NSF Engineering Research Center (ERC) for

Reconfigurable Manufacturing Systems (RMS)

Networked Plant Automation and Control.

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Hari Bharat Molabanti, James Moyne and Dawn Tilbury

May, 2009

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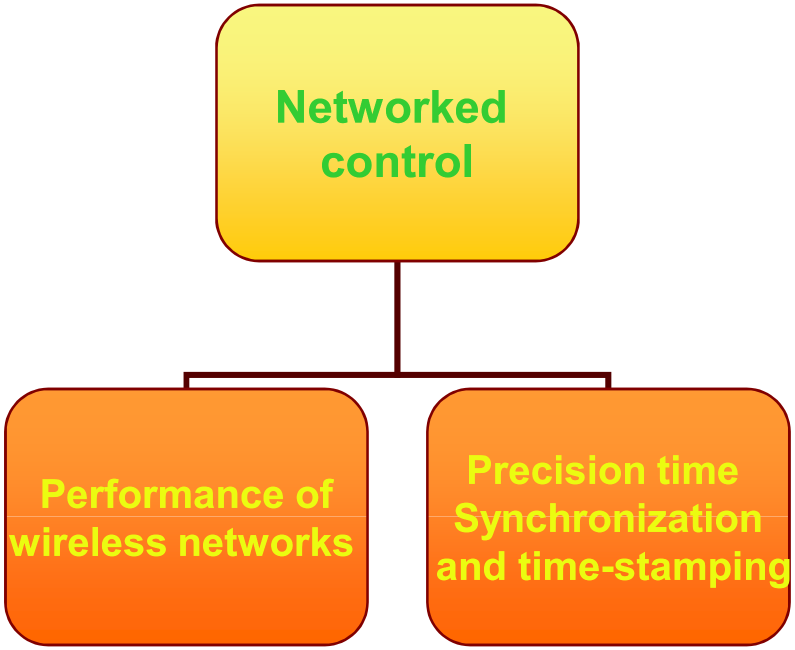
The University of Michigan, College of Engineering

Project Overview



Networked control

Performance of wireless networks

Precision time Synchronization and time-stamping

USCAR

UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

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ABB

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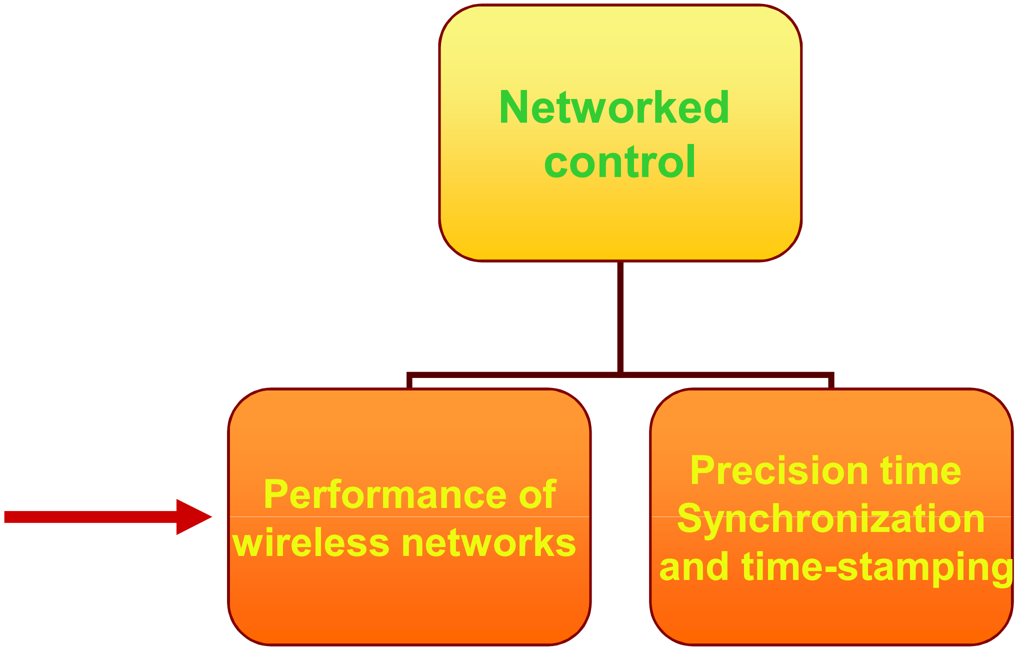


