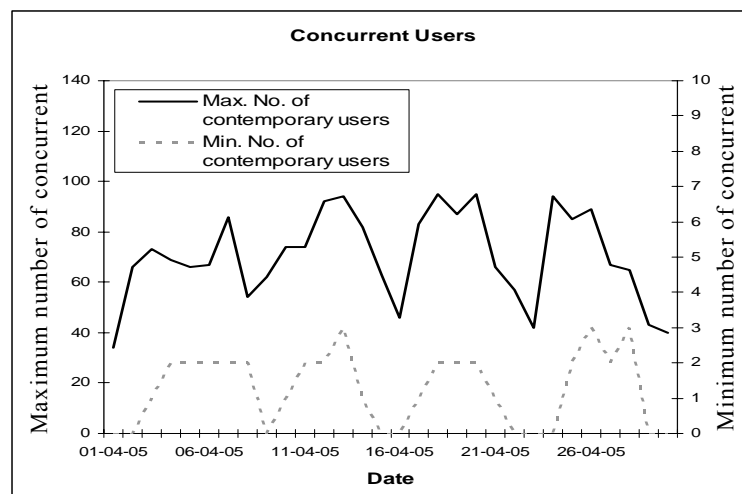
Figure 32, User Statistics for "TVAvisen" a popular news on demand service in Denmark

Figure 31 and Figure 32 illustrate transmission and user statistics for the period. Dividing the transmission rates by average number of concurrent users throughout the period yields an average streaming rate

of 240 kbps. Assuming 2 Mbps streaming rate required for high quality service, DR could expect an eightfold increase in capacity, which again can be interpreted as an eightfold increase in TCO.

This can be compared to 2 Mb/s streaming service using SIP2P. Assuming a 10% seeding percentage and neither an inducement factor nor opportunity cost for participating peers. A comparison of the relative TCO for the three scenarios is depicted in Table 10.

Table 10, Service Cost Comparison

	Traditional	Traditional	SIP2P
Rate	240 kbps	2 Mbps	2 Mbps
Relative TCO	1	8,3	0,9

The experimental study suggests that DR could serve the same number of customers as currently, while improving the quality by an eightfold higher streaming rate at 90% of the cost.

Regarding future directions in the convergence of radio and TV broadcasting with Internet applications, an interesting field trial has been carried out by the BBC for testing their integrated media player (iMP) (BBC 2006). They used a peer-to-peer networking approach to make a part of their TV and radio programme available for watching and viewing for seven days after the broadcast transmission date. The software included a digital rights management system that made downloads expire after seven days and to invalidate further transfers of the data via email or disc.

A field trial included 5000 registered users from UK in a time frame from November 2005 until February 2006. Several hundred hours of TV and radio programme were offered for P2P download. While being restricted to rights-cleared productions, the offered programs appeared to be attractive to the involved users.

The field trial gave BBC hints about on-demand user behaviour. They reported shifts being observed during the field trial regarding the popularity of niche programmes and peak viewing hours as compared to usual assumptions. For the TV viewers and radio listeners the opportunity of on-demand selection according to individual preferences

can be an attractive next step towards an integrated IPTV and multi media future.

2.13. Summary

This chapter has analysed development and deployment of packet-based voice, video, and data services. The study began by challenging conventional definitions of broadband that only use transmission speeds to characterise broadband. Instead the thesis argues that broadband should be defined dynamically through the services which it is to carry. These services are constantly evolving and thus the transmission requirements and ultimately the definition of broadband are bound to change as well.

To understand the nature and development of multimedia services the chapter brushed up the fundamentals for packet-based networks and the transmission properties that govern their use. The study highlighted the difference between the provision of services over the general Internet which only supports one "best effort" class of service in comparison to managed networks that can support a wide range of Quality of Service parameters for individual services and applications.

When analysing service types the analysis shows that service selection and traffic volume has been growing fast, but apparently without affecting traditional content distribution. This indicates that broadband services have rather been supplements than substitutes to e.g. PSTN and broadcast TV. As an example there were 25 million worldwide paid VoIP subscriptions at the end of 2005 as compared to roughly 1.2 billion PSTN subscriptions. However, when considering the disruptive nature of Instant Messaging and Peer-to-Peer networks, broadband services have greater potentials. This becomes evident when looking at the roughly 350 million active IM users and the dominance of P2P traffic in backbone networks.

In addition to foreseen success, the nature of multimedia services is likely to change. The distinction between data services and other types of services is likely to disappear as applications increasingly interweave different media streams in an interactive manner. Measures by operators to fully capture the value and service delivery of all of these applications are not likely to work, and therefore network access providers have to embrace disruptive services and be prepared to tailor transmission offerings to needs, rather than trying to steer service development into predefined business models.

Many incumbent operators in Europe are gearing up to offer new multimedia services, most notably by IPTV. Despite great efforts by equipment vendors and high profile industry collaborations, there are several roadblocks on the path of IPTV. These range from the lack of an overall standardisation framework, low margins, to the threat of applications competition from the Internet. For success, operators have to utilise the back-channel that broadband provides to offer interactive content through innovative business models.

To evaluate the effect of emerging services and technologies on transmission requirements the thesis studied available methods of demand forecasting. Using extrapolation of historical data the transmission requirements of multimedia services for an average household were estimated to increase from 20 to between 50 and 100 Mb/s in the coming 5 years. However, at any point in time this nominal value only indicates a point in a distribution that can vary greatly depending on individual demand, demographics etc.

Chapter 3

Residential Broadband Networks

This chapter analyses available deployment strategies for broadband access networks required to support the near-future transmission requirements of converged voice, video, and data services. The approach of telecoms using Digital Subscriber Line technology is compared to entry strategies based on Fibre-to-the-Home. The aim is to study the technological characteristic of DSL and FTTH that affect deployment and selection of deployment strategies.

3.1.   Introduction

Despite technological advancements the general rule of existing copper-based access networks remains that maximum transmission speeds decrease with increased copper cable distance. This limits provision of broadband services over the current copper infrastructure by reducing the customer group that can be offered higher transmission speed. As a consequence, operators are looking at ways of upgrading or replacing "bottleneck" infrastructures.

All of these strategies are based on replacing parts of the copper wire with optical fibre. Decreasing the copper length increases the possible transmission capacity but requires civil work and equipment outside the local exchange. The aim of this chapter is to analyse available evolutionary paths for upgrades in existing residential areas (often called brownfield) as well as new deployment in greenfield scenarios. The study

focuses on structural composition, equipment and cabling requirements, and the resulting transmission capabilities.

The strategies will be presented as solutions for two distinct types of operators, first for Incumbent / Competitive Local Exchange Carriers (ILEC/CLEC) that deploy fibre to a node and use Digital Subscriber Line (DSL) technology over the remaining copper loop. The second is presented as an entry strategy for Energy Utility Companies that deploy fibre all the way to subscriber's premises[66].

3.1.1. Methodology and research question

Which migration or replacement strategies are available for telecom operators of the current copper local loop infrastructure, in comparison to entrants, to support future multimedia services?

3.2.   Literature Study

Most current residential broadband networks were designed to offer limited capacity "best effort" data transmission. With the foreseen addition of voice and video services in the broadband service portfolio, operators have to redefine their role and redesign their networks[67]. The migration strategy chosen not only affects the technical performance of the network, but can also have profound effects on the development and competition in service provisioning.

3.2.1. List of contributions

- *Tadayoni, R. and Sigurdsson H.M. (2007) Drivers and barriers for development of alternative broadband. Accepted for publication in Telematics and Informatics, Elsevier.*
  Alternative broadband infrastructures are emerging and developing fast. These networks are based on different technologies and offer assorted services, applied through

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[66] In reality this strategy is also an alternative for incumbents but as the chapter will demonstrate, telecoms tend to chose a different type of FTTH networks, based on passive optical networks.

[67] As an example of this transformation is reported in TVinternational (2006) which reports that Danish incumbent TDC 'is embarking on a major network upgrade to enable most of its system to support a triple play of video, broadband and telephony'.

various organizational structures, using diverse business models. Due to their alternative nature, these emerging infrastructures are operated on other premises than within existing operators and face different potentials and challenges in their operations.

This article uses four detailed case studies from Denmark to identify the technological, economic and political/regulatory drivers and barriers of alternative broadband infrastructures, including the role of the government in fostering their existence.

- *Sigurdsson, H.M. (2006) Service Differentiation in Residential Broadband Networks, Revised version of paper originally published in proceedings of CICT's International conference on "VoIP, Potentials and Challenges, Drivers and Barriers", Copenhagen, Denmark.*
  This paper discusses the role of network access providers in multipurpose packet-based access networks and the available migration strategies for supporting multimedia services in digital subscriber line (DSL) based residential broadband networks. Four possible implementation scenarios and their technical characteristics and implications are described. To conclude, the paper discusses implications of alternative strategies on two currently experienced trends of i) vertically integrated business models and ii) open access.

- *Thorsteinsson, S.E., Richardsson, N. and Sigurdsson, H.M. (2003) Home Area Networks, Yearbook of the Association of Charted Engineers in Iceland, Reykjavik, Iceland.*
  This paper describes home area networks (HAN) with a special focus on the development of customer premises equipment (CPE) and home gateways. The paper highlights the important role of HAN in adoption and use of broadband connections.

- *Contribution to "Second report on the multi-technological analysis of the "broadband for all" concept, focus on the listing of multi-technological key issues and practical roadmaps on how to tackle these issues", BROADBAND in Europe for All: A Multidisciplinary Approach ; FP6-IST-507554/JCP/R/Pub/D2.2-3.2, 2005.*
  This deliverable provides a multi-technological analysis of the 'broadband for all' concept, with an update of the listing of key issues, a first gap analysis, and roadmaps on how to tackle these issues. The deliverable also contains information on ongoing

regional and national broadband initiatives in Europe (EU25) and around the world. The information includes an analysis of the broadband market in these countries with overview of available technologies, infrastructures, operators, pricing,…. It also includes a summary of the broadband policy in these countries.

3.2.2.   Literature review

During the late 1980 and early 1990 there was a strong belief that telecoms would take over video distribution through packet-based transmission over fibre (Maxwell 1999). According to Chen et al. (1994) this was spurred by the FCC's so-called 'Video Dial Tone' ruling in 1991. The result was that telephone companies started "aggressively pursuing plans to enter the video distribution business" (Chen et al. 1994; p. 102).

This spurred active research into different technologies that telephone companies could use in their access network evolutionary plan. Local Exchange Carriers (LEC) preferred fibre but to reduce deployment cost other proposals came forth such as Hybrid Coaxial Fibre (Green et al. 2001). Digital Subscriber Line (DSL) was also proposed as a "technology to facilitate a graceful transition from copper to fiber" (Waring et al. 1991).

Many of the proposed solutions were tested through operator driven multimedia field trials of the 1990s in Europe (AMUSE 1996), Asia (Song and Lee 2006), and the US (Lin 2006). Conccetto et al. (1999) describe the findings of the European Amuse project where in 1996 residential users were provided with interactive multimedia services, including VOD, News on Demand, etc.

While the field trials all demonstrated the functionality and availability of technological solutions capable of providing advanced multimedia services, Conccetto et al. (1999) describe experiences from the European Amuse project, where high cost of equipment, limitations of services delivery platforms, lack of standardisation, and immature user interfaces result in damaging effect on customers, which at the time were technology disenchanted.

But what sparked the technological development and drove the efforts towards diversification in the 1990s? The market was at the time dominated by national and incumbent operators that sat comfortably on

the PSTN market and made ample profits. Data services were in their infancy and therefore little evidence of demand-sided pull. Maxwell (1999) primarily accredits this diversification by telecom operators on competition from cable operators that in the early 1990s were threatening to implement telephone and interactive broadband services over the existing CATV networks (Maxwell 1999, p. 6).

Despite the ambitious goals of the 1990s neither the telecom nor the cable operators successfully diversified and the world has not witnessed any wide-scale upgrades to the existing copper access network *yet*[68]. As a result ADSL dominates the broadband market in all OECD countries apart from the US and Canada (OECD 2006). However, with increasing transmission demand ADSL is giving way to new DSL standards. Kapovits (2005) draws on Eurescom (2005) study P1551 and reports that broadband access networks are reaching a new deployment phase. According to him "most operators in Europe are currently deploying ADSL2+ in their access networks and experimenting with VDSL2".

In contrast to ADSL that can be deployed from existing structures over existing access networks, VDSL requires shorter copper loop and therefore more expensive deployment of fibre to the node (FTTN). Elnegaard and Stordahl (2002) propose real options methodology to evaluate deployment strategies available to incumbents under service competition. The real options approach is adopted from financial theory where investment opportunity (real option) has an analogy to a call option in the financial world. In this way they capture the value of flexibility and uncertainty in future VDSL rollout strategies. This value is generally not incorporated in traditional techno-economic frameworks where discounted cash flow and net present value are calculated for static deployment scenarios. They show that for the case of optimum predicted by static profit maximisation may shift when real options are considered.

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[68] During the late 1990s and early 2000s there was a considerable HFC deployment by telecom operators around the world but these network plans did not live up to their expected success in broadband provision and are not treated in this thesis. For introduction to HFC see Green and Dutta-Roy's "The emergence of integrated broadband cable networks - an overview of cable modem technology and the market perspectives"

Along this way, but using a game theoretic model, Woroch (2004) shows that in a race between two firms, the firm that is more eager to deploy, will deploy first but not necessarily at the time that yields maximum profits. Instead, it deploys an instant before its rival finds it preferable to be the leader rather than being relegated to the role of the follower. This highlights the importance of strategic deployment decisions that aim at forestalling or delaying entry.

Vendors, such as Alcatel and Ericsson provide subjective (but often good) white papers on advanced DSL systems but in general there is a lack of textbooks covering advanced DSL networks and services (probably due to the fast paced development). Rauschmayer (1998) and Bates (2002) provide rather tedious overviews of DSL from technical perspectives, focusing on practical issues such as crosstalk. More interestingly (for this study at least) Maxwell (1999), NRC (2002), IST-BREAD (2005) and Chlamtac (2005) provide an overview of DSL technology and put it into perspectives with services, usability, and regulation.

Empirical evidence also shows that FTTX deployment is finally taking off, lead by Japan that now has 6.3 million fibre subscribers, outnumbering total broadband subscribers in 22 of the 30 OECD countries (OECD 2006). Literature provides a better and more up to date account of this trend, of which the technology review of Green (2006) and deployment overview of Lin (2006) can be recommended. These neutral accounts are balanced by vendor reports, of whom Alcatel Telecommunications Review was most consulted.

What emerging DSL and FTTX technologies have in common is that they follow the general structure of Next Generation Networks (NGN). Knightson (2003) provides a general overview of the trends and concepts that NGN is comprised off. EURESCOM (2001) goes to the depth with implementation analysis of the technological aspects of NGN as well as service provisioning. Elixmann and Schimmel (2003) and Devoteam Siticom (2003) look at the regulatory implications of NGN and finally, in Sigurdsson (2003; 2004d) the author analysed the financial consequences of implementing Next-Generation-Networks in Iceland.

Despite increasing deployment of fibre in access networks, optimal architectures and technologies are still being debated. The current technical and vendor literature has focused on network architectures and data protocols. The current debate is largely focused on Ethernet

over Active Star, Asynchronous Transfer Mode over Passive Optical Network (PON) and Ethernet over PON architectures. On the future horizon Dense Wavelength Division Multiplexing (DWDM) over PON is seen as a means of increasing the capacity of PON.

Industry reports of deployment show that when incumbents decide to deploy fibre, they predominantly choose PON. In 2006, German incumbent, Deutsche Telekom, presented plans to connect 2.9 millions homes in 10 major cities in Germany with FTTN + VDSL2. Furthermore, at year-end 2006 France Telecom (FT) announced plans of extending existing FTTH trials in Paris, and from June 2007, to 12 other French cities. By the end of 2008 FT plans to have spent €270 million in CAPEX to pass 1 million homes with its fibre, and have between 150,000 and 200,000 customers hooked up to the network (expected take-up rate of 15%-20%) (LightReading 2006f).

The technological solution that FT chose is a GPON architecture, with 64 customers provisioned by a single fibre, as that approach is according to FT the most CAPEX efficient and saves on operational costs at the central office. The service offers a 100-Mbit/s symmetrical broadband connection, high-definition TV (HDTV), unlimited VOIP services, and connection and support services for €70 per month. FT says that among the main services and applications used by those that signed up were HDTV, video on demand, photo storage, and the "sharing of user-generated content." (LightReading 2006f).

A broad body of literature discusses and proposes quality of service mechanisms that can facilitate multimedia services in residential broadband networks (Courcoubetis 2003; Ram 2004; Mandjes 2003). However, there are practical concerns about realising these proposals, as well as criticism that many of the proposed schemes are ”overly concerned with congestion control to the detriment of the primary pricing function of return on investment” (Roberts 2004, p.1389). In line with this, equipment vendors have proposed more simple and inexpensive ways using a combination of bandwidth over provisioning and service differentiation (Alcatel 2004c).

The chosen service delivery model is also affected by the role that network access providers assume in the broadband value chain. An ideal position for customers is to have open access to different service providers for different types of content. In theory, this should increase service selection, innovation, and competition (Bourreau and Dogan 2003). In a commercial networking context, this is likely to happen

when the viability of the network access provider is assured by the sale of transport services. However, in the case of dominant Incumbent Local Exchange Carriers (ILECs), they also act as competing service providers. Because they are guarding their own interest at the service level and also determining the future structure of residential broadband networks can cause conflicts of interest and affect the path of network and service evolution.

This chapter assumes that the choice of migration strategy of residential broadband networks is intertwined with the role that network access providers assume in the broadband value chain. By analysing the technical requirements of multimedia services and putting them into context with possible implementation scenarios, this chapter tries to describe the likely deployment path of multimedia services in residential broadband networks.

3.3.   *Next Generation Networks*

In traditional network architecture, different voice, data and television services are integrated with the particular technology that transports and switches them. The networks are separate, and vertically integrated. This means that to provide one household with all the demanded multimedia services, several independent networks are required, all comprising the same fundamental architectural components: management, switching, transport and access layers (see Figure 33).
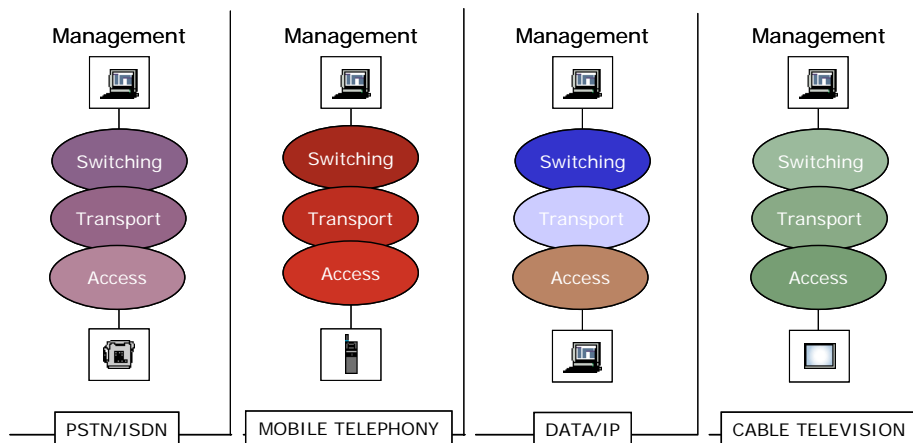
Figure 33, Traditional communications network architecture
source: Ericsson

Through the past two decades each of these networks has started to show the same characteristics and in many cases they use the same physical medium, optical fibre, although on separated virtual channels. The thought of constructing a single network that consolidates all the others therefore holds a promise of economics of scale and scope that could reduce the total cost of providing all services. However, until recently, this option has neither been feasible nor technically possible.

As discussed in the previous chapter recent advances in networks and services have now made this technically possible. In network terms this convergence is frequently called Next Generation Networks (NGN) and is based on using one packet-based transport network that can fulfil the QoS requirements of all the formerly separated services. After a hefty debate on whether ATM or IP should provide the underlying switching and transmission, IP won and now dominates all core/backbone networks.
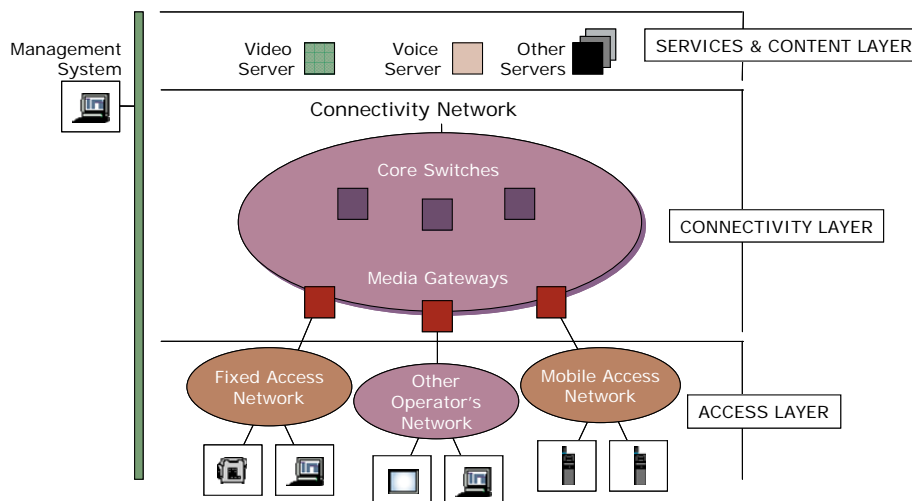
Figure 34, Architecture of the future NGN (source: Ericsson)

What distinct NGN from earlier networks is the decoupling of services from transmission. In the NGN ideology there is a clear separation between layers that provide functionality through open interfaces (application programming interface or API). This allows services to be offered separately and to evolve independently. Therefore NGN allows the provisioning of new and existing services independently of the network and the access type used.

While both IETF and ITU are working on standardisation of NGN, vendors have gone their own way in product development to meet industry needs. Key equipment vendors of the telecom incumbents (such as Ericsson, Alcatel and Nortel) promoted a migration strategy while emerging IP vendors (such as Cisco) advocated for scrapping the PSTN and building a completely new IP network from scratch (Faynberg et al. 2000).

Regardless of the strategy chosen most traditional operators have in the past five years upgraded their core networks based on MPLS technology and now have ample capacity that they can control and manage through advanced traffic management (Awduche 1999; Li 1999). With core networks capable of supporting advanced multimedia services the access networks have become bottlenecks in deploying multimedia services.

Another problem for operators is that the various managed networks using NGN concepts are not interoperable, i.e. the service layer of one operator can not offer guaranteed services in another domain. While this problem has been solved technically (Li 1999), the business models needed to facilitate this functionality remain an unsolved problem. Why should operators facilitate application provision for a competitor if they get nothing in return?

3.4.   The Role of Network Access Providers

Central to an efficient deployment of multimedia services is the role that network access providers (NAP) assume in the broadband value chain. Alcatel identifies three basic service models for telecommunications operators (Alcatel 2004a). The current Internet is an example of the so called "public garden" model, where the application layer is independent of an open access transportation layer and users can freely choose service providers.

The second model is called the "walled garden" model, where the operator locks the customers solely to his platform. Throughout the history of telecommunication, this model has been the goal of operators. Examples are the early telephony and the current satellite broadcasting industry.

The third model, called the "gated garden" model, is becoming the preferred model of many modern telecommunication operators where they can control the supply of services by specifically granting access to third-

party service providers. Being service gatekeepers rather than sole service providers increases innovation and service diversity. Networks access providers can then focus on their core business while reaping profits from service provision through fixed fees or profit-sharing. An example of successful implementation of this model is NTT DoCoMo's i-mode in Japan.
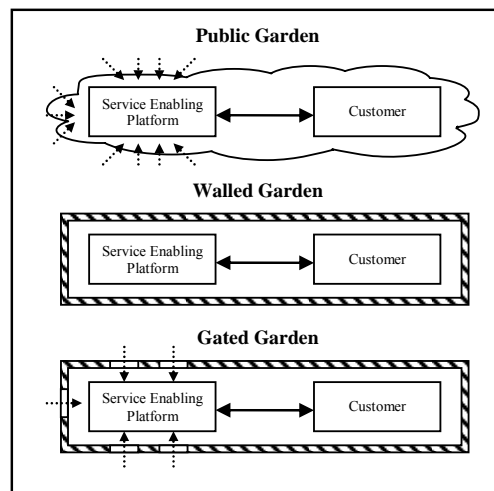

Figure 35, Service Models for Broadband Services

Most EUCs in Denmark aim at becoming a "gated garden" network access provider. However, there are still technical challenges to implementing the strategy, such as service admission control (i.e. how to control services from the Internet). In earlier broadband networks, the network access was limited by bottlenecks in the access network that forced service providers to offer services in cooperation with the network access provider. In emerging FTTH there is less pressure on Internet based service providers to make revenue sharing agreements.
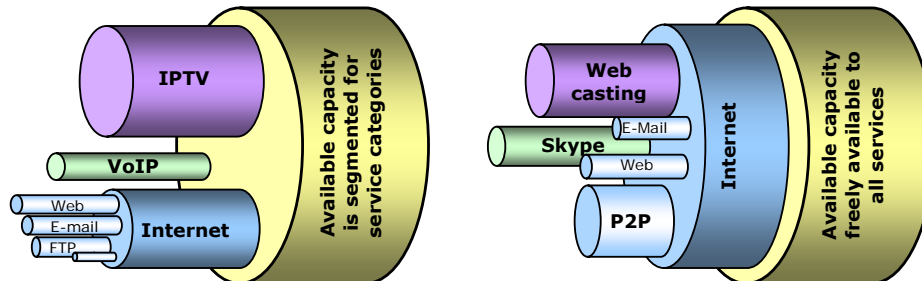
Figure 36, Alternative implementations of service provisioning in residential broadband networks

The challenge for the NAP becomes selecting the right provisional model, and if that is based on gated garden business models to differentiate their services from those available over the general Internet. A second alternative, which is not recommended, is to try to block certain types of services, either based on the ports they use or other characteristics of the traffic. The author explores these issues and alternative methods of implementing service differentiation in Sigurdsson (2006c).

3.5.   *Existing copper access networks*

Copper based access networks still represent the overwhelming share of fixed telecommunications access network infrastructures around the world. These networks have been developing gradually over the past several decades but all share the same principle of connecting households within a given area to a local exchange[69] (LE) with an individual pair of unshielded twisted pair (UTP), called the local loop. Along the way from LE to the network termination point (NTP) at the subscriber's premises, cables run in bundles to levels of intermediary nodes, first the Primary Distribution Points (PDP), and later at Secondary Distribution Points (SDP) from where they run individually to the NTP. At the LE, local loops terminate in a Remote Subscriber Stage (RSS). If the subscriber is located in the proximity of an LE, the RSS is positioned within the LE. If however a group of subscribers

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[69]   The terminology within telecommunications differs between countries/continents, where in the US a local exchange is referred to as "central office", and the copper segment from the local exchange to a household is called "local loop" or "last mile".

are located far away from the LE, they connect to a detached RSS that connects to the nearest LE with trunk lines (see Figure 37).
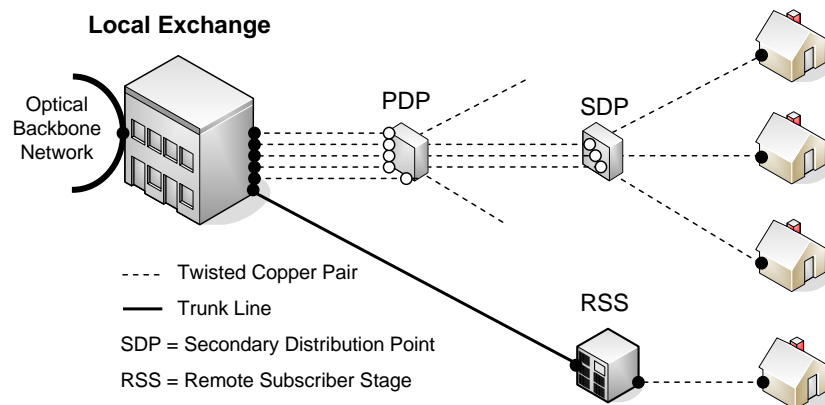

Figure 37, Structural overview of PSTN copper networks

According to the Danish NRA, there were 105 LEs with PSTN switches in Denmark, and 1588 RSS locations in Denmark in 2002 (ITST 2002). TDC (2006) uses another terminology and groups them together and counts 1188 centrals and 637 "technical sheds"[70] in 2006. Regardless of the number and terminology, the area that a point of transmission can serve is limited by the maximum cable length to which the analogue voice signals of the Public Switched Telephone System (PSTN) can be carried without amplification. While the general concepts of the PSTN are uniform worldwide, local conditions and practises, as well as deployment time have affected the structure of systems, e.g. with the result that average copper cable lengths vary from country to country. This difference affects the upgrade strategies, especially with regards to DSL, where the general rule is that the longer the loop the less transmission it can support.

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[70] Direct translation of the Danish term "teknikhuse"
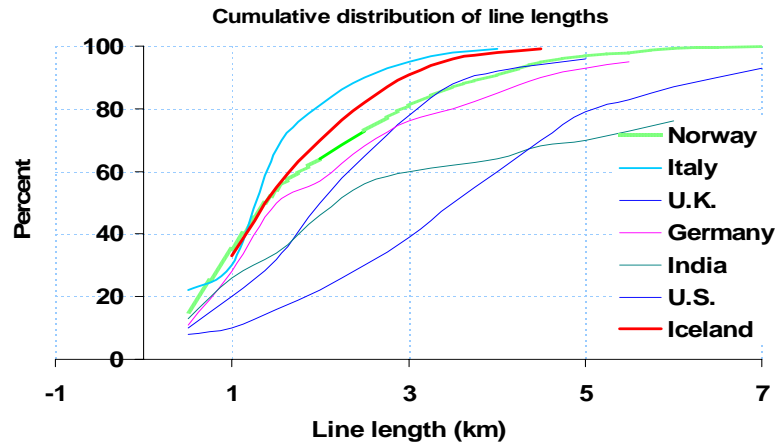
Figure 38, Cumulative distribution of copper line lengths (source: Thorsteinsson 2005) [71]

In international comparison, the Nordic countries possess relatively modern PSTN structures with among the shortest average line lengths (see Figure 38)[71]. While earlier cabling offered only a single wire-pair to every customer, upgrades during the last decades have resulted in 85% of the Danish households being connected with at least two pairs (Frimer 2006). In non-upgraded regions (especially where larger buildings have been divided up into several smaller apartments), a line shortage is not uncommon and there multiplexing equipment is used with the available network resources to provide adequate services (Thorisson 2002).

3.6. *Digital Subscriber Line (DSL)*

The PSTN uses the frequency range between 300 and 3400 Hz to transmit human speech, leaving the whole frequency band above 3400 free for other use. This sparked the development of Digital Subscriber Line (DSL) based overlay data transmission technologies. In DSL the frequency band of UTP is shared by the low frequency PSTN signals and high frequency

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[71] As seen in Figure 38, Denmark is missing from the list. The author unsuccessfully tried to get structural information about the PSTN in Denmark from the incumbent and the national regulatory agency. To compensate for this lack the study makes extensive use of a dataset of sample areas described in the Danish LRAIC model presented in Section 4.3.

DSL. At each end of the UTP the signals are separated and sent to the appropriate equipment.

In DSL the frequency range above 30^{72} kHz is split into several 4312.5 Hz wide channels that are either used for upload or download traffic. Each channel is evaluated for usability and the pool of usable channels is then split into groups of upstream and downstream traffic according to a predefined ratio. Each channel is monitored throughout the duration of the connection and operates in a similar way to an individual modem. More usable channels equates to more available bandwidth.

There are several variants of the DSL technology, such as Asymmetric DSL (ADSL), ADSL2+, and Very high bit rate (VDSL)[73]. Each of these variants has distinctive characteristics but to simplify, transmission properties are determined by the frequency band used (i.e. the number of potential channels) and the symmetry ratio. The maximum downstream data-rate and distance performance of the currently most used DSL standards are depicted in Figure 5. The figure represents theoretical maximum values[74] calculated and by the simulation model developed and described in Chapter 4.

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[72] This value can vary between DSL standards and implementations.

[73] Broadwan D15, p. 85 finds it likely that VDSL in Europe will be based on the future VDSL2 standard, which is expected to be finalised in 2006 or 2007. This thesis uses VDSL to refer to the future VDSL standard that will dominate the market (regardless of whether it will be VDSL or VDSL2+).

[74] This means that in real environments, such as in the presence of crosstalk and other disturbances, the transmission speeds can be considerably lower. The maximum value is also affected by the symmetry ratio of the connection, where generally with increased symmetry the maximum one way transmission speed is reduced. Note also that the VDSL2 values are unreliable as standardisation work is not finished.

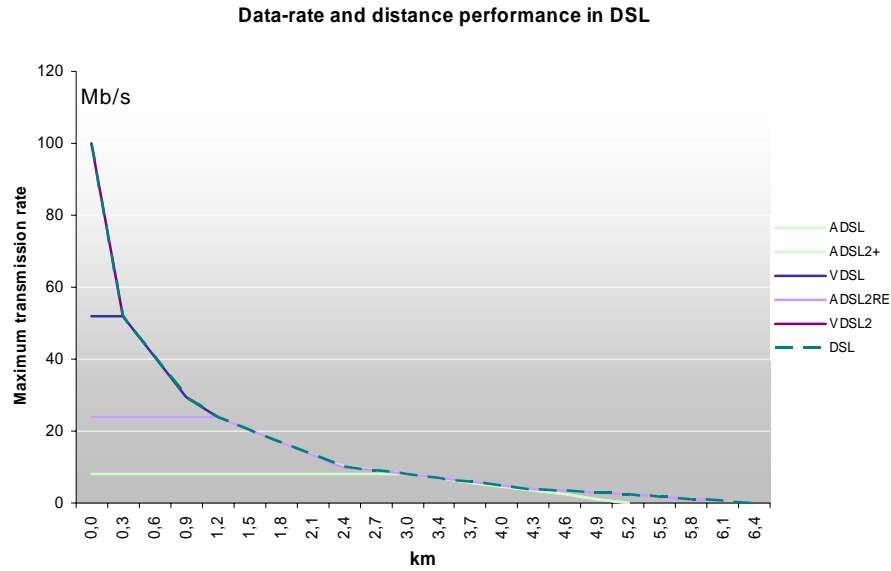**Data-rate and distance performance in DSL**

Figure 39, Downstream data-rates and distance performance for DSL (the figure is based on calculated values from the simulation model used in the thesis).

