Overlaid Mesh Topology Design and Deadlock Free Routing in Wireless Network-on-Chip

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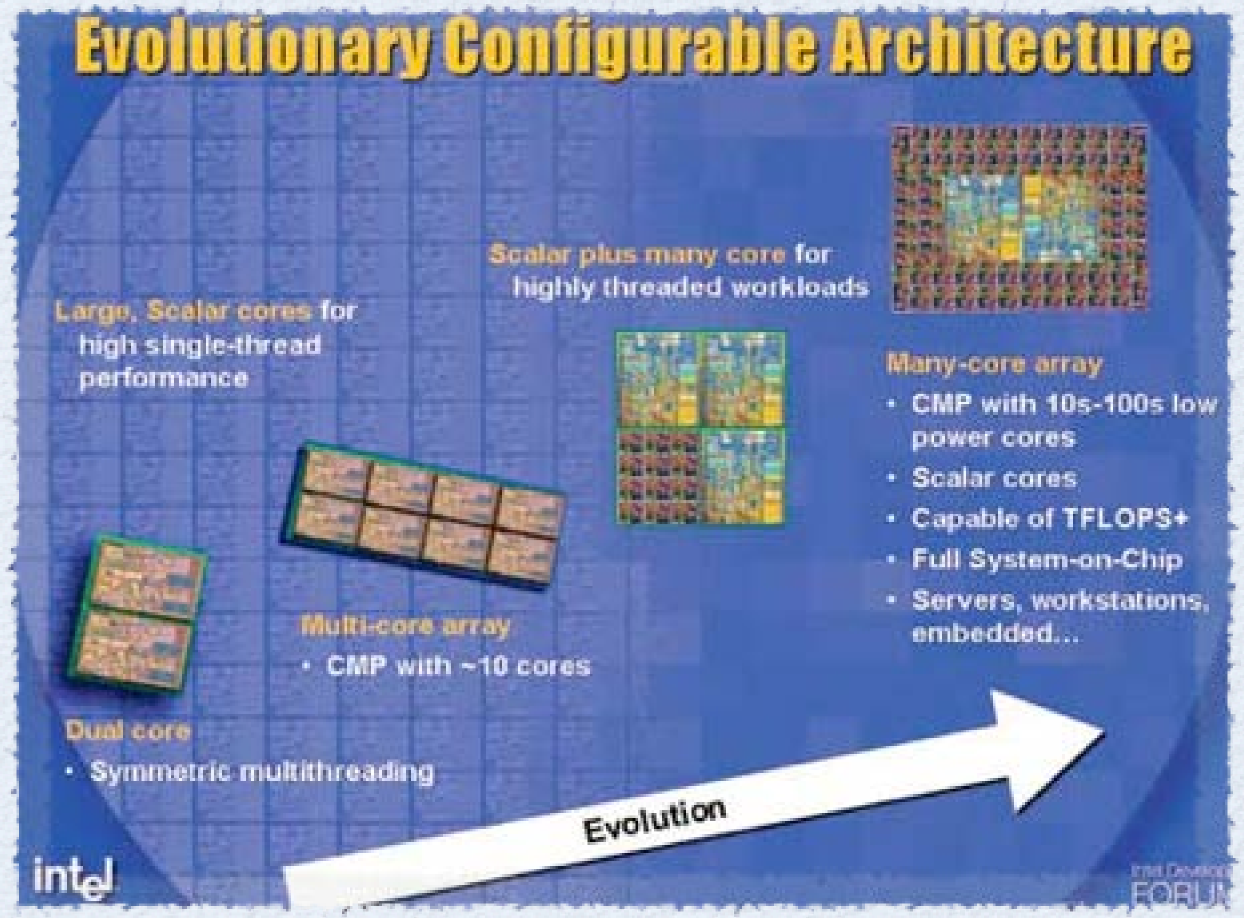
Outline

- Introduction
- Overview of WiNoC system architecture
- Overlaid mesh topology design
- Zone-aided routing
- Performance evaluation

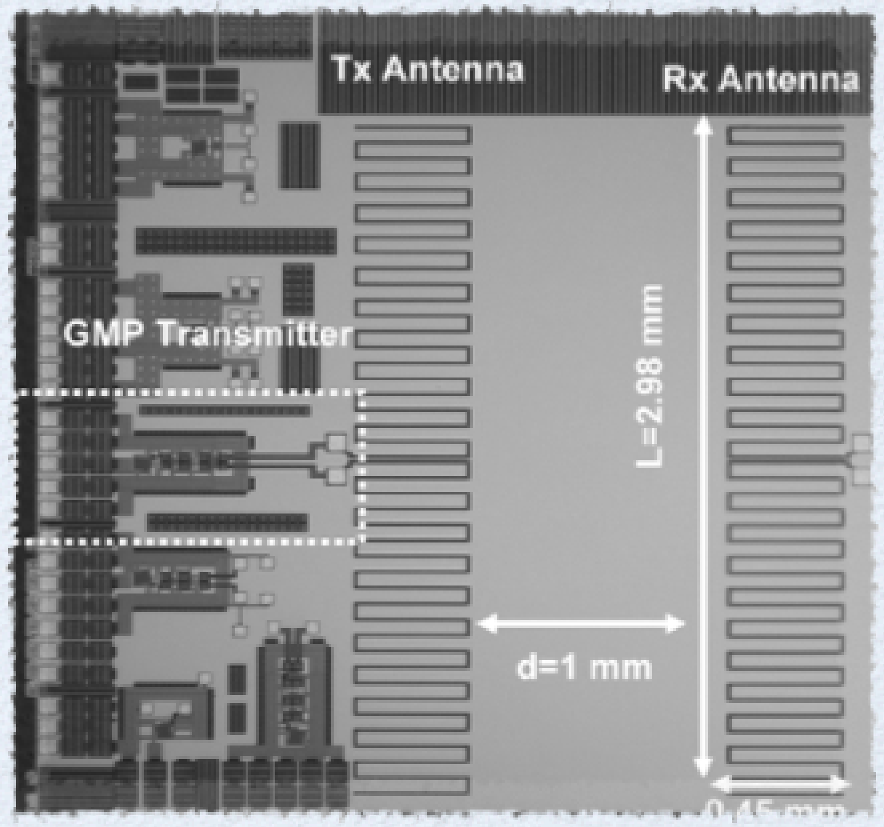
Introduction

- Multi-processor chips are moving towards many-core structures to achieve energy-efficient performance
- Network-on-chips are in replace of conventional shared-bus architectures to provide scalable and energy-efficient communication for CMPs using integrated switching network
- RF/wireless interconnect technology has emerged recently to bring in a new on-chip communication paradigm



UWB Interconnect

- UWB-I uses transverse electromagnetic wave propagation
- High data rate is achieved by increasing BW (C = B log2(1 + S/N))
- Low power due to very low duty cycle (< 0.1%)
- Simpler RF circuits are granted to carrier free design
- Pulse position modulation is to modulate a sequence of very sharp GMPs
- Multiple channeling can be provided by time hopping PPM
- CMOS-integrated on-chip dipole antennas
- Efficient interference suppression schemes to achieve sufficient transmission gain



UWB-I implementation @ 0.18um
Courtesy: Prof. Kikkawa @ Hiroshima U.

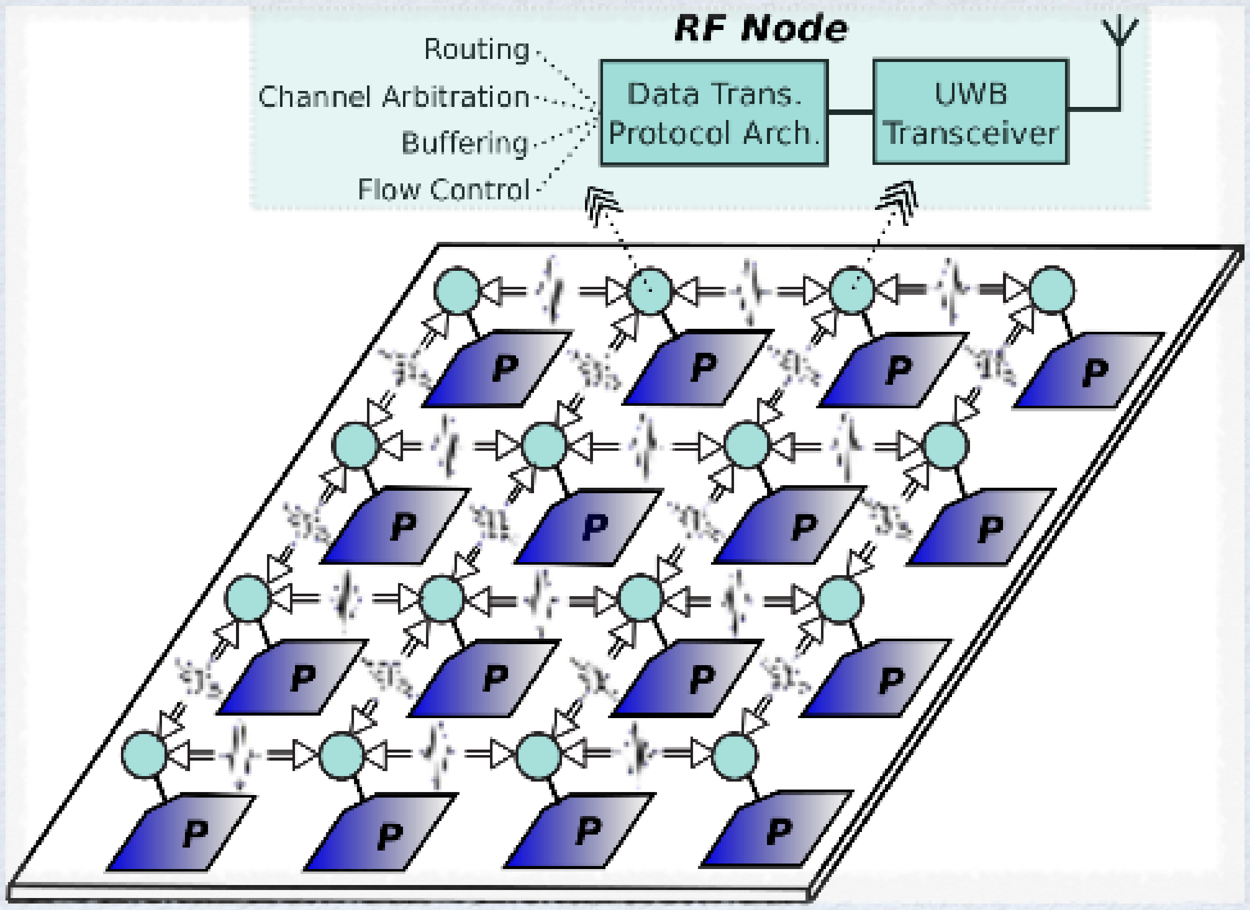
UWB-I Scaling

- UWB-I scalability facilitates the fundamental architectural shift to many-core and Tera-scale computing
  - Antenna size scales with the frequency
  - Transmission gain decreases inversely with the distance