Networked control

Performance of wireless networks

Precision time Synchronization and time-stamping

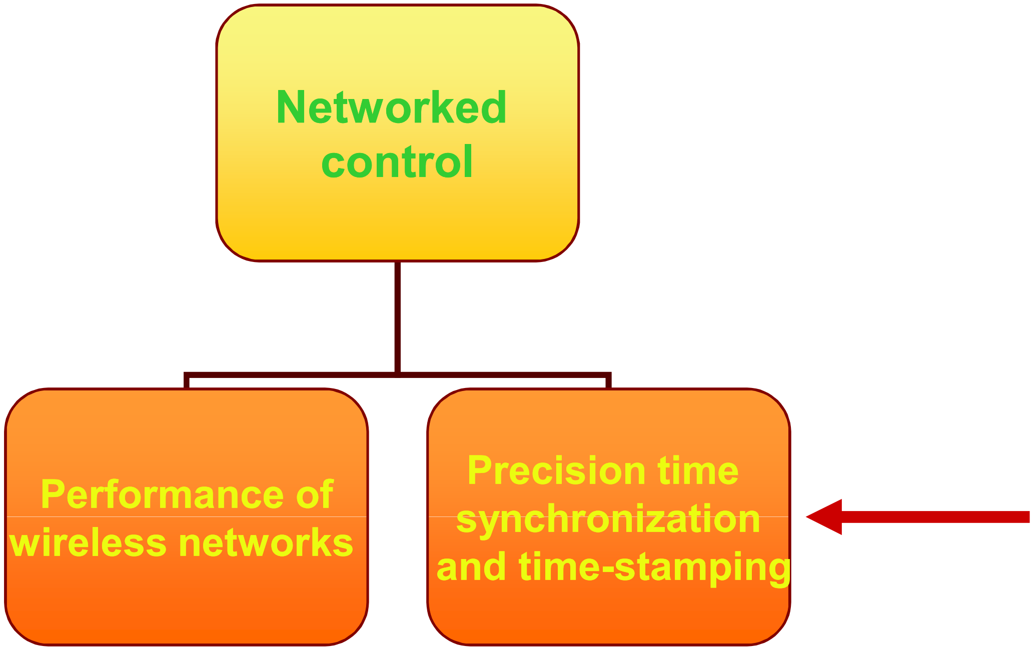
Summary

Goals:

- Understand how to use wireless in diagnostics, control and safety applications.
- Work with USCAR, help the automotive industry migrate cost effectively to wireless on the factory floor.
- Interact with Vendor Partners and Standards organizations .

Deliverables:

- Provide a standardized testing mechanism and test plan.
- Define best practices for wireless operation in factories.
- Tools for real time fault diagnosis and QoS assessment.
- Provide a capability for "record / playback" style investigation of interference phenomenon.
- Provide design tools for the planning stage of a wireless setup.
- Report on technology trends in wireless systems for control.



