TrueTime: Simulation of Networked and Embedded Control Systems

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Outline of Lecture

1. Time and scheduling
2. Interrupt handlers and task synchronization
3. The network blocks
4. Summary
5. Specification of “mini-project”

Time primitives

- Simulink provides a global time base
- Each kernel block has its own local clock, with possible offset and drift
- Tasks may self-suspend (sleep)

```
ttCurrentTime
ttCurrentTime(time)
ttSleep(duration)
ttSleepUntil(time)
```

Priority functions

- The ready queue of the kernel is sorted by a priority function, which is a function of the task attributes
- Pre-defined priority functions exist for fixed-priority (`prioFP`), deadline-monotonic (`prioDM`), and earliest-deadline-first scheduling (`prioEDF`)
- Individual tasks can be made non-preemptible (`ttNonpreemptible`)
- Example: the EDF priority function (C++):

```
double prioEDF(UserTask* t)
   return t->absDeadline;
}
```

Scheduling Hooks (C++ only)

Pieces of user code that are executed at different stages during the execution of a task

- Arrival hook – when a job is created
- Release hook – when the job is first inserted in the ready queue
- Start hook – when the job executes its first segment
- Suspend hook – when the job is preempted, blocked or voluntarily goes to sleep
- Resume hook – when the job resumes execution
- Finish hook – when the job has executed its last segment

```
ttAttachHook(char* taskname, int ID, void (*hook)(UserTask*))
```

Constant Bandwidth Servers (CBS)

- Version 2.0 has built-in support for CBS scheduling [Abeni and Buttazzo, 1998]
- Assumes an EDF kernel (`prioEDF` must be selected)
- A CBS is characterized by
  - a period T_s
  - a budget Q_s
- A task associated with a CBS cannot execute more than the server budget period each server period (“sandboxing”)
- Implemented using scheduling hooks

```
ttCreateCBS(name, Qs, Ts, type)
ttAttachCBS(taskname, CBSname)
ttSetCBSParameters(name, Qs, Ts)
```

Multicore Scheduling

- Version 2.0 supports partitioned multicore scheduling
  - One ready queue per core
  - The same local scheduling policy in each core
- Tasks can be migrated between cores during runtime

```
ttSetNumberOfCPUs(nbr)
ttSetCPUAffinity(taskname, CPUnbr)
```

Data Logging

- Arbitrary events, intervals and values may be logged from the user code
- Written to MATLAB workspace when the simulation terminates
- Automatic task attribute logging provided for
  - Response time
  - Release latency
  - Start latency
  - Task execution time

```
ttCreateLog(logname, variable, size)
ttLogNow(logname)
ttLogStart(logname)
ttLogStop(logname)
ttLogValue(logname,value)
ttCreateLog(taskname, type, variable, size)
```

Example: Three Controllers on one CPU

- Three controller tasks controlling three different DC-servo processes
- Sampling periods $h_i = [0.006 \;\; 0.005 \;\; 0.004]$ s
- Execution time of 0.002 s for all three tasks for a total utilization of $U = 1.23$
- Evaluate the effect of various scheduling policies on the control performance
- Use the logging functionality to monitor the response times and sampling latency under the different scheduling schemes

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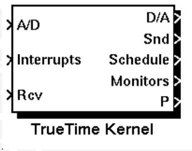
Interrupt Handlers

- Code executed in response to interrupts
- Scheduled on a higher priority level than tasks, using fixed priorities
- Interrupt types
  - Timers (periodic or one-shot)
  - External (hardware) interrupts
  - Task overruns
  - Network interface




```
ttCreateHandler(hdlname, priority, codeFcn, data)
ttCreateTimer(timername, time, hdlname)
ttCreatePeriodicTimer(timername, start, period, hdlname)
ttRemoveTimer(timername)
ttAttachTriggerHandler(trignbr, hdlname)
```

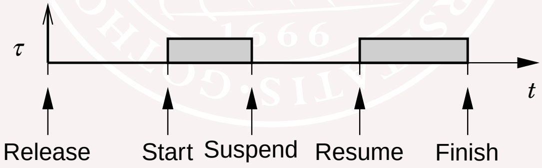
Overrun Handlers

- Two special interrupt handlers may be associated with each task (similar to Real-time Java)
  - A deadline overrun handler
  - An execution time overrun handler
- Can be used to dynamically handle prolonged computations and missed deadlines
- Implemented by internal timers and scheduling hooks

```
ttAttachDLHandler(taskname, hdlname)
ttAttachWCETHandler(taskname, hdlname)
```