3.6.1.   DSL Equipment

Providing DSL services requires DSL modems on both sides of an adequate copper transmission line. At the operator side the "modems" of several customers are provided as line cards, installable in DSL Access Multiplexers (DSLAM). To isolate the high frequency signals from the PSTN, frequency splitters are used in front of electronic equipment at both sides. For a visual representation of ADSL provision see Figure 40.
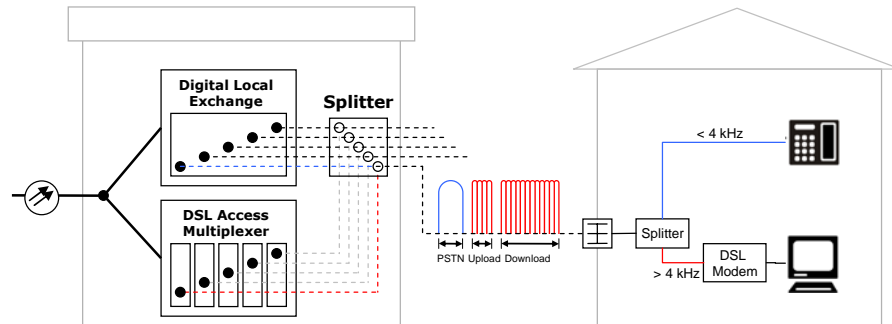
Figure 40, Provisional overview of ADSL

In a typical DSL deployment, DSLAM equipment is collocated in existing local exchanges, where a single DSLAM can serve up to 768 users. In recent years, operators and equipment manufacturers have been developing smaller 'detached' DSLAMs that can be located remotely. The object of these small DSLAMs is twofold, i) to move the equipment closer to the end-user, thereby reducing the copper length and increase the possible transmission speeds, ii) to serve customers that are outside the reach of centrally located equipment.

Detached DSLAMs are the key equipment in Fibre-to-the-Curb (FTTC) solutions where fibre is extended to nodes close to customers, such as street cabinets. In this way, detached DSLAMs have the possibility of increasing service levels and the customer base of DSL technology. However, the equipment is more expensive than centrally located solutions due to: structural cost (i.e. erecting a new cabinet) and the cost of providing electricity and cable feeds to the equipment, less economical units (both in size and in terms of environmental hardening), and finally as fewer customers share each unit.

3.6.2. *Early ADLS systems*

Commercial DSL deployment started in the late 1990s based on the system configuration of the ADSL PHY recommendations[75]. This setup uses ATM running over the ADSL physical layer and can provide downstream data rates up to 6,144 Mbps and upstream data rates up to

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[75] More specifically the specifications were based on ANSI T1.413 issue 2, ITU-T G.992.1 (G.dmt), and ITU-T G.992.2 (G.lite).

640 kbps[76]. In the most common setup, ATM Permanent Virtual Channels (PVC) are aggregated at the local exchange, either using RFC-1483 bridging over ATM or IP tunnelling based on PPP/L2TP (Fryxell 2002).

By aggregating all incoming connections to a common PVC, the cost and complexity of having to manage a large number of virtual circuits is eliminated. This is at the cost of traffic management, where all traffic of the 768 potential users of a single DSLAM is usually aggregated to a common STM1 (155 Mbps) connection. An ATM backbone network used to aggregate traffic to a Broadband Remote Access Server (BRAS).
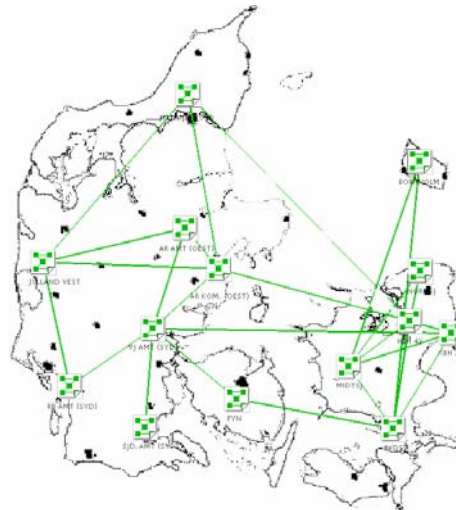
Figure 41, Danish ATM backbone (Source: Madsen 2004)

Like the name indicates, ADSL was designed based on assumptions of asymmetric content consumption patterns. Despite individual connections from a customer to the DSLAM, the aggregated traffic is shared and multiplexing ratios of 1/30-1/60 commonly used according to Alcatel (Alcatel 2003). While these multiplexing rates as well as connectivity specifics make early ADSL platforms efficient for

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[76] Higher data rates are optional. Most ADSL products currently in the market allow downstream data rates up to 8 Mbps and upstream data rates up to 1 Mbps.

provision of web based (bursty) content, it renders them inefficient for providing video services. This is particularly true since early DSLAMs do not support multicasting and can not provide service differentiation (Sigurdsson 2006c).

3.6.3.   DSL Equipment Cost

Since the introduction of ADSL, the number of deployments and subscribers has soared to over 164 million world wide subscribers according to the DSL Forum and industry analyst Point Topic (DSL Forum 2006). Europe has been in the forefront of this development with on average 73% DSL market share in the 30 OECD countries (OECD 2006). One of the results of this remarkable rate of growth across the world has been a drop in component prices. IST-BROADWAN (2005) reports price cuts of DSL line cards and Customer Premises Equipment (CPE) to around ¼ of the 1999/2000-level. A more detailed breakdown of the expected cost reductions is reported by Newman (2002) who uses data from a McKinsey and JPMS report that also include operational costs. This study estimates up to 90% price reductions in hardware (on average roughly 50%) but indicates that with maturing market and increased competition, operational costs have either stayed the same or increased. Neither the methodology nor the assumptions of the McKinsey JPMS analysis report are public.
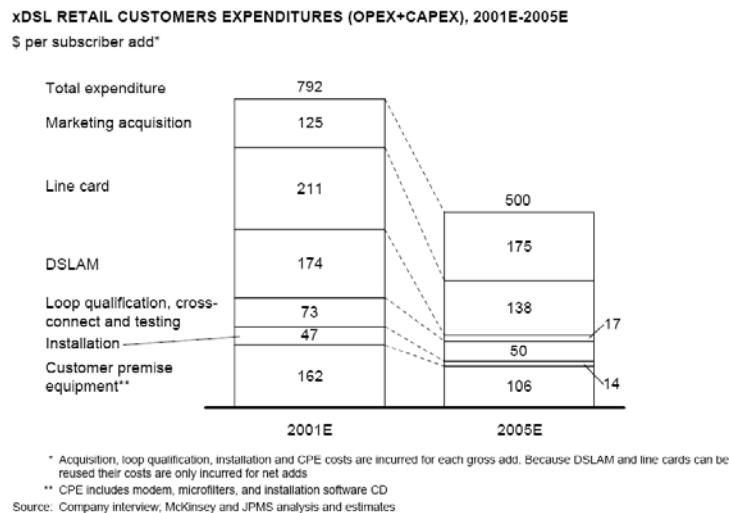
Figure 42, Cost development for DSL provision 2001-2005
Source: Newman (2002)

To understand the characteristics of these changes and predict price reductions in hardware prices Olsen and Stordahl (2004) provide forecasting models based on learning curve. They develop extended learning curve models that take as input price in reference year, relative accumulated volume sold, time period of the life cycle, and learning curve coefficient. They test the model on ADSL line cards assuming an eight year growth period from 10% to 90% production level and while the model predicts more price reductions than Figure 42, the mismatch between the model predictions and the actual data they use may be due to new high capacity line cards (such as ADSL2+).

3.6.4. Supporting multimedia services in DSL

Today, equipment manufacturers are promoting DSL systems based on ADSL2+ and VDSL technology that in addition to higher transmission capacities can support voice, and video services through Quality of Service (QoS) management according to concepts of Next Generation Networks. Currently there is not a widespread agreement on technical solutions to providing service differentiation and as a key development issue in future residential broadband networks this problem is analysed further in Chapter 4. Regardless of the technical solution there is a tendency towards the use of Virtual Local Area Network (VLAN) tags as a form to categorise traffic. (Alcatel 2004a; 2004b; 2005)
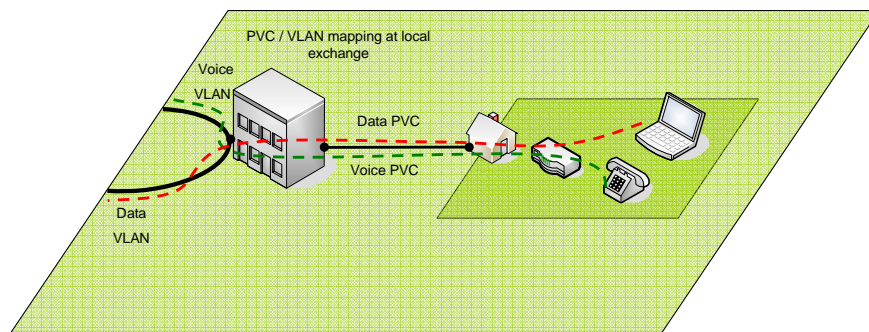

Figure 43, DSL with PVC/VLAN service differentiation

A prominent new deployment platform from Alcatel, Alcatel 7302 Intelligent Services Access Manager (Alcatel 2006) offers 1 Gbps per line card (which can be different DSL variants), support for IGMP multicasting, and up to seven Gigabit Ethernet backbone connections. This solution uses separate PVC for different service types in the DSL connection to the end user and then maps them to VLANs at the

DSLAM. This enables the platform to deliver voice, video, and data services each with specific QoS parameters. Other vendors present in the Nordic countries[77], have gone similar ways in offering IP based multi-service platforms.

3.6.5. DSL Deployment in Denmark

In contrast to ADSL that could serve the majority of customers from local exchanges, new DSL variants such as VDSL require shorter loops if higher transmission rates are to be offered. VDSL deployment therefore goes hand in hand with infrastructure upgrades where new nodes are established in the deployment area. These nodes are connected with fibre and consequently called Fibre to the Node (FTTN). The remaining copper length used dictates the number of nodes needed and can be estimated with Equation 1.

Equation 1

$$Nodes = \frac{1}{(remaining \quad copper \quad percentage)^2}$$

If carefully designed, the node can be reused as part of future FTTH upgrades depending on the technology and architecture chosen (see below). Today, most operators are considering establishing nodes within a few hundred meters from the customers, e.g. in street cabinets of the PSTN. In the presence of more than one pair of PSTN two or more copper loops can be bound together, enabling higher transmission rates and longer reach but although an alternatives for increasing rate and reach from local exchanges it has not been widely used in FTTN upgrade scenarios. Figure 44 illustrates the rate vs. reach relationship in DSL.

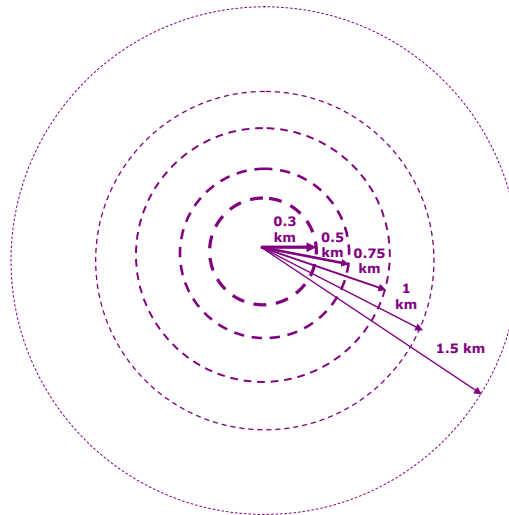
[77] These include Ericsson, Cisco, Simens and Zyxel

Figure 44, Rate / reach map for DSL

Prior to new DSL deployment, operators need to upgrade backbone and aggregation networks and as a result ATM backbone networks are likely to be phased out. Today, operators in all the Nordic countries have implemented IP based core and aggregation networks using MPLS technology, offering QoS support to differentiated services. In Denmark TDC has extended its IP backbone to 89 towns/cities (Lund 2006), ensuring ample capacity to distribute voice, video, and data all around the country. As a next step, TDC is about to embark on a programme of deploying DSLAMs deeper into the access network than at the LE and expects to deploy 1,500 new detached DSLAMs in Street Cabinets in the near future (Europe Economics 2006), although the specifics of the deployment have not been made public.

In contrast to current ATM-based DSLAMs the new DSLAMs used for the upgrade programme will be Ethernet based. TDC expects over time that the existing ATM-based LE DSLAMS will also be upgraded or replaced by this current technology, although the time frame for this is not at all certain. The resulting network structure will most likely be based on switched Layer 2 connections from each detached DSLAM to the nearest one of the 105 local exchanges. The local exchange then connects to a Layer 3 routed national backbone router in one of 89 locations.

Figure 45, Danish backbone and aggregation network (Source: Madsen 2006)

Based on the provided information the thesis will analyse the deployment alternatives under the presumption that all local exchanges are connected to IP based backbone networks and offer QoS management. The same set of alternatives is available to a CLEC that has established a backbone connection at the LE and therefore the deployment will be presented as a telecom strategy, referring to both ILEC and CLEC.

3.6.6.   Competition in DSL

According to Henten and Skouby (2005) the Danish local loop regulation "walks on two legs", where both infrastructure and service competition have been promoted. To accomplish its goals the legislation defines three types of service competition: complete unbundling, shared access, and bit stream access. In unbundling and shared access[78] a CLEC establishes DSLAMs that are collocated within an incumbent's LE and used to offer DSL services over the copper loop. In contrast, bit stream access does not require new physical equipment and can be considered as wholesale services of DSL from the ILEC to a CLEC.

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[78] Shared access can be seen as a subgroup of unbundling, where different providers provide DSL and PSTN services. With regards to DSL provision, unbundling and shared access can be considered the same.

Several technical alternatives exist to provide bit stream access, depending on the type of interconnection to the incumbent network. All types have in common that the incumbent's access network and active equipment is used to establish connectivity to the user. The connection is then forwarded to the operator, who either connects to the backbone network at national level (connecting to the TDC backbone network) or regional level (connecting to own backbone network e.g. at the local exchange).

Like in the previous ATM network structure, the interconnection point influences where and how the operator buying the bit stream access service connects to the customer. If the connectivity is local at Layer 2, the operator buying the service has the possibility of supporting service differentiation within its own network. If the connection is on Layer 3 all streams with the same ToS classification would be aggregated on a common VLAN, which would ensure quality for the services of the operator as long as he buys ample aggregation connections from the incumbent. The reason for not supporting VLAN tagging for individual streams on Layer 3 for all service competitors is the limited number of available VLANs meaning that then VLAN tagging would have to be nested, i.e. in two layers, which is currently not supported[79].
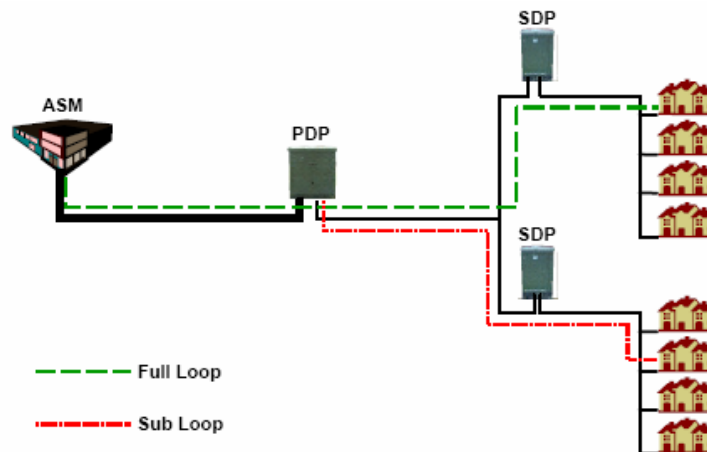

Figure 46, Sub-loop unbundling
Source: Europe Economics (2006)

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[79] For a further discussion of VLAN tagging see Alcatel (2004c) and Alcatel (2004d).

Unbundling and shared access will be affected by deployment of detached DSLAMs in remote nodes. The required updates are called sub-loop unbundling. Sub-loop unbundling involves the interconnection of a CLEC (which under this doctrine has gotten the new name alternative operator, abbreviated OAO, since deployment is no longer from the local exchange as the CLEC name implies) to the local loop infrastructure of the ILEC at a point somewhere between the LE and the NTP. The Danish NRA is currently working on updates to allow sub-loop unbundling and incorporating it into the LRAIC model (Europe Economics 2006).

3.6.7.   Limitations of DSL

Due to attenuation in copper local loops the maximum transmission speeds decrease with copper local loop length. The result is an upper bound on the maximum transmission speeds that operators can offer customers over the current copper access network. Combining the information from the cumulative distribution of copper line lengths of Figure 38 with the maximum transmission speeds of Figure 39 gives an estimate of the transmission speeds that the current access networks can support.
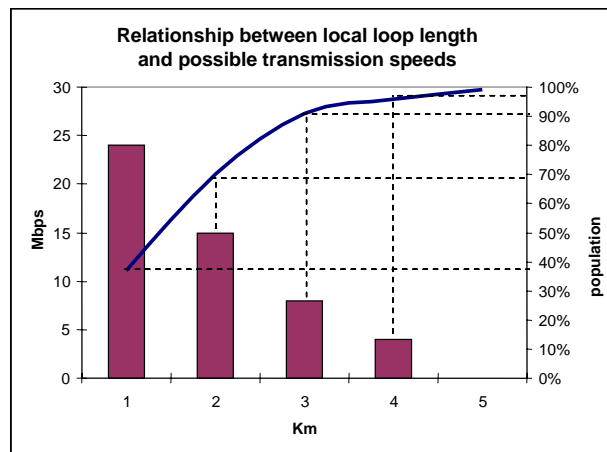

Figure 47, Transmission capacity of current copper access network in Iceland

In the absence of detailed information about distribution of loop length in Denmark, the analysis of Figure 47 is based on information from Iceland[80]. The result indicates that without any upgrades to the copper network, only 40% of the population could be offered above 24 Mbps, meaning that 60% of the population would have to accept less than the estimated near-future demand from Section 2.10[81]. To increase the possible transmission speeds operators need to replace parts (or all) of the copper loop with optical fibre.

In addition to limitations due to attenuation, frequency disturbances from cross-talk can limit provision of DSL services. Cross-talk refers to the noise interference between nearby cables that can have negative impact on transmission properties in DSL systems. There are two very different types of crosstalk: Near-End Crosstalk (NEXT) and Far-End Crosstalk (FEXT). NEXT is interference that appears on another pair at the same end of the cable as the source of the interference while FEXT is interference that appears on another pair at the opposite or far end of the cable to the source of the interference. NEXT affects any systems that transmit in both directions at once (e.g. echo-cancelling systems), and where it occurs it invariably dominates over FEXT[82].

The effect of cross-talk and other frequency disturbances escalates in sub-loop unbundling, i.e. when DSL is deployed from more than one point of origin or when different types of modulation schemes are used. This would be an issue when e.g. an incumbent deploys DSL from PDP while a CLEC provides DSL from the LE. One technical solution is to separate the frequency band, e.g. such that ADSL or ADSL2+ get up to 2.2 MHz, while VDSL/VDSL2 gets frequencies from 2.2 to 30 MHz. The result is however, performance restrictions for both operators. TDC (2006) proposes a variant of frequency division called spectral shaping, where the power level from the remote DSLAM is reduced for frequencies below 2.2 MHz. With spectral shaping, TDC maintains that

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[80] The results of this analysis are not used further in the techno-economic models but merely used to illustrate the limitations of current DSL networks.

[81] These are rough estimates that are based on theoretical transmission rates and do not take into account bonded DSL and other means of increasing the reach of DSL

[82] For a detailed analysis of nature and effect of crosstalk in DSL see Rauschmayer (1998).

obligation to preserve the transmission quality on unbundled copper from the LE can be maintained[83].

3.7.   *Fibre to the X (FTTX)*

In comparison to copper wires that carry electrical signals, optical fibre uses lasers or light emitting diodes (LED) to transmit pulses of light down fine strands of glass or plastic fibre by means of total internal reflection[84]. Since its invention in the 1950s and commercial introduction in the 1970s the use of optical fibre has escalated in telecommunications. Low attenuation and broad frequency spectrum make optical fibre an ideal transmission medium for telecommunications.

Fibre cables come in two types, single mode and multi mode. Multi mode fibre has a bigger core where light can travel in many rays. In single mode fibre the core diameter is reduced to a few wavelengths of light, forcing the light to propagate in a straight line. In earlier FTTH deployments multi mode fibre was used but today single mode fibre has become dominant.

Several alternative wavelengths can and have been used optical fibre communications. In single fibre transmission the standard is to use the frequency band from 1260-1360 nm for upstream transmission and 1480 to 1500 nm for downstream. Additionally light with different wavelengths (colours) can be transmitted simultaneously within each band using wavelength division multiplexing (WDM). This allows for a multiplication in capacity, in addition to making it possible to perform bidirectional communications over one strand of fibre.

Initially the cost of fibre cable and end equipment limited deployment to backbone connections. Today, the cost of fibre cables has dropped to similar levels as compared to copper (ITU 2003) and existing operators as well as entrants have started deploying fibre rather than copper in new

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[83]   The author would like to thank Steen Krogh Nielsen, manager in TDC network strategy for his valuable input to this subject.

[84]   For a good "engineering" description of FTTH principles and available technological standards see Green (2006) and Lin (2006) for empirical case studies.

access networks (called greenfield)[85]. In existing residential areas (sometimes called brownfield) operators are increasingly replacing parts of the copper infrastructure with optical fibre and deploying DSL from nodes over the remaining copper loop (see Figure 48).
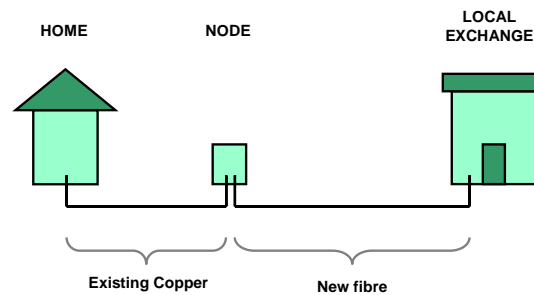

Figure 48, Fibre to the Node schematic

In contrast to the Danish PSTN network architecture with two levels of intermediary nodes that cables pass on their way from the local exchange, FTTN is likely to follow a single node level structure. The reason for this difference is changes in network architecture that reduce the benefits of aggregating large numbers of loops into large bundled lines. In FTTN connections from nodes are over a singe (or few) optical fibres and therefore not a need for two levels of aggregation nodes[86].

Despite increasing deployment of fibre in access networks, optimal architectures and technologies are still being debated. Two main categories of architectures exist: active star and passive optical networks (PON). On top of the network infrastructures the transmission protocol dictates how efficiently the networks can support the required services. The current debate is largely focused on Ethernet over Active Star, Asynchronous Transfer Mode over Passive Optical Network (PON) and Ethernet over PON architectures. On the future horizon Dense Wavelength Division Multiplexing (DWDM) over PON is seen as a future upgrade to increasing the capacity of PON.

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[85] In November 2005, the Danish incumbent, TDC, declared that from that time on, all its greenfield deployment would be based on FTTH (Nielsen 2005)

[86] This might be different if homerun topology or Passive Optical Networks are applied, requiring a structure with more levels.

For the purpose of this study the parameters of interest are those that affect the deployment cost directly, these are: topology, cables length and type, active and passive equipment. This will be the focus of the following analysis of PON and active star networks.

3.7.1.   *Passive Optical Networks*

Passive Optical Networks do not include any active electronics in the deployment field and can share optical fibre among a number of users, typically between 8 and 64. This is done by splitting the optical fibre one or more times on the way to the customer. If the splitting is accomplished in the deployment field the network structure is called Point to Multipoint (P2M). If splitting is done at the central exchange the deployment is called homerun. While using P2M reduces the amount of required optical cable the strength of homerun deployment is easier upgrade possibilities. Additionally homerun deployment enables unbundling of fibre in similar ways to existing copper loop rather than P2M which would require time, frequency or wave multiplexing over a common infrastructure [87]. Due to the lower attenuation of fibre as compared to copper, PON can reach up to 20 km[88].
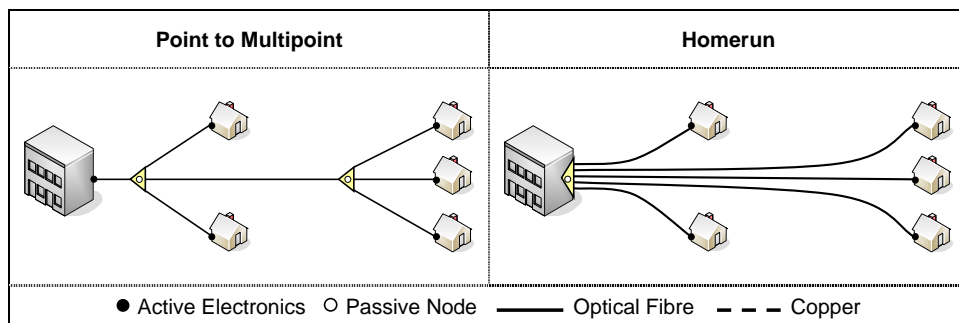

Figure 49, Network architectures in PON

As mentioned above there are several transmission standards within PON networks. According to Paul Green, a widely respected authority

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[87]   Tseng (2001, pp. 57-62) analyses alternatives for multiplexing in fibre access networks and how alternative methods can affect competition.

[88]   Although the reach can be less depending on the power-budget.

within FTTH, EPON and their descendents will become the de facto standard in the near-future. To support this claim he uses four reasons (Green 2006; p. 65). First, that EPON's relative design simplicity will lead to lower development cost. Second, Ethernet components have enjoyed a 25-year learning curve and have been implemented in a variety of networks. Third, IP packets flow natively over an EPON, rather than requiring protocol conversion. Forth, that it will be easy and inexpensive to upgrade other PON networks to EPON.

In general is should make little difference whether the internals of the PON are based on Ethernet or ATM, since the interfaces to the user and to the CO equipment are identical in both cases. The important issue will be cost to the end user and speed of acceptance. In view of the superior component cost for Ethernet chips compared to ATM chips, Green predicts that in the long run APONs will go the way of ISDN – "not completely dead, but a minority player".

3.7.2. Active Ethernet

In active Ethernet fibre is terminated in a dedicated port of an Ethernet switch. The network architecture can either be point-to-point or homerun as illustrated in Figure 50, with the same consequences on optical cable lengths and structure as in PON. The most important design issue is the number of field switches that control the length of optical cables, electronic equipment required as well as effecting operation and maintenance. In contrast to the passive splitters in PON, the switches in Active Ethernet require electricity that needs to be fed to them e.g. from the central exchange or the electricity grid in the case of EUC. In comparison to PON which shares the optical cable and thus the available bandwidth between multiple subscribers, Active Ethernet provides a dedicated duplex transmission capacity to a switch, and shares the bandwidth from there and onwards.
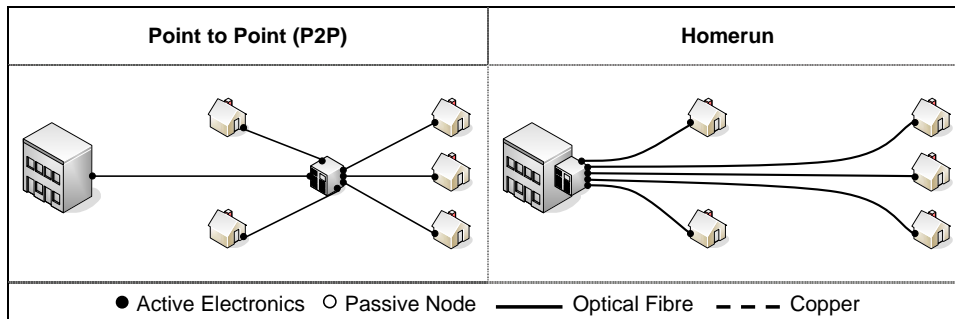
Figure 50, Network architectures in Active Ethernet

3.7.3. *Deployment and development of FTTH*

In contrast to DSL where equipment only has to be installed on both ends of an existing copper local loop, FTTX deployment is characterised by the need for new optical fibre from the LE to an aggregation node and from there to each customer. The main cost component when laying new optical fibre is civil cost and therefore the economics of FTTX are primarily controlled by the cost of digging trenches. This limits the possible price reductions of FTTH deployment as labour is stable over time in comparison to decreasing cost of electronics.
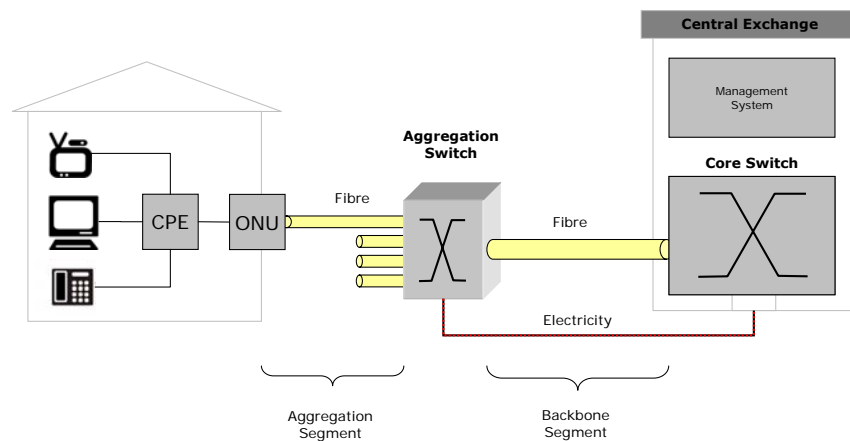
Figure 51, Provisional overview of FTTH

After being almost nonexistent in world statistics before 2003, FTTH had in 2005 grown to 11% of the current roughly 250 million broadband subscriptions (PointTopic 2006). When looking at

deployment by region it becomes evident that this growth mainly stems from Asia which accounts for 89% of these subscribers according to the same source. However, according to Montagne (2006) deployment in the EU 18 countries increased 23% in the period from mid year 2005 to the same time 2006, ending in 2.7 million connected households of which 28% had on average adopted the service.

The last year, 2006, also marked the beginning of wide scale incumbent based FTTX deployment in Europe. First German incumbent, Deutsche Telekom, presented plans to deploy FTTN + VDSL2 to 2.9 millions homes in 10 major cities in Germany, followed by France Telecom's (FT) announcement to extend existing FTTH trials in Paris to 12 other French cities. While these plans are not represented in deployment statistics, Montagne (2006) nonetheless reports an increase of 130% in deployment of FTTx + VDSL/VDSL2 between the years 2005 and 2006, ending in 5.5 million connected households and roughly 0.8 million subscribers, yielding an uptake of 14%.

EU 18 totals	Deployment in Europe		
	Mid-2005	Mid-2006	Growth
Total households with FTTx + VDSL/VDSL2................................	2.413.873	5.562.696	130%
Total subscribers with FTTx + VDSL/VDSL2...............................	616.120	756.629	23%

Table 11, FTTx deployment in Europe
Source: Montagne (2006)

To estimate the potential effect of changes in equipment price, knowledge of the distribution between Active Ethernet and PON is needed. According to IDATE (2005), active Ethernet dominated the 2.3 million passed households in Europe in 2005. According to IDATE the reason for Active Ethernet dominance in Europe is the small size of current FTTx deployments and the involvement of municipalities / power utilities. Active Ethernet is simpler to design and implement (Green 2006) and scales more easily in smaller deployments.

Sectors	Number	Percentage
Incumbent Operators	8	7.8 %
Municipalities / Power Utilities	72	69,9 %
Alternative Operators / ISPs	9	8,7 %
Housing companies & Other	14	13,6 %

Table 12, Segmentation of FTTH deployment in June 2004
Source: IDATE (2005)

Despite, a small footprint in the 2005 statistics, industry projections indicate that the number of new PON ports deployed each year will grow from 2.2 million in 2005 to 13.4 million in 2009 (LightReading.com 2006g). This increase is manly contributed to incumbent operators that are expected to deploy FTTH swiftly once they find it feasible, primarily using PON technology rather than AON. However, for Europe, Wieland (2006) predicts that there still are at least three to five years until most incumbents start this transformation. Wieland also notes that competition can significantly reduce this time. With major US and Asian operators on the verge of wide-scale PON deployment, the resulting likelihood of price decreases in PON equipment can additionally shorten this time. If industry projections are accurate, the number of PON ports can be expected to overtake active Ethernet in the near future.

3.7.4.   *Providing multimedia services in FTTH*

Bandwidth and capacity in PON is shared as opposed to dedicated in active Ethernet. Both have open issues on QoS but can support all types of multimedia services. BPON has built in possibility of offering analogue overlay video broadcasting at 1550 nm (Perkin 2004). This is manly used by cable operators that wish to use their existing service delivery platforms but less used by telecoms operators that dominantly use IPTV.

Parameter	BPON (G.983)	GPON (G.984)	EPON (802.3ah)
Bit rates down	155 or 622 Mbps	1.2 or 2.4 Gbps	1.25 Gbps
Bit rates up	155 Mbps	155 to 2.4 Gbps	1.25 Gbps
Analogue video	Specified	Not specified	Not specified

Table 13, Comparison of the most used PON standards

The principal difference between PONs and Active Ethernet lies in the equipment used at both ends of the fibre. Active Ethernet uses a powered switching device that employs intelligence to forwards downstream traffic to the end users by performing look-ups on packet or cell headers to determine the appropriate output port. This functionality can either be on layer 2 or layer 3, which affects how the network handles QoS. The signals in an active network are converted from optical to electrical and back to optical on their way through the

network. This requires two optical transceivers per subscriber (compared to (1+1/N) transceivers for a PON), increasing the component cost. Additionally electronic equipment in the outside plant must be placed in a controlled environment, if they are not environmentally hardened for temperature and weather changes. The result is that active nodes require more maintenance and therefore incur higher operational expenditure (OPEX) than passive nodes (Wldon and Zane 2003). Finally a power feed is needed in active nodes which would require a new power grid and backup for telecom operators. This is less of a problem for electricity utility companies that have an existing electricity grid, and might be one of the reasons for their dominant use of Active Ethernet.

While the increased cost associated with Active Ethernet makes PON more feasible to most telecom operators there are also downsides to it. The use of a shared medium both affects the capacity available to each user but more importantly for the deployment cost it puts additional requirements on the optical components. Specifically, time slots must be allocated to each transceiver in which the transceiver must burst on very quickly but otherwise be tuned off. This burst mode requirement, dynamic gain settings needed to calibrate signal-to-noise reception of differently attenuated signals, as well as the need for a reference clock at head-end and CPE, increase the complexity and cost of all equipment in PON networks[89]. Compensating for the higher equipment cost, PON networks typically require less expensive housing, lower associated civil work and lower cabinet costs.