Technology (*nm*)	90	65	45	32	22
Cut-off freq. (*GHz*)	105	170	280	400	550
Data rate per band (*Gbps*)	5.25	8.5	14	20	27.5
Dipole antenna length (*mm*)	8.28	5.12	3.11	2.17	1.58
Meander type dipole antenna area (mm^2)	0.738	0.429	0.279	0.194	0.14
Power (*mW*)	33	40	44	54	58
Energy per bit (*pJ*)	6	4.7	3.1	2.7	2.1

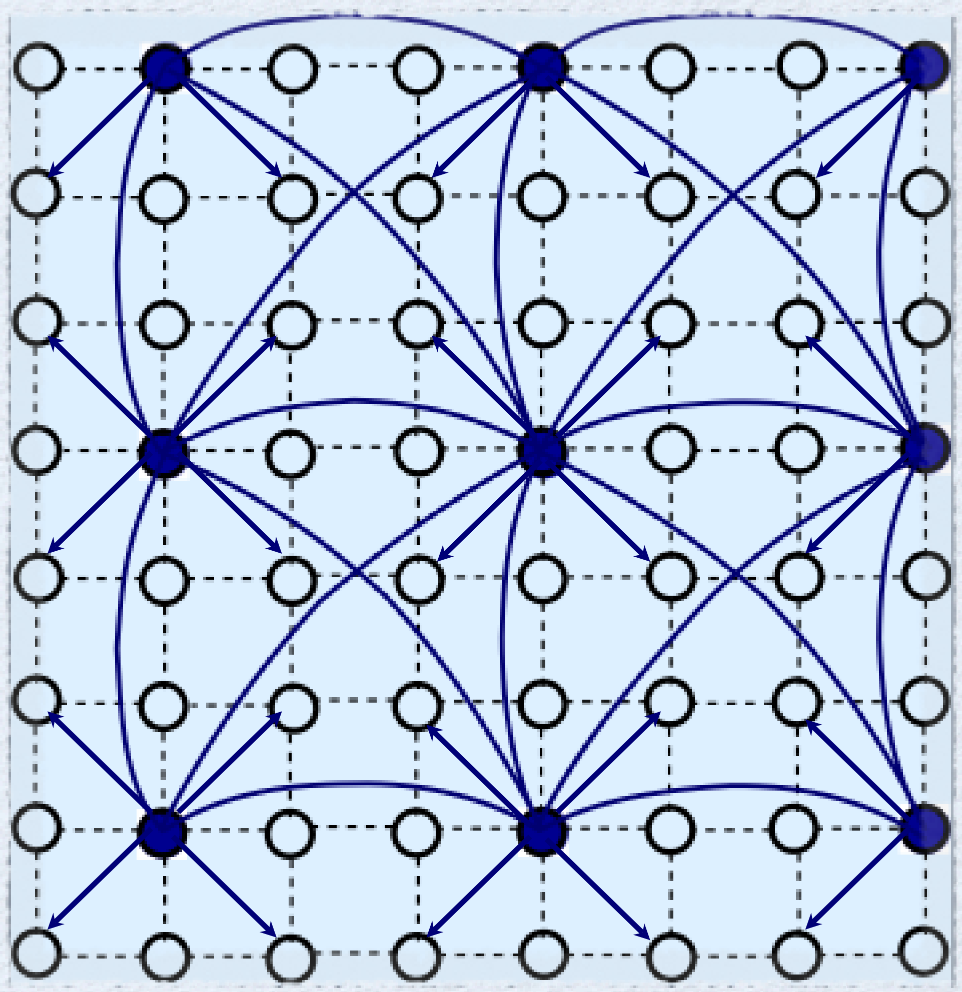
Overview of WiNoC System Architecture

- With UWB-I, the wireless radios are deployed on chip in replace of wires to establish Wireless Network-on-Chip
  - A WiNoC consists of a number of RF nodes, each associated with a processor tile
  - Packets are delivered through multi-hops across the network
  - A node may receive packets from its neighbors fall within its transmission range along dedicated channels
  - Multiple channels are assigned to ensure transmission parallelism and reduce channel contention



Overlaid Mesh WiNoC

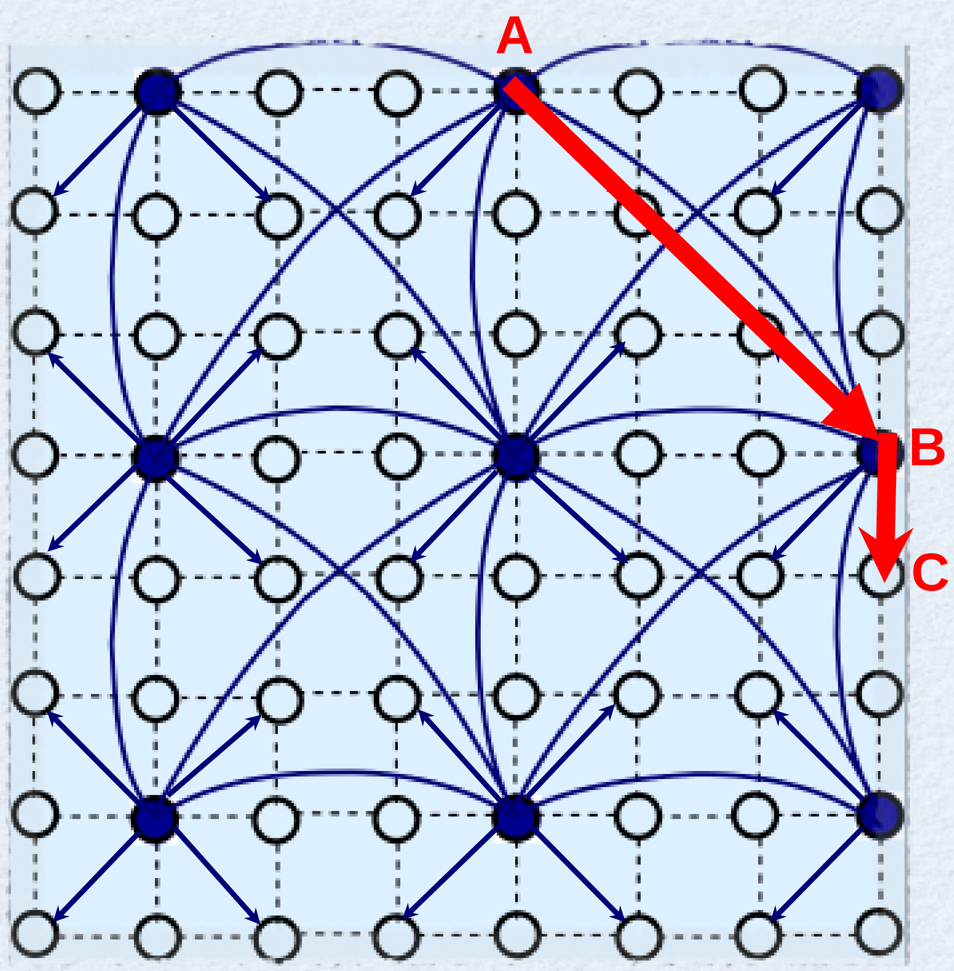
- Unequal RF nodes are dispersed on-chip as wireless routers to forward data
  - *Small RF* nodes have shorter transmission range T and lower link bandwidth
  - *Big RF* nodes are distributed at distance of nT with longer transmission range of $\sqrt{2}nT$ and higher link bandwidth
- Two types of meshes are deployed to form an overlaid mesh
  - A regular 2D *base mesh* is formed by both small and big nodes
  - A *full mesh* formed only by big nodes where the big nodes within a grid are fully connected to each other
  - The big node has starry ends constituting with unidirectional direct links to the small nodes



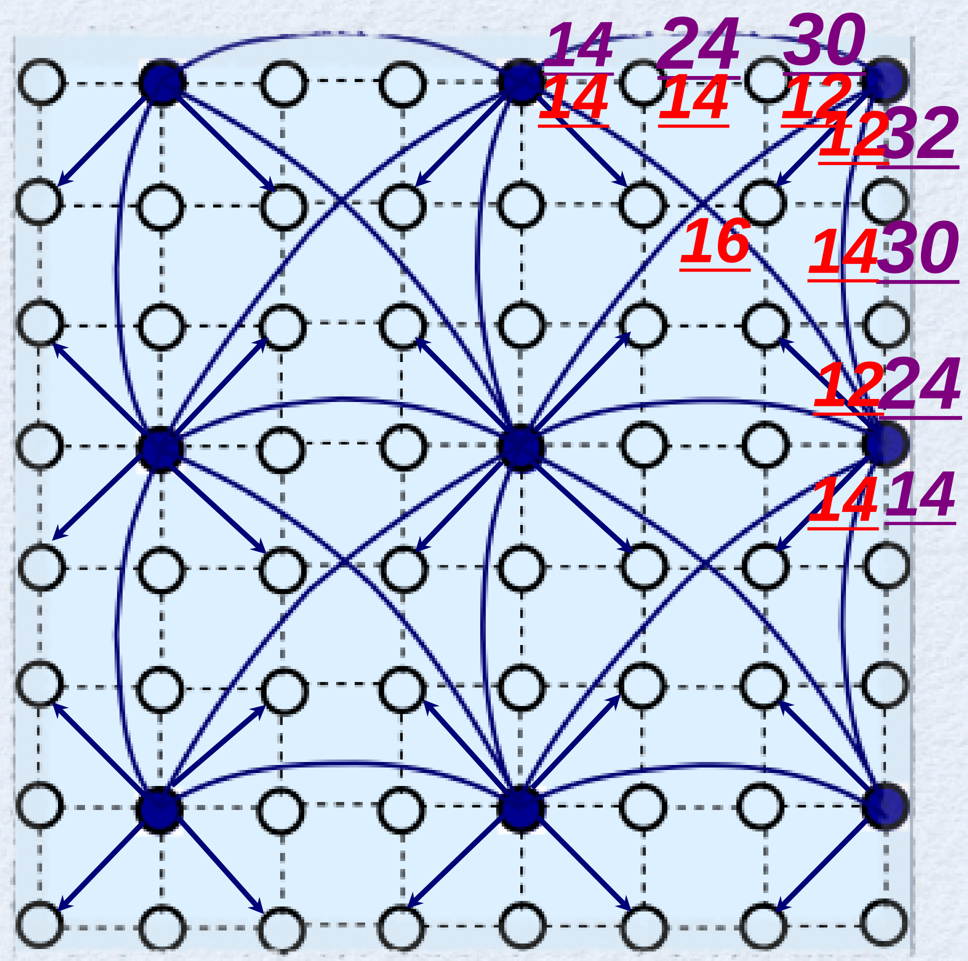
A 8x8 overlaid mesh

Topology Performance Impact

- An overlaid mesh potentially improves WiNoC performance
  - Reduce hop count with long range wireless links
  - Reduce traffic congestion due to efficient traffic distribution