Networked control

Performance of wireless networks

Precision time synchronization and time-stamping

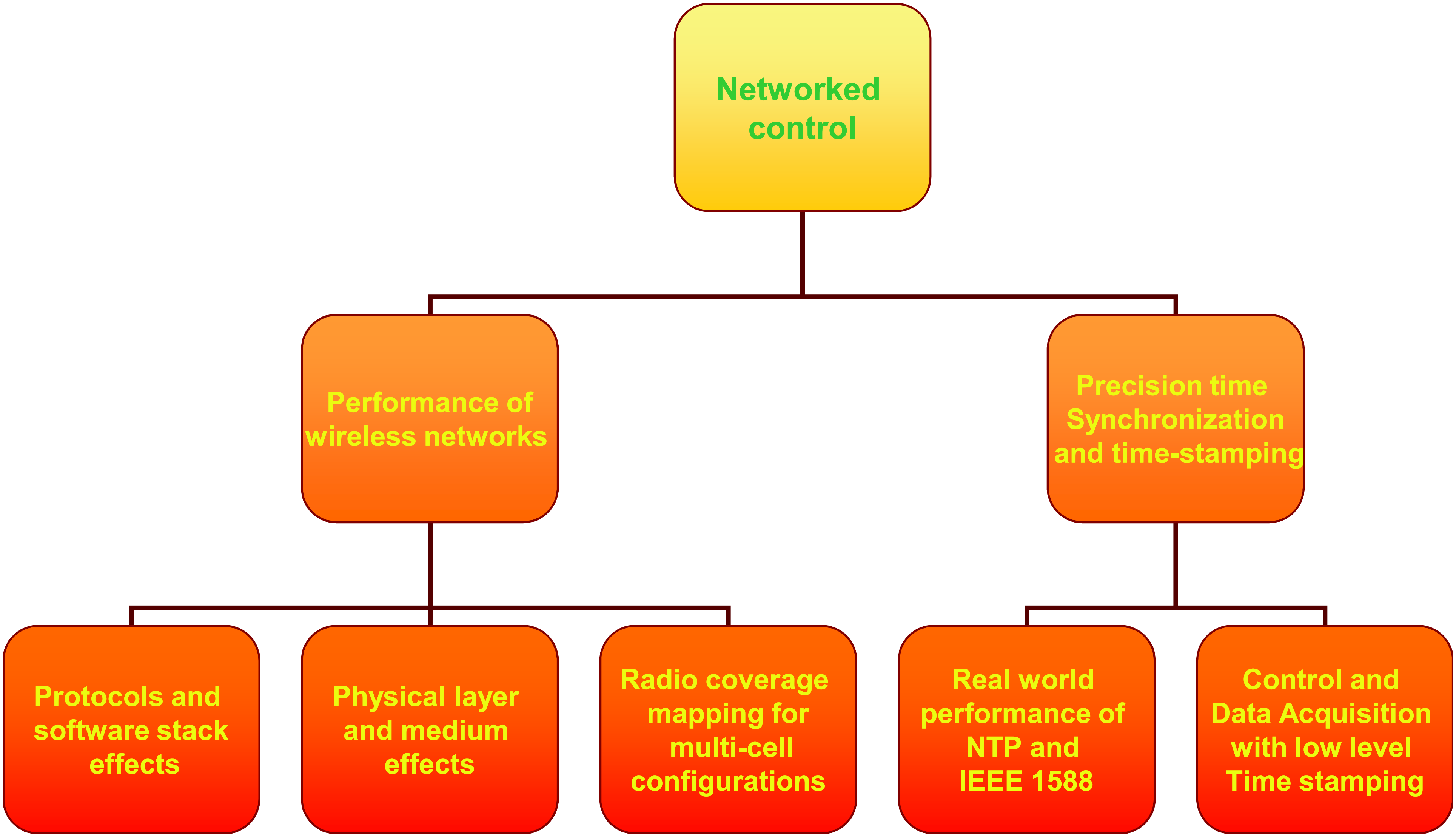
Summary

Goals:

- Understand industry requirements for time synchronization.
- Evaluate the capabilities of IEEE 1588 hardware time synchronization for control, diagnostics and safety systems.
- Study factors affecting time precision in an industrial setting for both wired and wireless networks.
- Develop formal approaches for controller design, to utilize time stamped data for robust operation in the face of network vagaries.

Deliverables:

- A comprehensive report on time synchronization requirements for industrial networks.
- A test-bed for characterizing the application of low level time stamping on a networked control system.
- A configurable factory scale simulation tool to evaluate synchronization and to assess the need for additional time synchronization capability.