From the comparison above it should be clear that comparing the cost of Active Ethernet and PON is difficult because many elements have to be considered. To make the comparison more complicated, the service levels that the solutions offer may be different.

3.7.5.   Competition in FTTH

The effect of service competition on infrastructure investment and especially the regulatory uncertainty of future unbundling requirements

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[89]   Green (2006) provides an excellent account of the technological challenges involved in providing PON which then can be understood through Weldon and Zane's (2003) techno-economic framework. Both of them highlight that a comparison is at best difficult and most often subjective.

of FTTH have been stated as a key reason for incumbent reticence to deploy advanced access networks in Europe (Wieland 2006). More generally the effect of service based competition is also disputed in literature[90]. Proponents of unbundling see it as a first step in a ladder of investment (Cave 2003), while opponents protest that such sharing destroys incentives to undertake the expense and risk of deploying new technologies.

The disagreement surrounding service competition culminates in unbundling discussion of fibre access networks. In the US the FCC has pre-empted operators from unbundling obligations according to the Triennial Review (FCC 2006). This means that operators that deploy new FTTX network do not have to allow competitors to use their loops. In Europe, The European Commission is currently undertaking a review of the competitive and regulatory framework for information policy and, as a part of that review, is considering whether fibre access networks should be defined as a new market free of ex ante regulation.

In contrast to the European Regulation, which only included unbundling of the 'raw copper' of the PSTN (Public Switched Telephone Network) access network, the current Danish unbundling regulation also encompasses optical fibres (Henten and Skouby 2005). In reality, however, foreseen implications are largely based on premature guessing as it has only been implemented over copper loops. Furthermore, none of the EUCs planning FTTH deployment have or are likely to have significant market power soon, which is a prerequisite to initiate service competition obligations.

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[90] For thorough information of unbundling of the local loop see e.g. Baake and Preissl ed. (2006), DotEcon (2003), and IDATE's Issue 57 of Communications & Strategies (2005). For a literature review see Baranes and Bourreau (2005).
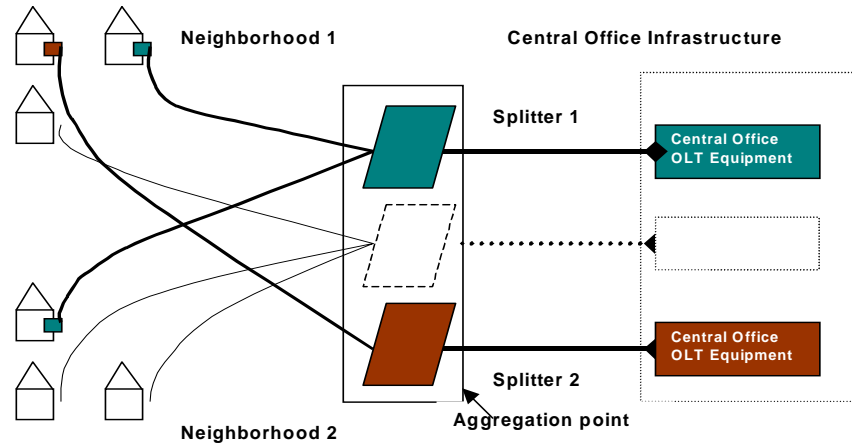
Figure 52, Proposed competitive model based on Optimal Fibre Aggregation
Point
Source: Sirbu (2005)

One of the main sources in literature of analysis of FTTH competition
is Marvin Sirbu. He has analysed alternative methods of supporting
local loop unbundling in FTTH network, both AON and PON. While he
and others (e.g. Sirbu 1988; 2005; 2006, and Tseng 2001) have shown
that service competition over FTTH is possible there has been little or
no discussion in Denmark about ex ante measures to ensure unbundling
of fibre based local loop. While it is outside the scope of this thesis to
solve this issue the thesis will seeks to constructively relate the
conclusions of the simulation models presented in the following chapter
to the regulatory debates and facilitate future work.

3.8.   *Deployment strategies for telecom operators*

Telecom operators[91] can select between a set of deployment strategies
which are characterised by path dependency and diminishing usage of
legacy copper loop. The selection space ranges based on how much of the
copper they use and consequently how far towards the customer they
deploy new fibre. This section will outline the available alternatives and
how they are interrelated through possible migration paths. How telecoms

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[91] The term telecom operator is used to refer to both ILEC and CLEC, or
in general an operator that has roots in broadband provision over
copper access networks.

select between the available options varies depending on which interests
govern the decision making. For simplification this thesis assumes that the
objective is to maximise monetary values[92].

Kapovits (2005) studies deployment strategies of European operators and
finds that most operators are already deploying ADSL2+ and
experimenting with VDSL/VDSL2. He maps the development of networks
and services for a typical incumbent on a time scale where the current time
(end of 2006) marks the beginning of FTTN and VDSL deployment.
Stordahl and Elnegaard (2004) have also analysed the roll-out strategies
available and provide guidelines for incumbent deployment, foreseeing
"cherry picking" strategy in early VDSL deployment.
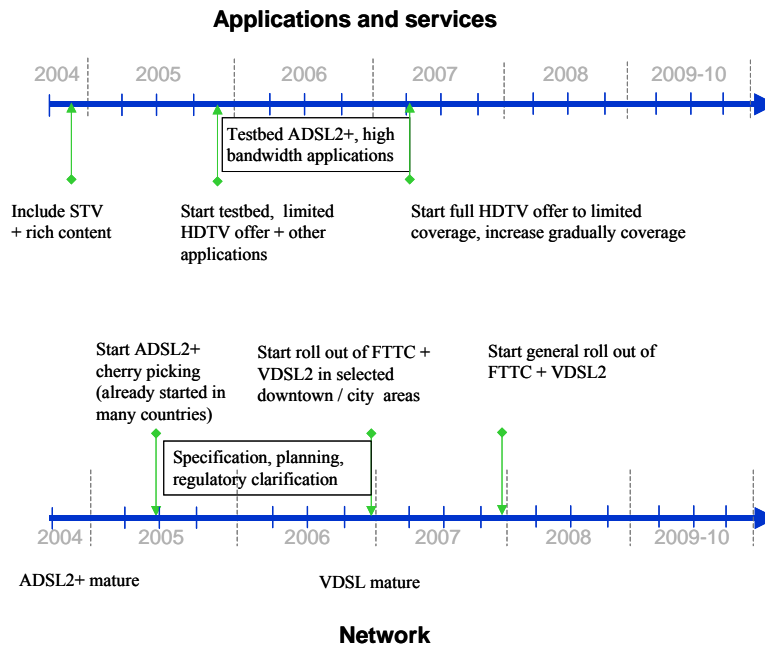
Figure 53, Residential network and service deployment by telecom operators
Source: Kapovits (2005)

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[92]   Under this assumption, a model should transfer all objectives into
monetary values which can be optimised. If the result of the model
does not yield the result that a decision maker would take, that would
mean that modelling of monetary values was not correct, rather than
that modelling in general can be blamed.

More generally the alternatives and resulting available evolutionary paths of telecoms based DSL deployment can be summarised in the three scenarios of Figure 54. In the first scenario operators test deployment in the vicinity of Local Exchanges where little or no infrastructure changes are needed. The feedback from these tests can be used to gather technical and operational experience and fine tune business models based on customer satisfaction, take-up rates, willingness to pay etc.
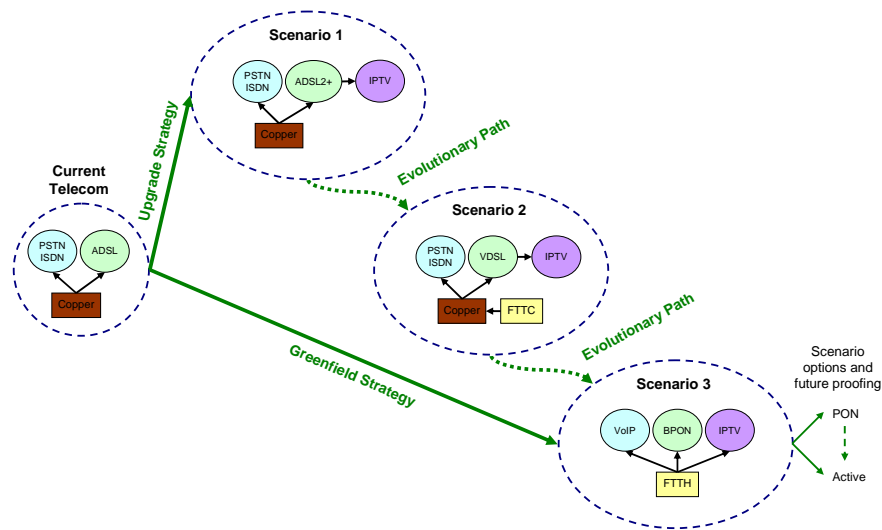

Figure 54, Evolutionary strategies for incumbent operators

With full knowledge of the cost, revenues and capabilities, operators hope for optimal evolutionary path towards Scenario 2. The key decision in this migration is how far towards the customer they should deploy fibre. Given the structure of existing PSTN copper network the two main alternatives that telecoms have is positioning the DSLAMS in the existing aggregation points, i.e. PDP or SDP of Figure 37.

The characteristics of deployment in both PDP and SDP vary depending on local conditions, but in general the deeper they penetrate, the higher transmission capacity they can offer but at the expense of increased groundwork, cables, and cabinets. The final step is to replace all of the copper with FTTH, which is called scenario 3. Within that scenario, FTTH can be implemented as either Active Ethernet or Passive Optical Networks but as described earlier in the chapter, most incumbent operators tend to select PON.

Within each scenario, incumbents have to fine-tune parameters such as network architecture and technological solutions used. Despite the preference of PON, operators may be interested in future proofing their PON infrastructure through upgrade possibilities towards Active Ethernet by using homerun instead of field split point to multipoint. Figure 55 depicts the scenarios based on the network type and architecture applied.
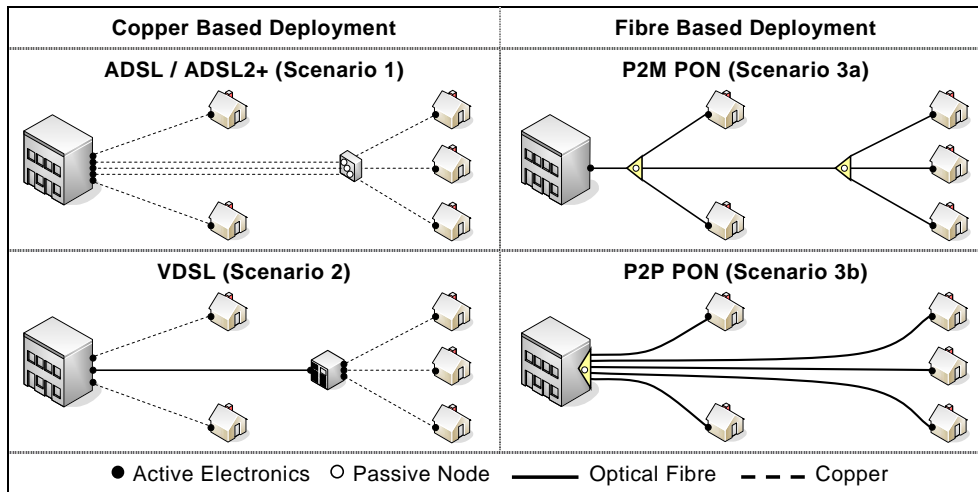

Figure 55, Network architectures of available deployment scenarios

The author has previously studied deployment cost of different deployment strategies in Sigurdsson et al. 2006b with results indicating that in the absence of competition, operators are most likely to use scenario 3a as greenfield strategy but migrate between the three scenarios in the case of brownfield. While studying deployment in the absence of competition is interesting to understand the characteristics of deployment cost it ignores the severe changes to deployment strategy that literature indicates competition has.

3.9.   Deployment Strategies for entrants

Entrants that do not possess an infrastructure have three options: renting infrastructure from other operators and offer only services, deploy a new infrastructure, or alternatively not participate at all. Additionally they have the option of migrating between the two, e.g. after establishing a customer base through service competition before embarking on expensive infrastructure deployment.
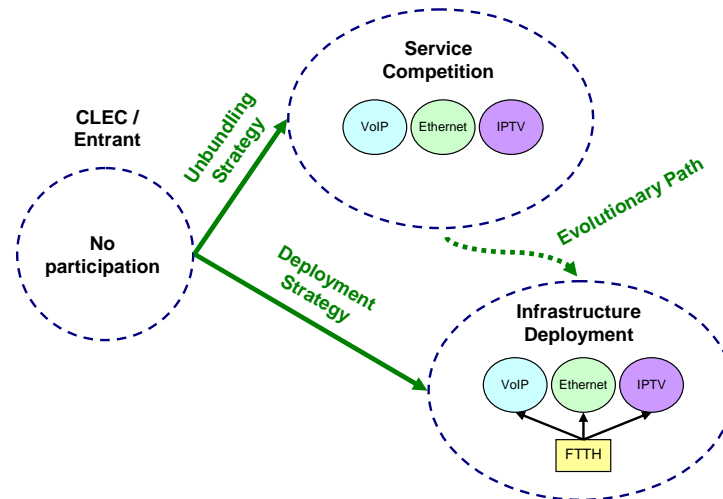
Figure 56, Deployment strategies for an entrant

While entrants have the theoretical alternative of building copper networks in reality that is not likely to happen. The strategic selection scope for deployment is therefore limited to the decision which type of FTTH to deploy. As indicated by the analysis above, earlier deployments, as well as those made by alternative operators tend to be Active Ethernet. This is also the case in Denmark, where the majority of all reported FTTH deployments by the energy utility sector are Active Ethernet.[93]

A key decision in active Ethernet FTTH deployment is how far from the subscriber the access node / switch should be placed. In contrast to telecoms that are limited to structural components in the PSTN, entrants can optimise their network structure. Typically, cost minimisation is then applied to find the access segment fibre distance that minimises the total cost of ownership. This optimal distance represents a point where the cost savings from decreasing trench/duct/cable costs is equal to the increased structural cost of nodes and equipment (see Figure 57).

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[93] According to Montagne (2006) the Danish EUC, EnergiMidt, has selected a BPON technology and passed 18 000 home by mid 2006. Also in Denmark, SEAS-NVE is deploying BPON while SEF is deploying EPON. This indicates that EUC deployment perhaps is moving towards PON but due to the late arrival of this information this trend was not analysed further in this thesis.
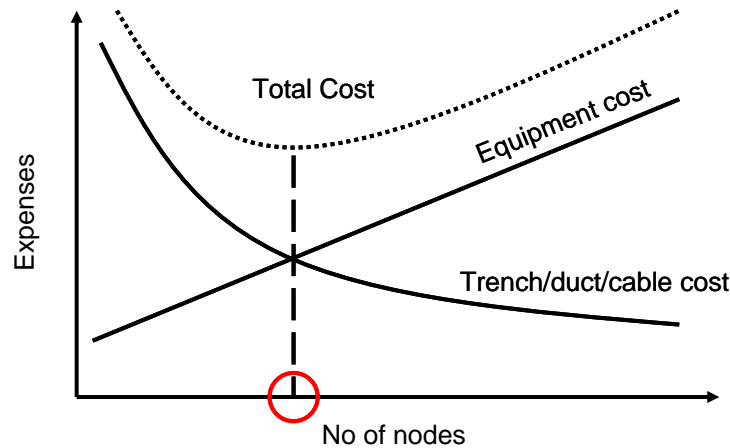
Figure 57, Optimisation of network structures in Active Ethernet FTTH

The author has in Sigurdsson (2004d) presented methods of cost minimisation in next generation networks. The Swedish electricity commission[94] has published a handbook on design consideration for Active Ethernet FTTH (SEK 2004) that has additionally been translated into Danish. Additionally, Madsen and Riaz (2004) provide a reference model for planning broadband network infrastructures, and ICV (2005) provides an overview of technological variants used in Denmark.

5.2. *Quality of Service in access networks*

This thesis looked at some of the open challenges of QoS management in access networks. The study draws on work by the author from Sigurdsson 2004c, which was focused on DSL platforms. The general issues of service differentiation are nonetheless equality as important in FTTH. There have been several proposals for measures to ensure QoS in communications networks where most fall into one of three main provisioning strategies: over provisioning, loose control, and strict admission. Each has its strengths and weaknesses, but none has yet reached widespread acceptance. Below is a short summary of the available solutions.

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[94] Svenska Elektriska Kommissionen (SEK) - http://www.sekom.se

Over provisioning

Over provisioning is based on circumventing the lack of resources by providing capacity that is far in excess of the total required load. While this does not guarantee available resources, it provides a viable solution when providing bandwidth is cheaper then controlling it. Over provisioning can be combined with measurements and monitoring that indicate when upgrades or decreasing capacity is advisable. The strength of over provisioning is cost effectiveness while the weakness is lack of explicit QoS management.

Loose Control

Loose control is based on prioritising portions of the traffic, eliminating the need for per flow admission control. Then the rest of the traffic competes in a best effort fashion for the remaining resources. In Differentiated Services (DS) (Blake 1998) and service differentiation in general, intelligence is distributed to the edge of the network, where traffic is aggregated into different classes and packet forwarding is scheduled for each class. The strength of service differentiation is scalability, because traffic aggregates correspond to connection types rather than individual connections. The weaknesses of service differentiation, is its loose quality guarantees, and lack of admission control and resource assurance.

Strict Admission

Strict admission is based on strict resource provisioning and admission control per flow. This solution is needed in scenarios where resources are scarce and portions of the traffic require QoS guaranties. The Resource ReSerVation Protocol (RSVP) (Braden, 1997) and Integrated Services (IS) (Braden 1994) architecture are based on resource reservation and conceptually similar to the end-to-end service architecture of ATM. Both can provide a controlled level of service to individual network connections. The strength of IS is its ability to provide strict quality guarantees. The weakness is scalability, setup delays, and additional per packet processing. Additionally, strict admission can not be implemented in current IP based network infrastructures and therefore requires wide scale infrastructure upgrades.

Implementing resource reservation is expensive and additionally suffers from technical challenges and therefore many believe that alternative

delivery models are needed (Goderis 2001). Among the proposed solution is admission control by implicit signalling (Ram 2004). This proposal supports premium and regular service categories for voice traffic and best effort service category for data traffic. More generally, this proposal is among those requiring elements of resource reservation in the access network and service differentiation in the aggregation network. These proposals have in common that voice and video traffic demand is limited by the application session control and/or using provisioning rules to ensure that services never oversubscribe to the available bandwidth. Queuing mechanisms can then give priority to voice and video applications with secondary priority to less delay sensitive applications.

Roberts (2004) uses analysis of the statistical nature of IP traffic and the way this impacts the performance of voice, video, and data services to question the appropriateness of commonly proposed quality-of-service mechanisms. He argues that many proposed schemes are overly concerned with congestion control. One of his observations is that despite disadvantages of simple over provisioning "an over provisioned best effort network can meet most requirements and has the advantage of relatively low capital and operational cost" (Roberts 2004, p. 1389). In line with his reasoning, Alcatel a major DSL equipment vendor proposes and has started offering equipment based on a combination of over provisioning and service differentiation, using Ethernet VLANs to differentiate between media flows (Alcatel 2004c). While these solutions can solve the current requirements of multimedia services in FTTH platforms other problems arise in DSL.

To date, most DSL solutions are focused on solving the downstream quality of service requirements, required by telecom operators to introduce new video services. Offering two-way service differentiation in DSL access networks is deadlocked since without service differentiation support in Customer Premises Equipment (CPE) there is no use in implementing it in the access network and vice versa. As a consequence, Network Access Providers (NAPs) can be expected to seek solutions that inexpensively result in new revenue generating services rather than making controversial infrastructure upgrades.

3.9.1.   Service Differentiation in DSL based access networks

The migration of service differentiation in access networks from the current model towards the future goal of content based service differentiation can be classified into four steps. They do not represent consecutive steps that operators should or will take, but rather

enumerate available development alternatives that operators can choose or migrate between.

In step 1, the CPE is neither able to differentiate nor prioritise traffic and therefore voice and video services have to compete with data traffic for resources. This is the situation in most access networks today and can be called a pure "best effort" model and can only work if resources are abundant, i.e. by over provisioning.

Step 2 is characterised by advances in equipment at the NAP side. It is based on prioritising downstream video and voice content over data at the BRAS. Since this is based on the same CPE as before, all upstream traffic still competes equally for resources. This model supports downstream prioritisation of voice and video content. If the solution is implemented using the Point-to-Point Protocol (PPP) as proposed by Alcatel (2003) streams of individual traffic are carried from centrally located BRAS making multicasting of broadcast television unfeasible. VoIP services that the NAP provides or recognises can be guarantied downstream priority, but third party voice services will be worse off then before as priority traffic uses capacity, hence VoIP traffic is competing with other data services for the remaining resources.
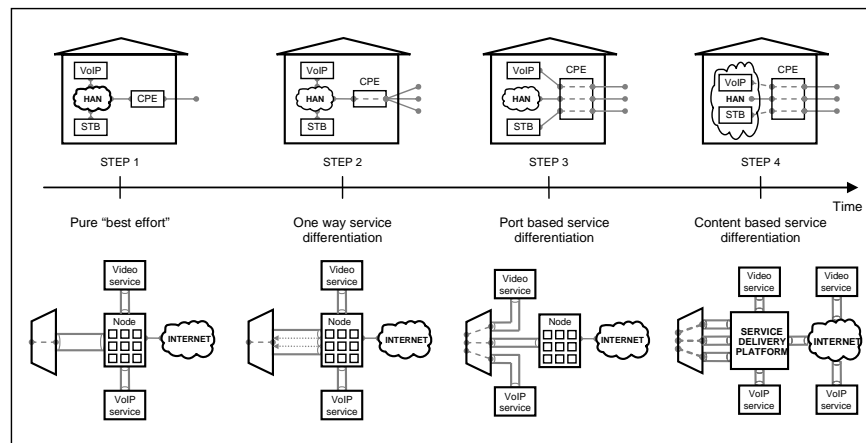

Figure 58, Migration path of service differentiation in broadband access networks

The third step is characterised by required upgrades of both CPE and DSLAM equipment to support two-way service differentiation. In this scenario, service differentiation is based on setting up separate virtual channels for each service and assigning services to specific ports on the

CPE. Service differentiation is then transparent to the applications and performed through virtual channels in the network rather than at packet level. Both the CPE and DSLAM then prioritise voice and video virtual channels before data. This solution can support multicasting and therefore enables Video on Demand (VoD), IP television (IPTV), and VoIP. This scenario is the preferred situation of many NAPs as it gives them control over the network resources and provides a competitive edge to traffic they select by ensuring transmission priority. Competing third party service providers have to offer services through low priority data services. While this does not necessarily affect transmission in the local loop for customers that have not subscribed to ILEC voice or video services, it may limit third party competitiveness in the aggregation network.

The fourth and last scenario is based on two way content based service differentiation. Here either the end devices or CPE must define the priority class of packets and forward them accordingly. This can be implemented according to DS, where the packet QoS class is identified through a label in the IP header. Here the NAPs assumes the role of pure transmission provider in a public garden scenario, leading according to traditional economic theory to fair service competition as well as service variety and lower prices for end customers. While most ILECs tend to prefer vertically integrated business models, gated garden business models (sometimes also referred to as "Open Access") are also gaining support through municipal, energy utility, and alternative broadband projects (Larsen 2006; Tadayoni and Sigurdsson 2005). However, more research is needed on implementation of this scenario within DSL based access networks.

3.10. Case Study: DSL in Hasselager

This section uses empirical data from Hasselager, a small suburban area in the south-western part of Aarhus in Denmark to demonstrate properties of the identified deployment alternatives of an incumbent possessing a copper local loop. The reason for selecting Hasselager is that it has properties that illustrate some of the strengths and weaknesses of upgrade strategies but also as it has already been studied by the incumbent, TDC (Nielsen 2005).

The studied area in Hesselager consists of a town area of approximately 4,5 km^2, of which 93% are single or detached houses (Post Denmark 2006). The local exchange is located 1.2 km out of the town (see Figure 59), increasing the average loop length by the same amount. This distance

can be broken down to average distance from LE to Primary Distribution Point (PDP), average distance from PDP to Secondary Distribution Point (SDP), and finally average distance from SDP to Network Termination Point (NTP).

The legacy position of the local exchange means that the lines are too long to offer VDSL from the LE and reduces the maximum transmission rates to 4 – 12 Mb/s for the majority of the households, as depicted in Figure 60. However, due to the position of the LE, a single trunk line carries all connections from LE to the first PDP, which is close to the geographical centre of the area, providing a natural position for a node with a detached DSLAM. With this single additional node, the majority of the households in Hesselager can be offered transmission speeds in the range of 20-50 Mbit/s[95] as illustrated in Figure 61.

Figure 59, Local conditions in Hasselager, Denmark

[95] These are rough estimates based on "crow flight" distance of the proposed node without taking consideration to the reduction factor applied in the LRAIC model.
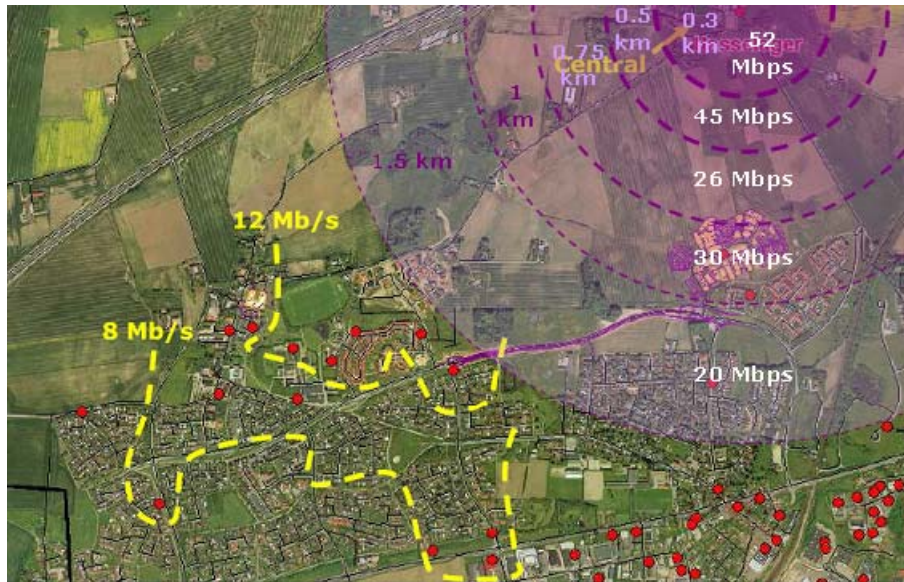
Figure 60, Non-upgraded transmission capacity in Hasselager
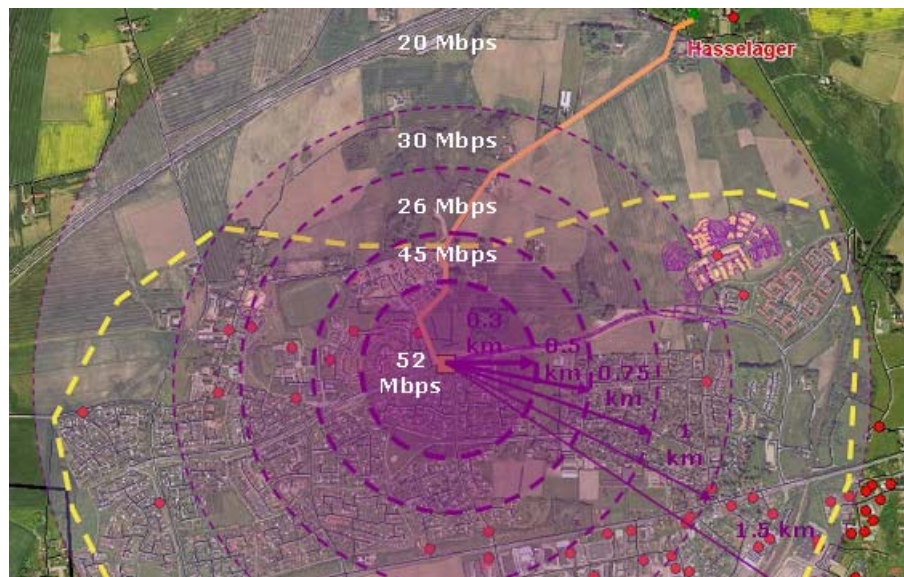

Figure 61, Transmission capacity of FTTN/DSL deployment in Hasselager
with one node.

To deploy DSL that can offer speeds in excess of 20 Mb/s to the majority of Hesselager the number of detached DSLAM sites must be increased to 4-11 depending on the target transmission capacity. While any number of nodes and thereby copper loop drop distances are possible, the most practical upgrades would involve reusing Secondary Distribution Points (SDP) from the PSTN. To facilitate later stage upgrades to Active / Passive optical networks the optimal distance and structure of FTTH should be considered in the network planning process as well as the number of strands in the trunk cable to the new nodes. An summary of the upgrade alternatives in Hasselager are provided in Figure 61.
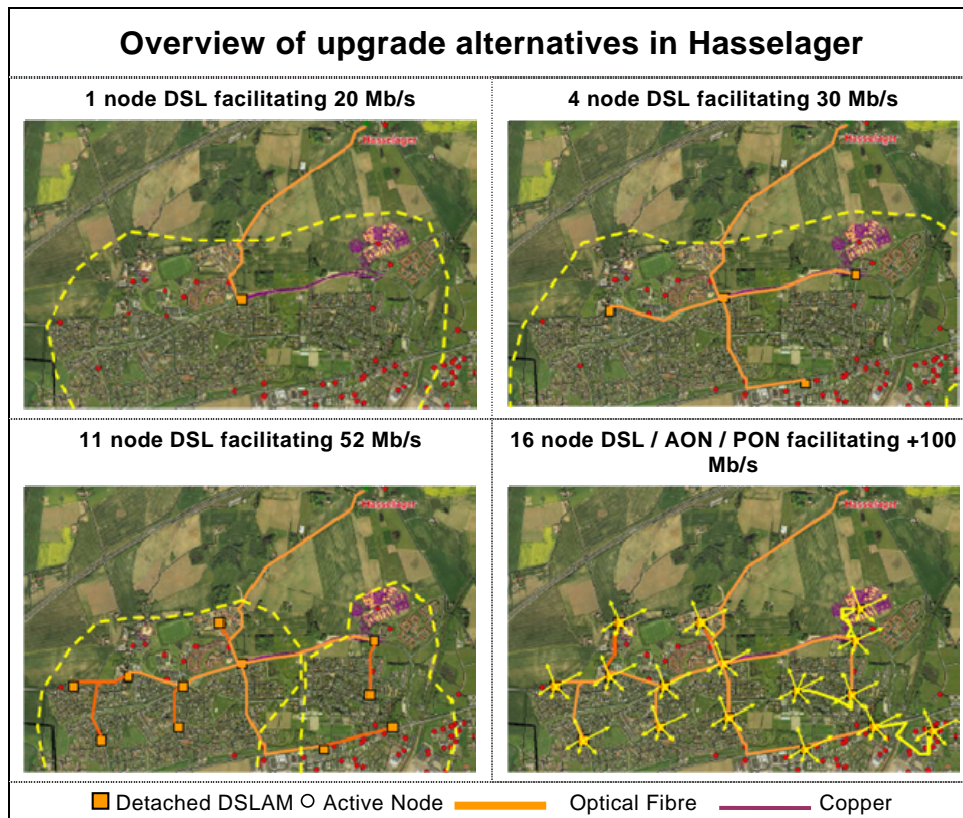

Figure 62, Summary of upgrade scenarios in Hasselager

3.11. *Case Study: FTTH by NESA*

NESA A/S is energy utility company operating in the vicinity of Copenhagen. The company has its core activities of electricity distribution and trade and is the biggest electricity provider in Denmark with 535 000

customers (Nesa 2005). For the past 15 years the company has been deploying fibre cables to support its core activities, e.g. through an IP based control system for electricity installations, and had deployed more than 25 000 km of fibre and more than 700 km of fibre ducts in 2005 (Tadoyani and Sigurdsson 2006).

In 2002 the company diversified into the broadband market with trial deployment of active Ethernet FTTH. At yearend 2004 the company had 800 homes participating in a commercial pilot project. The deployment strategy of the company is to lay empty micro ducts with power cables, for subsequent blowing of fibre. The company has already connected 20 000 homes with ducts and intends to increase that number to 200 000 during the course of the next 5-7 years. The company has not yet taken decision about fibre roll-out in the tubes and according to it there is a need for political support in role-out of fibre infrastructure, as they phrase it: "all important infrastructure projects require political support" (Tadoyani and Sigurdsson 2006).

According to NESA there are several important synergies between electricity supply and fibre optic infrastructure supply: a) common network planning, b) common digging projects, c) common network control and monitoring, and d) common service organization. According to NESA the cost of the fibre cable itself is minor in relation to the groundwork and as a NESA representative phrased it: "It should be illegal not to establish fibre connections to the household when a digging project is ongoing".

To build up the FTTH network, NESA contracted IBM Denmark as system integrator for the project using a technical solution from Cisco and PacketFront. The network is based on a two tiered MPLS backbone network from Cisco, connecting up to 10 access switches with 24 ports each, in a bus topology. At the customer side NESA installs customer premises equipment (CPE) that terminates the fibre. From the CPE, users are self responsible for installing POT or Ethernet cables to their devices.

NESA follows a business model based on "open access" or what can be called operator independent network, where different service providers can access the households through NESA network. NESA however owns, controls and maintains the physical infrastructure and the transmission equipment. Today there are five service providers competing in four service types. In the initial pilot project, customers paid a fixed monthly fee of € 50 for access to the infrastructure and then bought services directly from service providers through a web portal.

In this approach there is no profit sharing or transportation fee for service providers and NESA covers all expenses from the customer connectivity fee (public garden model). However, the specifics of the future business model are under development and as a part of that, NESA is considering introducing transportation fees for service providers. With this transportation fee, NESA hopes to reduce the customer fee, which otherwise can be a barrier to attracting new customers, and to better represent the real transportation cost of different service requirements.

NESA believes very strongly in the 'open access' business structure and see that as their main success criteria in competition with traditional operators and over for other FTTH projects. They adopt a rather disintegrated service and infrastructure approach, by not providing any additional services or functions that have to do with the services themselves, e.g. not providing set-top boxes, billing nor product support. They believe that distancing themselves from service providers is the only way to ensure fair competition.