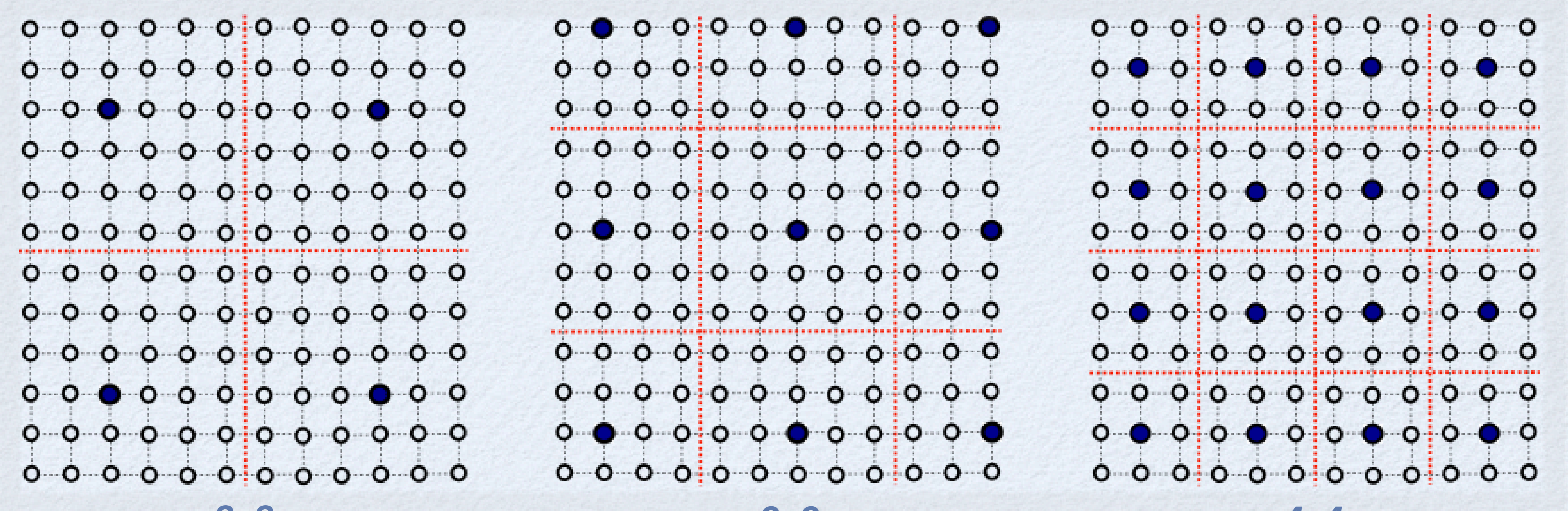
2 hops instead of 7 hops in 2D mesh!



Avoid traffic hot spots formed in 2D mesh!

Topology Configuration

- For a NxN WiNoC with big nodes deployed at distance of nT, we may generate several different topologies by changing the big nodes placement distance
  - When increasing n, a packet may be delivered to the destination with less hops by using longer links
  - The traffic would be more congested at big nodes, as farther separated big nodes have higher radix



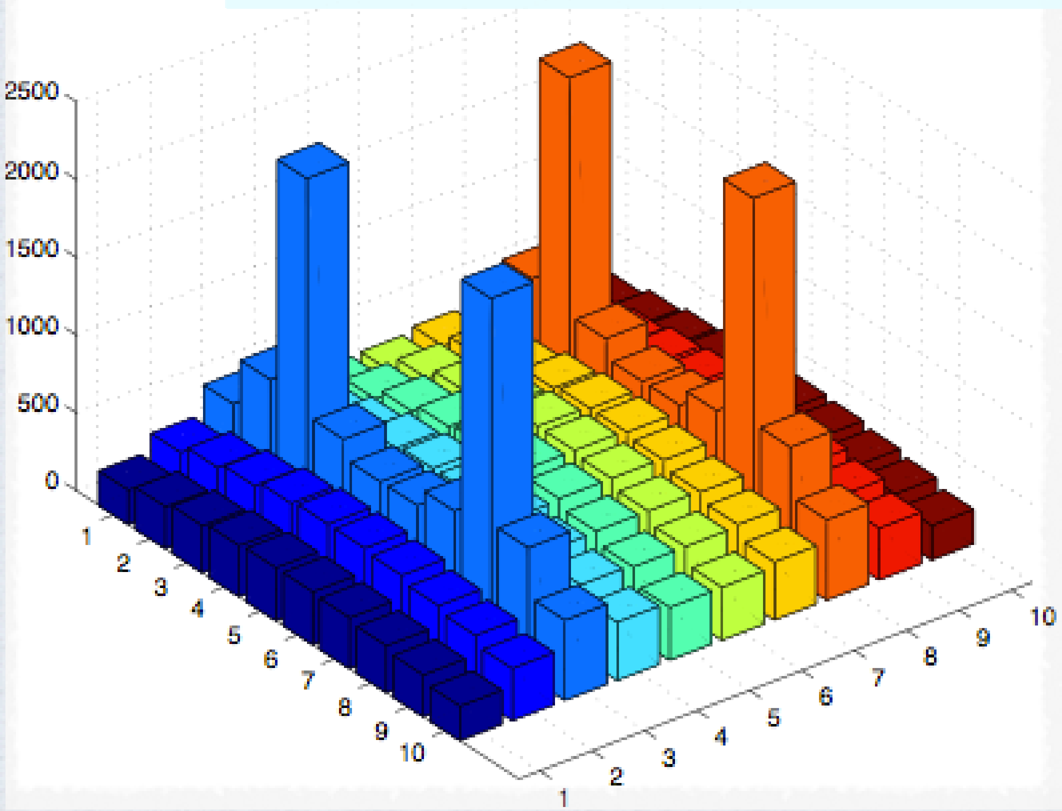
2x2 *3x3* *4x4*

Topology design - RF nodes placement

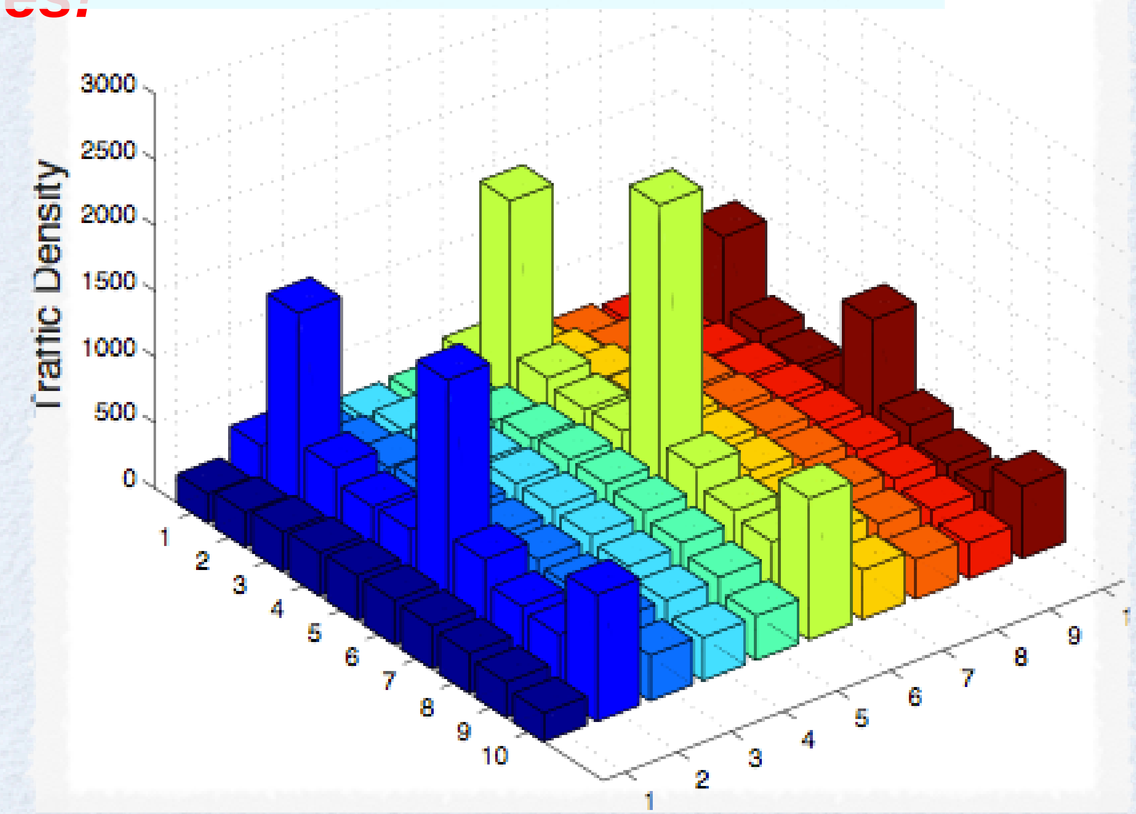
- Big RF nodes are placed in a way to tradeoff between routing path cost and network congestion
- Which placement may result in the best possible network performance at given network scale?

When the big nodes separation distance reduces, the traffic would be more evenly distributed!

Much higher traffic is crowded at big nodes than the small nodes!



Traffic density @ distance of 5T



Traffic density @ distance of 4T

Network Capacity modeling

- We derive an efficient network capacity modeling scheme to fast approach an optimal topology configuration without running comprehensive WiNoC network simulation

$$Net\_Cap(N \times N) = \sum_{j=1\ldots N}^{i=1\ldots N} Path\_Cap(S_i \rightarrow D_j)$$