Hooks for Overrun Handling

- **Release hook**: Set up a timer to expire at the absolute deadline of the task. The associated deadline overrun handler is called if the timer expires
- **Start hook**: Set up a timer corresponding to the worst-case execution time (WCET) of the task
- **Suspend hook**: Update execution time budget and remove WCET timer
- **Resume hook**: Set up the WCET timer for the remaining budget
- **Finish hook**: Remove both overrun timers



Task synchronization and communication

Four different simulated mechanisms of synchronization and communcation are supported:

- Monitors
- Events
- Mailboxes
- Semaphores

Monitors

- Monitors are used to model mutual exclusion between tasks that share common data
- Tasks waiting for monitor access are arranged according to their respective priorities
- The implementation supports standard priority inheritance to avoid priority inversion

`ttCreateMonitor(name)`

`ttEnterMonitor(name)` (blocking)

`ttExitMonitor(name)`

Events

- Events are used for task synchronization and may be free or associated with a monitor (condition variable)
- `ttNotifyAll` will move all waiting tasks to the monitor waiting queue or directly to the ready queue (if it is a free event)
- Events may, e.g., be used to trigger event-based controllers from an interrupt handler

`ttCreateEvent(name, monitorname)`

`ttWait(name)` (blocking)

`ttNotifyAll(name)`

Mailboxes

- Communication of data between tasks is supported by mailboxes
- A ring buffer is used to store incoming messages

```
ttCreateMailbox(name, maxsize)
ttTryPost(name, msg)
ttPost(name, msg) (blocking)
msg = ttTryFetch(name)
ttFetch(name) (blocking)
msg = ttRetrieve(name)
```

Semaphores

- Tasks can also be synchronized using counting semaphores

```
ttCreateSemaphone(name, initval, maxval)
ttTake(name) (blocking)
ttGive(name)
```

Readers–Writers Example

- Shared memory area must be protected using mutual exclusion
- Writers must wait for the buffer to be non-full
- Readers must wait for the buffer to be non-empty
- More sophisticated versions are possible (e.g. allowing multiple readers but only one writer)

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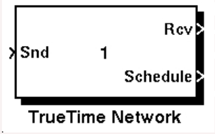
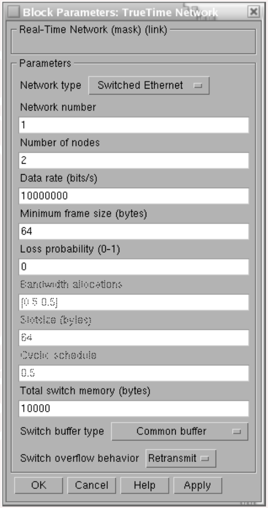
The Network Blocks

- Wired, wireless and ultrasound network blocks
- Each network is identified by a unique number
- Automatic connections between the kernel and network blocks (via hidden Goto blocks)
  - Needed only to trigger the blocks – no data is passed through the Simulink block connections

The Wired Network Block

- Supports eight common MAC layer policies:
  - CSMA/CD (Ethernet)
  - CSMA/AMP (CAN)
  - Round Robin (Token bus)
  - FDMA
  - TDMA
  - Switched Ethernet
  - Flexray
  - PROFINET IO
- Policy-dependent network parameters
- Generates a transmission schedule





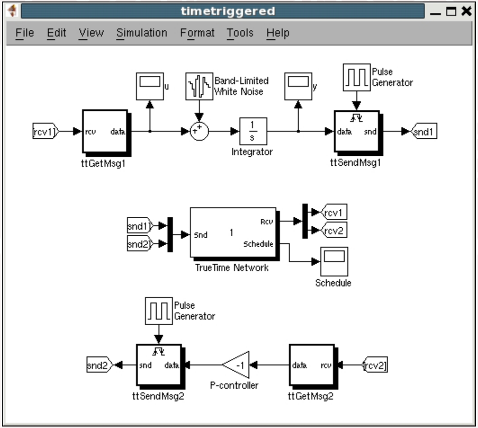
Network Communication

- Each node (kernel block) may be connected to several network blocks
- A dedicated interrupt handler may be associated with each network
  - Triggered as a packet arrives
- The actual message data can be an arbitrary MATLAB variable (scalar, struct, cell array, etc)
- Broadcast by specifying receiver number 0