Dam (2006) provides a technical description of the Nesa network. According to him the backbone networks consists of 4 Extreme Diamond 8810 core switches, each with 10 Gb/s capacity. The regional aggregation switches are Extreme Summit X450 and connect to the core switches at 10 Gb/s upstream and downstream to access node switches at 1 Gb/s. The access switches are 24 port PacketFront ASR4xxx, connecting each customer with 100 Mbps.
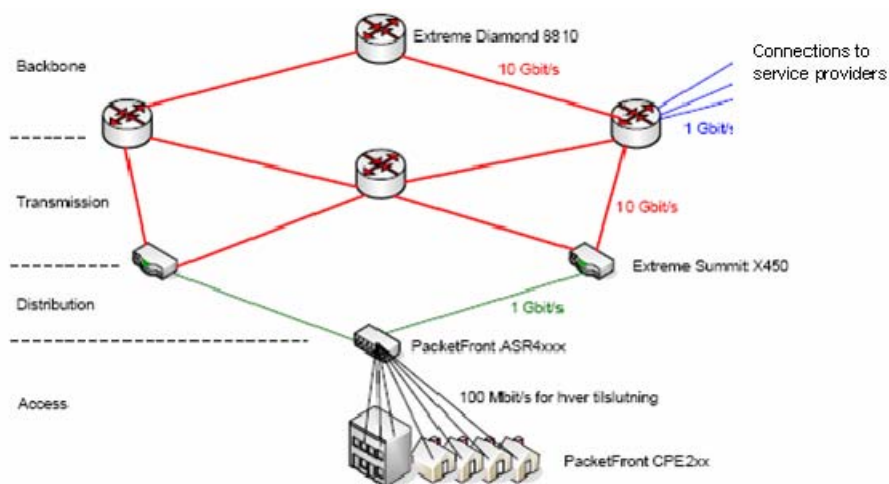

Figure 63, Nesa network structure (Source: Dam 2006)

At the customer side, the optical fibre is terminated in a Packet Front CPE279 in the case of single apartment houses or CPE218 for multi-dwelling houses. The network provides service differentiation through the following 5 classes of service: management, VoIP, TV, VoD, data transmission.

3.12. Summary

This chapter has analysed alternative methods of offering residential broadband using Digital Subscriber Line (DSL) technology over the existing copper loop infrastructure in comparison to laying fibre all the way to subscriber's premises, i.e. FTTH. The study has revealed that both solutions build upon the concept of Next-Generation-Networks (NGN) where different types of multimedia services are carried over a single IP infrastructure that can support different QoS requirements. However, there have not emerged any widely accepted "future-proof" methods of providing end-to-end QoS, reducing the expected lifetime of current equipment.

The study has also shown that the imminent network and service convergence will affect the role that network access providers assume in the provisional value chain. While telecoms generally prefer vertically integrated service development and deployment offered through walled garden business models, emerging EUC deployment is often based on "open access" where external service providers are contracted through revenue sharing.

A detailed study of DSL technology and its provision showed how reliant DSL is on the existing copper infrastructure that signals are carried over. Local conditions dictate service provision where cooper loop lengths are the most important parameter due to signal attenuation. However, telecoms have the option of deploying equipment closer to the end users, thereby reducing the loop length and increasing transmission speeds. Two plausible upgrade strategies exist in Denmark where detached DSLAMs can be located in existing PSTN cable aggregation nodes (called primary and secondary distribution nodes). A prerequisite to deployment in detached nodes is that the Danish regulation implements sub-loop unbundling.

In contrast, EUC based FTTH deployment does not build on existing access networks. Instead new optical fibre is deployed to each household in a given area, offering a "future-proof" transmission medium. As the study revealed the end equipment of FTTH as well as DSL is undergoing constant development and wholesale prices are highly reliant on mass production. Therefore deployment can be greatly effected by global trends, which

currently indicate that Passive Optical Networks will be the most widely deployed FTTH standard once incumbent telecom operators start migrating over to FTTH.

The chapter ended with two case studies of deployment in Denmark. The first was an empirical study of DSL upgrade alternatives for the incumbent, TDC, in the suburban area of Hasselager. The latter analysed the deployment approach of Danish EUC Nesa, which deploys active Ethernet FTTH around the capital area using the "open access" approach..

Chapter 4

Modelling Framework

This chapter describes the techno-economic evaluation framework developed to analyse financial feasibility of residential broadband deployment. The chapter introduces an implementation based on Microsoft Excel before describing the three sub-modules of the model: cost-benefit module, feasibility module, and competition module.

4.1.   Introduction

This chapter describes the design issues of a techno-economic evaluation framework for financial feasibility of access networks. The framework consists of three sub-models that together will be implemented with the goal of estimating the financial feasibility of EUC based FTTH deployment in Denmark under competition from incumbent / competitive local exchange carriers (ILEC/CLEC).

The first part is a cost-benefit model that feeds a second part consisting of an appraisal model that has been developed to estimate pre-tax profit. The last step evaluates the affect of competition. The scenarios defined are taken from Chapter 2 and Chapter 3. Summed up the model will simulate the following components:

- *Access Technologies*
  DSL from LE
  DSL from PDP
  DSL from SDP
  FTTH Active Ethernet

- *Service Profiles*
  S0: No Service
  S1: Internet Browsing
  S2: Multimedia
  S3: Interactive
  Multimedia
  S4: Future Multimedia

- *Geographic Profiles*
  City
  Town
  Rural A
  Rural B

- *Financial feasibility*
  Revenues
  Tilted annuity
  Pre-tax profit

- *Infrastructure Competition*
  Von Stackelberg game

-

4.2.   Literature Study

The literature study of this chapter builds on the theoretical introduction of Section 1.6 and does therefore not add further to the literature review of modelling but is rather short and focused on topics within the subfield of techno-economic models and game-theory. The study of game-theoretic approaches was motivated by an external stay at the Faculty of Applied Economics at the University of Cambridge. The work and study of techno-economic modelling was mostly influenced by participation and extensive work within the European research project IST-BREAD. For that reason an additional review of related research projects is also provided.

4.2.1.   List of contributions

The publications by the author related to this part of the study draws on participation in the IST-BREAD project as described in Appendix I in additions to publications of results from a M.Sc. thesis carried out by the author at CICT prior to this study.

- *Sigurdsson, H.M., Thorsteinsson, S.E. and Stidsen, T.K. (2004). Cost Optimization Methods in the Design of Next Generation Networks, IEEE Communications Magazine, vol: 42, issue: 9, pages: 118-122., 2004.*
  This paper is probably the most renowned publication from the list of contributions during the course of the project. It is the

result of cooperation with Iceland Telecom and analyses the migration of their PSTN from circuit switched into a multipurpose packet switched network based on the ENGINE solution from Ericsson. The paper describes a cost model developed to enable cost and benefits analysis of transforming the network to NGN. Methods of optimization and their application to determine the optimal number and position of nodes in the future network are furthermore described. The optimization produces a network structure with the lowest possible total cost of ownership, and the model can also indicate how deviations from the optimum affect cost. The feasibility of NGN is assessed by comparing the cost of NGN migration to that of maintaining the current circuit-switched network.

- *Sigurdsson, H.M. (2006) Techno-Economic Study, Deliverable FP6-IST-507554/JCP/R/Pub/D2.4-3.4,   FP6-IST-507554 BREAD.*
  This deliverable describes a techno-economic model developed for analysing and comparing broadband deployment strategies. The deliverable presents results from simulation of Capital Expenditure (CAPEX) of dominating broadband technologies in different types of demographic areas. The study reveals the competitiveness and applicability of different access technologies in the future broadband market as well as providing sensitivity analysis of the most influential factors controlling market development.

- *Sigurdsson, H.M. and Skouby, K.E. (2005). Techno-economic evaluation of broadband access technologies: The BREAD approach. In proceedings of the Wireless Personal Multimedia Communications Conference WPMC, Århus, Denmark*
  This paper presents the techno-economic model developed by the author for the IST-BREAD project. The model compares capital expenditure (CAPEX) and operation expenditure (OPEX) values for a predefined service selection in an increasing customer base for four access technologies: DSL, Cable, FTTH and FWA and models this in four different geographic scenarios: Dense urban, Urban, Suburban and Rural. The paper presents preliminary results of simulations and concludes with implications on policy and regulation.

4.2.2.   Review of Related Research Projects

The model developed in this report draws on the work carried out in various other research projects. The terminology, methodology, and theoretical framework are influenced by European techno-economic research projects: TONIC, TETRA, ECOSYS and BROADWAN while the infrastructure and technology aspects draw from BREAD, FAN and BROADWAN. More specifically the relationship to these projects is as follows:

- *IST-BREAD*
  Broadband in Europe for All: a multi-disciplinary approach aims at developing a roadmap for the deployment of broadband and realisation of the 'broadband for all' concept within Europe. For this thesis the technological overview of access and backbone networks provided in deliverable 2.2-3.2 was most useful as well as case studies of residential broadband deployment.

- *IST-TONIC*
  IST-2000-25172 TONIC (TechnO-EcoNomICs of IP optimised networks and services) concentrates on techno-economic evaluation of new communication networks and services. Following up on older projects, TONIC was carried out in 1998-2002 and provides the foundation of most theoretical and methodological work on techno-economic studies. This project therefore provided a starting point for development of the simulation model.

- *ECOSYS*
  Ecosys is an ongoing research project within the Celtic framework on the techno-economics of integrated communication systems and services. The most interesting part of the ECOSYS project for this study is the advancement and evolution of the theoretical and methodological framework developed for techno-economic analysis of telecommunications networks in the TONIC project.

- *IST-BROADWAN*
  The goal of the "Broadband services for everyone over fixed wireless access networks" is to investigate how wireless networks can be used to provide true broadband services. The most interesting aspects of the BROADWAN project for this study are the analysis of market potential and deployment

scenarios and future development of wireless access technologies. Additionally, the project has developed a simulation model for deployment cost based on methods developed in the TONIC project.

- *IST-MUSE*
  IST-MUSE is a large integrated R&D project that analyses the future of multi-service access networks from a technological perspective. For this thesis the most relevant contributions are techno-economic studies performed within the project.

- *P1117-FAN*
  EURESCOM P1117-FAN evaluated the technical specifications of future access networks, the impact of IP and infrastructure architectures. For this thesis it was used to reinforce the infrastructure and access technology selection.

- *P1551- Applications and services for ADSL2+ and beyond*
  EURESCOM P1551 evaluates the requirements of future residential broadband services and DSL based access network roll-out strategies that can meet these requirements.

4.2.3. Literature review

The effect of infrastructure competition has been a key issue in ownership and development of telecommunication networks around the world. After existing for decades at the beginning of the last century, most countries declared telecommunications as statutory monopolies during the course of the century and banned competition (Olsen 1993). Under this regime, a national operator was responsible for deploying a single access network that could provide all members of society with access to a common telephone service. According to economic theory this would lead to a higher level of social welfare through economics of scale and prevent inefficiencies involved in duplication of an existing infrastructure.

With the liberalisation of the telecommunications industry during the 1980s and 1990s the responsibility and control of market development shifted from monopoly operators, to national regulatory authorities. In Europe, each national regulatory authority is obligated to define and implement local policies based on general rules formulated by the European Commission. In this framework, national regulatory authorities aim at maximising the social benefit from

telecommunications networks and services through a combination of i) service competition on existing infrastructures and ii) infrastructure competition.

Whether service competition or infrastructure competition is more favourable for broadband development has been disputed in theory and praxis but in general infrastructure competition is favoured by regulators, since it is expected to induce long term efficiency and remove heavy regulation requirements in the industry (Bourreau and Dogan 2003). Infrastructure competition is well understood theoretically for the Public Switched Telecommunications Network PSTN) (see e.g. Laffont and Triole 2000 and Cave, Majumdar and Vogelsang 2002) but less is know about which effect prevails empirically for the case of residential broadband networks and services.

A variety of forecasting models have been developed for predicting subscriber uptake of telecommunications services. Fildes and Kumar (2002) provide a good review of the broad topic of telecommunications demand forecasting while Stordahl (2003a/b, 2004) focuses on broadband diffusion and describes what has been done in techno-economic research projects. Most recently Olsen et al. (2006) uses a four-parameter logistic diffusion model to predict broadband penetration and market share evolution between cable modems and DSL.

Kranton (2003) finds that when firms compete for market share, perfect equilibrium in which firms produce high-quality goods need not exist. Competition for customers can eliminate the price premium needed to induce firms to maintain a reputation for high-quality production.

4.3.   *The Danish LRAIC Model*

The Danish Long Run Average Incremental Cost (LRAIC) model was a starting point for the cost model analysis of this thesis. The current version of the model, version 2.4 (ITST 2006b), is implemented in Excel and downloadable on the Internet. The model is a bottom up cost model based on the forward looking cost principle[96], i.e. developed to estimate the cost

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[96]   Norden (2004) defines forward looking costs as "Prices are calculated on the basis of expectations for future equipment prices and efficient usage. Entrant thus do not risk paying too high prices due to

of constructing a new optimised network based only on the structural components of the current infrastructure in Denmark. In its current form the model is divided into three main modules: access networks, core networks, as well as collocation issues. For the purpose of this study only the access module was considered.

The access network is essentially modelled in two ways: the trench and ducts are modelled on a national basis, whereas the cable is modelled on the basis of 20 sample areas. Based on these 20 sample areas the model divides Denmark into segments, each with the same characteristics as one of the sample areas. In this way the model calculates the total cost of connections between the LE (called ASM - local/remote concentrator in the model) and the NTP (customer network termination point).

According to Europe Economics (2006) the Danish NRA has initiated work on a revised model that from 1 January 2007 should extend the existing LRAIC model for determining interconnection prices for bit stream access (BSA), which is the description used within Denmark for the resale of xDSL connection via TDC's network. However, as this model will first be publicly available after the publication of this thesis, it is not considered.

4.4.   Model Design and Implementation

One of the main goals of this thesis is to develop a quantitative simulation model for residential broadband deployment. The first thing to decide when implementing a simulation model is the modelling language to be used. Several modelling languages have previously been used and typically each model type from Table 2 has a preferred modelling language. As an example most Techno-Economic models have been implemented in Microsoft Excel (see e.g. Ims 1998, Ecosys) or Matlab (Nordjysk Netforum 2003), while game-theoretic models often use Mathematica (Bijl and Peitz 2002). These were subsequently evaluated to find the appropriate programming language for the study.

4.4.1.   Selecting the programming language

inefficient investment strategies employed by the incumbents. Incumbents on the other hand cannot be certain to recover costs".

Each of the three programming languages has its virtues and drawbacks, dependent on the characteristics of the project at hand and the programmer implementing it. For the purpose of this study the author made a subjective evaluation of each of the languages according to the expected project requirements. The result of this comparison can be seen in table 14.

Requirements:	Mathematica	Matlab	Excel
Handle advanced mathematics	☆☆☆	☆☆☆	☆☆
Handle large problems	☆☆☆	☆☆☆	☆☆
Equilibrium Analysis / optimisation	☆☆☆	☆☆☆	☆
Easy to implement	☆	☆	☆☆☆
Understandable for others	☆	☆☆	☆☆☆
Possible to implement GUI[97]	☆	☆	☆☆☆
Programmer experience	☆	☆☆	☆☆☆

Score to indicate a subjective evaluation of "advantage" by the author:
Optimum: ☆☆☆, Good: ☆☆, Fair: ☆.

Table 14, Programming languages scorecard

Based on the scorecard, the decision to use Excel was reached. As indicated in table 14, the drawbacks of using Excel are mostly in forming and solving advanced mathematical models. However, the advantages related to easy implementation, knowledge and the general applicability of Excel were considered to weigh more.

4.4.2.   Developing the Model

Having selected a programming language it is imperative when taking on complicated programming projects to have a clear structure in beforehand. This prevents deadlock in implementations and ensures correctness. Ragsdale (2001) describes methodology and problem solving procedures and methodology for designing similar models as the targeted model of this study. This process can be seen in Figure 64, where the steps of improving the model are highlighted in the dashed box.

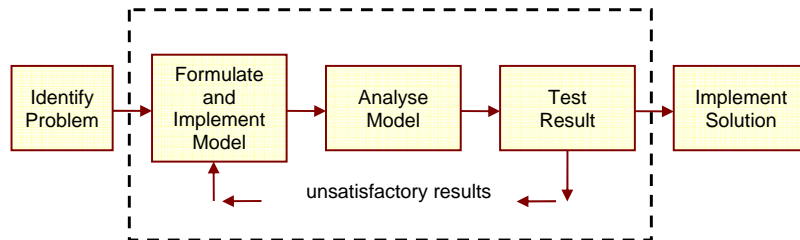
[97]   Graphical User Interface (GUI)

Figure 64: A visual model of the problem solving process
Source: Ragsdale (2001)

During the design and implementation process of this model two books were perused, and can be recommended. These are "Spreadsheet Modelling and Decision Analysis" by Cliff T. Ragsdale (2001) and "VBA for Modelers ; Developing Decision Support Systems with Microsoft Excel" by S. Christian Albright (2001). The targeted (and what proved to be the resulting model structure) is depicted in Figure 65.
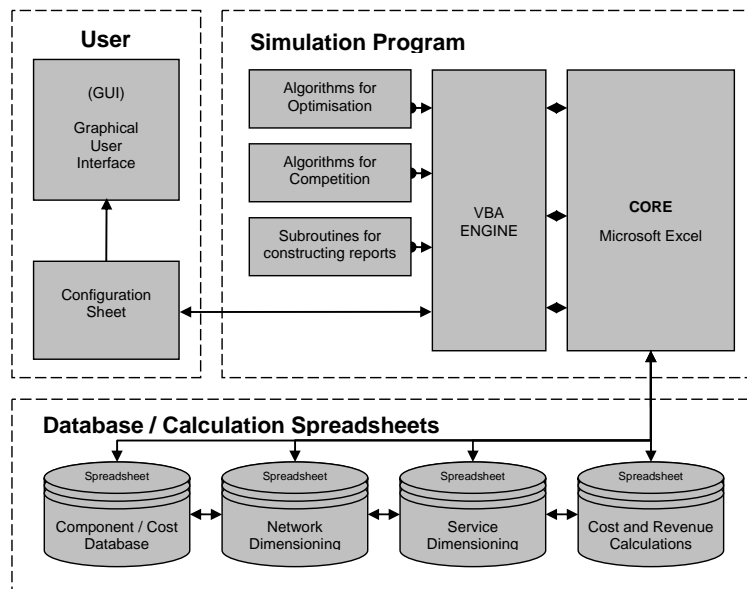

Figure 65, Model Structure in Excel

4.5.   Modelling Cost-Benefit

Below is a description of the cost-benefit model developed for the thesis. The model is based on the cost simulation model developed by the author for the IST-BREAD project as described in Sigurdsson (2006). In addition, the BREAD model was adapted to the Danish LRAIC legislation (ITST 2002) and augmented with revenue calculation capability.

The overall model structure is based on dividing the network into two segments: Access Segment and Aggregation Segment. The Access Segment covers the so called "first mile", i.e. connectivity from a household to the nearest active aggregation node (AN), and is copper in the case of DSL and fibre in the case of FTTH. The aggregation segment covers the network from the AN to a centralised service node (SN), which is fibre in the case of both DSL and FTTH. In this terminology the Access Node therefore represents the X in FTTX and can be everywhere on the way from the local exchange to the home/premises of the customer.

4.5.1.   Model structure and functionality

To calculate the required amount of trenches, ducts, and cables the model follows the methodology of the Tonic project, described in TONIC D7 (2002), which assumes a rectangular geographic area divided among homogeneously distributed buildings. All buildings are assumed to connect through vertical and horizontal trenches to the nearest Aggregation Node (AN). DSL and FTTH variants analysed in this study use star topology to AN as described in Chapter 4. In the same manner, all aggregation nodes are assumed to connect to a centralised Service Node (SN) / Local Exchange (LE) using star topology[98]. See Figure 66.

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[98] The Danish LRAIC model uses a different terminology stemming from the PSTN with two levels of intermediary nodes that cables pass on their way from the local exchange (i.e. four points in total in contrast to three in this model). In the LRAIC model, the point of demarcation at the customer premises is called Network Termination Point (NTP) (in contrast to CPE here), on the way to the Local Exchange (LE), cables are aggregated in Primary Distribution Point (PDP) and Secondary Distribution Point (SDP). As discussed in Section 3.7 the reason for using a different terminology and structure here is that DSL / FTTH only requires one level.
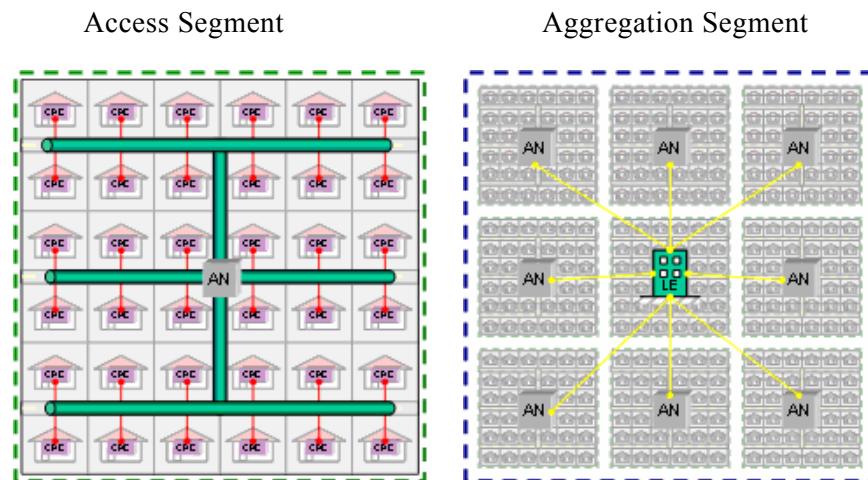
Access Segment   Aggregation Segment

Figure 66, Geometric Model

Network dimensioning is based on using average cable length in each deployment area to divide the total geographic area into equally sized access segments (see Figure 66). Each access segment is again divided into n units where each unit hosts one building. The result is a square area of unit breadth and width a = √n. Each building has a certain number of households, each of which connects individually to the nearest access node (AN). The geographic terminology is explained in Figure 67.
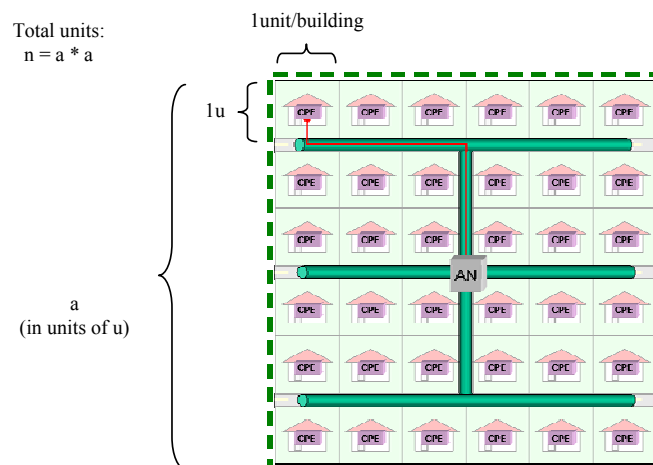

Figure 67, Geometric terminology and maximum cable distance

4.5.2.   *Trenches*

Trench length represents the civil work required for digging down ducts and cables. A duct or sub-duct is a pipe, tube or conduit through which cables or wires are passed. These ducts protect the cables and facilitate the installation of more cables at a later stage without re-opening the pavement or road surface. Due to the cost involved in digging a trench, all households in an area are usually connected with ducts and cables if trenches are to be dug. This thesis makes the assumption that in the access segment a single mini-duct carries all passing cables in a shared trench (i.e. there are never parallel ducts in a single trench). In the aggregation segment a larger duct is used, using the same assumptions. The total length of ducts in each segment thus becomes equal to that of the required trenches. Using the terminology of Section 4.5.1 the general formula for duct and trench length in the geometric model becomes:

Equation 2

$$l_d(a) = a^2 - 1 = u \cdot (n - 1)$$

The cost of digging a trench varies greatly depending on the geographic settings and the terrain encountered. This thesis follows the structure of the LRAIC model and categorises the four geographical profiles by the amount of six types of terrain encountered. Using the empirical results of the 20 test sites gives the following distribution and resulting cost pr. km for trenches in Denmark.

Terrain Type	Share of distance				COST	Cost components			
	Down-town	Urban	Sub-urban	Rural		Down-town	Urban	Sub-urban	Rural
Earth	4%	37%	79%	73%	**10.216**	362	3.798	8.100	7.498
Large stones, eg slabs	33%	30%	2%	0%	**25.933**	8.541	7.671	586	17
Asphalt / tarmac	20%	14%	4%	3%	**49.333**	9.696	6.692	1.863	1.553
Tunnell, eg under roads	17%	12%	3%	2%	**50.667**	8.828	6.213	1.487	1.007
Small stones	26%	5%	0%	0%	**25.933**	6.857	1.352	117	17
Soil, eg ploughed cable	0%	2%	11%	21%	**3.316**	-	73	375	708
Total:	**100%**	**100%**	**100%**	**100%**		**34.284**	**25.798**	**12.527**	**10.799**

Table 15, Breakdown of cost of trenches (Based on ITST 2006b)

4.5.3.   *Cable lengths*

The required length of cables is determined by the size of the area, topology used and the relative location of the access node in the access segment. Assuming that cables are laid the shortest path and only vertically and horizontally, in an area of unit length a and b, with the

coordinates of each unit denoted (i,j), and with the coordinate of the aggregation node (x,y) the total cable length can be calculated by the following formula:

Equation 3

$$l_c(a,b,x,y) = \sum_{i=0}^{b-1}\sum_{j=0}^{a-1}\left[|i-y|+|j-x|\right]$$

Tonic D7 (2002) has demonstrated using calculus that the formula can be expressed as:

Equation 4

$$l_c(a,b,x,y) = \frac{a}{2}\left[(b-y-1)^2 + y^2 + b - 1\right] + \frac{b}{2}\left[(a-x-1)^2 + x^2 + a - 1\right]$$

Which for the star topology used by the technologies analysed in this thesis, assuming a rectangular area of unit length and breadth a, and central location of the aggregation/service node quite elegantly becomes:

Equation 5

$$l_c(a,b,x,y) = \frac{a^3}{2} = u \cdot \frac{n^{\frac{3}{2}}}{2}$$

In addition to the length of the cable, the type and capacity are essential parameters to calculate the cost of deployment. These properties are determined by the technology deployed where e.g. PON technology only uses one shared single mode optical fibre cable between common splitters, in contrast to AON where each end user may require a dedicated fibre pair. In this model each technology calculates average cable capacity requirements based on the average number of households in a building.

4.5.4. Equipment

Equipment can be positioned at the customer side, access node, and at the service node. Definitions of type and position of equipment are statically defined for each technology but their requirements calculated by matching the limiting capacity of items with available equipment from a "shopping list". The shopping list of each technology was

populated from literature, the LRAIC model, and industry cooperation to represent 2006 prices.

An accepted trend in equipment cost is related to the maturity of a technology, where in theory production prices drop with mass production, economics of scale and vendor competition. Other techno-economic models, such as Ecosys Deliverable 8 and Broadwan Deliverable 15 rely on confidential databases that have been built up through cooperation with operators, where the characteristics of these future changes are mapped to each equipment component, e.g. using Olsen and Stordahl's (2004) forecasting models based on learning curve. This model follows the recommendations of the Danish National Telecom Agency described in ITST (2001) of a linear yearly price reductions incorporated into tilted annuity calculations (as described in Section 4.6), using price development values reported in (ITST 2002, p. 16), augmented with updates for equipment not present in the LRAIC model[99] as listed below:

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[99] The modifications were aimed at adapting the values to both DSL and FTTH in access networks. The author would like to thank Sæmundur E. Þorsteinsson, director of Iceland Telecom for useful comments and review of the list.

Component	Type	Transmission Capacity	Unit Capacity	CAPEX 2006	Asset Life	Price Developm.
Access Segment						
CPE	FTTH	1200 [Mbps]	1 [Users]	200 €	5 Y	-8%
Ducts	Residential		1 [km]	858 €	40 Y	3%
Node Cabinet	Structure		24 [Users]	3.000 €	15 Y	1%
Node Cabinet	Structure		150 [Users]	6.000 €	15 Y	1%
Node Cabinet	Structure		512 [Users]	10.000 €	15 Y	1%
Node Cabinet	Structure		2048 [Users]	15.000 €	15 Y	1%
Access Node - Switches	FTTH		24 [Users]	6.000 €	10 Y	-8%
Access Node - Switches	FTTH		48 [Users]	12.000 €	10 Y	-8%
Access Node - Switches	FTTH		192 [Users]	38.400 €	10 Y	-8%
Aggregation Segment						
Trench	Down-town		1 [km]	34.283 €	40 Y	3%
Trench	Urban		1 [km]	25.798 €	40 Y	3%
Trench	Rural A		1 [km]	12.527 €	40 Y	3%
Trench	Rural B		1 [km]	10.799 €	40 Y	3%
Ducts	Street trench		1 [km]	1.998 €	40 Y	3%
Ducts	Large-ducts		1 [km]	2.754 €	40 Y	3%
Transmisison Cables	Optical fibre	2 Strands	1 [km]	540 €	20 Y	-5%
Transmisison Cables	Optical fibre	4 Strands	1 [km]	620 €	20 Y	-5%
Transmisison Cables	Optical fibre	8 Strands	1 [km]	730 €	20 Y	-5%
Transmisison Cables	Optical fibre	12 Strands	1 [km]	850 €	20 Y	-5%
Transmisison Cables	Optical fibre	24 Strands	1 [km]	1.220 €	20 Y	-5%
Transmisison Cables	Optical fibre	48 Strands	1 [km]	2.020 €	20 Y	-5%
Transmisison Cables	Optical fibre	72 Strands	1 [km]	2.810 €	20 Y	-5%
Transmisison Cables	Optical fibre	96 Strands	1 [km]	3.580 €	20 Y	-5%

Table 16, Cost Sheet for FTTH technology used in the model

Component	Type	Transmission Capacity	Unit Capacity	CAPEX 2006	Asset Life	Price Developm.
DSL Cost						
CPE	DSL	8 [Mbps]	1 [Users]	40 €	5 Y	-8%
CPE	ADSL2+	20 [Mbps]	1 [Users]	50 €	5 Y	-8%
CPE	VDSL	52 [Mbps]	1 [Users]	60 €	5 Y	-8%
DSLAM Micro	DSL		24 [Users]	720 €	5 Y	-8%
DSLAM Mini	DSL		192 [Users]	3.840 €	5 Y	-8%
DSLAM LE	DSL		768 [Users]	7.680 €	5 Y	-8%
Line-cards	ADSL	8 [Mbps]	24 [Users]	840 €	5 Y	-8%
Line-cards	ADSL2+	20 [Mbps]	24 [Users]	960 €	5 Y	-8%
Line-cards	VDSL	52 [Mbps]	24 [Users]	1.080 €	5 Y	-8%
FTTN Cost						
Node Cabinet	Structure		24 [Users]	3.000 €	15 Y	1%
Node Cabinet	Structure		150 [Users]	6.000 €	15 Y	1%
Node Cabinet	Structure		512 [Users]	10.000 €	15 Y	1%
Node Cabinet	Structure		2048 [Users]	15.000 €	15 Y	1%
Trench	Down-town		1 [km]	34.284 €	30 Y	3%
Trench	Urban		1 [km]	25.798 €	30 Y	3%
Trench	Rural A		1 [km]	12.527 €	30 Y	3%
Trench	Rural B		1 [km]	10.799 €	30 Y	3%
Ducts	Residential		1 [km]	858 €	40 Y	3%
Ducts	Street trench		1 [km]	1.998 €	40 Y	3%
Ducts	Large-ducts		1 [km]	2.754 €	40 Y	3%
Transmisison Cables	Optical fibre	2 Strands	1 [km]	540 €	20 Y	-5%
Transmisison Cables	Optical fibre	4 Strands	1 [km]	620 €	20 Y	-5%
Transmisison Cables	Optical fibre	8 Strands	1 [km]	730 €	20 Y	-5%
Transmisison Cables	Optical fibre	12 Strands	1 [km]	850 €	20 Y	-5%
Transmisison Cables	Optical fibre	24 Strands	1 [km]	1.220 €	20 Y	-5%
Transmisison Cables	Optical fibre	48 Strands	1 [km]	2.020 €	20 Y	-5%
Transmisison Cables	Optical fibre	72 Strands	1 [km]	2.810 €	20 Y	-5%
Transmisison Cables	Optical fibre	96 Strands	1 [km]	3.580 €	20 Y	-5%

Table 17, Cost Sheet for DSL technology used in the model

4.5.5.   *Scenario Descriptions*

This model is aimed at complying with the definitions of content and use of the Danish LRAIC Pricing Method as described in (ISTS 2002). According to that geographical areas are to be split into the following four profiles:

- City (Danish: Storby), which has a line density of more than 1,000 lines per square kilometre.
- Town (Danish: by), which has a line density between 100 and 1,000 lines per square kilometre.
- Rural A (Danish: Land A), which has a line density between 10 and 100 lines per square kilometre.

- Rural B (Danish: Land B), which has a line density between 1 and 10 lines per square kilometre.

The current LRAIC model (ITST 2006b) uses an empirical sample of 20 areas, which are then extrapolated to represent whole Denmark. The model does therefore not describe each geographical profile but rather how Denmark is comprised of numerous areas similar to the sample areas. While this is appropriate for calculating average prices across Denmark it is not suited for studies of specific areas. Therefore this thesis had to augment the available dataset from the LRAIC model with a cluster analysis of statistical information on the communes in Denmark to group them according to the four profiles. The dataset was taken from the webpage of the Ministry of Internal affairs and does not include information about copper lines per square kilometre. A starting point in the analysis was therefore the total area size of each profile from the LRAIC model:

- Total area in Denmark falling into the city profile: 500 km^2
- Total area in Denmark falling into the town profile: 4.000 km^2
- Total area in Denmark falling into the rural A profile: 32.000 km^2
- Total area in Denmark falling into the rural B profile: 6.000 km2

Using the size of each profile type as a proxy for categorisation, 18 communes with the highest population density (down to 750 inhabitants/square kilometre) fall into the city profile, the next 33 communes with density ranging from 750 down to 235 represent town, 188 communes with population density ranging from 235 down to 31 represent rural A, and the remaining 14 communes represent rural B[100]. A summary of the geographic profiles used in the model is described in Table 18.

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[100] The dataset, taken from the webpage of the Ministry of Internal affairs on April 8, 2005 originally included 271 registrations but after taking the areas already accounted for (city, town, Rural A) as well as uninhabited islands the dataset was down to 249. Since the dataset was acquired and analysed a communal reform has been implemented in Denmark, severely altering a new dataset from the one used in this study.