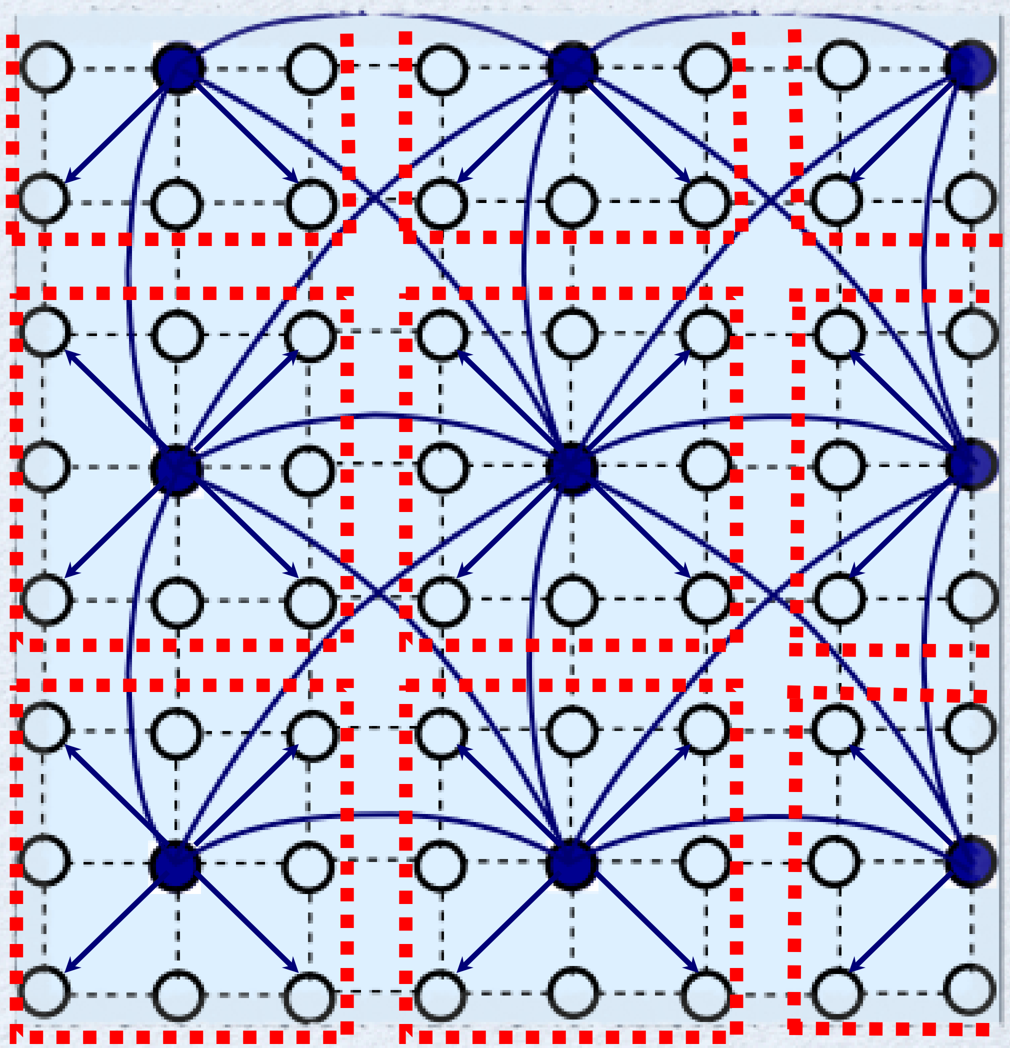
- A simple and fast estimator is developed to estimate the overall network capacity under different topology configuration
  - The one which delivers the maximum capacity is chosen to be the optimized topology design under given network scale

DEADLOCK-FREE OVERLAID ROUTING

- Benefited from long link transmission, we develop a *zone-aided routing* scheme for distributed and deadlock-free routing
    - It facilitates simple and efficient logic-based implementation
    - It shortens to the maximum possible routing paths by using long links
    - Division of virtual zones ensures long link utilization
    - An enhancement technique improves transmission concurrency via evenly distributed traffic density
    - Deadlock is avoided by restricting the turns based on the modified turn model and a virtual channeling scheme with classified buffers

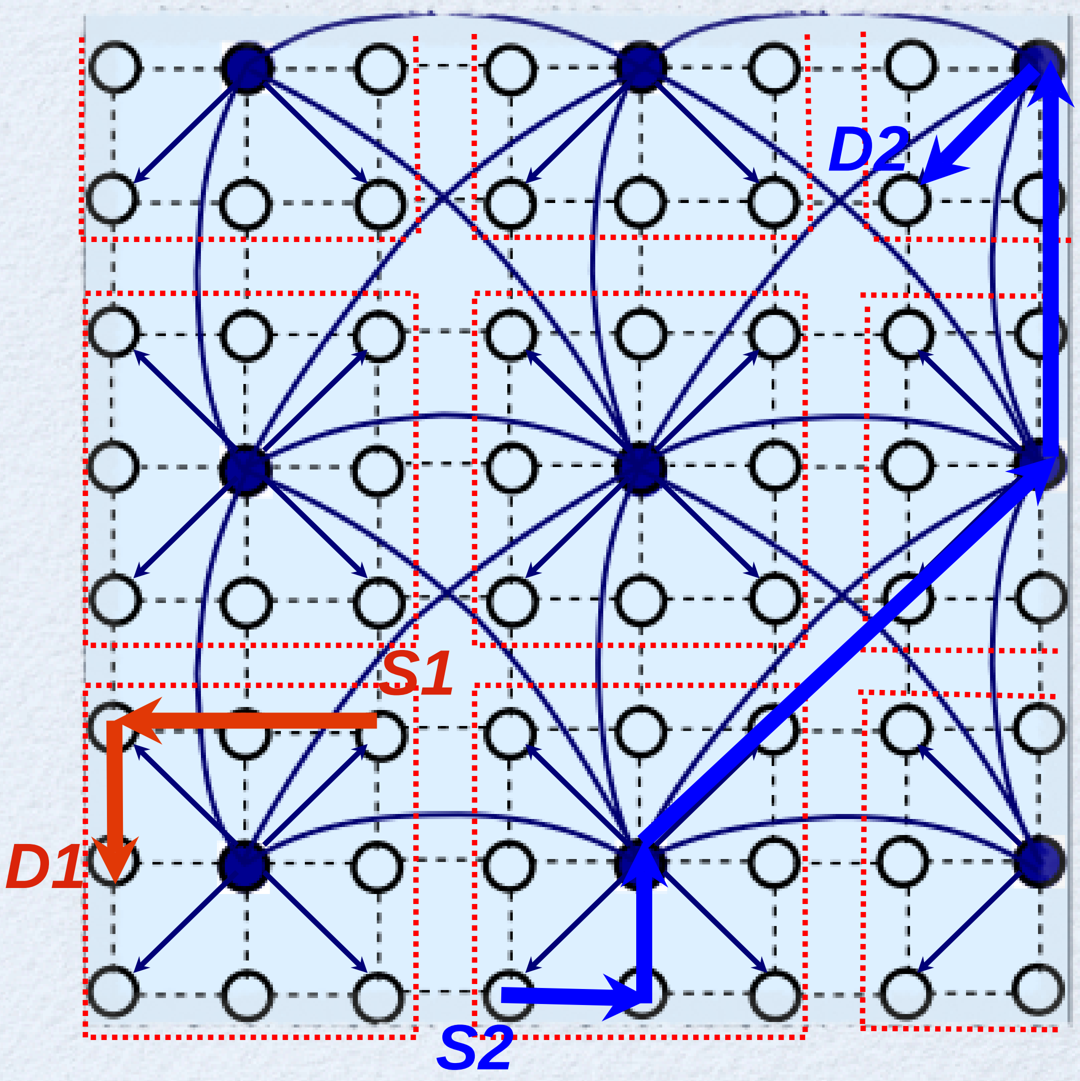
Virtual zone division

- In order to efficiently utilize the long links, the packet is first delivered from a small node to the closest big node and then traverses along the long links as further as possible
- The whole network is divided into several *virtual zones*
  - All the small nodes which will forward their packets to the same big node will be grouped into one virtual zone
  - The big node serves as the *header* of the zone
  - The zone headers are located at the center of zones



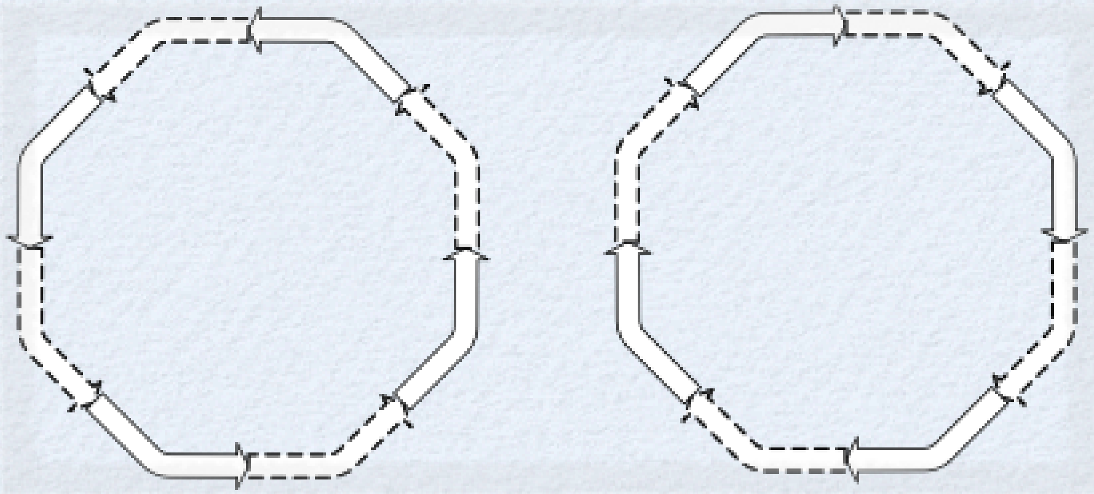
Zone-aided routing

- Packet forwarding is based on the source and destination nodes' position in the zones
  - If source and destination nodes fall within the same zone, perform XY-routing on base mesh
  - If S and D belong to different zones, the packet is first XY-routed to S's zone header and routed along the overlaid fully mesh with long links using turn-restricted shortest routing, until D's zone header and from where XY-routed to D