Networked control

Performance of wireless networks

Precision time Synchronization and time-stamping

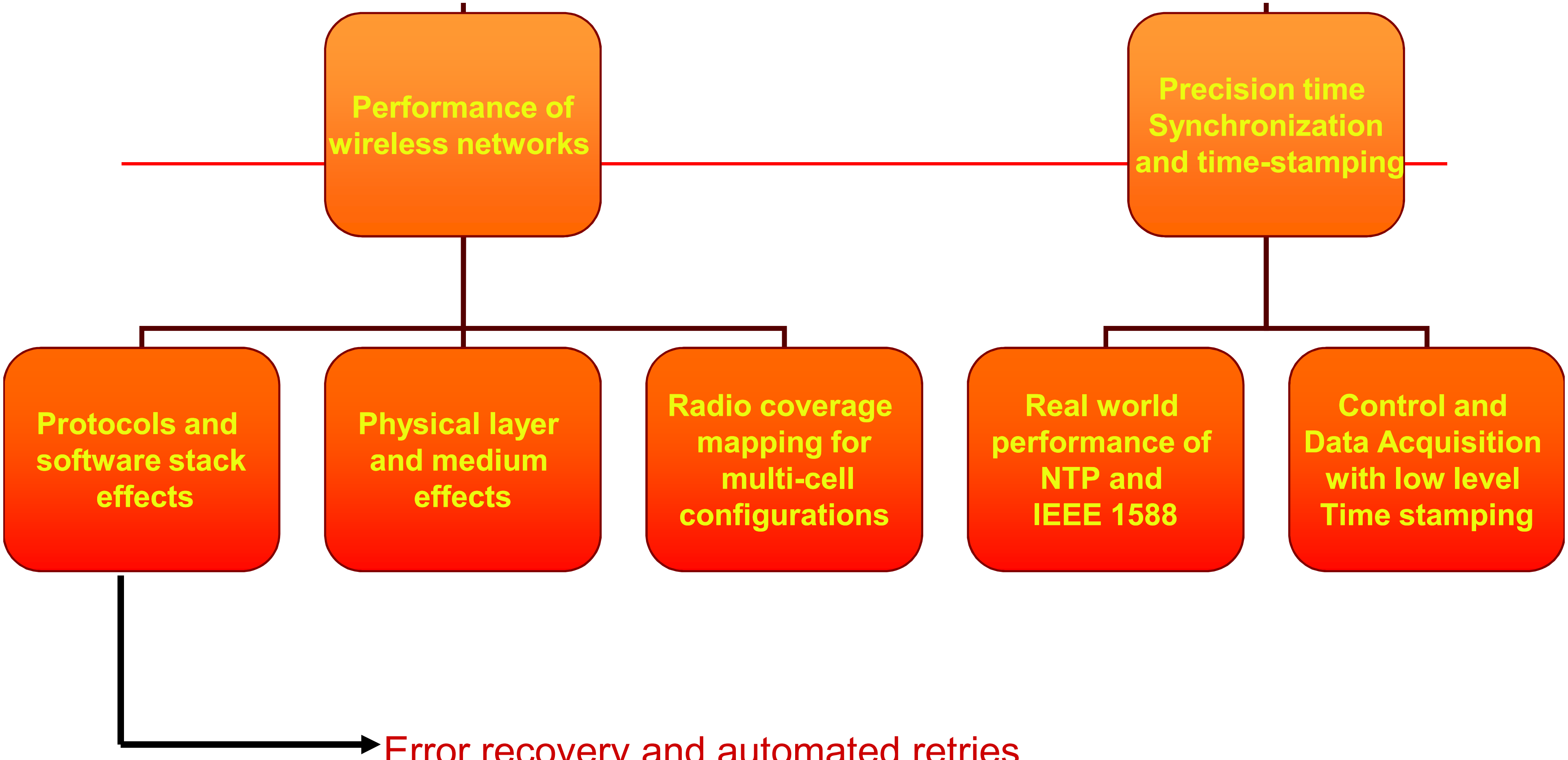
Protocols and software stack effects

Physical layer and medium effects

Radio coverage mapping for multi-cell configurations

Real world performance of NTP and IEEE 1588

Control and Data Acquisition with low level Time stamping



Performance of wireless networks