Geographic Profiles

Selected Profile	1	2	3	4	
	City	*Town*	*Rural A*	*Rural B*	
Total Area [Km2]..................................	500	4.000	32.000	6.000	N1
Population Density [Inhabitants/Km2]....	2.290	411	71	26	N2
Inhabitants pr. household.......................	1,7	2,0	2,4	2,6	N3
Households pr. building.........................	5,6	1,5	1,0	1,0	N4
Households..	673.529	822.000	946.667	60.000	
Buildings..	121.322	533.294	946.667	60.000	N5

☐ Static Configuration Parameter
☐ Calculated Parameters
N1　Values reported in the LRAIC model (Row 279 of I_GIS Zones worksheet) appart from City which is from the author (see report notes)
N2　Calculated values from national statistical database
N3　Estimates based on (Danmarks Statistik 2006; p. 2)
N4　Calculated averages from the 20 sample areas in the LRAIC model (Row 106 of I_GIS Zones) but 1 if value is less than zero
N5　The total is in accordance with Post Denmark's information of 2.665.680 households in Denmark 2006

Table 18, Geographic profiles used in the model

4.5.6.　*Existing Infrastructure*

The model assumes the existence of a copper infrastructure. The model assumes that both incumbents and entrants aggregate traffic to service nodes that serve an area of the same size as the existing local exchange serving areas. This is based on the assumption that both the incumbent and the entrant already have or otherwise indented to establish backbone networks covering service node segments with the same characteristics as in the current infrastructure[101]. This approach is adapted from the LRAIC model that calculates the cost of an optimised network that only takes as input location of structural components (the so-called scorched node approach). To goal is to represent the cost for competitors of establishing a new network on basis of the existing network (Henten 2005c). To accomplish this, this thesis used the lengths of line segments measured and reported in the LRAIC model dataset. From that value the number of all types of nodes can be calculated. The results are summaries in Table 19.

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[101]　For the case of EUC based FTTH the assumption becomes that structures from existing utility provision are roughly of the same size and characteristics as the service node segments in the existing telecommunications infrastructure.

Existing Infrastructure	City	Town	Rural A	Rural B	
Average total cable length.....................	**1,95**	**1,59**	**2,29**	**3,35**	N6
LE to PDP...	1,23	0,87	1,00	1,75	N6
PDP to SDP..	0,66	0,62	1,11	1,39	N6
SDP to NTP	0,07	0,09	0,18	0,21	
Total number of existing LE...................	**32**	**160**	**865**	**125**	N8
Total number of existing PDP...............	540	2.200	7.975	885	
Total number of existing SDP................	55.392	139.680	220.575	15.750	
Number of PDP pr. LE..........................	17	14	9	7	
Number of SDP pr. LE..........................	1.731	873	255	126	
Households pr LE..................................	21.048	5.138	1.094	480	
Households pr PDP...............................	1.247	374	119	68	
Households pr SDP...............................	12,2	5,9	4,3	3,8	

Static Configuration Parameter
Calculated Parameters

N6   Calculated actual averages from the 20 sample areas in the LRAIC model (Row 779 of C_Cables and Nodes worksheet)

Table 19, Existing infrastructure considered in the model

As described in Chapter 3, the maximum attainable transmission speeds of DSL are related to copper loop length used. While the empirical dataset includes average loop lengths, which dictate the size of access segments, more detailed information is required of the distribution of line lengths. This is e.g. required to evaluate distribution of maximum transmission speed within access zones, and ultimately the service profiles that households can be offered. Combining the geographical model with the empirical data over loop lengths yields the following distribution functions:

**Simulated distribution of line lengths
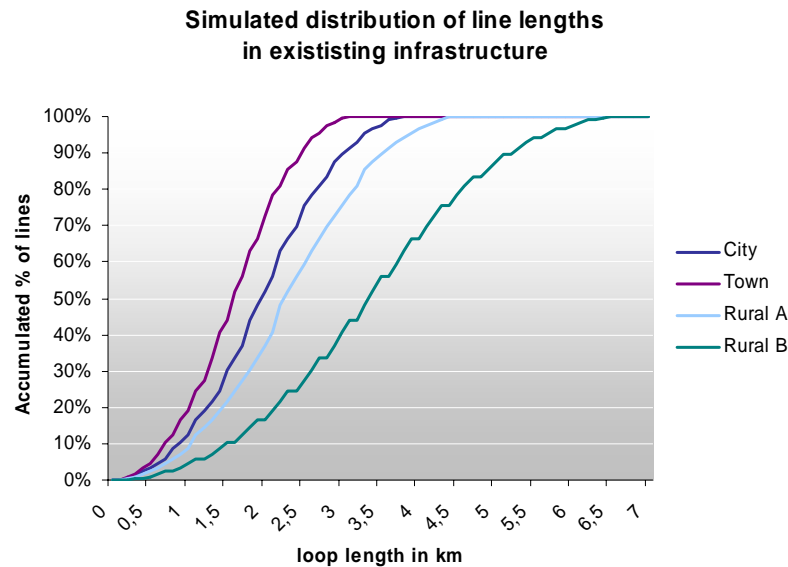in exististing infrastructure**

Figure 68, Simulated distribution of copper loop lengths

When examining Figure 68 and the empirical data from Table 18 the interesting fact that average copper loop lengths are longer in Cities in Denmark than in towns. To make sure that this is correct, all data from the LRAIC model were double-checked.

4.5.7. Market uptake

This model uses the OECD (2006) data of Danish broadband penetration rates and DSL market share to represent the market situation today. This information is supplemented by the perditions of Olsen et al. (2006) to predict the broadband penetration for the next five ears. The results is an estimated growth from 29,3% to 46% broadband penetration for the next five years. This estimate is common for all geographical areas but with varying number of inhabitants per household as described in Table 18 the result is varying household penetration in each area. With higher number of inhabitants pr household the result is a higher penetration in rural areas. While this contradicts most empirical studies that indicate that broadband adoption is lower in rural areas (see eg. GAO 2006), there is little evidence that this would also be the case given the same availability of broadband access, including quality and prices (i.e. that willingness to pay is lower

in rural areas in Denmark[102]). The decision was therefore taken to use a common broadband penetration rate for all areas. The initial market share of DSL in the overall broadband market is taken from OECD (2006) statistics for Denmark, 59,38%. The thesis does not take any position on the development of this market share but rather uses the value as a parameter to estimate which take-up rate each technology needs[103].

4.5.8.   *Calculating Total Capital Expenditure*

The Capital Expenditure of each scenario/technology is summed up in a special Expense Sheet given strategic selections for each player. Figure 69, illustrates the configuration of deployment strategies in a duopoly between an incumbent and entrant. An Expense Sheet sums up CAPEX for each cost component, grouped into access segment and aggregation segment. Total CAPEX, is furthermore then broken down to: i) per customer, and ii) per passed home. Summary of the cost of extending the DSL roll-out to PDP in City scenario is provided in Figure 70.

Deployment Strategies

Incumbent strategy	2	1	2	3
DSLAM position	PDP	LE	PDP	SDP
Entrant strategy	1	1	2	
Deploy FTTH	YES	YES	NO	

	Urban	Market share	Entrant
Market Uptake	64%	50%	50%
Incumbent customers	215.669		
Entrant customers	215.669		

Figure 69, Configuration of Deployment Strategies in the Model

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[102] For empirical analysis of broadband household data see e.g. Savage and Waldman (2005)

[103] According to Olsen et al. (2006) the market share of DSL will increase in Europe at the expense of cable/HFC. However, this data does not consider wide-scale FTTH deployment.

DSL - Expense Sheet

Cost overview for DSLAM at PDP in City
Providing 39 Mb/s on average

DSL (from all nodes)	CAPEX SUMMARY				
	No Nodes	pr. node	total	Unit price	CAPEX
Customer Premises Equipment (CPE)	540	399	215.669	50	10.783.446
DSLAM	540	3	1.620	3.840	6.220.800
Line-cards	540	17	9.180	840	7.711.200
Cabinets	540	3	1.620	6.000	9.720.000
Total [€]					**34.435.446**
FTTN (to new nodes)					
Trenches [Km]	540	1,23	664	34.284	22.771.357
Ducts [Km]	540	1,23	664	2.754	1.829.207
Transmission Cables [Km]	540	1,23	664	3.580	2.377.836
Total Network structures [€]					**26.978.400**
Total [€]					**61.413.847**
CAPEX pr. passed home [€]					**91**
CAPEX pr. Subscriber [€]					**285**

Figure 70, Expense Sheet for DSL from PDP in City scenario

4.5.9. Service Profiles

This thesis defines four service profiles that span the expected subscription packages for near-future broadband connectivity. The service profiles vary in their upstream and downstream bit-rates in both access and backbone segments. Backbone bandwidth requirements are calculated by dividing access segment traffic by a multiplex ratio which determines how easily the traffic can be shared. This value is generally lower for traditional web browsing than for multimedia services and peer-to-peer traffic. The following four service profiles represent disparity in demand, as well as limitations in supply in some geographic areas:

      SP1 -   Slow Internet Browsing

      SP2 -   Fast Internet Browsing

      SP3 -   Multimedia

      SP4 -   Interactive Multimedia

For most technologies, there is not a direct cost relationship with bandwidth in the access network, although in reality operators might

use different bandwidth offers for price differentiation. The importance of the service profiles stems from their influence on network infrastructure design and in most cases the maximum allowable cable length in addition to controlling the resources in the backbone network.

Service Profiles	Access Network		Multiplexing Ratio	Aggregation Network	
	Upstream	Downstream		Upstream	Downstream
S0: No Service....................................	0,0	0,0	0	0,000	0,0
S1: Slow Internet Browsing [Mbps]........	0,2	2,0	30	0,007	0,1
S2: Fast Internet Browsing [Mbps].........	0,8	8,0	15	0,053	0,5
S3: Multimedia [Mbps]............................	2,0	20,0	15	0,1	1,3
S4: Interactive Multimedia [Mbps]..........	20,0	50,0	5	4,0	10,0

Figure 71, Service Profile specifications

Each service profile has voice, video, and data tariff components. A study by the Nordic Regulatory Authorities (2007) of the broadband prices in the Nordic countries revealed that broadband prices in Denmark can be estimated from transmission capacity using regression analysis. The result is plotted in Figure 72.
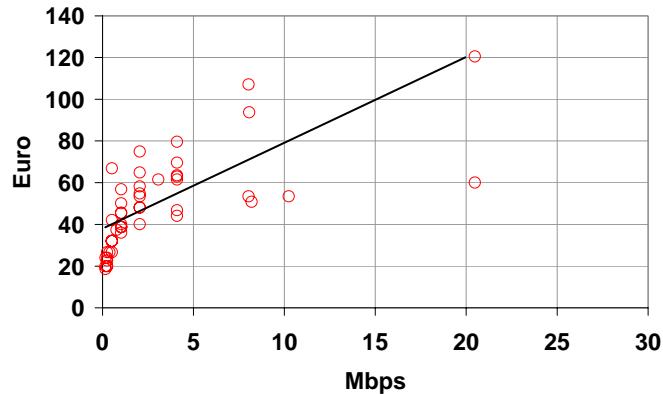
Figure 72, Broadband subscriptions prices in Denmark
(Source: Nordic Regulatory Authorities 2007)

Dam (2006) also analysed the price of packet-based multimedia services in Denmark. He looked at the tariff structure of EUC based FTTH service bundles and shows that total monthly service fees range from € 60 to € 118 per month. These figures include voice and broadcast TV services.

Service / Provider	Tariff structure in Danish EUC based FTTH deployment [€]						
	EnergiFyn	TREFOR	EnergiMidt	SydFyn	NVE	MVB	NESA
Voice Services............................	16	11	31	12	13	20	23
Broadcast TV..............................	33	16	33	25	33	44	33
Internet	39	20	53	35	39	0	26
Connectivity Fee..........................	13	13	0	18	13	40	24
Monthlty Service Total	**101**	**60**	**118**	**90**	**97**	**104**	**106**
FTTH Establishment....................	1.809	13	467	320	501	0	459
Total Monthlty Charge *	**135**	**60**	**126**	**96**	**107**	**104**	**115**

* Establishment cost is transferred to constant payments over 6 year at 10% interest rate

Table 20, Tariff structure in Danish EUC based FTTH
Source: Dam (2006)

Based on the data from Dam (2006) and the study by the Nordic Regulatory Authorities this model estimates tariffs for each service profile as illustrated in Figure 73. Assumptions and implications of EBIDTA are discussed in Section 4.6.

Revenue Model Assumptions	[% of revenues]	[€ pr. Month]			[€ pr. Year]
	EBIDTA	Data	Voice	TV	EBIDTA
S0: No Service...	0%	0	0	0	0
S1: Slow Internet Browsing....................	20%	20	20	0	96
S2: Fast Internet Browsing....................	20%	33	20	20	176
S3: Multimedia..	20%	47	20	20	208
S4: Interactive Multimedia.....................	20%	60	20	30	264

Figure 73, Revenue Model Assumptions

4.5.10. Calculating Revenues

The revenue model is based on estimating the highest service level that can be offered to customers, i.e. the results represent the maximum revenue for a given broadband penetration and market share. The result is an upper bound on the obtainable revenues for a given infrastructure. This is relatively straight forward in the case of FTTH, as optical fibre can accommodate the highest service level (service profile S4 according to Figure 71). In contrast, the service offerings of a telecom using DSL is determined by the length of the copper loop to each household. For the purpose of this study three VBA functions were developed:

List of VBA Programming functions	
DSL_SPEED(arg_distance)..	This function calculates the maximum loop length for a given transmission speed.
DSL_RANGE(arg_speed),..	This function calculates the maximum transmission speed that DSL can provide for a given loop length.
DSL_COVERAGE(arg_looplength;arg_totalmaxlength).........	This function calculates the percentage of households that have less then arg_looplength distance to a local exchange, given a maximum distance of arg_totalmaxlength in the area.

Table 21, List of VBA programming functions

By applying the VBA functions to loop lengths of the available upgrade strategies for the incumbent the market potentials of each service profile can be assessed. A summary of the market potentials are displayed in Figure 74.

Incumbent upgrade alternatives

	City	Town	Rural A	Rural B
Average DSL speed from LE [Mb/s]......	16	20	12	7
Market coverage of S1 from LE.............	100%	100%	100%	92%
Market coverage of S2 from LE.............	90%	100%	78%	41%
Market coverage of S3 from LE.............	32%	49%	23%	11%
Market coverage of S4 from LE.............	2%	3%	1%	1%
Average DSL speed from PDP [Mb/s]...	39	40	23	20
Market coverage of S1 from PDP..........	100%	100%	100%	100%
Market coverage of S2 from PDP..........	100%	100%	100%	100%
Market coverage of S3 from PDP..........	100%	100%	69%	48%
Market coverage of S4 from PDP..........	13%	14%	4%	3%
Average DSL speed from SDP [Mb/s]...	90	86	72	67
Market coverage of S1 from SDP..........	100%	100%	100%	100%
Market coverage of S2 from SDP..........	100%	100%	100%	100%
Market coverage of S3 from SDP..........	100%	100%	100%	100%
Market coverage of S4 from SDP..........	100%	100%	100%	97%

Figure 74, Market potentials of defined service profiles for DSL

The final step in the revenue calculations involves combining the tariff information from Figure 73 with the market potentials of a given deployment strategy from Figure 74. In the case of FTTH the highest service profile, S4 has 100% market potentials for all connected households. A summary of the yearly revenue potentials of DSL deployed in PDP for Rural A is displayed in Figure 75.

Total Revenues

	Yearly Revenue Potentials				EBITDA
	Market	Customers	Revenues	EBITDA	EBITDA
S0: No Service	0%	0	0	0%	0
S1: Slow Internet Browsing [Mbps]	0%	0	480	20%	0
S2: Fast Internet Browsing [Mbps]	31%	131.581	880	20%	23.158.194
S3: Multimedia [Mbps]	65%	278.734	1.040	20%	57.976.580
S4: Interactive Multimedia [Mbps]	4%	17.633	1.320	20%	4.655.172
Total [€]	100%	427.947			85.789.945
Pr. passed home [€]					91
Pr. Subscriber [€]					200

Figure 75, Summary of yearly revenue potentials

4.6. *Modelling Financial Feasibility*

In general, the purpose of feasibility calculations is to compare investment alternatives and find the investment that is most feasible, i.e. that fulfils the objectives of the investor in the best way. Choosing the optimal investment therefore requires knowledge of the investor's objectives. This thesis only considers the monetary objectives of an investment. The object of the investor undertaking the deployment can therefore be defined as maximising the accumulated profit from operating the access network.

In its most simple form, the profit is a function of three parameters, the income, the operational cost and capital cost (Djurup 1996). From a cash flow perspective capital cost is the amount that an investor must pay back each year to a bank if he borrows the money for the investment. In operational terms this is equal to depreciation and interests.

A widely used accounting method is based on calculating EBITDA (Earnings Before Interests, Taxes, Depreciation, and Amortisation) (Higgins 2007). EBITDA is calculated by subtracting operational expenditure (OPEX) from revenues. EBITDA can further be reduced to EBIT (Earnings Before Interests and Taxes) by deducting depreciation and amortization[104]. While profit, also called net income, can be calculated by

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[104] Anthony and Breitner (2006) define amortisation as "The process of writing off the cost of intangible assets". Since no intangible assets (such as goodwill) are considered in this thesis, amortisation is always zero.

further subtracting interests and taxes, this thesis avoids divergent and complex taxation calculations by only considering interests and therefore ending with pre-tax profits. This methodology is inspired by Ecosys D6.
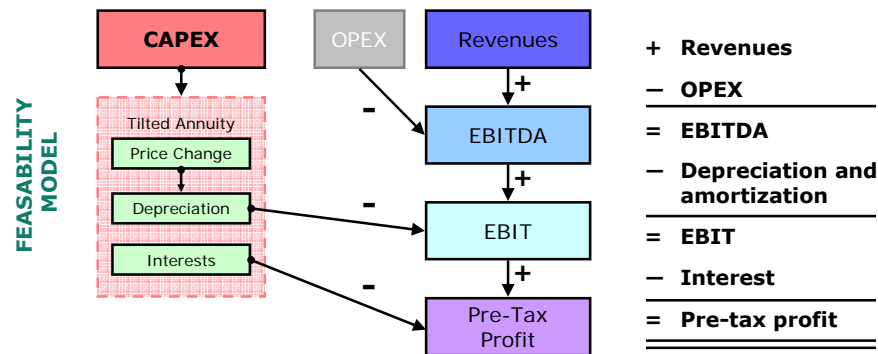
Figure 76, Proposed framework estimation of financial feasibility
(Inspired by Ecosys D6;p. 32)

As Ecosys D6 goes on to describe, "the rules to determine if a cost component is CAPEX or OPEX are strongly dependent on individual accounting methods". It can therefore be difficult to assess OPEX and even more difficult when an operator has many profit centres that share common cost components. The LRAIC model does this by using empirical OPEX data for each component while Ecosys proposes a general model for each component that takes even more component specific data such as Mean-Time-Before-Failure (MTBF) as input. In the absence of such empirical data, and to limit the scope of this project, the thesis uses reported industry averages of OPEX to calculate EBITDA. Newman (2003; 2005) builds on a McKinsey and JPM study when he estimates that depreciation and interests account for 23% of an incumbents cost of providing DSL[105] (see Figure 9 on page 28). In line with this, and following agreement with industry partners, this thesis will use 20% of revenues to estimate EBITDA.

4.6.1.   Investment Appraisal

Normally an investment process starts with a number of down-payments, followed by a flow of income. The difference of down-

[105] Weingarten and Stuck (2004) report similar figures from the US but these are none the less more difficult to use due to different accounting terminology.

payments and income at any given time is called net-payments. An investment can therefore be defined as "a collection of payments, where the down-payment precedes the income" (Lynggaard 1999). But an investment is not necessarily feasible although income exceeds payments. A part of the outcome must compensate the time difference of the payments, since the value of a payment is dependent on the timeframe it occurs in. The measurement of how much the uncertainty of time affects a payment is measured with an interest rate. To calculate the feasibility of an investment the sum of all net-payments must be taken after the effect of time has been deducted.

According to Lynggaard (1999), the main methods used for calculating the feasibility of investments are:

- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Constant Payment (PMT)
- Payback-method

Each of these methods uses a special angle to look at the same problem. The NPV method sums up "today's" value of all payments given an interest rate to see if the net result is positive or negative (i.e. if the investment is feasible or not). The IRR calculates the interest rate that would result in a NPV sum of zero. The PMT distributes the down-payment equally over the investment time to see if the net payments for each time period are positive or negative. The payback-method calculates how long time it will take to repay the investment.

All of the above mentioned methods have been and are being applied in techno-economic studies as well as in appraisal projects. According to Cassimatis (1988) surveys indicate that the preferred methods in industry are IRR and NPV. Of these two he further notes that although most managers favour the IRR, economists believe that the NPV is the best method.

When comparing isolated projects both IRR and NPV yield the same result but when evaluating mutually exclusive projects a conflict can occur[106]. This occurs when there is a difference in the timing and

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[106] For a detailed comparison of net present value and internal rate of return methods see Chapter 8, Section 2 of Ferguson, Ferguson, and Rothschild (1993) and Higgins (2007), Chapter 4 where he quite

magnitude of cash flows because the implicit assumptions differ with respect to the reinvestment of cash flows under each method. The IRR method assumes that all cash flows are reinvested at the IRR of the project, whereas the NPV is based on the assumption that cash flows are reinvested at the cost of capital and all projects are evaluated at that same rate (Cassimatis 1988; p 86).

When comparing two mutually exclusive projects with different economic lives, like in the case of DSL and FTTH, Cassimatis therefore concludes that "the correct method is using the annual equivalent method (PMT) of appraisal" (Cassimatis 1988; p 87). There are several available methods of calculating PMT which in reality are all variations of the net present value method. The Danish NRA recommends using one of these variant, tilted annuity, for constructing bottom-up cost models. For this reason, the design decision was taken to follow both recommendations and use PMT for the model.

4.6.2.   Calculating PMT

Stated in words, the PMT method says that:

> *"An investment is financially feasible, if its average net-payments each year are positive (or equal to zero)"*
>
> *Lynggaard 1999*

In mathematical form this is ensured by first calculating net present value of the capital cost C_0 and then distribute that equally over the n years of expected lifetime of operation to get the average yearly cost $\overline{C}$, given the interest rate i[107]. The interest rate used in this thesis is 8,60% as mandated in ITST (2006).

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amusingly concludes "... the IRR is much like Bill Clinton: appealing but flawed".

[107] In finance this rate is determined by taking a weighted average of the interest rate of the proportion of the investment financed with capital and the proportion financed through loans. This methodology is know as Capital Asset Price Model (CAPM). For more information about CAPM see e.g. Lynggaard (1999), Chapter 2 and Higgins (2007), Chapter 8.

Equation 6

$$C_0 = \sum_{t=0}^{n} P_t (1+i)^{-t}$$

Equation 7

$$\overline{C} = \frac{C_0}{\overline{\alpha n} \rceil \cdot i}$$

While Equation 6 and Equation 7 account for deprecation and interests, it lacks some of the properties that the Danish NRA describes as required for an accurate annuity charge, i.e. that it "should have a depreciation profile which (accurately) reflects the expected levels and changes in replacement cost, operating costs, output levels and asset productivity".

Theoretically there are models available that describe price development such as the forecasting models based on learning curve by Olsen and Stordahl (2004). However, for applicability these models require regression analysis of components. In stead this thesis follows the recommendations of the Danish NRA, using tilted annuity with a linear price development model based on published price development values from (ITST 2002).

A tilted annuity calculates an annuity cost that varies from year to year at the same rate as the price of the asset is expected to vary. This results in a falling annuity cost if the price is expected to fall over time. If the tilt is sufficiently large, the depreciation profile may even get a negative inclination. The tilted annuity results in costs which, after discounting, cover the purchase price and financing costs of the asset (ISTS 2001b). The tilted annuity cost is estimated by Equation 8.

Equation 8

$$\frac{(r-p)}{1 - \left(\dfrac{1+p}{1+r}\right)^t} \times I$$

Where r is return on capital, p is price change, t is expected asset life, and I is the investment. The result of applying Equation 8 on the calculated CAPEX using the asset lifetime, and price development of

each component listed in Table 16 and Table 17 is summed in the cost sheet of Figure 77. In these calculations the return on capital is taken from the Danish NRA recommendations as 8,6% (ITST 2006, p.4).

DSL (from all nodes)		Yearly Tilted Annuity			
	CAPEX	Asset Life	Price Change	Tilted	Annuity
Customer Premises Equipment (CPE)	21.397.371	5	-8,0%	29,4%	6.285.716
DSLAM	17.226.000	5	-8,0%	29,4%	5.060.329
Line-cards	20.097.000	5	-8,0%	29,4%	5.903.717
Cabinets	71.775.000	15	1,0%	11,4%	8.174.671
Total [€]	130.495.371				25.424.434
FTTN (to new nodes)					
Trenches [Km]	99.905.235	30	3,0%	7,0%	6.955.450
Ducts [Km]	21.963.150	40	3,0%	6,3%	1.380.264
Transmission Cables [Km]	28.550.500	20	-5,0%	14,5%	4.144.988
Total Network structures [€]	150.418.885				12.480.702
Total [€]	280.914.257				37.905.136
CAPEX pr. passed home [€]	297				40
CAPEX pr. Subscriber [€]	656				89

Figure 77, Cost sheet for yearly tilted annuity for DSL

4.6.3.   Notes about solution method

While the selected method of tilted annuity fulfils the requirements of this project as well as the Danish NRA, there are some assumptions in the methodology that need to be highlighted. The first has to do with the terminal value[108] of fibre, ducts, and trenches. The model assumes that at then end of the expected lifetime of cost structures they have a terminal value of zero, after being linearly depreciated.

A similar problem stems from evaluation of the opportunity cost[109] of deployment. Lets assume that an EUC argues that due to already planed civil work, not deploying fibre would be foolish. Seen from investment appraisal there are two ways of evaluating the validity of this assertion

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[108] In finance, the term "terminal value" is defined as the present value at a future point in time of all future cash flows (Higgins 2007).

[109] Higgins (2007) defines "opportunity cost" as "Income forgone by an investor when he or she chooses one action over another. Expected income on next best alternative".

where the outcome depends on the salvage price that we put on the fibre and trenches:

1.   If we assume that the value of the fibre and trenches is equal to the price that a competitor would experience when digging down a new fibre.

2.   If we assume that the value of the fibre and trenches is equal to the depreciated terminal value of the incurred cost.

If the first approach is the one chosen, the result is increased terminal value of the trenches and fibres. This model only considers approach 2.

4.7.   Modelling Competition

The analysis of the competitive environment within which firms operate has traditionally been in terms of three features: *structure, behaviour* and *performance* (Ferguson et al. 1993). This is illustrated in Figure 78 along with the main parameters affected by this model.
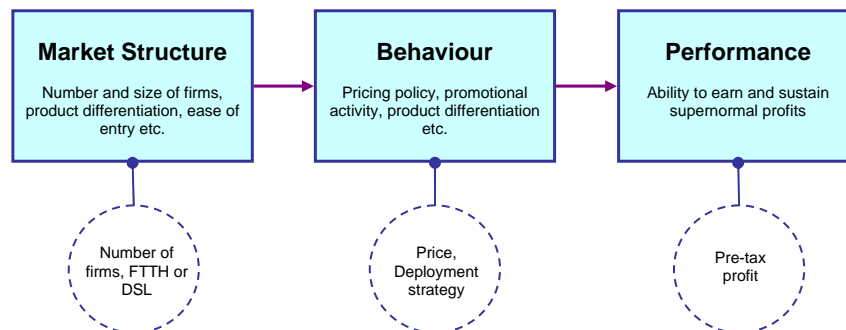
Figure 78, Conceptual model for competition model

Market structures differ on two important dimensions: the number of firms and the nature of product differentiation. After years of homogeneous services offered through a monopoly provider, telecommunications of today is a competitive market with several competing firms providing differentiated services. However, due to the substantial investment

required for building wired telecommunications access network, that market is at best an oligopoly market[110].

The behaviour of firms within a given market is described in terms of their power to determine price and the efforts these firms will devote to excluding potential competitors. Tirole (2003) classifies these behaviour according to the speed at which they can be altered. In the short run, price and production quantity are often the main instrument that a firm can change easily. Changes to either of these parameters are called strategic interactions and can be systematically analysed as through the theory of non-cooperative games. On a longer time scale, cost structures and product characteristics can be altered.

The performance of firms within markets is reflected in terms of their profitability and their ability to maintain this profitability in the long run. In traditional economic theory, under the profit maximisation hypothesis, a company increases its production level as long as each additional unit adds more to total revenue than it does to total cost. However, when analysing broadband deployment the high sunken cost of the infrastructure results in low marginal cost and therefore the most profitable state is always 100% market penetration / take-up rate.

An objective in economic modelling is determining the equilibrium positions that a model implies. This stems from the overall goal of explaining and predicting changes in market values such as prices and quantities. A prerequisite to finding equilibrium is to have a theory that explains how an initial condition arises and how a new condition arises when circumstances change[111]. The challenge for this project was to develop a competition model that can relate the behaviour of firms (under a fixed market size) to their market share, and ultimately the profit.

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[110] Market condition in which a small number of firms controls the total supply of a given commodity or service.

[111] Liebowitz and Margolis (2001) define equilibrium "as a condition such that no change will occur unless some outside vent intrudes. They further distinguish between stable equilibriums in which the system will return to the equilibrium in the event of small perturbations away from the position, and unstable equilibriums in which a system will not return if there is a small perturbation.

Microeconomic theory provides three main competition models for oligopoly that can aid in this process: Cournot, Bertrand, and Stackelberg (Besanko and Braeutigam 2005), of which the first two are most widely used. In the Cournot model, each firm selects a quantity to produce, and the resulting total output determines the market price. Alternatively, in the Bertrand model each firm selects a price and meets demand for its product at that price, taking as given the prices of other firms.

To successfully apply either Cournot or Bertrand models on residential broadband deployment knowledge of how customers value FTTH and DSL is necessary, in addition to analysis about the willingness of the competitors to lower prices. In the absence of this data, this thesis can only make very rough estimates on how companies will behave and how customers will react. Additionally competitive actions are likely to be different for different geographical areas, given differences in profitability of different strategies.

Using intuition, the most likely competitive situation would be one where the DSL provider would use lower marginal price to compete on price, and FTTH providers would try to focus on the technological superiority of fibre to differentiate the products. One way of solving this kind of a problem is to use a Bertrand price competition with horizontally differentiated products (Besanko and Braeutigam 2005). When successfully implemented, this model can predict equilibrium prices and market shares of each firm. However, to implement and solve the model for the residential broadband market empirical information about the demand function is needed. Gasmi, Vuong, and Laffont (1992) solve this by using statistical methods of estimating residual demand curves for two horizontally differentiated products.

However, if the market under analysis can only sustain one firm in the long run, the competition can be expected to be different. Then the firms would not seek equilibrium of coexistence but rather to prevent the competing firm from getting a foothold on the market. For this kind of a market situation the third competition model, called von Stackelberg models, could be of use. Von Stackelberg models generally pertain to situations in which one firm acts as a leader. For this reason von Stackelbeg models are particularly well suited for analysing entry deterrence, i.e. situations when an existing provider makes non-optimal decisions to reduce the likelihood of entry from a competitor. Kreps (1990) suggests this type of model for analysing competition between a monopoly firm and a potential entrant.

More recently Bijl and Peitz (2000 and 2002) have taken competition and entry models in telecommunications to new heights through an advanced game-theoretic model that additionally considers features such as consumer switching cost[112], and product bundling, that otherwise skew competition. Their analysis is however limited to the homogeneous PSTN service, and firms compete on price. Bijl and Peitz freely distribute their model with the textbook facilitating further studies.

The author made two initial attempts to construct new competition models for residential broadband deployment. The first was based on the provided model of Bijl and Peitz (2002) and the other based on the Gasmi, Vuong, and Laffont (1992) approach. The first approach was abandoned as the Bijl and Peitz model is implemented in Mathematica and could not be ported easily over to the Excel model of this study. While the second approach provides insight into competition between firms, given the early stage of FTTH deployment in Denmark (and therefore lack of empirical data on price or quality competition between the two), the result is as unreliable as pure guessing.

The approach of this thesis is therefore focused on using the von Stackelberg model to predict the foreseen dominant strategy of DSL deployment. This is also the first step towards analysing price competition using either of the previously mentioned models in competition between FTTH and DSL. The solution is based on mapping out the extensive form of the games and solving the game using backwards induction. This solution is in most cases a Nash equilibrium and represents a dominant strategy that where each player's strategy is an optimal response to the other player's strategies.

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[112] Shapiro and Varian (2003) define switching cost as "the monetary equivalent of the inconvenience imposed on the user due to changing providers".
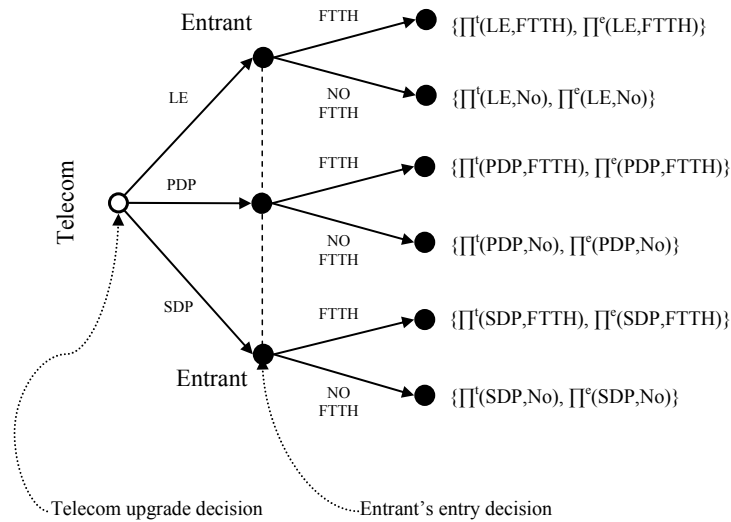
Figure 79, The von Stackelberg game (Adapted from Kreps 1990, p. 46)

Using the game from Figure 79 as an example, the telecom first has to decide which of the three alternatives to choose {LE, PDP, SDP}. Finding the solution to the game is based on backwards reasoning. The telecom knows that the entrant chooses a response to its action that maximises its pay-off. The telecom therefore finds the response by the entrant for each of its alternatives and from that subset selects the action that grants the highest payoff.

4.8.   Summary

This chapter has described a modelling framework developed to analyse the financial feasibility of residential broadband deployment. The framework builds on existing techno-economic models, using a bottom-up approach to simulating deployment cost. The model was implemented in Microsoft Excel and uses an empirical dataset from the Danish Long-Run Average Incremental Cost (LRAIC) to estimate the cost up upgrading the existing copper infrastructure in comparison to building a new FTTH network.