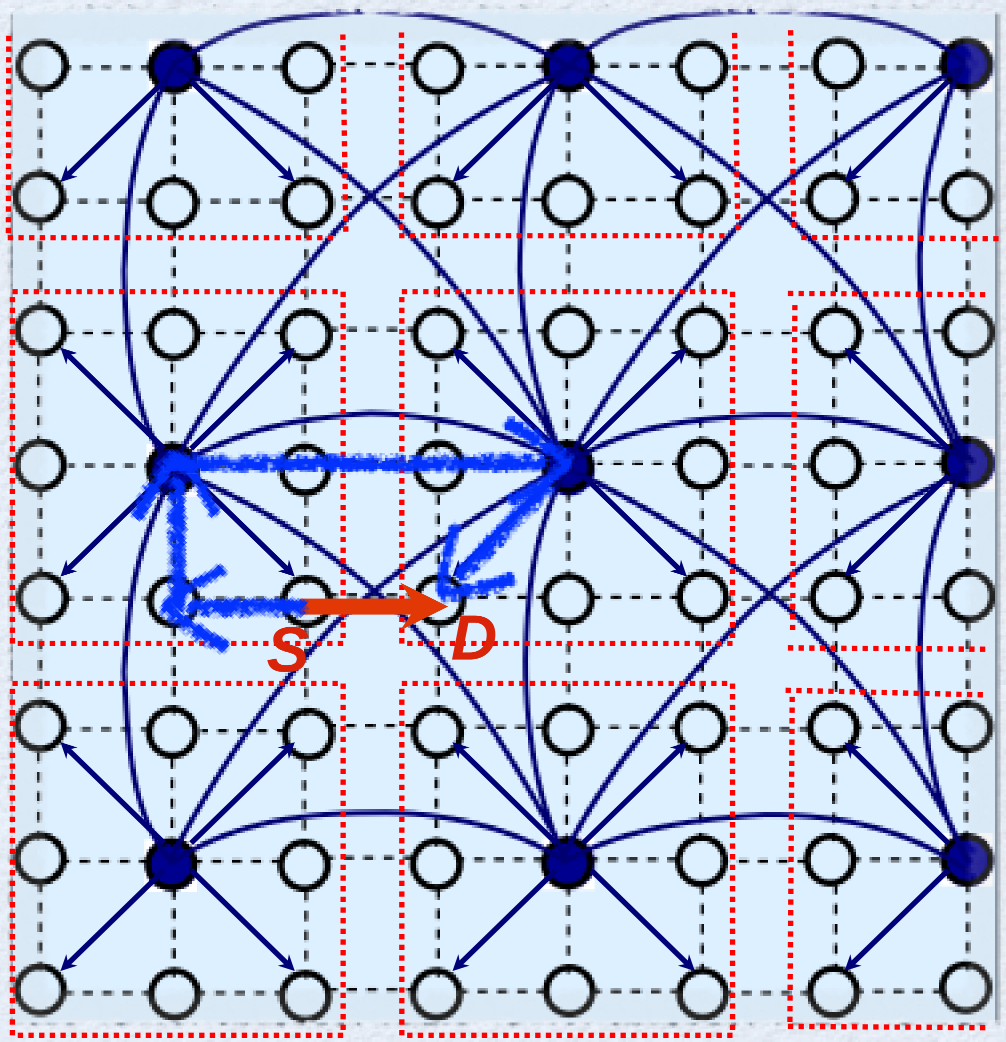
The basic "ZAR" is deadlock free

- To ensure deadlock free routing in full mesh, a new *octagon turn model* is proposed
  - The model involves two abstract cycles, a clockwise cycle and a counter clockwise cycle, each formed by eight turns
  - **Rule 1**. Any packet is not allowed to make the four turns i.e., W → SE, N → SW, E → NW, and S → NE at a node as in the clockwise abstract cycle
  - **Rule 2**. Any packet is not allowed to make the four turns i.e., NE → S, NW → E, SW → N, and SE → W at a node as in the counter clockwise abstract cycle
- The turn-restricted shortest-path routing is performed in full mesh based on the octagon turn model.



Routing efficiency enhancement

- Routing enhancement is applied to alleviate traffic congestion at big nodes
  - If any pair of source and destination are not located in the same zone while their Manhattan distance $|y_D - y_S| + |x_D - x_S|$ falls within a threshold distance, XY-routing is performed instead of the turn-restricted shortest-path routing
  - It may reduce hop count if a source-destination pair is located near the border of two adjacent zones

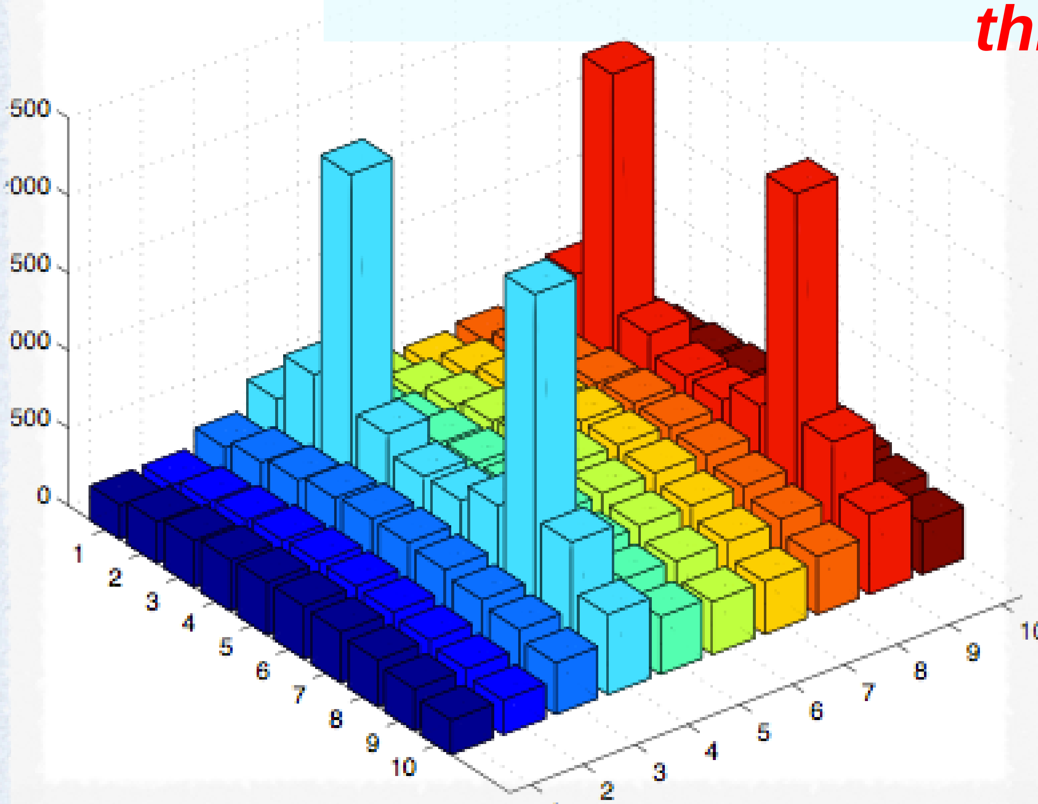


Hop count reduced from 4 to only 1!

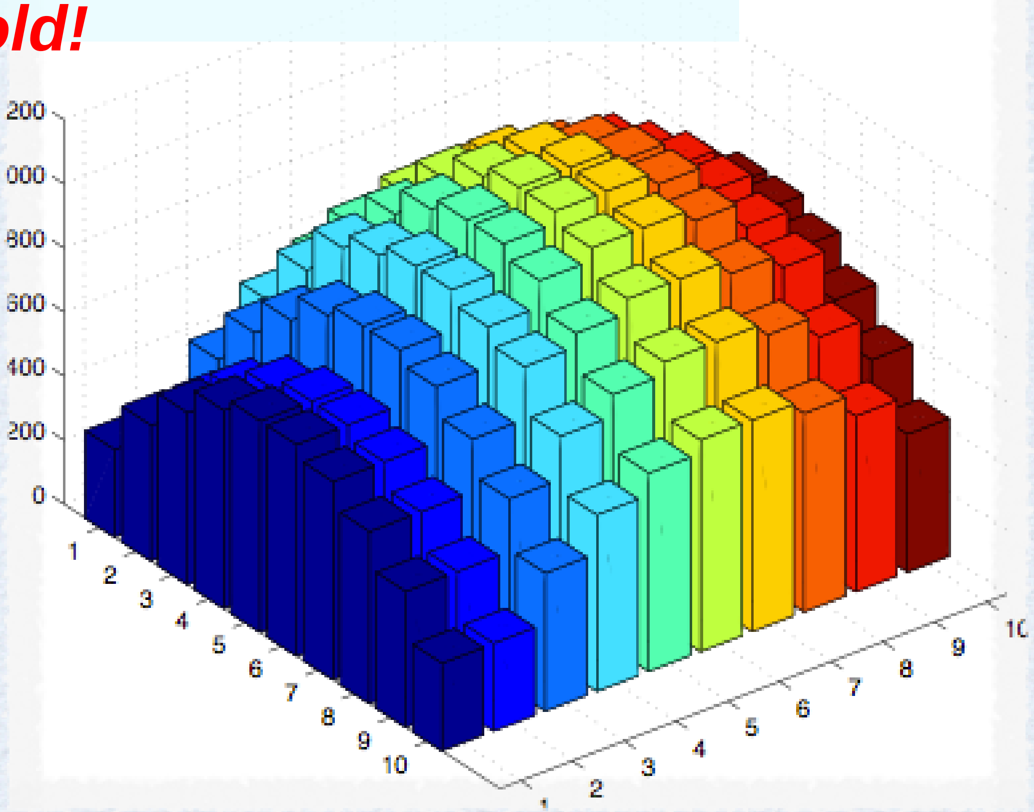
Threshold Setting

- The routing efficiency with enhancement varies with threshold setting
  - When the threshold arises, the traffic is more evenly distributed
  - A larger threshold may lead to longer routing paths without using long links
  - To quickly latch on the best threshold setting, we determine the threshold searching space $n < Thr < 2(N-1) - n$

Traffic density would be evened out at higher threshold!



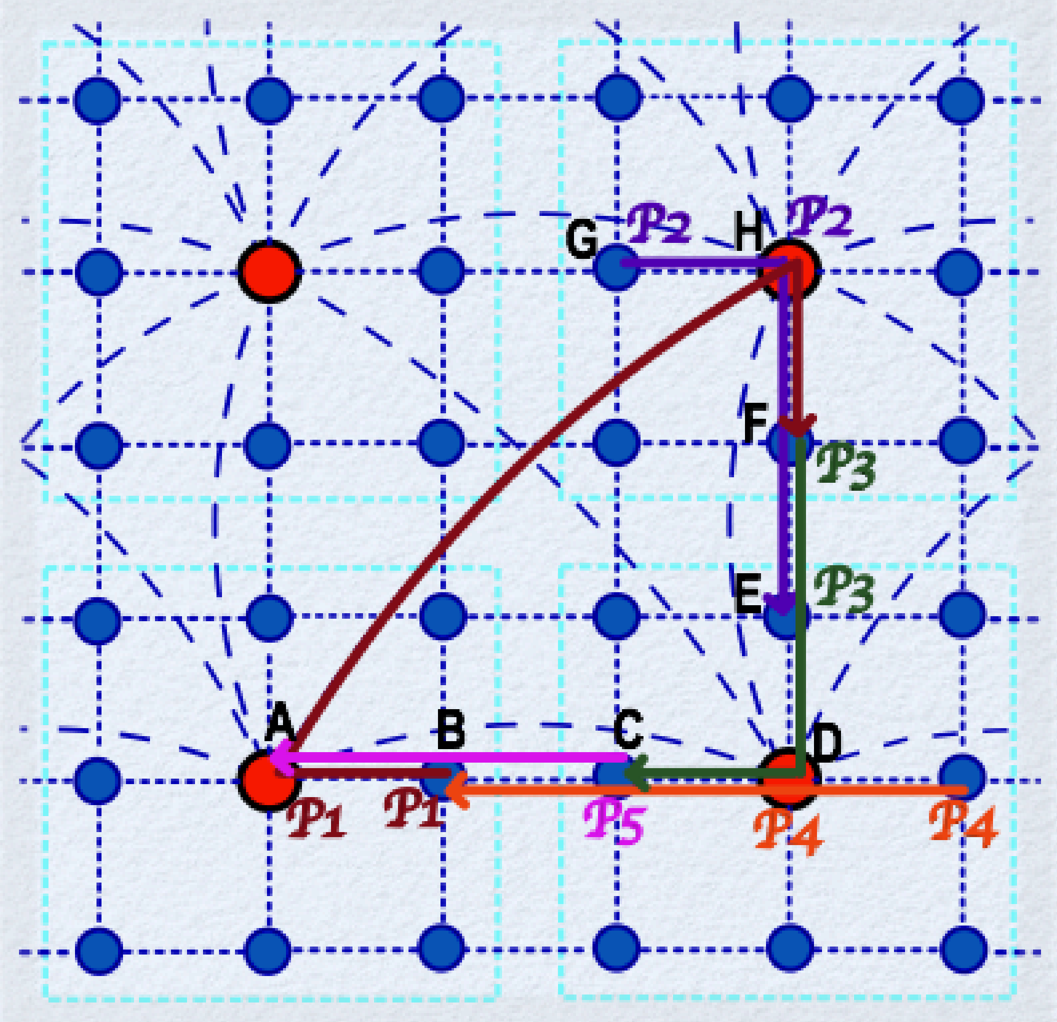
Traffic density @ Thr = 7



Traffic density @ Thr = 15

Deadlock avoidance

- Improving routing efficiency by enhancement may cause deadlock because the introduced XY-routes cross the borders of multiple zones
- Deadlock can be avoided by a buffer ordering scheme
  - Each VQ will maintain two units of buffer which are ordered into two numbered buffer classes
  - The 1st class buffer is used to store the packets delivered along the basic zone-aided routing paths
  - The 2nd class buffer is reserved for storage of packets sent along enhanced XY-routes