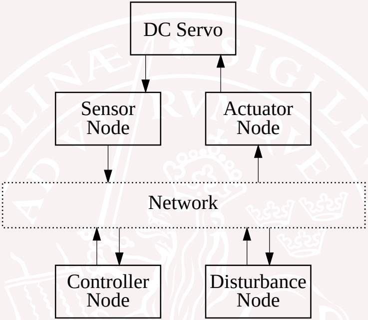
```
ttSendMsg([network receiver], data, length, priority)
ttGetMsg(network)
ttAttachNetworkHandler(network, hdlname)
```

Stand-Alone Network Interface Blocks

- Eliminates the need of Kernel blocks
- Event-triggered transmission of vector values



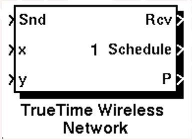
Example: Networked Control Loop

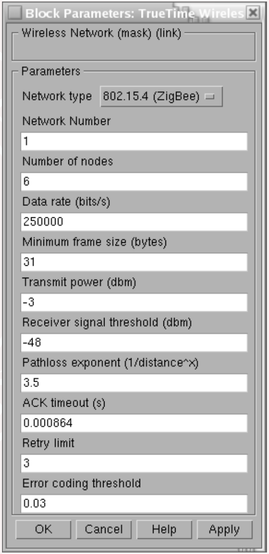


- Sensor/actuator node with time-driven sampler and event-driven actuator
- Event-driven controller node
- Disturbance node generating high-priority traffic

The Wireless Network Block

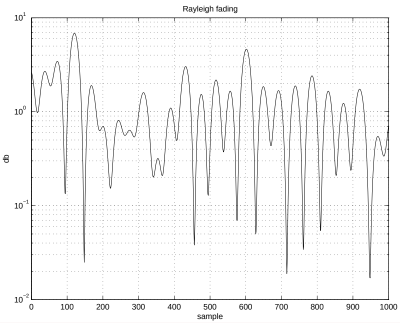
- Used in basically the same way as the wired network block
- Supports two common MAC layer policies:
  - 802.11b/g (WLAN)
  - 802.15.4 (ZigBee)
- Variable network parameters
- x and y inputs for node locations
- Generates a transmission schedule





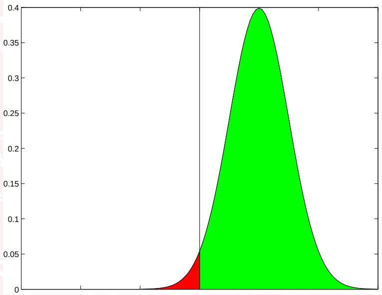
The Wireless Network Model

- Isotropic antennas
- Default path-loss formula: $$\frac{1}{d^a}$$
  - d – distance between nodes $\left(= \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}\right)$
  - a – environment parameter (e.g., 2–4)
- User-defined path-loss formula can be used to simulate e.g. Rayleigh fading



Transmission Errors

- The signal-to-interference ratio in the receiver is calculated
- Assuming additive Gaussian noise, the number of bit errors is drawn from a probability distribution



- If the number of bit error exceeds the specified error coding threshold, the packet is lost

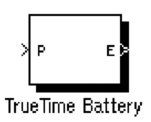
Wireless Network Parameters

- Data rate (bits/s)
- Transmit power (dBm)
  - configurable on a per node basis, can be reconfigured during run-time
- Receiver sensitivity (dBm)
- Path-loss exponent *or* used-defined path-loss function
- ACK timeout (s)
- Maximum number of retransmissions
- Error coding threshold

Higher-level network protocols

- Layers above MAC are not supported by TrueTime
- Higher-level protocols can however be implemented as applications
- Some examples we have implemented:
  - TCP with random early detection (RED)
  - AODV routing

The Battery Block



- Simulation of battery-powered devices
- Simple integrator model
  - Discharged or charged
- Energy sinks:
  - Computations, radio transmissions, usage of sensors and actuators, . . .
- If the power input to a kernel block reaches zero, the kernel freezes

```
ttSetKernelParameter('energyconsumption',value)
```