In addition to cost analysis a module for calculating revenues has been developed, resulting in a method of estimating financial feasibility. This is accomplished by calculating the tilted annuity cost for each year that is matched with EBITDA. The tilted annuity considers the expected asset life and

changes in price development, evening out long-time comparison of different cost structures.

Finally the chapter uses game theory to explain the strategic interactions between competing infrastructures using the von Stackelberg model. This game can be used to explain situations where an established market player leads with initial deployment that competitors subsequently decide their actions based on.

Chapter 5

Simulation Results

A model framework for analysing and comparing broadband deployment strategies has been established as described in Chapter 4. This chapter presents results from a simulation study of telecom based DSL strategies versus entrant based FTTH deployment in different geographic settings in Denmark. The resulting simulation shows the cost structure and pre-tax profit of each deployment alternative, and feeds these results into a von Stackelberg game to analyse the effect of competition between the ILEC, CLEC, and EUC on the Danish broadband market.

5.1.   Introduction

In the previous chapters the thesis has analysed the transmission requirements of near-future multimedia service, identified technological solutions for building and upgrading access networks that can meet these requirements, as well as developed a framework for evaluating the financial consequences of deployment under competition. Based on that work, this chapter presents the results of a simulation study of the Danish broadband market.

A starting point for the study is the current situation on the market where, the incumbent local exchange carrier (ILEC) has roughly 50% market share, no single competitive local exchange carrier (CLEC), has more than 20%, and the EUCs have 0% market share. The study presents capital

expenditure (CAPEX) of each alternative followed by forward looking tilted annuity, revenues and resulting pre-tax feasibility (see Section 4.6 for more information on financial feasibility modelling).

5.2.   DSL Based Strategies

This section describes the results of the simulation for DSL deployment under the current market conditions, i.e. assuming that the market share of DSL on the broadband market will stay fixed at 59,38% (OECD 2006). As described in Section 4.5.7 the overall broadband penetration is extrapolated over five years based on the market growth predictions by Olsen et al (2006), and the average penetration for that period used, yielding 37,67 subscribers per 100 inhabitants. The result is a DSL market of 22 subscribers per 100 inhabitants. The analysis is presented as alternatives for an incumbent but the cost structures would be the same for a CLEC that has already established connectivity to the LE.

The cost structure is analysed for three deployment strategies as identified in Chapter 3, i.e. DSL provided from: local exchange (LE), Primary Distribution Point (PDP), and Secondary Distribution Point (SDP). The simulation is run for the four geographical profiles in Denmark: City, Town, Rural A, Rural B. Each deployment strategy affects the average loop length in each scenario and thus the services that can be offered. Figure 80 summarises the average transmission speeds of each alternative, as well as the market potentials of each service profile[113].

The first column of the summary reveals several issues than have affected roll-out strategies in Denmark. First of all it shows that the local loop in Denmark is relatively well suited for providing broadband data services using DSL technology. When provided from the LE, the local loop facilitates slow broadband connectivity to 99,8% of all households[114] and on average 15 Mb/s to all households[113]. When comparing this to the current demand level this explains why telecoms have not started

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[113]   Note that the transmission speeds displayed in Figure 80 are theoretical maximum speeds. This means that in real environments, such as in the presence of crosstalk and other disturbances, the transmission speeds can be considerably lower.

[114]   The difference between this value and the reported ADSL coverage in Denmark would then be explained by lacking DSL equipment in some local exchanges, rather than too long lines.

upgrading the network yet, i.e. the current local loop can on average provide the demanded services.

However, as the broadband moves over to multimedia services the market potentials of DSL provided from the LE fall quickly. With IPTV as a strategic gaol, the telecoms can only offer video to 11-32% of households and when aiming for the interactive multimedia of service profile 4, this is reduced to mere 1-3%, i.e. only the closes vicinity of the LE. The summary therefore explains the forces that are driving build-out of the DSL network, i.e. the requirement of higher transmission rates that can facilitate multimedia services.

Incumbent upgrade alternatives	City	Town	Rural A	Rural B	Denmark
Average DSL speed from LE [Mb/s]......	16	20	12	7	15
Market coverage of S1 from LE.............	100%	100%	100%	92%	100%
Market coverage of S2 from LE.............	90%	100%	78%	41%	87%
Market coverage of S3 from LE.............	32%	49%	23%	11%	34%
Market coverage of S4 from LE.............	2%	3%	1%	1%	2%
Average DSL speed from PDP [Mb/s]...	39	40	23	20	33
Market coverage of S1 from PDP..........	100%	100%	100%	100%	100%
Market coverage of S2 from PDP..........	100%	100%	100%	100%	100%
Market coverage of S3 from PDP..........	100%	100%	69%	48%	87%
Market coverage of S4 from PDP..........	13%	14%	4%	3%	10%
Average DSL speed from SDP [Mb/s]...	90	86	72	67	81
Market coverage of S1 from SDP..........	100%	100%	100%	100%	100%
Market coverage of S2 from SDP..........	100%	100%	100%	100%	100%
Market coverage of S3 from SDP..........	100%	100%	100%	100%	100%
Market coverage of S4 from SDP..........	100%	100%	100%	97%	100%

Figure 80, Market potentials of available upgrade strategies for DSL

Depending on the financial benefit of increasing the service level, the incumbent makes the decision whether to upgrade or not. However, it is also quite conceivable that a telecom decides to upgrade, although providing services from the LE is more profitable. In that case the decision would be strategic, either meant to deter entry of possible competitors or to increase the competitiveness against existing firms.

For accomplishing this telecoms have two alternatives, either a stepwise upgrade, beginning at the PDP, before moving to the SDP or going directly

to the SDP[115]. The higher the risk of competition from FTTH, the more likely it is that the telecom goes directly to upgrades in the SDP. When comparing the average transmission rates from PDP, 20-40 Mb/s, to that of SDP, 81 Mb/s, going for SDP would seem to fulfil the estimated future demand better (i.e. the estimated demand of 100 Mb/s in 2010). However, when considering the service coverage, PDP covers the majority of the possible revenue.
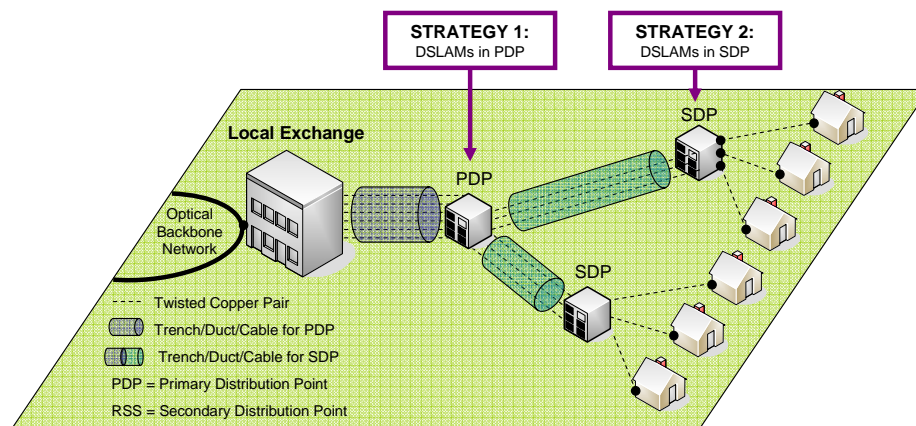
Figure 81, Schematic outline of upgrade alternatives

Additionally, there are great differences in the cost associated with deployment in PDP and SDP. To reason is the great difference in the number of new nodes that have to be built and connected with new fibre cables. As shown in Table 19 on page 171, the number of PDP for each LE ranges from 7 to 17, whereas the number of SDP for each LE is from 160-1731. In each geographical area, the number of customers that share the cost of each new node additionally limits the possible income. To analyse this further the two following sections analyse the cost structures of providing DSL from PDP and SDP. The result is displayed in two forms, first in CAPEX per subscriber, followed by annuity per subscriber. The reason for CAPEX per subscriber is that the scope of the required investment is a critical parameter for taking decisions as well as for comparing the cost to that of FTTH later on. The reason for displaying annuity is that, the annuity controls the feasibility of the project, i.e. it

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[115] The telecom also has the alternative of deploying FTTH. In that case, the cost would be the same as for an FTTH entrant, analysed later in the chapter.

takes into account the life-time and price development of each cost components.

5.2.1.   Upgrade Strategy 1 : DSLAMs at PDP

> **Strategy Description**
>
> *In this strategy a telecom reduces the average length of the existing copper cable by installing active equipment (DSLAM) to offer DSL services from the same location as existing primary distribution points (PDP) in the existing copper network. To accomplish that the telecom has to erect new cabinets and dig trenches for new ducts and cables between the LE and PDP using star topology.*

The results are presented for one operator that has 50% market share on the DSL market (i.e. the incumbent TDC). The price structure would be the same for a CLEC that migrates towards infrastructure completion but then the market share would be different, resulting in different cost structures. Breakdown of the CAPEX (Figure 82) shows that despite a relatively few nodes and short distances, trenches, cables, and cabinets nonetheless dominate the cost, accounting for from 58% to whole 89% of the total cost.

CAPEX breakdown for DSL provided from PDP
for 50% of DSL market share (11 subscribers per 100 inhabitants)
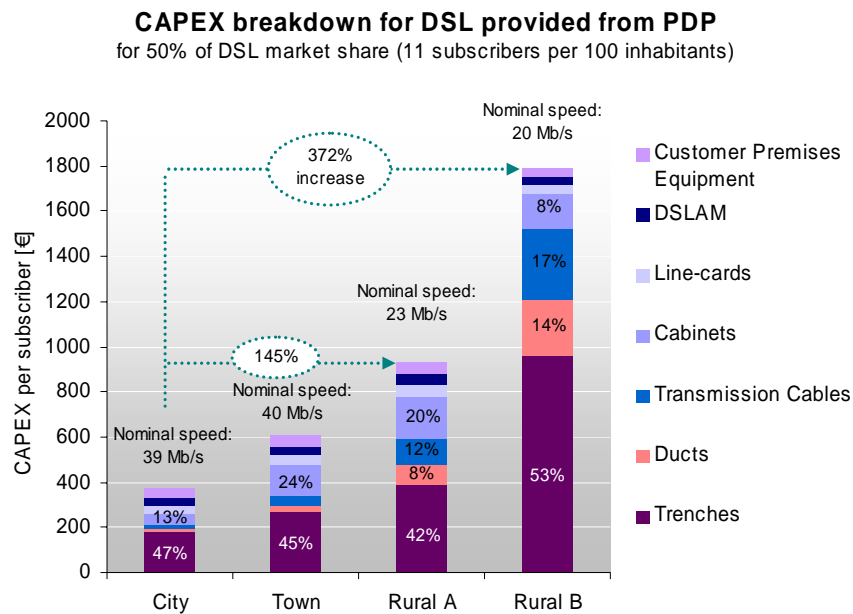
Figure 82, CAPEX breakdown for DSL provided from PDP

Additionally, the general trend of increasing cost in dispersedly populated areas is registered. Upgrades are 59% more expensive in towns than in cities, increasing to 145% for Rural A, and 372% for Rural B. The comparison also shows that with the longer distances between subscribers, the cost of trenches, ducts, and cabinets starts accounting for a higher share in rural areas. This is due to two reasons, one is that there are more nodes and longer distances, and the other is that there are fewer subscribers that the cost is divided among.

Annuity breakdown for DSL provided from PDP

for 50% of DSL market share (11 subscribers per 100 inhabitants)
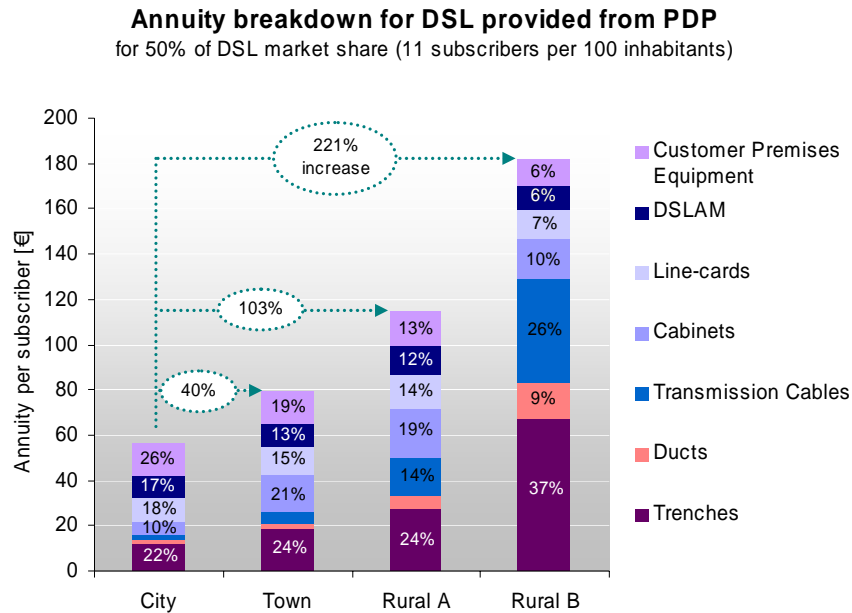
Figure 83, Annuity breakdown for DSL provided from PDP

When looking at annuity, the effect of lifetime and price development becomes clear. The hardware starts accounting for a higher percentage, or 61% in cities decreasing to 19% in Rural B. The difference between city and rural areas is also decreased, showing that although the cost of broadband in rural areas is higher, it is partly balanced by higher share of cost components that have long expected lifetime, such as trenches and ducts. It is therefore "only" 221% more expensive to upgrade the DSL infrastructure in Rural B in comparison to the City.

When summing up the cost and benefit analysis the main conclusions are that upgrades in all geographical areas are profitable, despite higher capital cost in rural areas. It is however important to notice that in these calculations the effect of service and infrastructure competition have not been analysed, i.e. the calculations assume provision of DSL in a stable environment. It is also interesting to compare the cost and revenues of PDP deployment to that of only doing equipment upgrades in the LE (this is summarised in Table 23 on page 205). The cost goes up 2-7 times while the revenue increases 10%-20%. That comparison shows that despite higher revenues, deployment from the LE is always more profitable than deployment from PDP. The result is that in the

absence of competition (or the threat of competition), the telecom would not deploy DSL in PDP, i.e. continue to offer services from the LE.

Cost-benefit overview for DSL from PDP

22 subscribers per 100 inhabitants
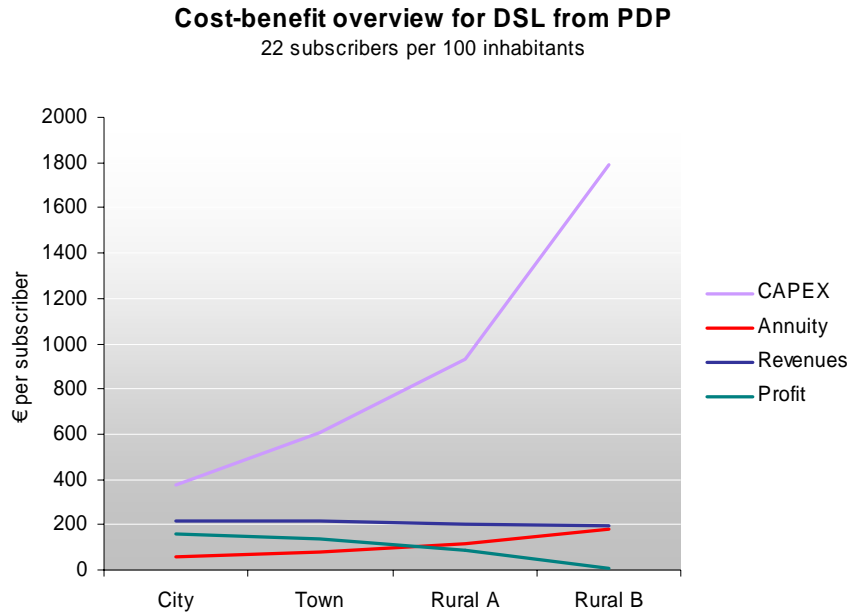
Figure 84, Cost-benefit overview for DSL provided from PDP

The profitability of deploying DSL from PDP indicates that there might be a sustainable future for more than one operator (this would result in what the Danish NRA calls sub loop unbundling competition, where the competitor deploys infrastructure to the PDP and relies on unbundling for the remaining part of the local loop). To analyse this possibility Figure 85 plots pre-tax profits as a function of market share. Equation 9 calculates the upper level of sustainable competition.

Equation 9

$$\bar{n} = 1 \,/\, (\text{market share at } \textstyle\prod(I)=0)$$

The resulting maximum level of sustainable competition given PDP deployment of all firms is illustrated in Table 22. The conclusion indicates that there is room for competition in DSL deployment at PDP level in all geographical areas apart from Rural B. This means that an

incumbent faces considerable threat from CLECs, that e.g. only have to acquire 10-15% market share in cities and towns to be profitable. However, by upgrading to PDP in Rural B, the incumbent could deter possible entry since competitors would have to aim for fully conquering the incumbent or alternatively loose.

	Maximum firms on PDP market			
	City	Town	Rural A	Rural B
Sustainable Compeition at PDP............................	9,1	6,3	3,7	1,6

Table 22, Maximum level of sustainable competition in PDP deployment

Competitive ability of DSL from PDP
22 DSL subscribers per 100 inhabitants
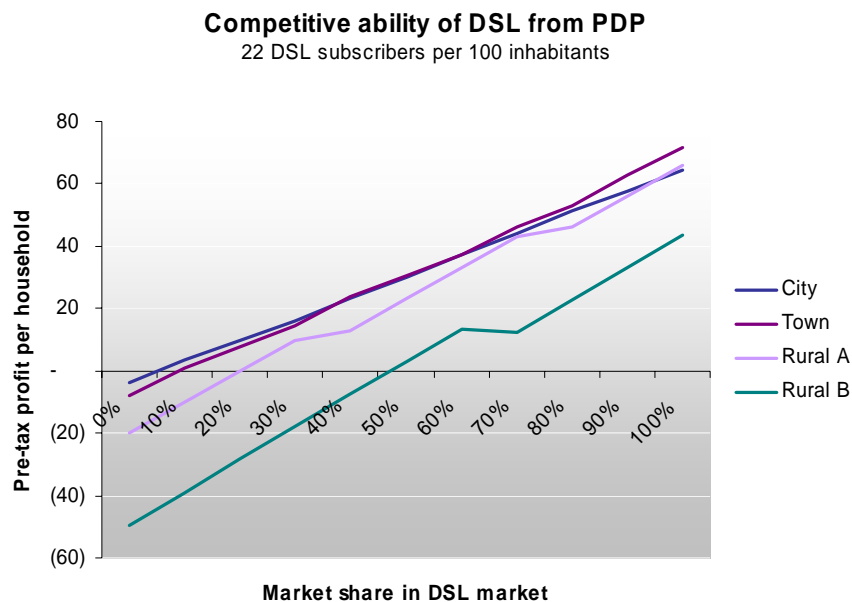
Figure 85, Competitive ability of DSL from PDP

5.2.2.   Upgrade Strategy 2 : DSLAMs at SDP

Strategy Description

In this strategy a telecom installs active equipment to offer DSL services (DSLAM) in each secondary distribution point (SDP) in the existing copper network, enabling transmission rates over 50 Mb/s. Due to the great number of new nodes (and the limited customers and area that

each serves) the operator is assumed to connect the nodes with ring/bus topology. The operator has to erect new cabinets and dig trenches for new ducts and cables between each of the new nodes.

This section presents the results for one operator that has 100% market share on the DSL market[116]. The strength of this strategy is that it facilitates offering of extremely high transmission bandwidth, on average 60-90 Mb/s, capable of supporting all near-future services and competing with FTTH on (almost) even ground. However, the downside is the cost and operational complexity related to replacing centralised DSLAM equipment in one LE with active equipment in several hundred small street cabinets[117].

The first thing to notice when analysing the CAPEX cost of DSL deployment from SDP, illustrated in Figure 86 is the change is scale from the PDP deployment graphs, i.e. CAPEX is 10-20 higher than for the PDP strategy (a summary is provided in Table 23 on page 205). Additionally the increased lengths from LE to SDP mean that trenches, ducts, and cables increase and dominate the cost, ranging in total from 42% to 64%.

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[116] The assumption here is that the investment required for full SDP deployment is such, and the superiority of the transmission capabilities in comparison to DSL from LE or PDP that the incumbent would only follow this strategy as an aggressive strategy aimed at acquiring full dominance on the DSL market.

[117] Industry reports show that operators are pursuing this strategy, e.g. the German incumbent Systems that is deploying VDSL over roughly 200 meter copper loops in 50 major cities in Germany. However, when installing DSLAM equipment in street cabinets the equipment requires environmental hardening and industry contacts report dissatisfactions with current market solutions, such as noise from active cooling required. These, and other "engineering" problems are however likely to be solved in the next year(s).

CAPEX breakdown for DSL provided from SDP

22 subscribers per 100 inhabitants
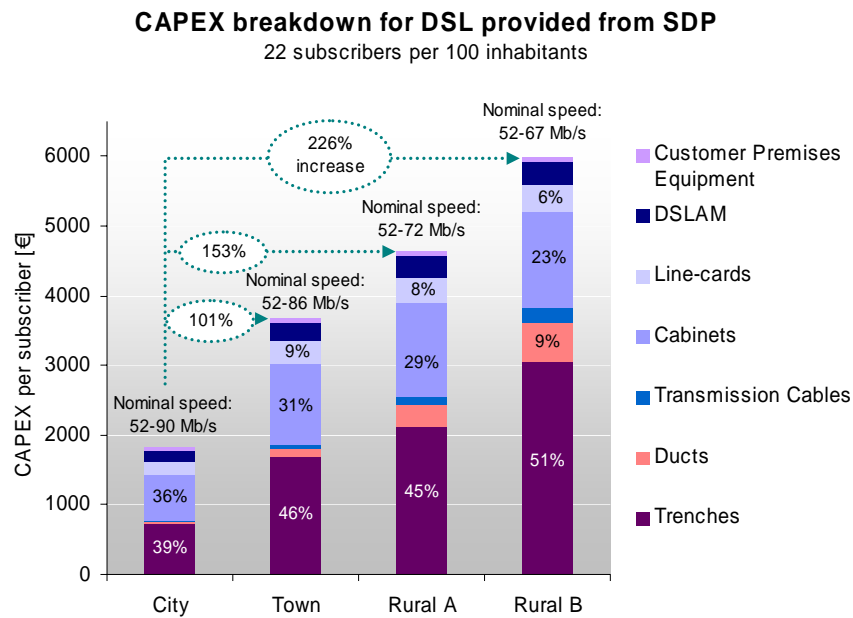
Figure 86, CAPEX breakdown for DSL provided from SDP

As before, the result of moving over to annuity reduces the effect of cost components with expected long lifetime by almost half, resulting in more disparity in cost components in comparison to the CAPEX. The total annuity for the SDP strategy is nonetheless at least five times higher for all scenarios than for the PDP strategy (a comparative summary is provided in Table 23). The difference between scenarios also changes, but the city scenario still sticks out with twice as low annuity than the rest of the scenarios.

Annuity breakdown for DSL provided from SDP

22 subscribers per 100 inhabitants
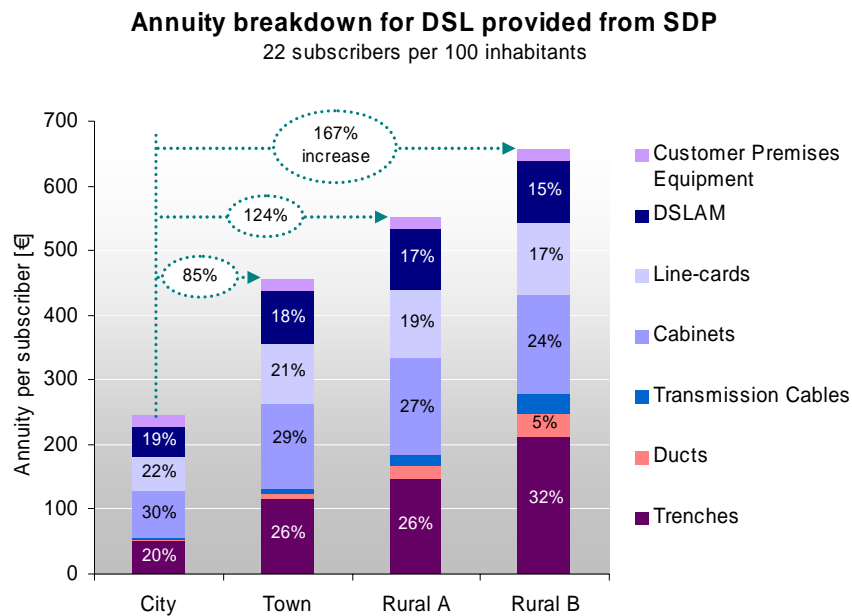
Figure 87, Annuity breakdown for DSL provided from SDP

When summarising the cost-benefit of the SDP strategy the profitability has moved below zero for all scenarios, although the city profile is very close to being profitable. The reason for this change from the PDP strategy is that cost has increased 5-8 times, while the revenues have only increased 22%-36%. The conclusion is that in the absence of competition (or the threat of competition), the telecom would not currently deploy DSL in SDP. However, when analysing the composition of the annuity cost for DSL in SDP, there is room for considerable changes in the business case with possible price development of advanced DSL hardware. Cabinets, DSLAMs, and line-cards account for 69% of the annuity and if these components become less expensive (which is likely) the business case can easily become positive both in cities and towns (roughly estimating, the annuity of in these two scenarios has the potentials of falling at least 30%-50%). The annuity from trench cost is higher than revenues in Rural A and Rural B and deployment is thus not likely to become positive.

Cost-benefit overview for DSL from SDP

22 subscribers per 100 inhabitants
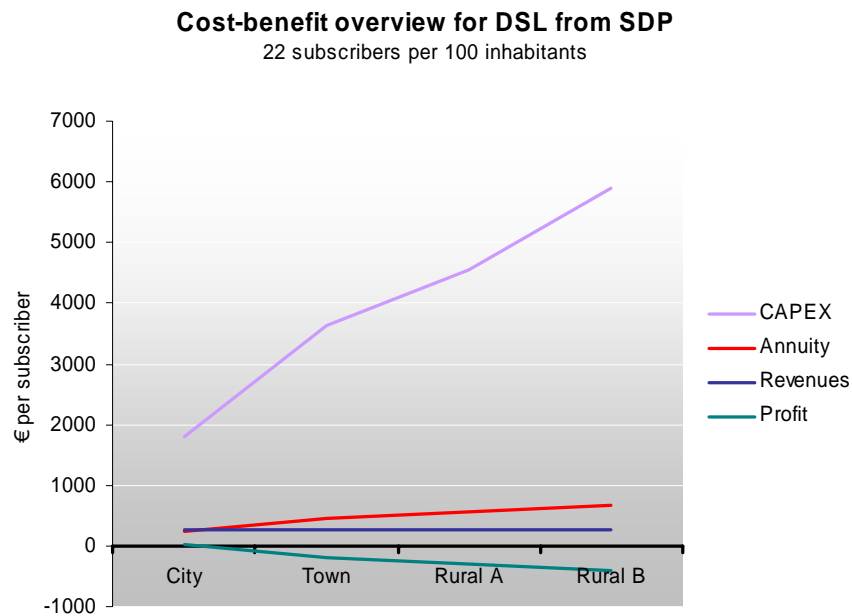
Figure 88, Cost-benefit overview for DSL from SDP

The negative outcome of the SDP strategy means that the upper level of sustainable competitive is always below 1. However, when relating this to the strategic decisions of entry deterrence, interesting alternatives arise. An incumbent could e.g. decide to follow an upgrade strategy at the SDP in cities to reduce threat of entry. In that case the incumbent would hope that the market share of DSL would increase, rendering his deployment feasible (this is likely as DSL from SDP offers much higher transmission rates than e.g. existing HFC networks). As displayed in Figure 89[118], the incumbent would only have to increase the take-up rate of DSL to around 24%. In this situation the likelihood of infrastructure competition is very unlikely as there is only room for one profitable operators and an entrant would have to win over all customers from the incumbent. Alternatively if seen from the eyes of an CLEC, if he would decide to challenge the incumbent by upgrading to

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[118] Note that the x-axis in Figure 89 is for the whole DSL market, while the x-axis in Figure 85 was for market share on a DSL market of fixed size.

SDP, he would face considerable risk as the incumbent would find it necessary to follow with the same strategy, and both of them would loose in competition.

Profitability of DSL from SDP
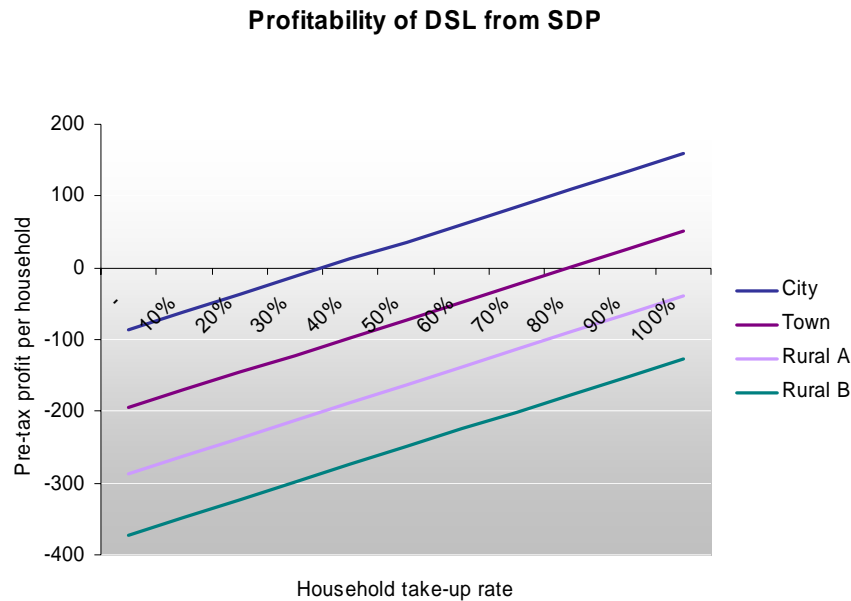
Figure 89, Profitability of DSL from SDP

5.2.3.   *Summary of strategic alternatives for telecoms*

Table 23 summarises the CAPEX, Annuity, Revenues, and profitability of the three strategies that telecoms have for upgrading their DSL platforms. Since the table only considers values per subscriber it does not allow for selection of dominant strategies as they are based on total profit, i.e. number of customers has to be multiplied. The number of customers is determined by the competitive situation in each deployment. Nonetheless the table summarises some of the interesting aspects of the strategic alternatives that telecoms have. The relative comparison shows the cost factor in comparison to deployment in LE. Taking rough averages, the table shows that PDP deployment is 5 times more expensive, and SDP deployment 50 times more expensive then deployment in LE. Another conclusion is that due to the high profitability of DSL in LE, other forces than increased revenues are needed to justify deployment in PDP or SDP. Given the decision to

upgrade, PDP deployment is generally feasible while deployment in SDP is at best risky. However, with foreseen price reductions of the required equipment for SDP, the business case of SDP is likely to become positive in the near-future. The analysis has also shown that DSL deployment in PDP and especially SDP can affect future level of infrastructure competition. Incumbents can therefore forestall competitive entry from CLECs by upgrading to SDP. The analysis has so far not included the effect of possible FTTH entry.

	CAPEX summary				Annuity summary			
	City	Town	Rural A	Rural B	City	Town	Rural A	Rural B
CAPEX for DSL deployment in LE [€/subscr]..........	85,6	85,1	101,9	103,6	25,2	25,1	30,0	30,5
CAPEX for DSL deployment in PDP [€/subscr].......	379,0	604,5	928,1	1.791,4	56,6	79,5	114,7	181,9
CAPEX for DSL deployment in SDP [€/subscr].......	1.836,0	3.685,4	4.636,4	5.984,3	280,9	525,2	640,1	772,7
	Relative to LE deployment in City				Relative to LE deployment in City			
Relative CAPEX for DSL deployment in LE............	1,0	1,0	1,2	1,2	1,0	1,0	1,2	1,2
Relative CAPEX for DSL deployment in PDP..........	4,4	7,1	10,8	20,9	2,2	3,2	4,6	7,2
Relative CAPEX for DSL deployment in SDP..........	21,4	43,1	54,2	69,9	11,1	20,8	25,4	30,7

	Revenue summary				Profitability summary			
	City	Town	Rural A	Rural B	City	Town	Rural A	Rural B
Annuity for DSL deployment in LE [€/subscr]..........	179,6	192,9	166,4	124,9	154,4	167,9	136,4	94,4
Annuity for DSL deployment in PDP [€/subscr].......	215,3	215,6	200,5	192,4	158,7	136,1	85,8	10,5
Annuity for DSL deployment in SDP [€/subscr].......	264,0	264,0	264,0	262,4	-16,9	-261,2	-376,1	-510,2
	Relative to LE deployment in City				Relative to LE deployment in City			
Relative annuity for DSL deployment in LE............	1,0	1,1	0,9	0,7	1,0	1,1	0,9	0,6
Relative annuity for DSL deployment in PDP..........	1,2	1,2	1,1	1,1	1,0	0,9	0,6	0,1
Relative annuity for DSL deployment in SDP..........	1,5	1,5	1,5	1,5	-0,1	-1,7	-2,4	-3,3

Table 23, Summary of CAPEX, Annuity, and Profit for all DSL Strategies

5.3.   *FTTH based strategies*

> ***Strategy Description***
>
> *In this strategy an entrant deploys FTTH in an established residential area. He has to decide how many access nodes to use and is assumed to connect them with ring/bus topology. At each node, the entrant has to erect new cabinets and dig trenches for new ducts and cables between each of the new nodes, as well as to each building. The cables from access nodes to households use star topology.*

This section analyses the cost and benefits of FTTH deployment. While the study is presented as an entry strategy for a competitor the results would be the same for an incumbent planning to deploy FTTH. Given the early stage of FTTH development in Denmark the empirical data on FTTH market share will not be used, but rather the focus will be on the market share that an operator that deploys FTTH would need to be profitable. The

same assumptions as before are taken on the overall broadband market, i.e. 37,67 subscribers per 100 inhabitants.

In contrast to DSL deployment that is shaped by the existing structure of the copper local loop, entrant based FTTH deployment does not have any predetermined positions for access nodes. The first thing to do is therefore to optimise the network structure, i.e. find a number of access nodes that minimises CAPEX. The optimum is an equilibrium point between economics of scale from few nodes, and additional length and thus cost of cables in fewer nodes. The optimum is found by simulating CAPEX as a function of access distance (drop segment fibre, i.e. the average distance from homes to access nodes). However, CAPEX is also a function of market share and therefore the optimisation has to be performed based on anticipated market share of the entrant. The optimal value is depicted in Figure 90 for anticipated 50% market share for all four scenarios.