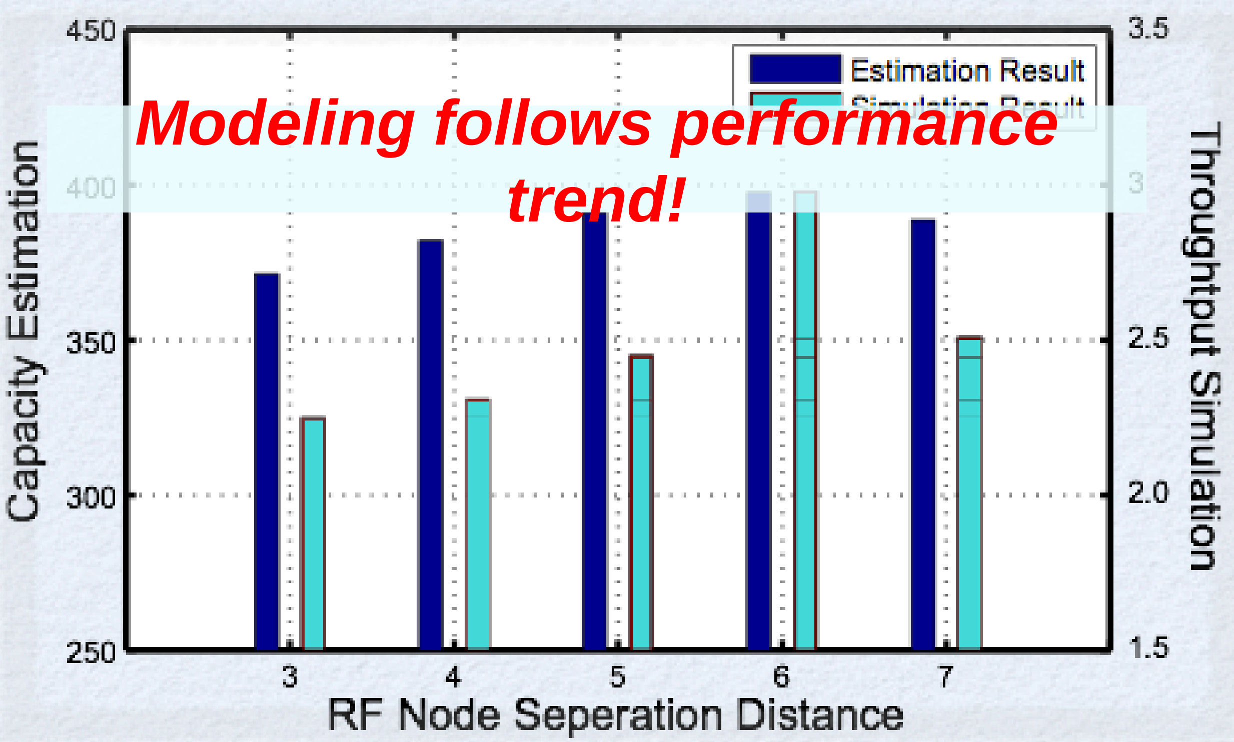
Simulation Setup

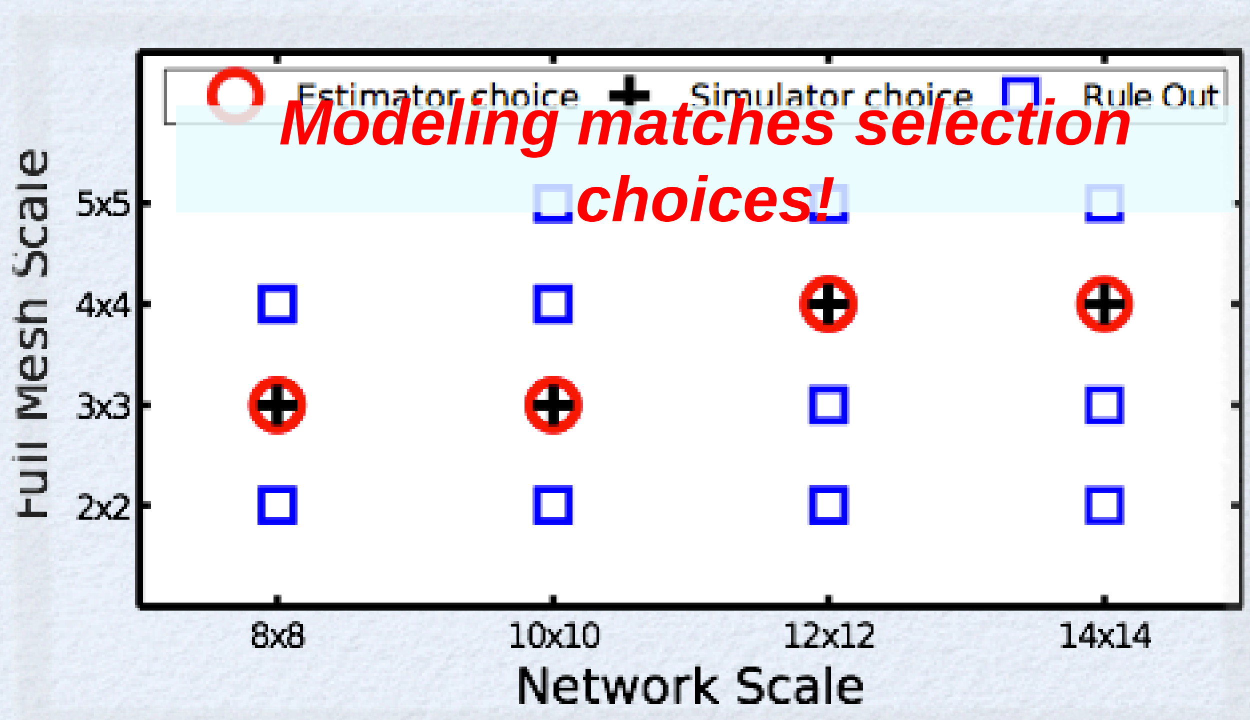
- A WiNoC simulator is developed to evaluate the performance of the overlaid mesh WiNoC platform under various network configurations, traffic patterns, and network scales
  - Unequal RF nodes are distributed to construct overlaid mesh topology
  - Overlaid mesh is configured by varying big nodes placement
  - Overlaid routing scheme is developed for efficient and cost-effective routing
  - Multi-channeling is facilitated to transmit on multiple RF nodes in parallel along distinct channels
  - A virtual output queuing strategy is used for cost efficient buffering
  - A backpressure based flow throttling scheme is implemented for congestion control (credits transmitted over wired channels to avoid packet overhead)

Topology Configuration Performance Impact

- We study the performance impact of topology configuration granting to big nodes placement
  - Verify how accurate of the network capacity modeling scheme and how effective of using it for fast and efficient topology configuration

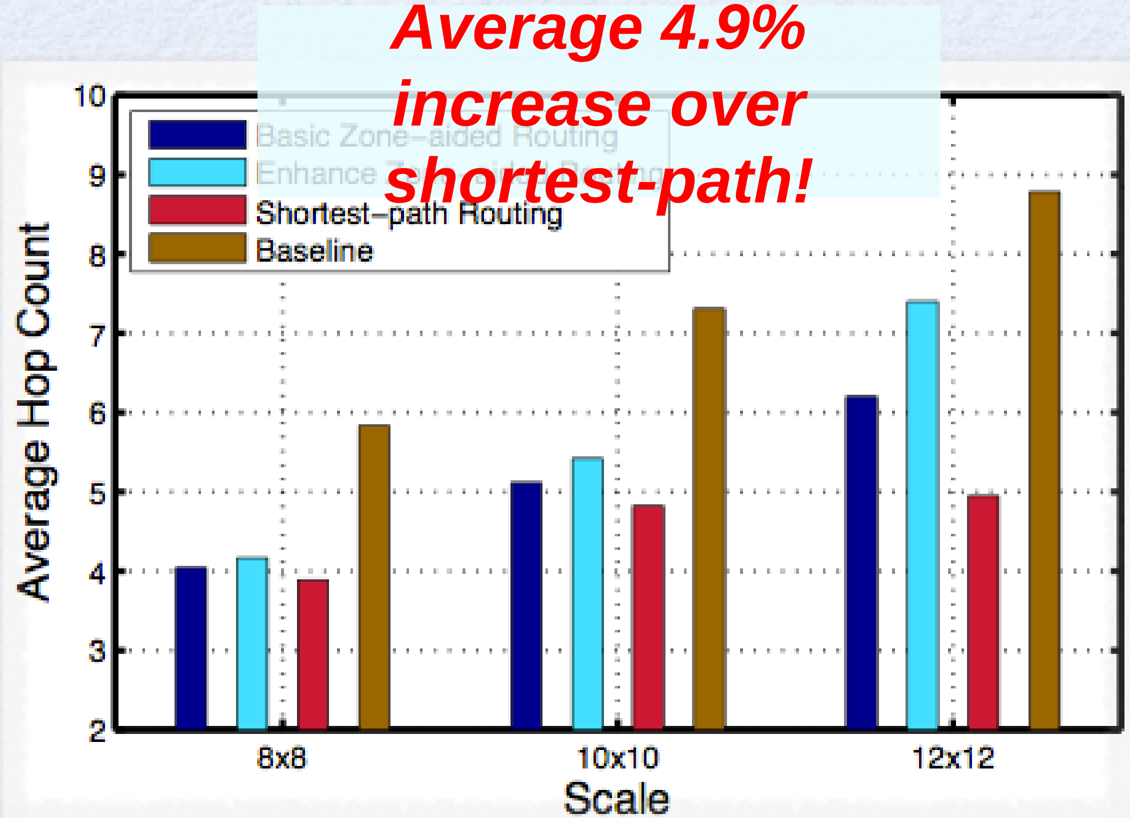
The network capacity estimator can be employed for fast searching of an optimal topology configuration!