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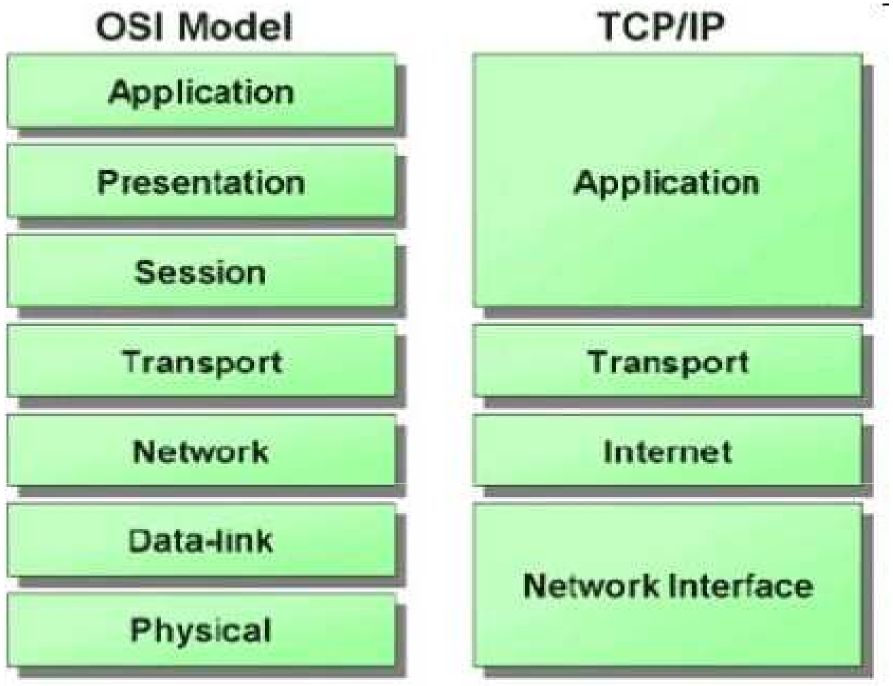
Error recovery and automated retries
Packet parsing
Network arbitration

Protocol Stacks for Bluetooth and Wi-Fi are designed for data applications.

For control systems where time precision of transmission is vital, the stack is a major source of time jitter in communication.

Also, an error in physical layer can propagate through the protocol stack to manifest as huge time delays.