Optimisation of FTTH network structure
at 50% broadband market share
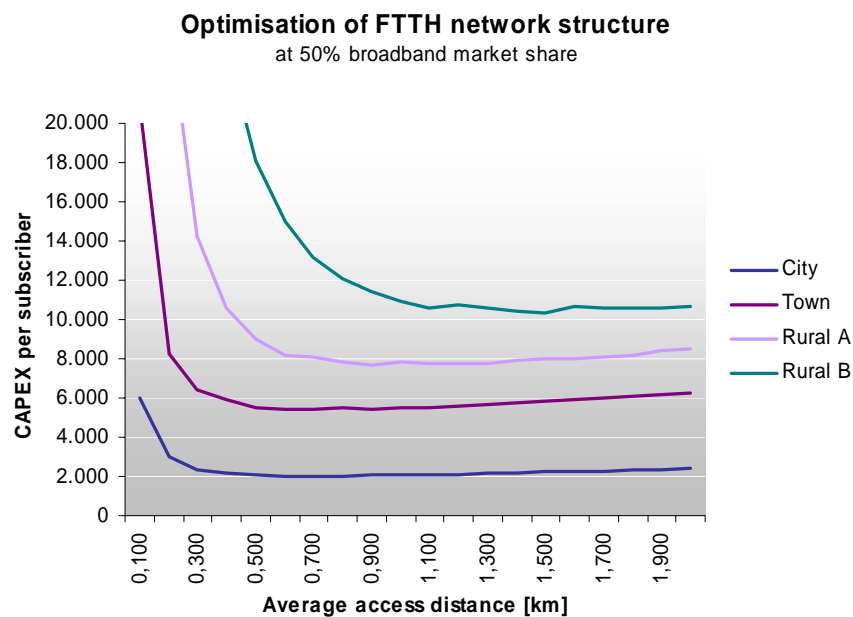
Figure 90, Optimising network dimensioning for FTTH

The optimisation shows that each scenario has a minimum access distance although the cost functions are relatively flat after the minimum value is reached. The results of the minimisation are listed in Table 24.

Cable type	Optimal access distance			
	City	Town	Rural A	Rural B
FTTH.....................................	0,7	0,7	0,9	1,5

Table 24, Optimal access distance in FTTH deployment

When analysing the cost structures of FTTH deployment, the well known dominance of trench cost is confirmed, counting for 64% - 72% of the total CAPEX (both access and aggregation trenches). The CAPEX per subscriber ranges from € 2 000 – 10 000, while the CAPEX value per passed household is €646, €2 030, €3 447, and €5 075. The comparison also shows that despite considerably lower digging cost per km in rural areas, trench cost is still a major factor in making fibre deployment in densely populated areas more expensive than in cities. As a result the total CAPEX is 167% higher in towns, 278% in Rural A, and 413% higher in Rural B.
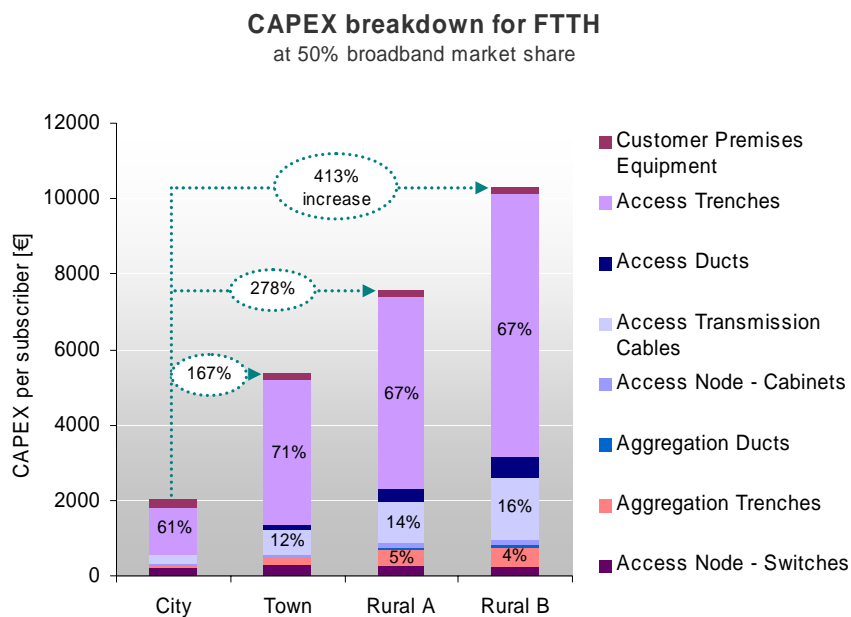
Figure 91, CAPEX breakdown for FTTH

When analysing the annuity, the composition of the effect of trench cost is evened out to some extent. This is especially true in cities,

where CPE accounts for 26% of the cost. This is due to the short lifetime of CPE in comparison to trenches, as well as the relatively high price of FTTH CPE in comparison to DSL CPE. In this sense the city deployment sticks out with the ratio of active equipment (CPE and switches) amounting roughly half of the total annuity (46% more precisely).
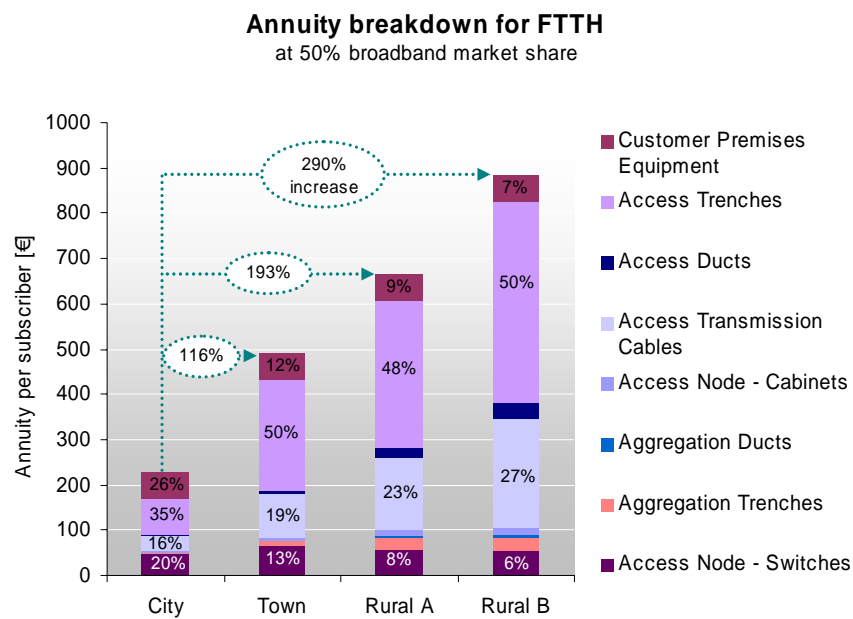
Figure 92, Annuity breakdown for FTTH

By comparing the FTTH annuity to the annuity of DSL deployment in SDP, it becomes obvious how competitive FTTH in Danish cities currently is, i.e. the annuity of FTTH in cities is €228 in comparison to €280 for DSL. This startling fact, i.e. that it is less expensive to deploy FTTH than DSL in SDP, stems from characteristics of the existing PSTN, where average distance of only 70 m means that mere 12,2 household share each access node in DSL (with even fewer subscribers). In contrast the optimisation of FTTH resulted in an average of 700 m drop cable in the same scenario. When analysing this for other scenarios, FTTH has lower annuity than DSL in SDP in both cities and towns, while DSL has lower annuity in Rural A and Rural B. However, as mentioned in Section 5.2.2 this is likely to change in the

near future with price reductions of detached DSL equipment. The same would partly be true for FTTH, where the most plausible price reductions would come from CPE, which currently accounts for 26% of the total annuity in cities. With trenches and cables dominating the cost, the prices of FTTH can not be expected to fall more than 10%-20% in the near-future.

Cost-benefit overview for FTTH
at 50% broadband market share
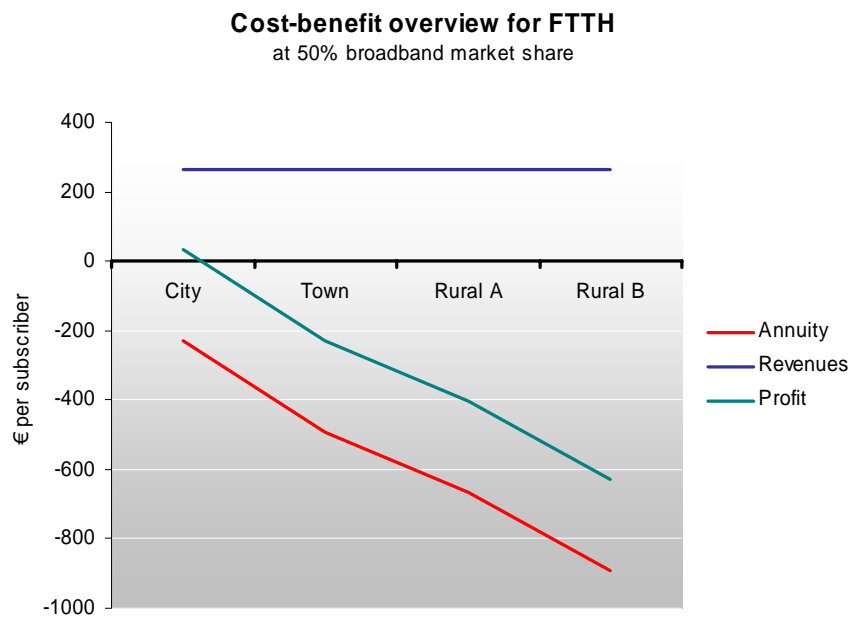
Figure 93, Cost-benefit overview for FTTH in Denmark

Summing up the cost-benefit of FTTH in Denmark, Figure 93 illustrates that FTTH in Denmark can be profitable[119]. Even with minimal economics of scope from other utility operation and no shared digging cost (i.e. this case) deployment is profitable in cities. However, the result also shows that given the same assumptions majority of the planned FTTH deployment in Denmark would be non-profitable. To

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[119] This assertion has the limitations of not answering the question whether it is likely. A witty illustration of the effect is Lloyd Christmas' answer after getting the success chances of one against a million in the film Dumb & Dumber: "So there is a chance".

analyse this further, the thesis will first look at the required up-take and how that affects profitability, in the next section the effect of shared digging cost is evaluated.

Profitability of FTTH

with and without annualised 1000 € connectivity fee
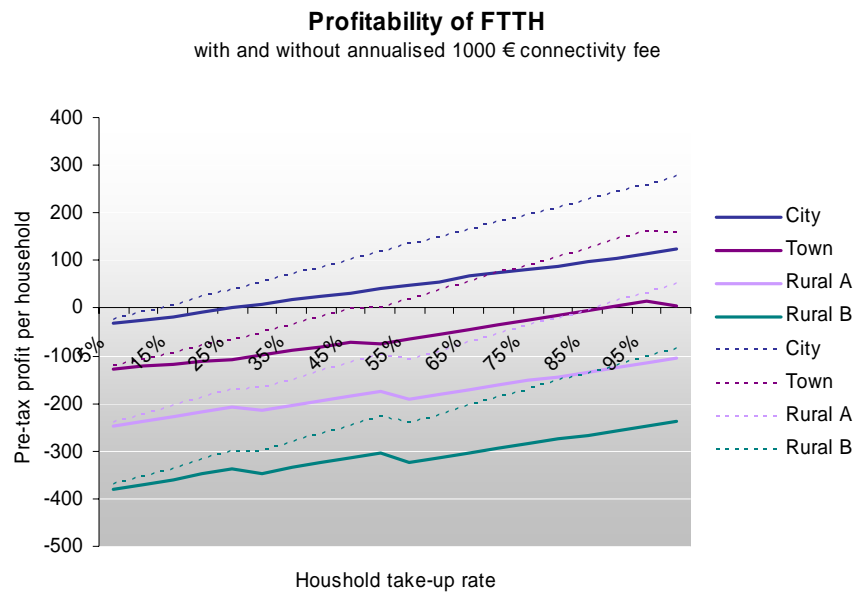
Figure 94, Profitability of FTTH in Denmark

Much like the earlier analysis, Figure 94 shows that FTTH in cities is profitable for take-up rates above 35%. It should be noted that the take-up rate is not the same as subscribers per 100 inhabitants, i.e. with 1,7 inhabitants per household 35% take-up equals 21% subscribers per 100 inhabitants in the area under considerations. While this does not seem much at first glance, it none-the less means that the entrant will have to get 50% market share on the broadband market.

5.4.   The effect of "shared digging" and "connectivity fee"

This section analyses the feasibility of FTTH deployment under shared trench cost. To prevent duplication cost and strengthen competition, many countries mandate trench sharing. In trench sharing, competitors have the right to lay cables in trenches that competitors dig, given that they share

the total cost. For splitting up the cost electric utilities and telephone companies in Denmark have predefined rules for distributing the cost, contingent upon the types of cables laid. In this section we use the cost distribution ratios reported by the Danish competitive authorities as described in Table 25 to investigate the effect on FTTH deployment.

Cable type and trench depth	Telephone	TV	Electr.	St. Lights
Telephone at 45 cm, electricity at 70 cm..	41%	-	59%	-
Telephone and TV at 45 cm, electricity and street lights at 70 cm..........	20%	20%	30%	30%
Telephone at 45 cm and TV, electricity, and street lights at 70 cm.........	20%	26%	27%	27%
Telephone, TV, electrrricity, and street lights at 70 cm...........................	20%	25%	25%	25%

Table 25, Distribution of cost in trench sharing
Source: Konkurrencestyrelsen (2005; p. 32)

This simulation in this section is based on FTTH deployment bearing 20% of the trench cost. Since trench cost greatly affects the network dimensioning of the platform, the optimisation is run again. The optimums result in shorter drop segments, or as Figure 95 shows, 700m, 500m, 600m and 1100m.

Optimisation of FTTH under shared digging cost
at 20% trench cost and 50% broadband market share
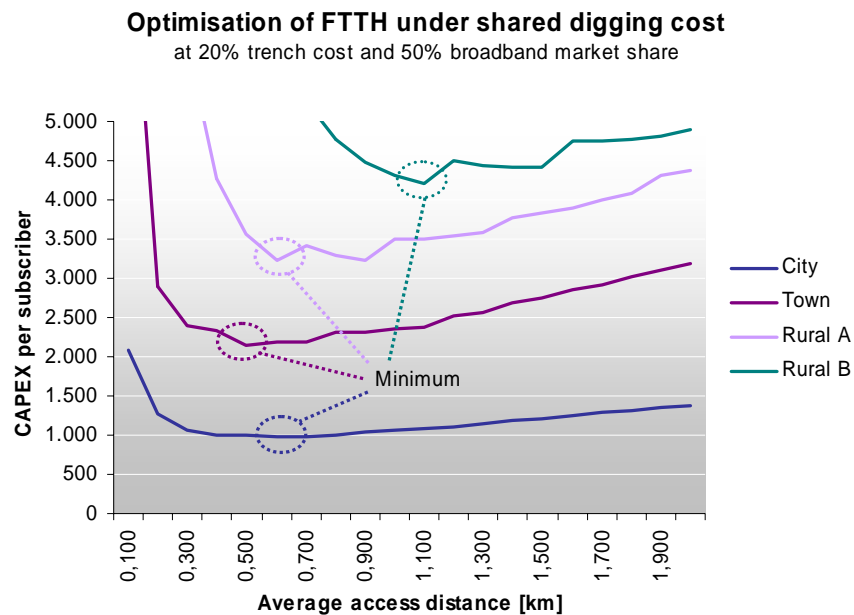
Figure 95, Optimisation of FTTH under shared digging cost

As Figure 96 illustrates the effect of shared digging cost is a reduction of CAPEX to roughly half of the previous values (of Figure 91). The composition also changes with trench cost falling from 61% down to 25% of the total cost. It is also interesting to compare the CAPEX of FTTH under shared digging cost to that of DSL. The FTTH CAPEX in towns is € 988 in comparison to €269 and €1836 for DSL provided from PDP and SDP, i.e. FTTH is less expensive than DSL from SDP but still four times as expensive than from PDP.

CAPEX breakdown for FTTH
at 20% trench cost and 50% broadband market share
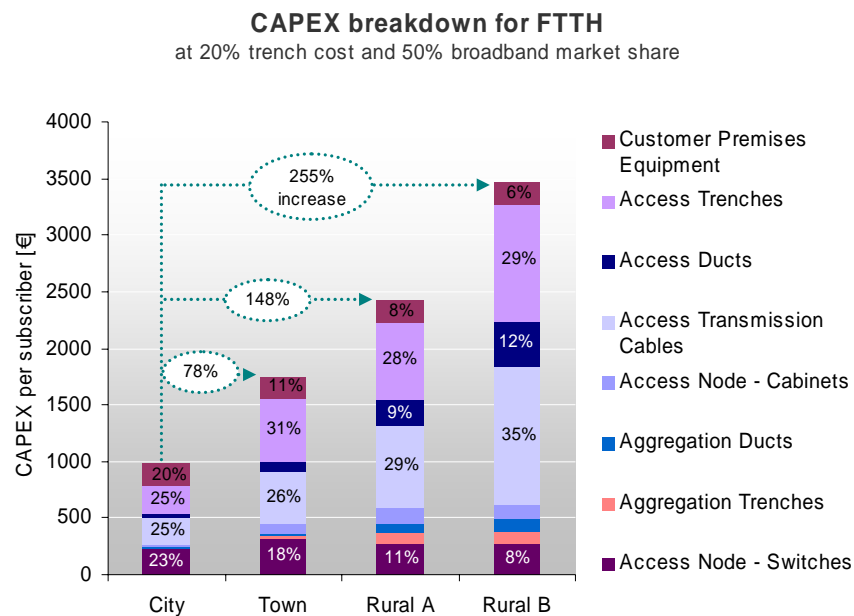
Figure 96, CAPEX breakdown for FTTH under shared digging cost

When analysing the annuity under shared digging cost, the first thing that catches the eye is that both city and town are now profitable and Rural B close to becoming it. It is also interesting to look at how the ratio of active and passive cost component changes, CPE and switches now account for 65% of the annuity. Especially the CPE is interesting since that is purchased over a longer period and therefore could be subject to price reductions. For the rural B case it is important to note how expensive the cables are. With annuity of cables alone taking 70% of the EBIDTA it would be difficult to construct a profitable business case, even though the

farmers would to the digging for free within their own land, like some FTTH advocates have suggested.

Annuity breakdown for FTTH
at 20% trench cost and 50% broadband market share
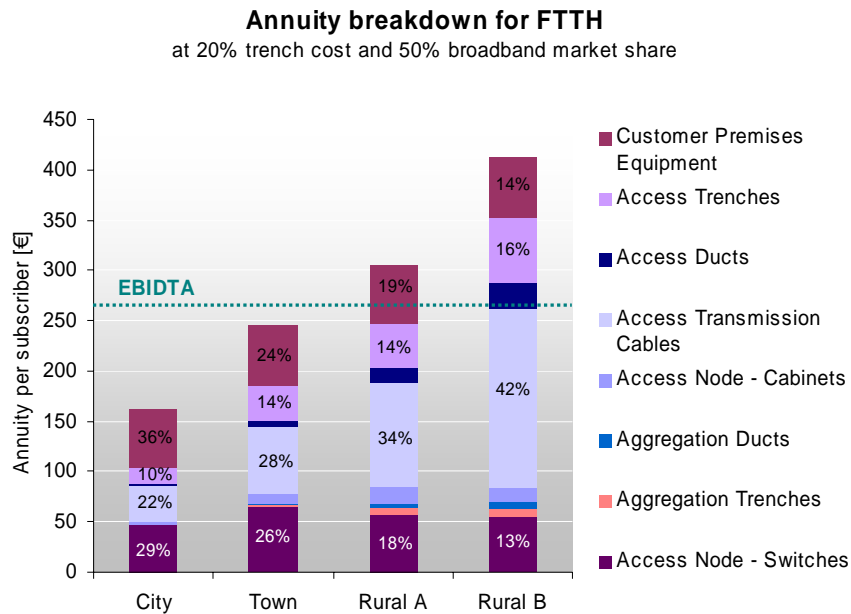
Figure 97, Annuity breakdown for FTTH under shared digging cost

When looking at the profitability as a function of market share Figure 98 shows that the entrant would need 20% household take-up rate in cities to be profitable. This amounts to roughly 12 subscribers per 100 inhabitants or 31% of the broadband market. In towns this ratio increases to 70% of the broadband market. For the Rural cases the entrant would have to increase the foreseen broadband market considerably to have a chance of being profitable. To prevent loss, several EUC in Denmark have taken up a "connectivity fee". This connectivity fee is a one-time cost that subscriber pay for "lighting" the fibre and ranges from €500 to €1000. Calculating annuity over 10 years this results in € 75 – 150. This raises the profitability curves. Assuming this, rural deployment could be profitable at take-up rates of 35% and 60%, while the cross-over take-up rate for cities goes down to 8% and 22% for towns. Both with and without the connectivity fee, applying Equation 9 shows that there is room for sustainable infrastructure competition in cities and towns while rural areas can only sustain limited DSL competition.

Profitability of FTTH in shared digging
at 20% trench cost (with and without connectivity fee)
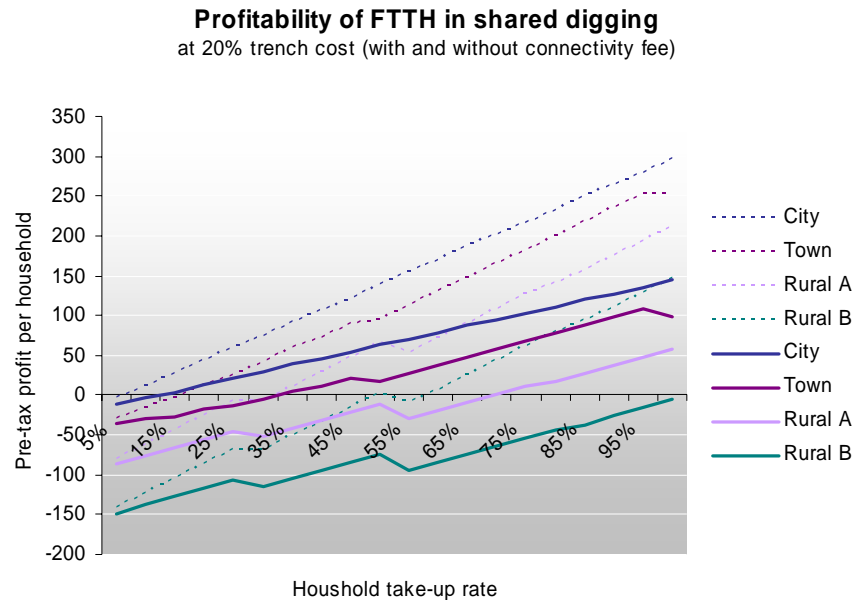
Figure 98, Profitability of FTTH in shared digging

5.5. *The Effect of Competition*

This section takes the results of the previous simulation from Denmark and maps them as strategic decisions in a von Stackelberg game between three players: an incumbent local exchange carrier (ILEC), an Energy Utility Company (EUC), and a competitive local exchange carrier (CLEC). The ILEC moves first, and can choose between deploying DSL from LE, PDP, or SDP. The EUC moves next and can either deploy fibre or not participate in the game (the outcome of the EUC assumes shared digging costs (as analysed in Section 5.4)). In a similar fashion the CLEC can choose between deploying DSL from the PDP or not participate[120].

A prerequisite to mapping out the effect of the strategies is anticipating how the market share between competitors will change with strategic decisions. As described in Section 4.7 there is no

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[120] The CLEC could also deploy from the LE or SDP, but for simplicity only the PDP option is shown as that is the dominant strategy of the CLEC.

empirical data for Denmark to construct demand functions, and outside the scope of this thesis to perform surveys. To compensate for this lack of information the thesis makes rough subjective estimates of the market share of ILEC, EUC, and CLEC as illustrated in Table 26. One period of the game is considered and the game analysed from the extensive form[121]. The solution is based on a backwards analysis of a von Stackelberg story, where each player selects the strategy that maximises his profits, given knowledge of the previous actions of the other players.

ILEC	No CLEC					
	FTTH			NO FTTH		
	ILEC	EUC	CLEC	ILEC	EUC	CLEC
LE	20%	80%	0%	50%	0%	0%
PDP	50%	50%	0%	80%	0%	0%
SDC	80%	20%	0%	100%	0%	0%
ILEC	CLEC from PDP					
	FTTH			NO FTTH		
	ILEC	EUC	CLEC	ILEC	EUC	CLEC
LE	10%	70%	20%	40%	0%	60%
PDP	45%	45%	10%	70%	0%	30%
SDC	77%	18%	5%	90%	0%	10%

Table 26, Market share of ILEC, EUC, and CLEC under competition

The market shares of Table 26 represent averages over a period, taken from an initial market share of 50% for the ILEC[122]. The ILEC thereby has a clear advantage, both the first movers advantage, as well as in the form of already established market share that the EUC has to fight for. This is a difficult fight for the EUC as Stordahl (2004) notes "The main results from the techno-economic calculations show that it is difficult for new broadband technologies to capture significant market share in areas where

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[121] The game could also be solved using dominance arguments or by looking for a Nash equilibrium. For a more detailed discussion of solving a von Stackelberg story see e.g. Kreps (1990; p 45)

[122] Additionally the table makes the assumption that DSL and FTTH saturates the broadband market. This assumption, as well as the exact number of the table, can not be expected to be realised in the market (e.g. due to prospects of other technologies such as fixed wireless access etc.) but represent rough estimates that are used to illustrate the functionality of the methodology used.

cable modem and/or DSL are already deployed". The payoffs displayed in the games, are in € million, calculated for each geographical profile from the model of the last section.

5.5.1.   City

The solution to the von Stackelberg game for the city profile is that the incumbent will chose to deploy DSL from the SDP, knowing that it will forestall entry by both the EUC and the CLEC. This is a dominant strategy as even though the threat of FTTH deployment from EUC is taken seriously, SDP deployment will yield a better result for the incumbent than taking the next best alternative which is deployment at the PDP. The result is not what the EUCs would wish for as SDP deployment will result in a loss rather than allowing coexistence, in the case of the ILEC selecting PDP deployment[123]. However, if the EUC was to enter the market is would not be profitable under the given assumptions, but as the estimates are sensitive towards the market share that the EUC would get, and as the loss is not high, the EUC could possibly be profitable and coexist with the incumbent none the less.

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[123] The solution to the game is based on backwards reasoning, e.g. for the first game: if the ILEC select PDP, the EUC select FTTH as that has higher return to it, and lastly the CLEC selects not to participate, i.e. the equilibrium given PDP is {PDP, FTTH, no CLEC} yielding 35,38 for the ILEC. Using the same reasoning for SDP, the EUC would choose not to participate (as otherwise it would loose), and the CLEC also chooses not to participate given the decisions of the other two, leading to the equilibrium {SDP, No FTTH, No CLEC} which yields 68,84 for the ILEC. SDP therefore maximises the profit for the ILEC.
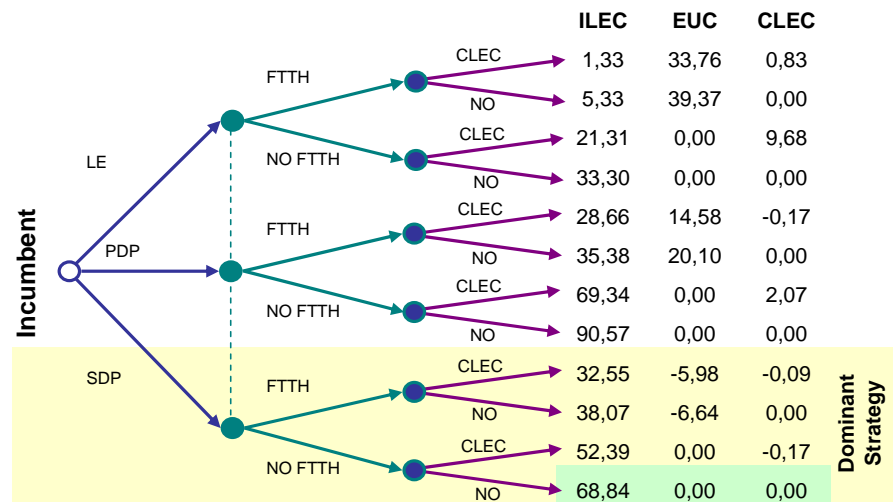
Figure 99, Von Stackelberg game for city profile

5.5.2. *Town*

In the town, the incumbent can be expected to deploy DSL at the PDP, resulting in competition between the incumbent and the CLEC. If the incumbent takes the threat of FTTH deployment from the EUC seriously, he is reinforced in his selection in PDP as that is also a dominant strategy for the ILEC under FTTH competition. However, the result would be that the CLEC would refrain from participation if the EUC participates. Like before the EUC has the possibility of marking changes either to its operation of to the market share to thus become profitable and coexist with the incumbent.

					ILEC	EUC	CLEC
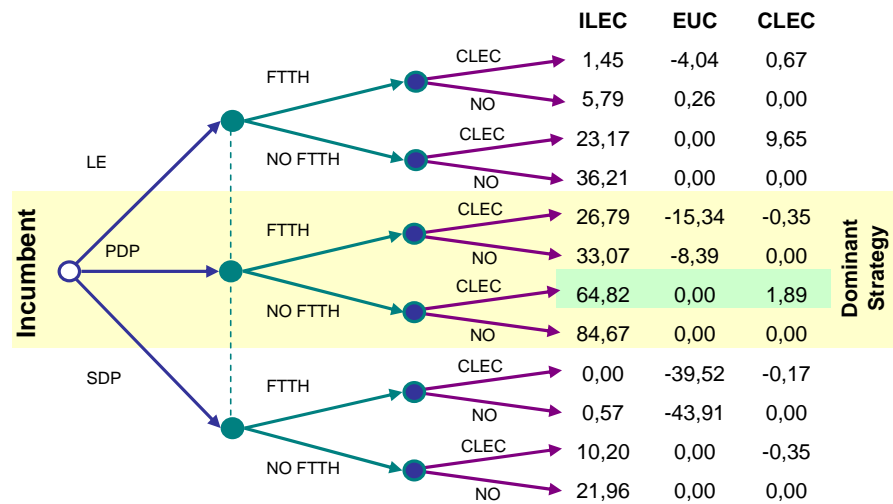
Figure 100, Von Stackelberg game for town profile

5.5.3. Rural A

The results for Rural A, are the same as for Rural B, i.e. that the ILEC will deploy DSL from the PDP, and the CLEC will chose to compete. The EUC would not compete but given that is realises its threats it looses severely, and the CLEC will not participate in that case. The expected loss to the EUC is such that it is unlikely that it can be changed to profit.

			ILEC	EUC	CLEC
LE	FTTH	CLEC	1,18	-39,38	-0,01
		NO	4,71	-34,58	0,00
	NO FTTH	CLEC	18,82	0,00	8,54
		NO	29,41	0,00	0,00
PDP	FTTH	CLEC	19,59	-68,30	-0,87
		NO	24,18	-58,83	0,00
	NO FTTH	CLEC	47,40	0,00	1,27
		NO	61,91	0,00	0,00
SDP	FTTH	CLEC	-33,67	-113,30	-0,43
		NO	-30,74	-125,89	0,00
	NO FTTH	CLEC	-25,02	0,00	-0,87
		NO	-17,17	0,00	0,00
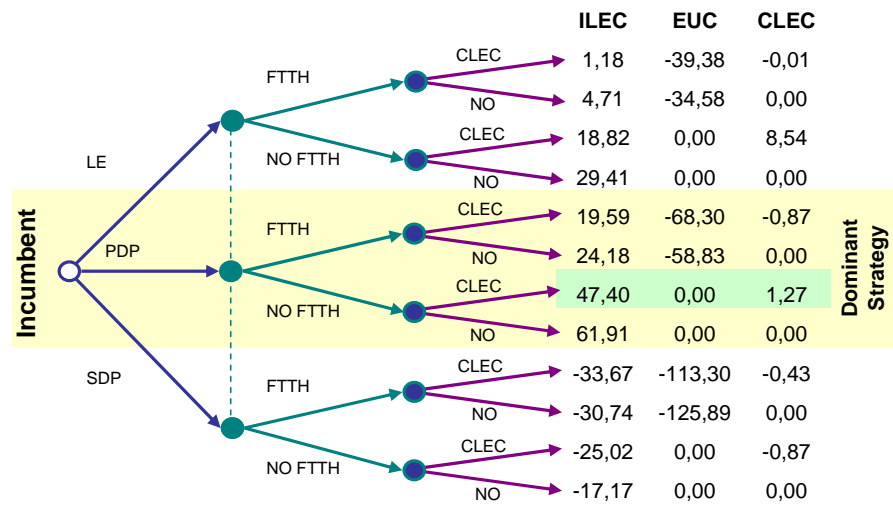
5.5.4. Rural B

In Rural B the ILEC again chooses to deploy DSL from the PDP but this time the CLEC chooses not to participate. The results are the same for the EUC here as in Rural A, with even more negative prospects for profitability.

				ILEC	EUC	CLEC
LE	FTTH		CLEC	0,81	-103,27	-2,46
			NO	3,26	-100,96	0,00
	NO FTTH		CLEC	13,03	0,00	3,51
			NO	20,35	0,00	0,00
PDP	FTTH		CLEC	9,54	-113,61	-2,13
			NO	11,77	-101,99	0,00
	NO FTTH		CLEC	23,07	0,00	-2,32
			NO	30,14	0,00	0,00
SDP	FTTH		CLEC	-62,53	-167,67	-1,07
			NO	-60,74	-186,30	0,00
	NO FTTH		CLEC	-58,83	0,00	-2,13
			NO	-54,81	0,00	0,00
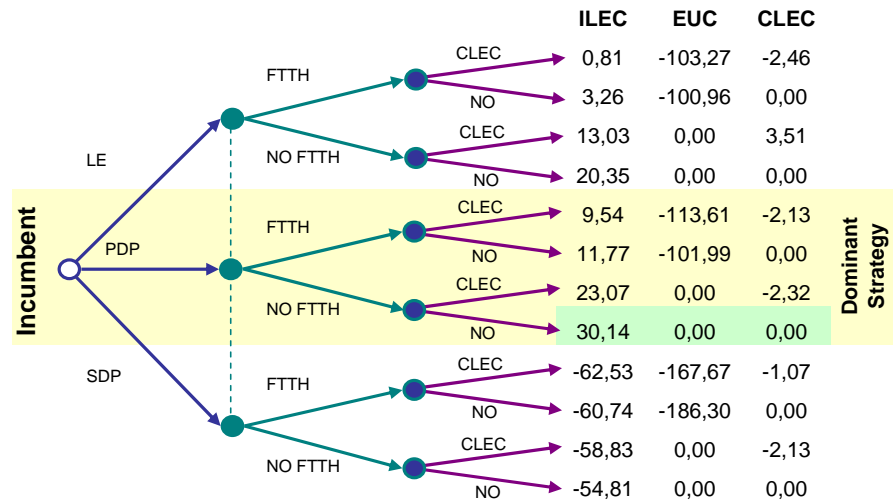
5.6.   Summary

This chapter has presented the results of a simulation study for residential broadband deployment in four geographical scenarios in Denmark. Two upgrade strategies based on DSL technology were analysed and compared to deployment of FTTH. Additionally the effect of "shared digging cost" and "connectivity fee" on the cost structures of FTTH were analysed. Lastly the chapter analysed the effect of competition between three players: ILEC, CLEC, and EUC and identified dominant strategies for each player in each geographic setting.