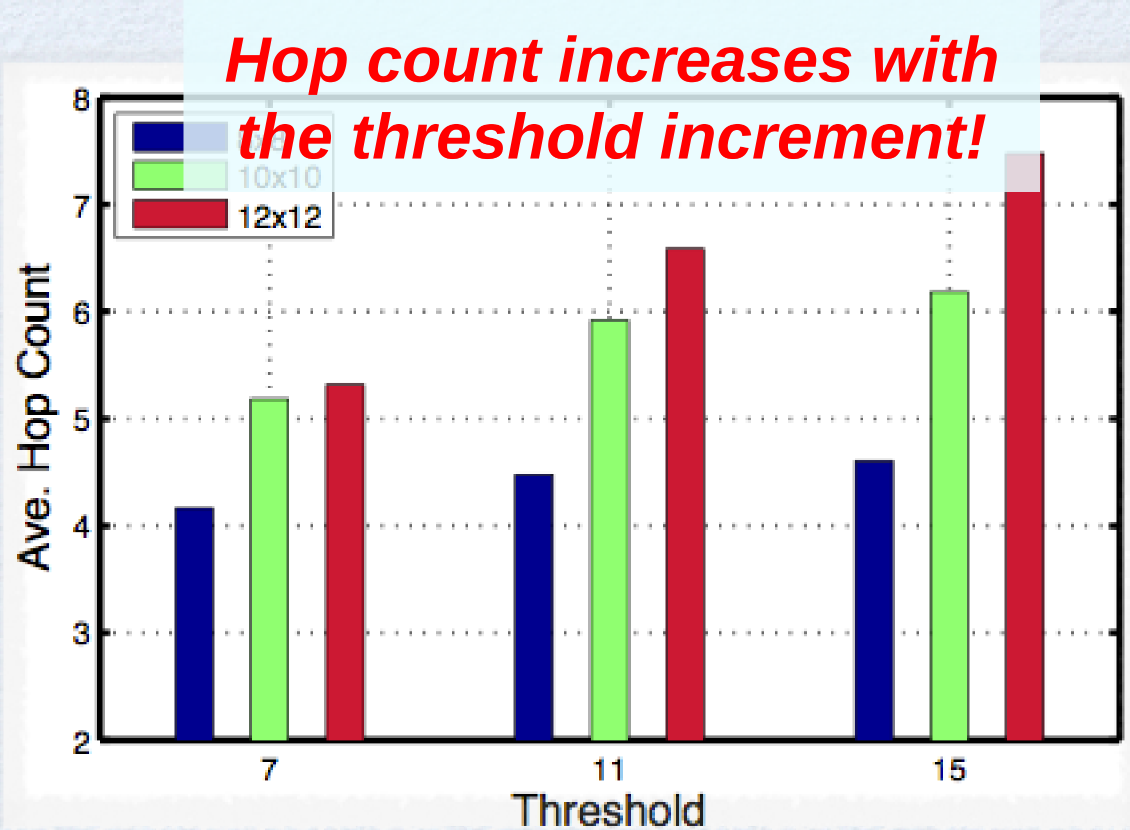




Routing efficiency and hop count cost

- We evaluate the routing performance in terms of hop count
  - The overlaid routing doesn't guarantee shortest-path, but very close to it
  - Study the average hop count changing with the threshold



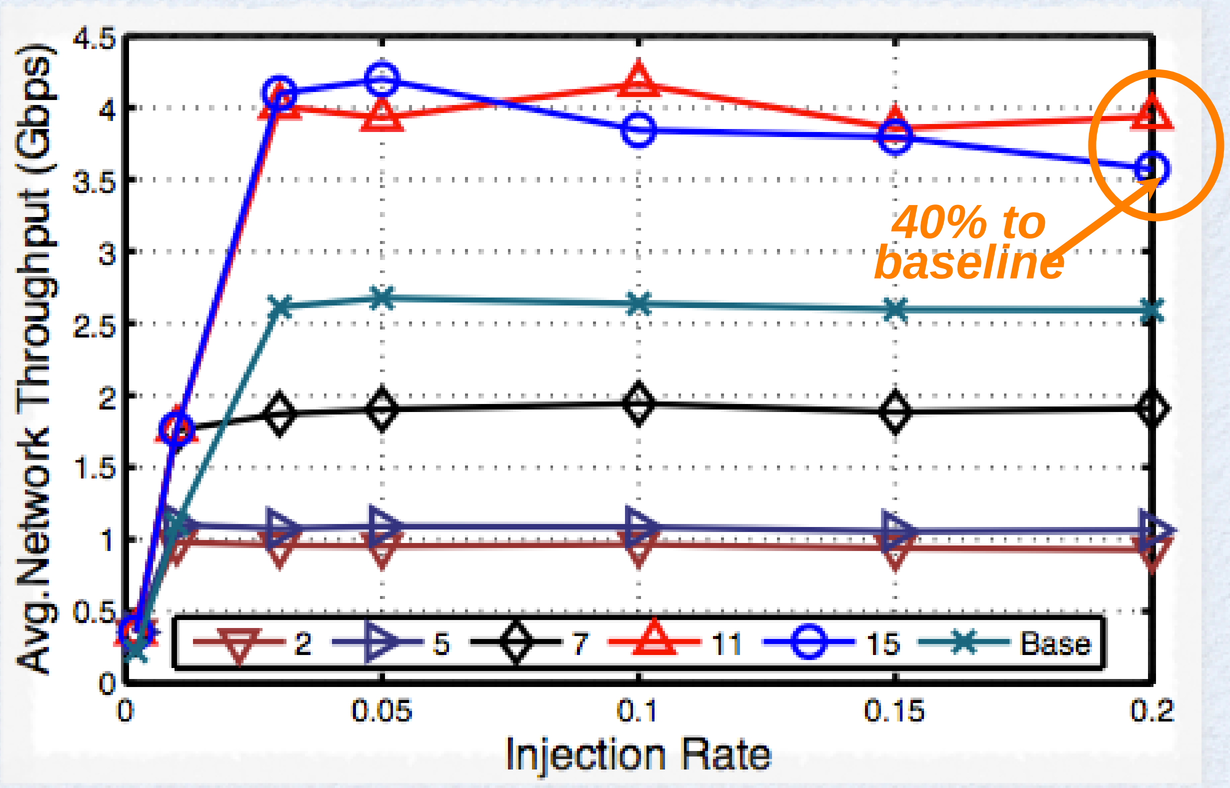


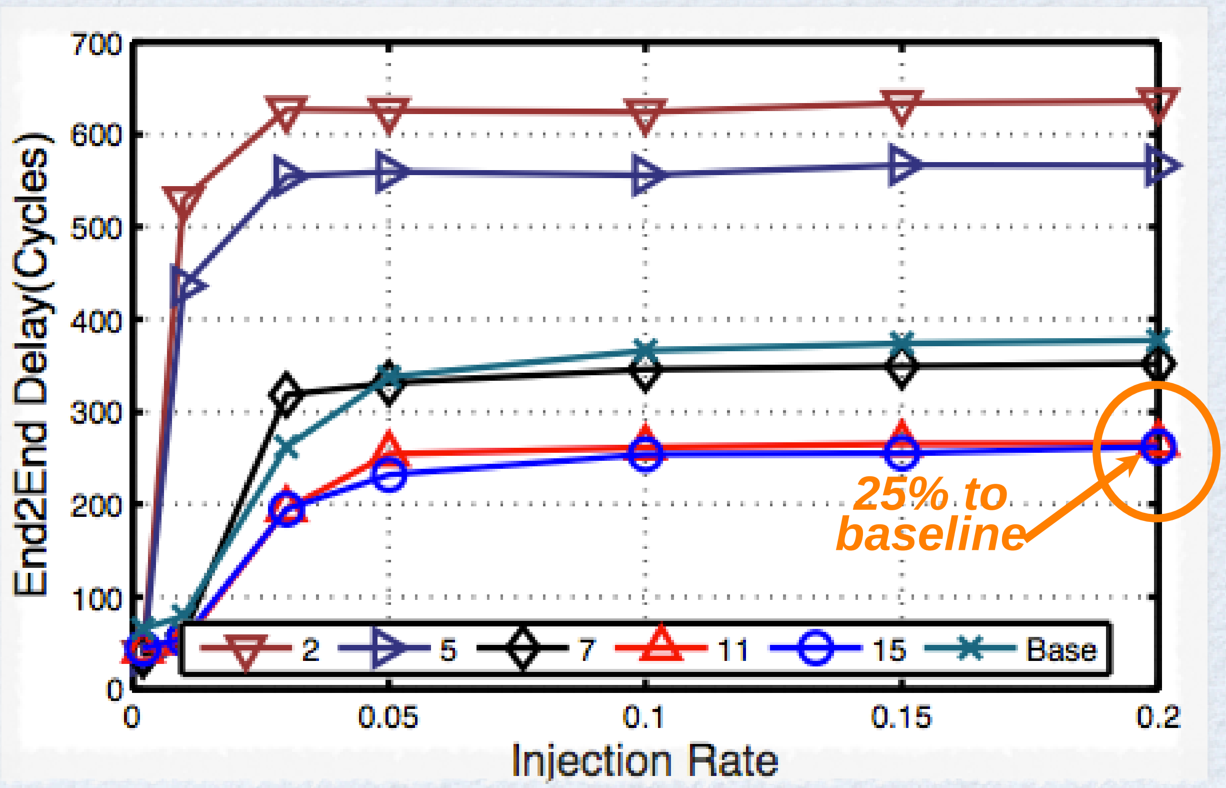
Baseline: 2D mesh, xy
Shortest-path routing: Dikjstra algorithm

Threshold Performance Impact

- We study the impact of threshold setting on the network performance
- Compare with baseline 2D mesh

A better performance is achieved at a higher threshold, as transmission concurrency is improved under more evenly distributed traffic!