Dynamic Voltage Scaling

- The kernel CPU speed can be changed from the application (e.g., to consume more or less power)
- Independent from the local clock

```
ttSetKernelParameter('cpuscaling',value)
```

The Ultrasound Network Block

- Works similar to the other network blocks, but also simulates a propagation delay (speed of sound)
- Cannot send messages, but only broadcast ultrasound pings

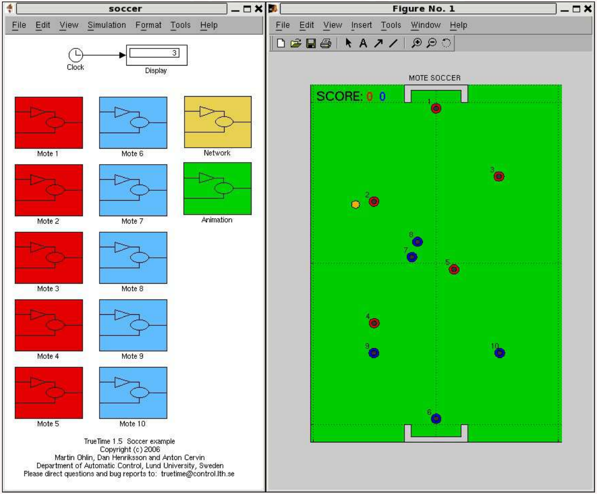
```
ttUltrasoundPing(network)
```

Example: Power Control

- Control of the DC-servo over a wireless network
- Two nodes:
  - sensor/actuator node
  - controller node
- Communication using wireless radio
- Dynamic control of radio transmission power
  - increase or decrease transmission power depending on link quality

Example: Soccer

- $5+5$ mobile robots communicating over a wireless network



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TrueTime – Summary

- Co-Simulation of:
  - computations inside the nodes
  - tasks, interrupt handlers, scheduling hooks
  - wired or wireless communication between nodes
  - sensor and actuator dynamics
  - mobile robot dynamics
  - dynamics of the environment
  - dynamics of the physical plant under control
  - the batteries in the nodes
- Control performance assessment
  - time domain
  - cost function calculations (via Monte Carlo simulations)

Some Limitations

- Developed as a research tool rather than as a tool for system developers
- Cannot express tasks and interrupt handlers directly using production code
  - Code must be divided into code segments and execution times must be assigned
- The zero-crossing functions generate quite a few events $\Rightarrow$ large models tend to be slow
- No built-in support for, e.g.,
  - higher-level network protocols
  - task migration between kernel blocks
  - ...

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“Mini-project”

- Simulation of a distributed consensus algorithm
- 6 mobile nodes should agree upon a location in the plane to meet
- Communication over a wireless network
- Each node is modeled by
  - A Kernel block
  - Two integrator blocks (for the x and y positions)

Distributed consensus

A simple algorithm to reach consensus regarding the state of n integrator agents with dynamics $\dot{z}_i = u_i$ can be expressed as

$$u_i(t) = K \sum_{j \in \mathcal{N}_i} \big(z_j(t) - z_i(t)\big) + b_i(t)$$

where K ăis a gain parameter and $\mathcal{N}_i$ are the neighbours of agent i (i.e., the nodes within communication range)

The bias term $b_i(t)$ should be zero if the nodes are to meet at a common location.

TrueTime Model

- A model with six integrator agents connected to a wireless network is provided (`consensus.mdl`)
- Each kernel block has to be configured – use the same initialization function and code function(s) for all blocks
- The consensus algorithm can be implemented as a simple periodic task (`ttCreatePeriodicTask`):
  - Collect all x and y values sent from your neighbours during the last period (repeated calls to `ttGetMsg`)
  - Read your own x and y coordinates (`ttAnalogIn`)
  - Compute the control signals in the x and y directions according to the formula
  - Output the control signals (`ttAnalogOut`)
  - Broadcast your own x and y position to your neighbours (`ttSendMsg` with receiver 0)

Extensions

- Add bias terms to the consensus algorithm to simulate “formation flight”
- Let one node lead (by not running the consensus algorithm) and let the other ones follow