The results confirm two well known facts about residential broadband deployment, i.e. increasing cost of deployment in dispersedly populated areas, and predominance of trench, duct and cable cost in the capital expenditure of all fixed-line broadband networks. However, the study also shows how annuity compensates for both trends by considering the long lifetime and stable price development of structural elements.

The study of telecom strategies highlights the highly profitable short-term business case of DSL provision from local exchanges but also quantifies the limitations on revenue that long copper loops incur. The simulation shows that telecoms can increase nominal transmission rates to 20-40 Mb/s by deploying detached DSLAMs at primary distribution points, or to 50-90 Mb/s by going to the secondary distribution point. However, the number of nodes increases by a factor of 10 for each step and the required civil work raises capital expenditure from € 400-1800 per subscriber to € 1800-6000,

depending on geographic scenarios. In conclusion deployment in PDP is financially feasible in all four scenarios while only in cities for SDP.

The main finding of the study of FTTH deployment is that despite high trench costs, deployment is cities is financially feasible if the EUC can get more than 25% take-up of the service. Translated into broadband penetration this equals roughly 40% market share. When considering economics of scope from other EUC operation, i.e. shared digging cost, this market share is reduced down to 27%. The possibility of financial feasibility of FTTH deployment deteriorates considerably for other geographical scenarios. However, given shared digging cost and connectivity fees, deployment in towns can be feasible if take-up is above 50%.

In the final part of the chapter the results from the model are fed into a von Stackelberg game model to study competitive strategies. The game assumes that the incumbent moves first and then deployment in SDP becomes a dominant strategy in cities. This can be seen as a defensive move by the incumbent, meant to forestall entry by the EUC and CLEC since in the absence of competition deployment from PDP would have been more feasible. For all other geographical scenarios PDP deployment becomes dominant for the incumbent. Due to the market power of ILECs and transmission capabilities well above the demand level, the conclusion is that EUC and CLEC will have a hard time attracting the required number of subscribers to their networks.

Chapter 6

Conclusions

This thesis has analysed residential broadband deployment from three angles: multimedia service development, access network alternatives, and financial feasibility of deployment. By analysing the near-future transmission requirements of converged voice, video, and data services, as well as available deployment strategies for broadband access networks, the thesis has identified a set of plausible deployment scenarios for telecoms and entrants. These scenarios provided the input for a techno-economic simulation model developed to estimate the financial feasibility of residential broadband deployment. This chapter provides a summary of the work carried out, lists the main findings, and proposes future work.

6.1.   Residential Broadband Services

This thesis has analysed the transformation from 'data centric' to 'multimedia' broadband services, characterised by coexisting provision of voice, video, and data over a common IP platform. The study included the challenges involved in introducing voice, and video services into the current data-centric broadband service portfolio, additional transmission and Quality of Service (QoS) requirements posed by real-time services, previously provided analysis of service development, empirical evidence of adoption, and concluded by forecasting near future transmission requirements.

The study began by challenging conventional definitions of broadband that only use transmission speeds to characterise broadband. Instead the thesis argues that broadband should be defined dynamically through the services which it is to carry. These services are constantly evolving and thus the transmission requirements and ultimately the definition of broadband are bound to change as well.

To understand the nature and development of multimedia services the thesis brushed up the fundamentals of packet-based networks and the transmission properties that govern their use. The study highlighted the difference between the provision of services over the general Internet, which only supports one "best effort" class of service in comparison to managed networks that can support a wide range of Quality of Service parameters for individual services and applications.

When analysing service types the analysis shows that service selection and traffic volume have been growing fast, but apparently without affecting traditional content distribution. This indicates that broadband services have been supplements rather than substitutes to e.g. PSTN and broadcast TV. As an example there were 25 million worldwide paid VoIP subscriptions at the end of 2005 as compared to roughly 1.2 billion PSTN subscriptions. However, when considering the disruptive nature of Instant Messaging and Peer-to-Peer networks, broadband services have greater potentials. This becomes evident when looking at the roughly 350 million active IM users and the dominance of P2P traffic in backbone networks.

In addition to foreseen success, the nature of multimedia services is likely to change. The distinction between data services and other types of services is likely to disappear as applications increasingly interweave different media streams in an interactive manner. Measures by operators to fully capture the value and service delivery of all of these applications are not likely to work and therefore network access providers have to embrace disruptive services and be prepared to tailor transmission offerings to their needs, rather than trying to steer service development into predefined business models.

Most incumbent operators in Europe are gearing up to offer new multimedia services, most notably IPTV. Despite great efforts by equipment vendors and high profile industry collaborations there are several roadblocks in the path of IPTV. These range from the lack of an overall standardisation framework, low margins, to the threat of applications competition from the Internet. For success operators have to

utilise the back-channel that broadband provides to offer interactive content through innovative business models.

To evaluate the effect of emerging services and technologies on transmission requirements the thesis studied available methods of demand forecasting. Using extrapolation of historical data the transmission requirements of multimedia services for an average household were estimated to increase from 20 to between 50 and 100 Mb/s in the coming 5 years. However, at each point in time this nominal value only indicates a point in a distribution that can vary greatly depending on individual demand, demographics etc.

To analyse the impact of emerging technological trends the thesis performed two case studies of prominent residential broadband services. The first analysed Skype, a well known VoIP service that innovatively uses peer-to-peer technology to build a global resilient infrastructure. The second analysed TV Avisen, the most popular Danish web casting news-on-demand service. Both studies highlighted the potentials of peer-to-peer technology for increasing efficiency in future content distribution.

6.2.   *Residential Broadband Networks*

This thesis has analysed alternative method of offering residential broadband using Digital Subscriber Line (DSL) technology over the existing copper loop infrastructure in comparison to laying fibre all the way to subscriber's premises, i.e. FTTH. The study has revealed that both solutions build upon the concept of Next-Generation-Networks (NGN) where different types of multimedia services are carried over a single IP infrastructure that can supports different QoS requirements. However, there have not emerged any widely accepted "future-proof" methods of providing end-to-end QoS, reducing the expected lifetime of current equipment.

The study discussed how the imminent network and service convergence will affect the role that network access providers assume in the provisional value chain. While telecoms have historically preferred vertically integrated service development and deployment offered through walled garden business models, emerging EUC deployment is often based on "open access" where external service providers are contracted through revenue sharing.

A detailed study of DSL technology and its provision showed how reliant DSL deployment is on the existing copper infrastructure that signals are carried over. Due to attenuation, cooper loop lengths are the most important parameter where the general rule is that with increased length, transmission throughput decreases. However, telecoms have the option of deploying equipment closer to end users, thereby reducing the loop length and increasing transmission speeds. Two plausible upgrade strategies exist in Denmark where detached DSLAMs can be located in existing PSTN cable aggregation nodes (called primary and secondary distribution nodes). A prerequisite to deployment in detached nodes is that problems with frequency disturbances are addressed, and sub-loop unbundling implemented.

In contrast to DSL, FTTH deployment does not build on existing access networks. Instead new optical fibre is deployed to each household in a given area, offering a "future-proof" transmission medium. As the study revealed, the end equipment used in FTTH as well as DSL is undergoing constant development and wholesale prices are highly reliant on mass production. Therefore deployment will be effected by global trends, which currently indicate that Passive Optical Networks will be the most widely deployed FTTH standard once incumbent telecom operators start migrating over to FTTH.

To analyse deployment in Denmark further, the thesis includes two empirical case studies of residential broadband deployment. The first of DSL upgrade alternatives for the incumbent, TDC, in the suburban area of Hasselager. The latter analysed the deployment approach of Danish EUC Nesa, which deploys active Ethernet FTTH around the capital area using the "open access" approach.

6.3.   *Residential Broadband Deployment*

The thesis has developed a modelling framework to analyse the financial feasibility of residential broadband deployment. The framework builds on existing techno-economic models, using a bottom-up approach to simulate deployment cost. The model was implemented in Microsoft Excel and uses an empirical dataset from the Danish Long-Run Average Incremental Cost (LRAIC) model to estimate the cost up upgrading the existing copper infrastructure in comparison to building a new FTTH network.

The model uses well known methods of calculating capital expenditure for given input scenarios. Additionally a module for calculating revenues

based on the transmission capacity of each scenario was developed. Together, these components form the basis of a cost-benefit analysis that was used to estimate financial feasibility. This was accomplished by calculating the tilted annuity cost for each year and matching that with earnings before interests, tax, depreciation and amortisation (EBITDA). The tilted annuity considers the expected asset life and changes in price development, evening out long-time comparison of different cost structures.

Finally the framework uses game theory to explain the strategic interactions between competing infrastructures analysed through a von Stackelberg model. This game can be used to explain situations where an established market player leads with initial deployment that competitors subsequently decide their actions based on. The framework was applied to four geographical scenarios in Denmark. Two upgrade strategies based on DSL technology were analysed and compared to deployment of FTTH. Additionally the thesis investigated the effect of "shared digging cost" and "connectivity fee" on the cost structures of FTTH. Lastly the simulation study analysed the effect of competition between three players: ILEC, CLEC, and EUC and identified dominant strategies for each player in each geographic setting.

The results confirm two well known facts about residential broadband deployment, i.e. increasing cost of deployment in dispersedly populated areas, and predominance of trench, duct and cable cost in the capital expenditure of all scenarios. However, the study also shows how annuity compensates for both trends by considering the long lifetime and stable price development of structural elements, such as trenches and ducts.

The study of telecom strategies highlights the highly profitable short-term business case of DSL provision from local exchanges but also quantifies the limitations on revenue that long copper loops incur. The simulation shows that telecoms can increase nominal transmission rates to 20-40 Mb/s by deploying detached DSLAMs at primary distribution points, or to 50-90 Mb/s by going to the secondary distribution point. However, the number of nodes increases by a factor of 10 for each step and the required civil work raises capital expenditure from € 400-1800 per subscriber to € 1800-6000, depending on geographic scenarios. In conclusion deployment in PDP is financially feasible in all four scenarios while only in cities for SDP.

The results from the cost-benefit study were fed into a von Stackelberg game model to study competitive strategies. The game assumes that the incumbent moves first and the results indicate that deployment in SDP

becomes a dominant strategy in cities. This can be seen as a defensive move by the incumbent, meant to forestall entry by the EUC and CLEC since in the absence of competition deployment from PDP would have been more feasible. For all other geographical scenarios PDP deployment becomes dominant for the incumbent. Given this course of actions, i.e. deployment in SDP in cities and in PDP in all other areas, EUC and CLEC can be expected to have a hard time in overcoming switching cost and market power of the ILEC when trying to attract the required number of subscribers to their networks.

6.4.   *Wide-scale FTTH Deployment in Denmark*

One of the main goals of this study was to analyse the prospects of wide-scale FTTH deployment by energy utility companies (EUC) in Denmark. For this purpose the study has evaluated the financial premises against two major parameters: take-up rate, and "shared digging cost". The results of this study are shown in Table 27. To sum up, FTTH is only financially feasible in cities given full cost of deployment but at 20% trench cost (i.e. shared digging) and assuming € 1.000 in connectivity fee FTTH deployment can be financially feasible in all areas.

	At full cost				At 20% tr. cost and €1.000 con. fee			
	City	Town	Rural A	Rural B	City	Town	Rural A	Rural B
Required take-up rate..	25%	88%	Not	Not	6%	16%	37%	49%
Broadband market share...	39%	117%	Feasible	Feasible	9%	21%	41%	50%

Table 27, Cross over take-up rates required for financial feasibility in FTTH

It should be noted that the cross-over values of Table 27 represent the take-up rate where EUC deployment starts being profitable. Given that they start without any market share there will be a period of loss, prior to reaching the cross-over value. This loss must be compensated with a period of profit, requiring a higher take-up value. The open issue is how customers value the services that EUC FTTH network offer in comparison to other alternatives and how easily they can be persuaded to switch.

In addition there are two major issues that EUCs need to consider. The first is that, unlike other EUC utility provision, residential broadband will face fierce competition. The study has shown that the incumbent is likely to retaliate with DSL deployment that can match the transmission capacity of current FTTH equipment. The odds are also stacked against a new and inexperienced entrant that has to "iron out" many technological and operational challenges.

A second major force is the development and dynamics of the technology required. The large, continual investment in infrastructure required to build a FTTH network may prove to be a financial albatross if newer technologies render that investment obsolete. The study reveals that most EUC have started FTTH deployment as early adopters, predominantly using Active Ethernet over star based topology. This is in sharp contrast to incumbent telecom operators that are currently flocking towards Passive Optical Networks. Given the effect of mass production on component prices, betting on the wrong technological standards, or just being too early, may prove costly, especially as this study has shown that over half of the annual cost of FTTH in cities is from active hardware components.

CAPEX per passed household	Full cost				Average
	City	Town	Rural A	Rural B	Denmark
Passive FTTH infrastructure...................................	502	1.806	3.170	4.777	**2.564**
At 50% broadband market share............................	646	2.030	3.448	5.075	**2.800**
At 50% houshold uptake...	715	2.126	3.458	5.077	**2.844**
At 100% houshold uptake.......................................	917	2.337	3.745	5.377	**3.094**
CAPEX per passed household	20% trench cost, €1.000 con. fee				Average
	City	Town	Rural A	Rural B	Denmark
Passive FTTH infrastructure...................................	172	550	1.155	1.781	**915**
At 50% broadband market share............................	349	893	1.466	2.253	**1.240**
At 50% houshold uptake...	385	901	1.466	2.253	**1.251**
At 100% houshold uptake.......................................	587	1.161	1.777	2.663	**1.547**

Table 28, Capital Expenditure per household for FTTH deployment

Total CAPEX	Total FTTH investment in Denmark				
	City	Town	Rural A	Rural B	Denmark
Housholds..	673.529	822.000	946.667	60.000	2.502.196
Passive FTTH infrastructure [€ billion]....................	0,34	1,48	3,00	0,29	**5,11**
At 50% broadband market share [€ billion]..............	0,44	1,67	3,26	0,30	**5,67**
At 50% houshold uptake [€ billion]...........................	0,48	1,75	3,27	0,30	**5,81**
At 100% houshold uptake [€ billion].........................	0,62	1,92	3,55	0,32	**6,41**
Total CAPEX	Total FTTH investment in Denmark at 20% trench cost, €1.000 con. Fee				
	City	Town	Rural A	Rural B	Denmark
Housholds..	673.529	822.000	946.667	60.000	2.502.196
Passive FTTH infrastructure [€ billion]....................	0,12	0,45	1,09	0,11	**1,77**
At 50% broadband market share [€ billion]..............	0,23	0,73	1,39	0,14	**2,49**
At 50% houshold uptake [€ billion]...........................	0,26	0,74	1,39	0,14	**2,52**
At 100% houshold uptake [€ billion].........................	0,40	0,95	1,68	0,16	**3,19**

Table 29, Total FTTH investment in Denmark

Table 28 and Table 29 summarise the magnitude and characteristics of FTTH deployment in Denmark. As the tables show the investment required varies greatly depending on geographical profiles and the amount of "lit" fibres. The cost of a passive infrastructure for each household is € 502 but assuming shared digging cost and connectivity fee this value drops to € 171. With increased take-up the cost per household increases (cost per subscriber decreases). The total investment for Denmark at 50% take-up is € 5.8 billion or € 2.5 assuming shared trench cost and connectivity fee. In comparison, the bridge across the Great Belt between Funen and Zealand had a cost of € 3.3 billion, and the planned bridge between Denmark and Germany across Fehmern Belt is expected to cost € 5.3 billion (Pedersen 2005).

6.5.   Regulatory implications

Competition among residential broadband infrastructures has been a central theme in this thesis. The study has shown that sustainable competition depends on the strategy chosen by both the incumbent and EUCs. The general rule is that with increased investment the room for competition decreases. At the same time the study shows that the cross-over market share is low enough in cities to facilitate coexisting DSL and FTTH, or two parallel FTTH infrastructures.

The study has also highlighted the effect of shared trench cost. When considering the low annual cost of passive FTTH infrastructures the possibility of mandating shared ducts or access to passive infrastructure arises. As an example the required investment for passive infrastructures in cities is € 172, resulting in a tilted annuity of € 17. Although this cost does not consider operational cost like the LRAIC price of the copper loop does, the results indicate that the cost of unbundled fibre loops would at least not necessarily be higher than that of the current copper infrastructure. However, unbundling of fibre loops as well as sub-loop unbundling of copper loops suffers from practical problems. Denmark is at the forefront of addressing these issues, which can additionally be expected to reduce the regulatory uncertainty and further stimulate deployment.

A key assumption in the analysis has been that incumbent operators wish to drive their operation over their own copper network, rather than as a service provider over a neutral FTTH infrastructure. This stems from an old telecom dogma that infrastructures and services are so tightly interwoven that it is dangerous or limiting, not to be the infrastructure

owner (or alternatively the assumption that the owner of the infrastructure can/will misuse his key-position). With increasing decoupling of networks and services through next-generation-networks, this might be changing and therefore the barrier that holds incumbents from embracing infrastructure deployment by energy utility companies, rather than criticising it.

6.6.   Summary of Findings

This section reflects on the findings of the study through bulletin points. Much of the issues raised are the same as those presented in the previous summary section but are taken up here to highlight individual findings.

The future is optical but the near-future not necessarily!

The future of residential broadband networks is based on converged voice, video, and data services that pose individual QoS requirements on transmission. While these services, and especially IPTV, can be expected to raise transmission requirements from 20 Mb/s to 50-100 Mb/s in the course the next five years, this thesis concludes that there currently are no strong demand sided requirements that call for FTTH rather than e.g. DSL, given that the DSL infrastructure is upgraded to meet these requirements.

Why spend money on upgrades when you can get the real thing?

Advocates for FTTH have proclaimed that spending money on upgrading DSL infrastructures is a waist when FTTH is available and can meet all future needs. This is partly in contrast to the whole theory of investment appraisal which argues that due to the time value of money and the incurred opportunity cost, using the argumentation of eventual demand is a fatal investment strategy if a less expensive solution exists that can meet all requirements. If there are additional fringe benefits from FTTH these need to be stated explicitly. However, from a societal perspective it is likely that FTTH deployment benefits subscribers through active competition and by driving competitive deployment.

Local copper conditions dictate telecom strategies

The study has shown that DSL deployment is highly reliant upon the existing copper infrastructure. The copper loop length determines the maximum transmission throughput and can thereby limit service selection and possible revenues. Upgrade strategies are in most cases based on co-

locating DSL equipment in existing copper aggregation nodes. In the case of Denmark, there are two levels of aggregation points. The first is on average located 0.7 -1.6 km from customer premises, enabling transmission throughput of up to 7-16 Mb/s, while the second is only on average 70 – 210 m from customer premises, enabling transmission throughput of 52-90 Mb/s. While this short distance to secondary nodes enables high throughput, the number of nodes (and thereby the cost) increases by a factor of 10 for each step, resulting in much higher deployment cost for short range DSL in Denmark than e.g. in Germany (where the average distance is 300m).

Deployment is the best defence

By applying game theory the thesis has show that telecoms are forced to embark on residential broadband deployment as a defensive move. This is especially true in densely populated cities where VDSL/VDSL2 deployment from secondary distribution points can offer transmission than fulfil expected near-future demand, reducing the competitive edge of FTTH. For other geographical areas than cities, deployment of DSL from primary distribution points captures the majority of potential revenue stream, while minimising deployment cost. In general the result is that the more aggressive the deployment is, the less room there is for competition.

Mass production is King[124]

While capital expenditure associated with deployment of all wire-line access networks is dominated by the cost of digging trenches, the long expected lifetime of ducts and cables reduces their weight in annual cost. The study has shown that half of the annual cost of dominant FTTH and DSL deployment strategies in cities is from active hardware that is only expected to last a few years. The price of these components can fluctuate greatly depending on global trends, maturity, and mass production. Selecting the right technological standard is therefore vital for successful implementation. The results of this study indicate that telecom deployment based on VDSL2 and G/EPON will become more widely deployed in the

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[124] This title refers to an ongoing debate about to which degree content controls the future of telecommunications. For an excellent discussion see "Communications: grit and glamour, or why content is not king" by Andrew Odlyzko

near future than Active Ethernet FTTH that most EUC deployment is based on.

Fibre to the Farm?

The study has shown that FTTH deployment in cities can be financially feasible if take-up rate is above 25% (translates to 40% of the foreseen residential broadband market). When considering economics of scope from other EUC operations, i.e. shared digging cost and connectivity fee, deployment in all areas can be financially feasible if take-up rate is above 16% for towns, 37% in rural A, and 49% in rural B. While it is outside the scope of this study to evaluate how likely they are at obtaining this market penetration the conclusion is that it is at least possible. However, as notated before the telecoms are not likely to give up this share of the market without a fight.

6.7.   Future work

During the course of this project several interesting aspects of residential broadband deployment have been identified that deserve more attention but have fallen outside the scope of the project. Among them are:

6.7.1.   Relationship between investment and regulation

According to Guthrie (2005) there is a close relationship between the nature of a regulatory regime and the investment behaviour of the firms subject to that regime. Furthermore, as Newbery (2001) has also described, changes in regulation have often been followed by changes in investment behaviour. This combined with the open issues surrounding implementation of unbundling and bit-stream access in FTTH, as well as in detached DSL deployment, are areas that deserves more academic focus.

As this study has shown, deployment of residential broadband networks requires increasing investment with increased population disparity. While there is an abundance of literature that deals with broadband deployment in rural areas (see e.g. Laffont and Tirole 2000, Nuechterlein and Weiser 2005, GAO 2006) the potentials of extending techno-economic models to investigate the cost of universal service and regulatory measures to reduce the "digital divide" arises. This work is already in progress by the author as published in Sigurdsson and Falch (2005).

6.7.2. Equilibrium analysis in game theory and the use of real-option theory

In contrast to using game theory like this thesis did, Elnegaard and Stordahl (2002) have proposed using real-options theory to investigate the effect of strategic alternatives within a deployment scenario. Implementing real-options and/or equilibrium analysis on top of the model developed in this thesis offers prospects of understanding the dynamic interactions between operators better. Both studies could be strengthened through empirical analysis of user valuation of multimedia services and different connectivity alternatives. This would also enable more accurate modelling of competition that could increase the credibility of the study carried out in Section 5.5 of this thesis.

6.7.3. Operational differences between telecoms and EUC

This study disregarded operational differences among telecoms and EUC. This is unlikely to be the reality in actual deployment. A starting point in analysing potential differences is looking at composition of total cost reported by Newman (2002). The results of that study are illustrated in Figure 9 and indicate that marketing, acquisition, and provisioning, as well as customer service / billing could be the main sources of differences between the two approaches.

6.7.4. The effect of "open access"

This study has shown that EUC deployment predominantly follows the "open access" approach. The effect of this shift in business models is not fully understood and would be an interesting new dimension to study. An additional problem that arises regardless of the business model applied, is the effect of applications competition from the Internet. The question of how operators can or to which degree they should try to fight against value added services that bypass their revenue streams is of interest to operators and regulators alike.

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List of Acronyms

ABR	Available bit rate
AN	Aggregation Node / Access Node
ATA	Analogue terminal adapter
ATM	Asynchronous Transfer Mode
BRAS	Broadband Remote Access Server
CA	Conditional Access
CAPEX	Capital Expenditure
CD	Compact Disk
CLEC	Competitive Local Exchange Carrier
DRM	Digital Rights Management
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DVD	Digital Video Disk
DWDM	Dense Wavelength Division Multiplexing
EBIDTA	Earnings Before Interests, Depreciation, Tax, and Amortisation
EBIT	Earnings Before Internets and Tax
EU	European Union
EUC	Energy Utility Company
FCC	Federal Communications Commission
FEC	Forward Error Correction

FEXT	Far-End Crosstalk
FTTx	Fibre to the Node / Curb / Premises / Home
IETF	Internet Engineering Task Force
IGMP	Internet Group Management Protocol
ILEC	Incumbent Local Exchange Carrier
IM	Instant messaging
IP	Internet Protocol
IPTV	IP Television
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ITU	International Telecommunications Union
L2TP	Layer 2 Tunnel Protocol
LEC	Locel Exchange Carrier
LED	Light Emitting Diode
LED	Light Emitting Diode
LSP	Label switched path
MAC	Media Access Control
MPEG	Moving Picture Expert Group
MPLS	Multi-protocol label switching
NAP	Network Access Provider
NEXT	Near-End Crosstalk
OPEX	Operational Expenditure
P2M	Point-to-Multipoint
P2P	Peer-to-Peer / Point-to-Point
PAL	Phase Alternating Line
PON	Passive Optical Network
PPP	Point-to-Point Protocol
PSTN	Public Switched Telecommunications Network
PVC	Permanent Virtual Channel
QOS	Quality of Service
RSVP	Resource Reservation Protocol
RTCP	Real-Time Control Protocol
RTP	Real-Time Protocol
SN	Service Node
STM	Synchronous Transfer Mode
TCP	Transmission Control Protocol

UBR	Unspecified bit rate
UDP	User Datagram Protocol
VLAN	Virtual Local Area Network
VoIP	Voice over IP
VPN	Virtual Private Network

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Appendix I: Information Gathering

Several definitions can be found in the literature that define, with varying degrees of detail, the steps and phases that should be followed when breaking down and analysing complex problems. Traditionally these sources distinguish between quantitative and qualitative research methodologies. However, when analysing concurrent or transformative processes such as residential broadband deployment, Creswell (2003) recommends a mixed methods approach. In mixed methods approaches 'the researcher tends to base knowledge claims on pragmatic grounds … employing strategies of inquiry that involve collecting data either simultaneously or sequentially to best understand research problems' (Creswell, 2003, p. 18). This is highly descriptive for the work procedure of this study where qualitative technical analysis of networks and services precede quantitative modelling through a mixed methods approach. To aid in the overall problem solving process this thesis followed the rigid problem solving principles of Operations Research[125] (OR) as listed by Hillier et al. (1995).

1. Qualitative Technical Analysis

This thesis argues that due to the inherent complexities and fast paced technological development, investment appraisal of broadband access

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[125] The term management science is sometimes used as a synonym for operations research.

networks can only take place given a fundamental understanding and analysis of the technological requirements of residential broadband services and the alternative network strategies capable of meeting these needs. In the absence of this, project appraisal runs the risk of "generating the right answer to a problem that does not exist" as Michaleqicz and Fogel (2002) describe. For this reason the thesis starts with two individual and self-contained studies, first of residential broadband services, followed by one on Residential Broadband Networks. In the absence of a grand theory of residential broadband networks and services, and considering the disparity of literature on the subject, each study follows a pragmatic methodology governed by an individual literature study and following a specifically defined set of research questions as summaries and described in Section 1.7.1.

2. Quantitative Simulation Model

Quantitative simulation models provide a core element in this thesis. As listed in 16, different approaches to simulation have been developed by the relevant disciplines of this study, i.e. engineering, economics, and policy & regulation, and therefore a variety of theoretical alternatives exist. Despite this, all models follow a common methodology of constructing a mathematical model that represents the essence of the problem under investigation. There are many pitfalls to be avoided when constructing a mathematical model and to aid in the process the rigid problem solving procedure of Operations Research (OR) was chosen for the quantitative models. Several definitions can be found in the OR literature that define, with varying degrees of detail, the steps or phases that should be followed when carrying out OR studies. The following list is based on Hillier et al. (1995) and was used for guidance in the modelling part of this study.

Define the problem of interest and gather relevant data

Formulate a mathematical model to represent the problem

Develop a computer-based procedure for deriving solutions to the problem from the model

Test the model and refine it as needed

Prepare for the ongoing application of the model as prescribed by management

Implement

3. Literature Study & External visits

This thesis includes three literature studies, each preceding the chapters dealing with the respective topics. While this approach has been criticised in textbooks on research design (Creswell 2003), the thesis argues that in a multi-disciplinary study like this one, a single literature study of all aspects would have been cumbersome. Additionally, each literature study was coloured by the author's background in telecommunications engineering and therefore started and ended with a focus on technology. However, the path from the start to the finish line represents an attempt to close a circle that encapsulates the required dimensions of the conceptual framework. During all phases of the literature study the selection of relevant material was highly influenced by local supervision during external stays. This followed a chronologic division of the project, and subsequently the literature studies, that fell in line with external stays aimed at providing synergies with local knowledge and facilitate construction of core competences.

4. Research Projects

A part of the work carried out for this Ph.D. project has been participation in the IST-BREAD research project. BREAD (BRoadband in Europe for All: a multi-Disciplinary approach) is carried out by eight European research institutes, aimed at performing a multi-disciplinary study of the technological evolution of broadband and 'study the techno-economic, societal and regulatory aspects of the "broadband for all" concept'. The study also includes regional "success stories" of actual deployment and the influence of government stimulus for accelerating the early rollout of broadband services. Societal aspects of introducing broadband access and sustainable economic business models for this will be taken into account.' (BREAD, 2006)

As evident from this description there are clear synergies between BREAD and this project. However, participation was not research oriented and mainly in the form of contributing to deliverable D2.2-3.2 (IST-BREAD D2.2-3.2, 2005) and writing deliverable D2.4-3.4 (IST-BREAD D2.4-3.4, 2006). None the less the project contributed to the focus and selection of the techno-economic methodology as a framework for analysis, as well as providing valuable input to the literature study.

The contribution of BREAD was therefore most in the form of pushing for a techno-economic model for analysing and comparing broadband

deployment strategies. The result was a simulation model capable of comparing Capital Expenditure (CAPEX) of dominating broadband technologies in different types of demographic areas. The study revealed the competitiveness and applicability of different access technologies in the future broadband market as well as providing sensitivity analysis of the most influential factors controlling market development. (IST-BREAD D2.4-3.4, 2006).

5. Industry collaboration and interviews

An integral part of developing techno-economic models is access to industry specific information about deployment scenarios as well as cost data. While some cost component data can be accessed through other research projects and literature, the accuracy and up-to-date nature of published information in the fast paced development of technology is difficult to assess. To ensure accuracy and relevance of assumptions research collaboration was established with selected members of the broadband value chain: equipment vendors, software developers, telecom operators (incumbents), Energy Utility Companies (EUC), as well as regulators.

While the general aim of the industry collaboration and interviews was to provide a neutral account of forces affecting broadband deployment at different levels, the amount of gathered data became biased towards Iceland, and especially the Icelandic incumbent, Iceland Telecom. While this can be identified as a weakness in data gathering process it also emphasises the strength of the study in the sense that it provides honest cost information in a market characterised by asymmetric information.

Throughout the project it became evident that industry collaboration in this highly competitive market is limited by the risk of information leakage between market players. Since most of the firms in the industry collaboration are related in some way through the value chain a prerequisite to discussions was signing Non Disclosure Agreements with most parties involved. After having done so, cooperation went more smoothly as described below.

Equipment Vendors

Collaboration with Alcatel A/S was carried out in the period of Q4 2004. Alcatel was chosen as it provides a full range of network and service products, in addition to being the main vendor of DSLAM

equipment in the Nordic countries. Alcatel provided product databases and access to their internal information on DSL and FTTH equipment. As vendor prices to telecommunications operators vary greatly between regions as well as with volume the specific prices were not used in the models of this study but rather the list of required components for each deployment scenario.

Software Developers

An external visit to Microsoft Research Asia was conducted in Q2 2005. The goal of the collaboration was to gain insight into software and service development by participating in MRA's Internet Media group working on IPTV development. The result was an intensive three month working period in Beijing, China, that additionally provided insight into network and service development in Asia.

Telecommunications Operators

To get an overview of ongoing development within incumbent operators an open dialog was kept with Iceland Telecom throughout the entire course of this study. Iceland Telecom was chosen as an incumbent operator with wide experience in deploying advanced multimedia services over all types of DSL networks and due to a FTTH based trial based on equipment from Alcatel. Excursions were conducted approximately twice a year, in addition to consistent electronic and voice communication. In addition to aiding in selecting the focus of the literature study Iceland Telecom provided access to information and results from other relevant research projects that Iceland Telecom R&D was participating in, e.g. within the Eurescom[126] research collaboration platform.

In the last year of this study the collaboration with Iceland Telecom took became more formal with participation in a FTTH field trial as well as a subsequent formation of a techno-economic working group that I led. The aim of the work group was to build a techno-economic framework capable of dynamically simulating, comparing, and

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[126] Eurescom (http://www.eurescom.de/) is a platform for collaborative R&D founded by major European telecommunications network operators in 1991. Among the members of Eurescom are Deutsche Telekom, France Telecom, Telenor, Iceland Telecom, and BT.

optimising the deployment cost of broadband access networks and services in Greenfield scenarios.

While participation in the field trial was limited to passive access to information the working group carried out scheduled telephone meetings with selected individuals from a broad range of departments involved in the trial. Three questionnaires were prepared and used to gather technical and cost related information from the field trial. The working group project definition report and working group conclusion report (in Icelandic) are available upon request.

A loose collaboration was maintained with the Danish incumbent TDC during the first year. All in all, three interviews were taken with TDC as well as one interview with a backbone network provider Song, later acquired by TDC. Additionally three Danish alternative broadband access providers were interviewed: Aarhus Net, Frederiksberg net, and DjurslandS Net.

Energy Utility Companies

The goal of collaboration and interviews with EUC were twofold, i) to get an overview of the nature and characteristics of their FTTH plans, ii) to identify drivers behind their involvement in telecommunication. For this purpose five excursions to Reykjavik Energy were carried out through the period, providing a total of eight interviews. In addition, representatives from Danish EUCs planning FTTH deployment were interviewed.

Regulators

To gain insight into regulatory views, interviews with the Icelandic and Danish Regulatory Authority were conducted during the last year of the study. These interviews were supplemented with three more general interviews with politicians in Iceland. Feedback and electronic correspondence was additionally carried out evenly throughout the project with the director of the Icelandic National Regulatory Agency.