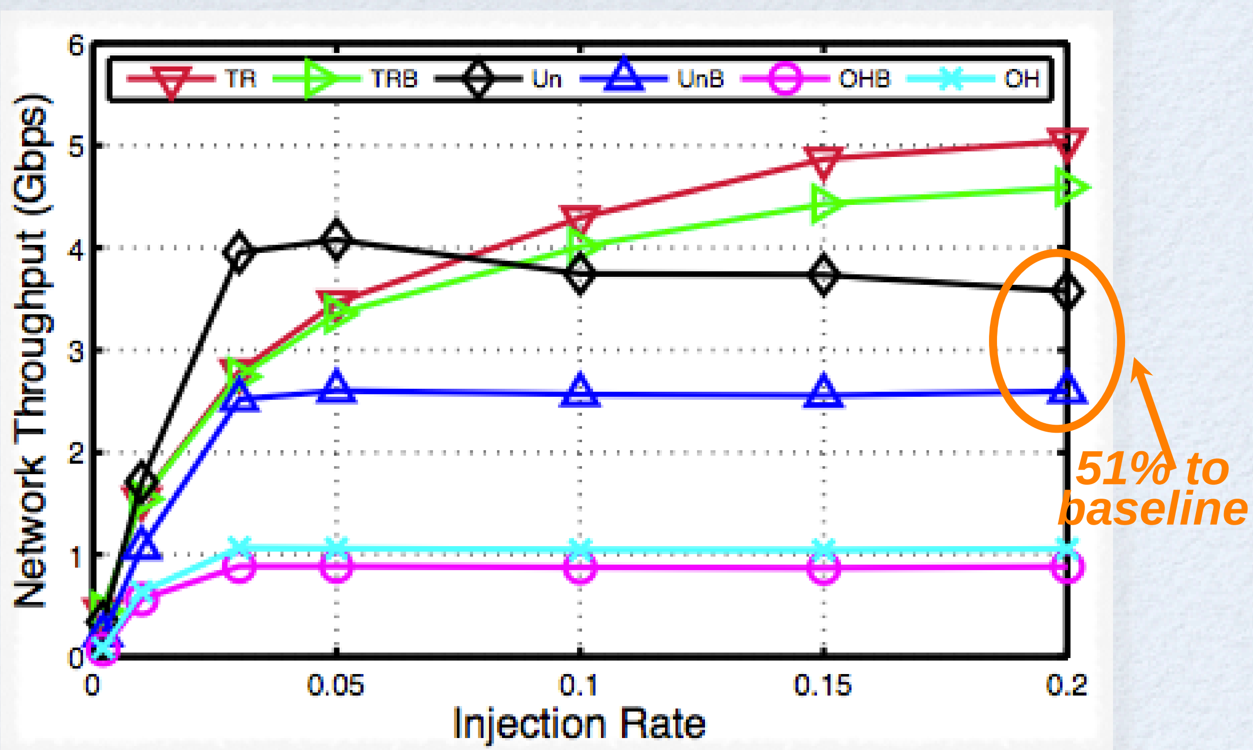


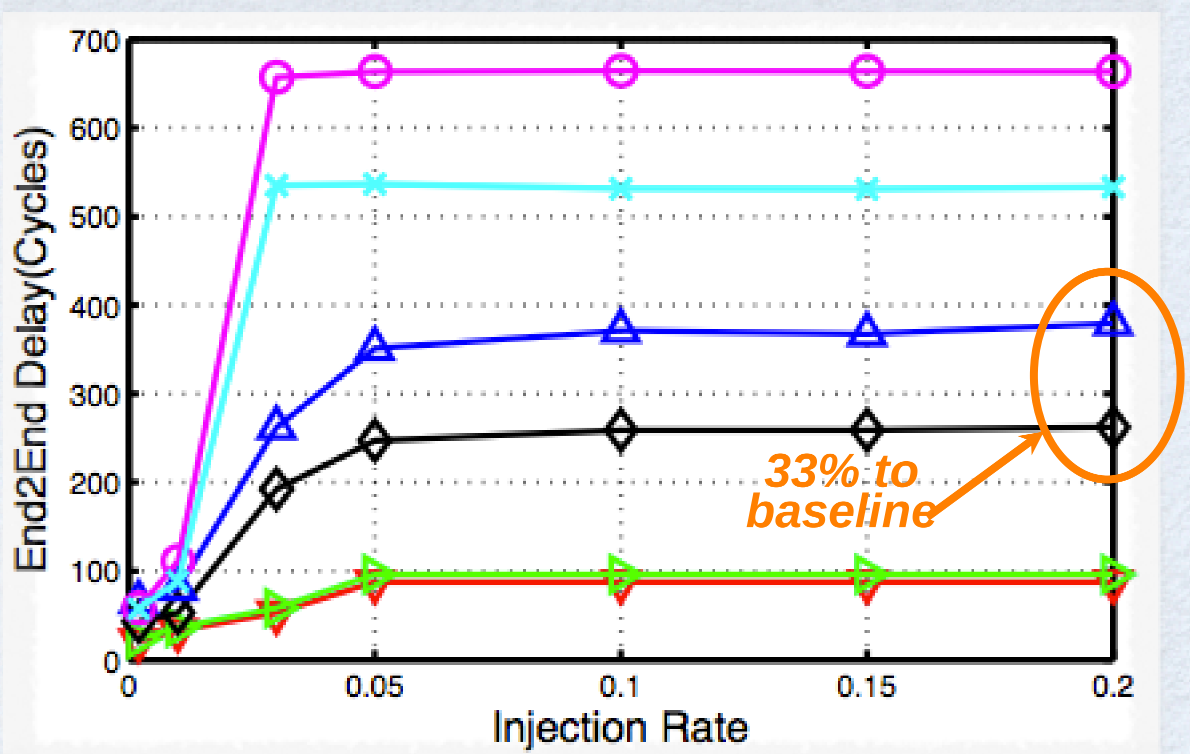


Traffic Pattern Performance Impact

- The network performance under three synthetic traffics is studied: uniform, transpose (neighboring, locality), and hot spot

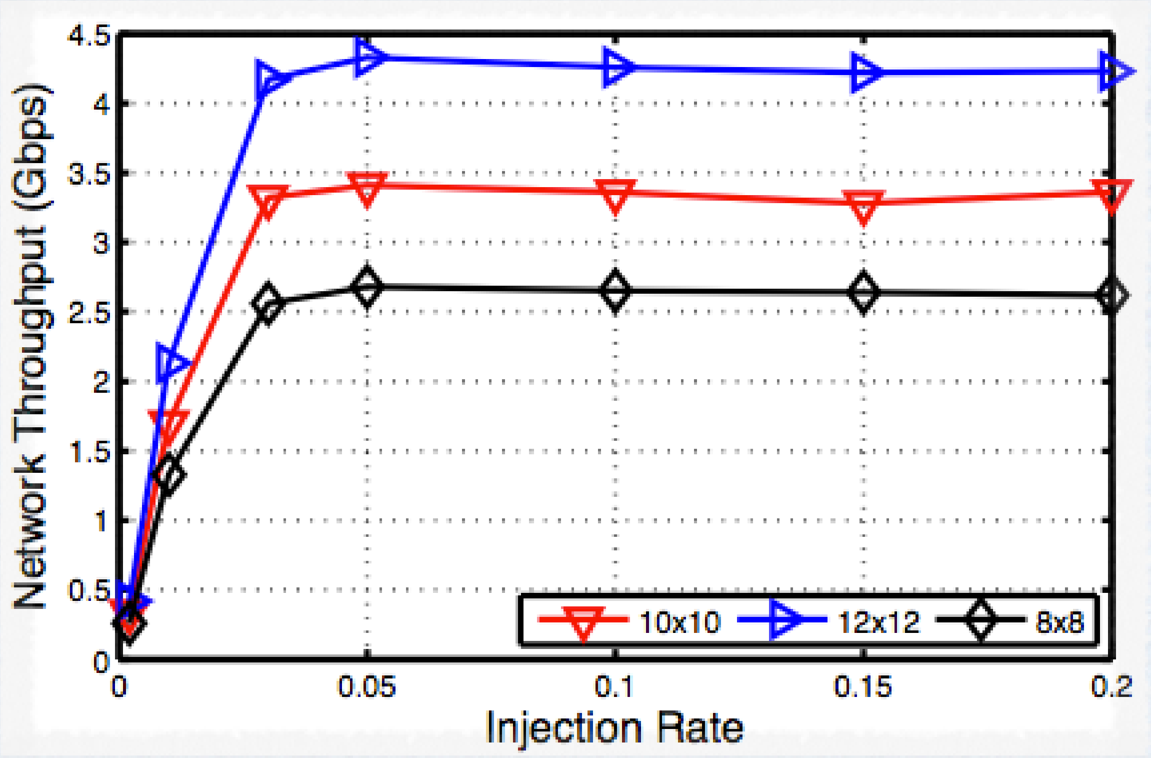
Overlaid mesh has performance advantage over long rangecommunication oriented applications!

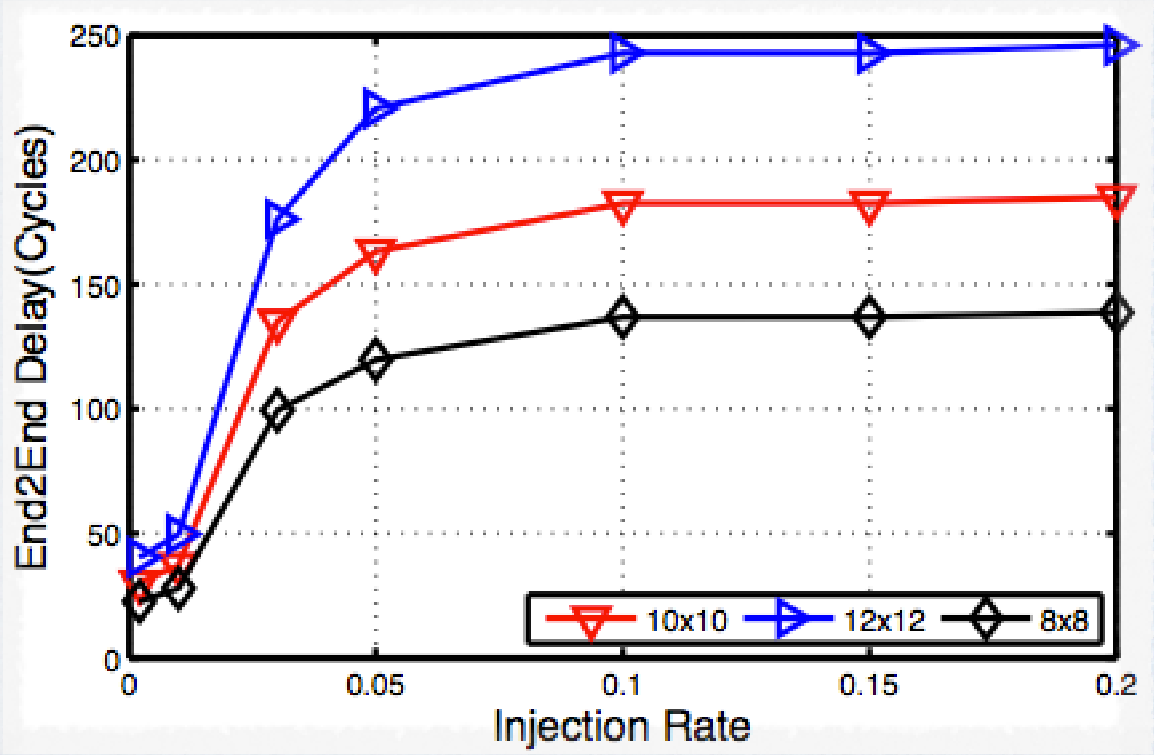




Scalability Study

- The scalability of overlaid mesh WiNoC is investigated with uniform traffic under three different network scales





Conclusion

- Proposed an overlaid mesh WiNoC platform
  - The WiNoC topology design achieved a performance optimized configuration by proper big nodes placement
  - An effective and efficient topology configuration model has been developed for fast searching through the design space
  - A high-efficient, low-cost zone-aided routing scheme has been designed to facilitate deadlock freedom while ensuring routing efficiency
  - The simulation study has demonstrated the promising network performance over a regular mesh

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