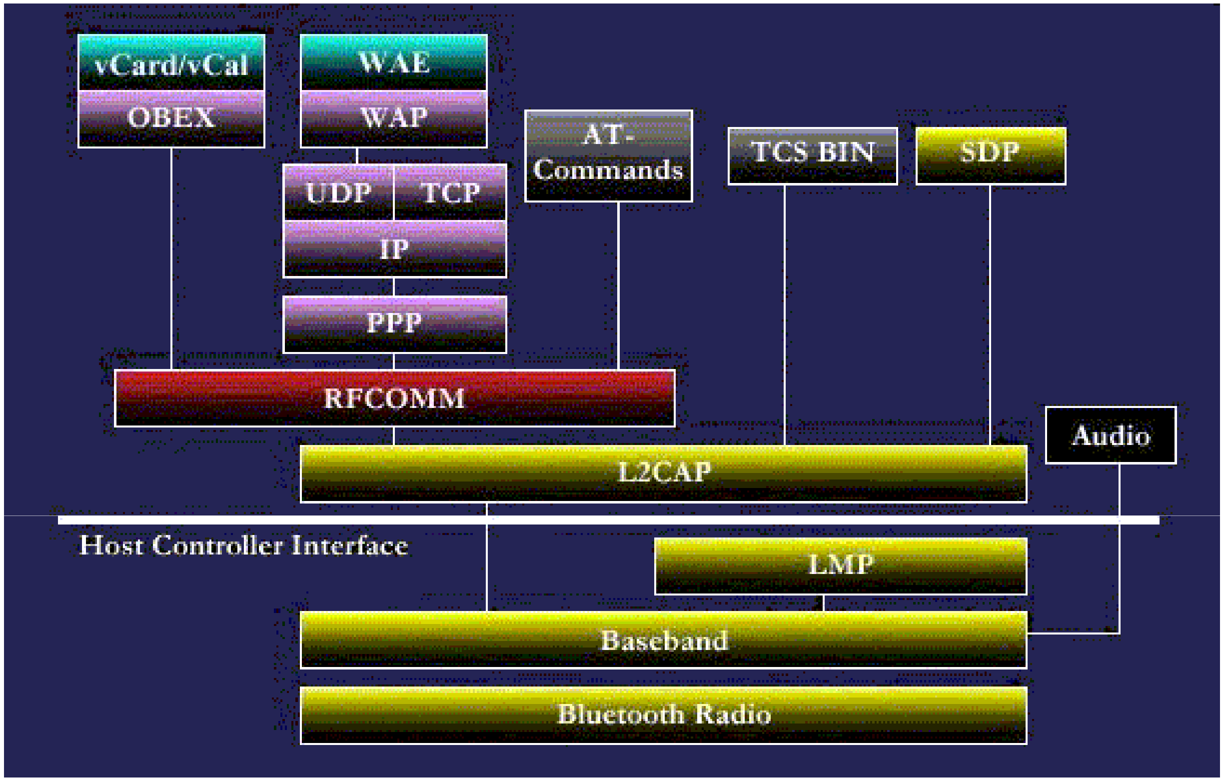


OSI model

We are currently in the process or isolating the time delay contribution from the protocol stack alone so that it is possible to compare protocols independent of the physical layer.

The Bluetooth protocol stack is particularly interesting from this perspective since it is offers a lot of flexibility in how data is handled at the lower layers.

This allows the user to write custom “profiles” for the system that can demand synchronous responses for instance. There are provisions for hardwiring data handling functions all the way to the baseband as well.

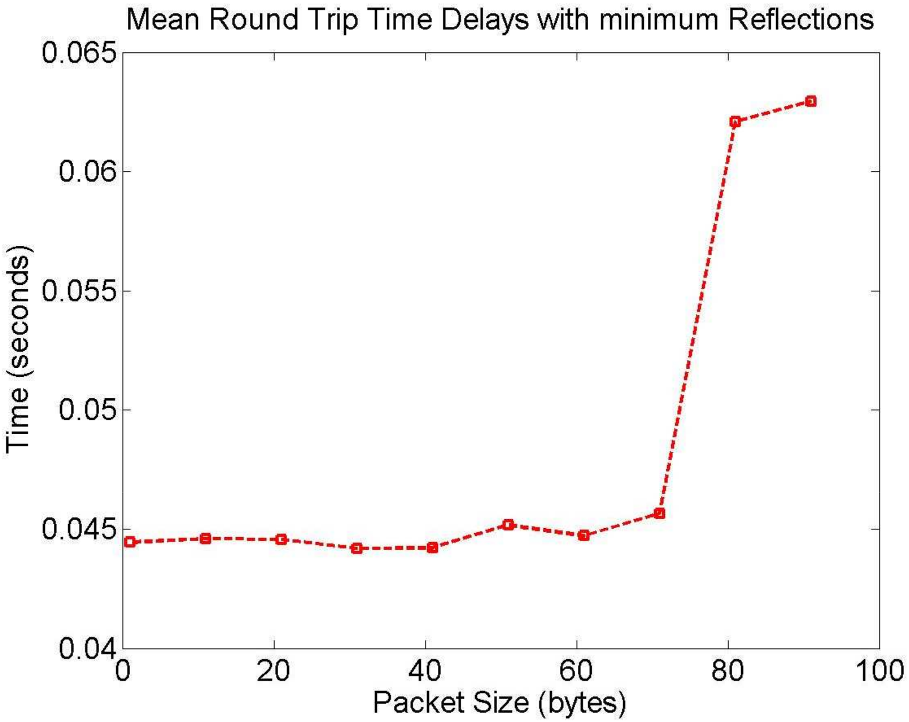


Some implementations that modify this stack to improve determinism already exist as COTS solutions.

New result

A very interesting illustration of effects introduced by the protocol stack in the Bluetooth system is plotted here on the right.

When the physical medium is maintained at close to ideal we see a distinct change in the average network latency when the data payload touches 75 Bytes



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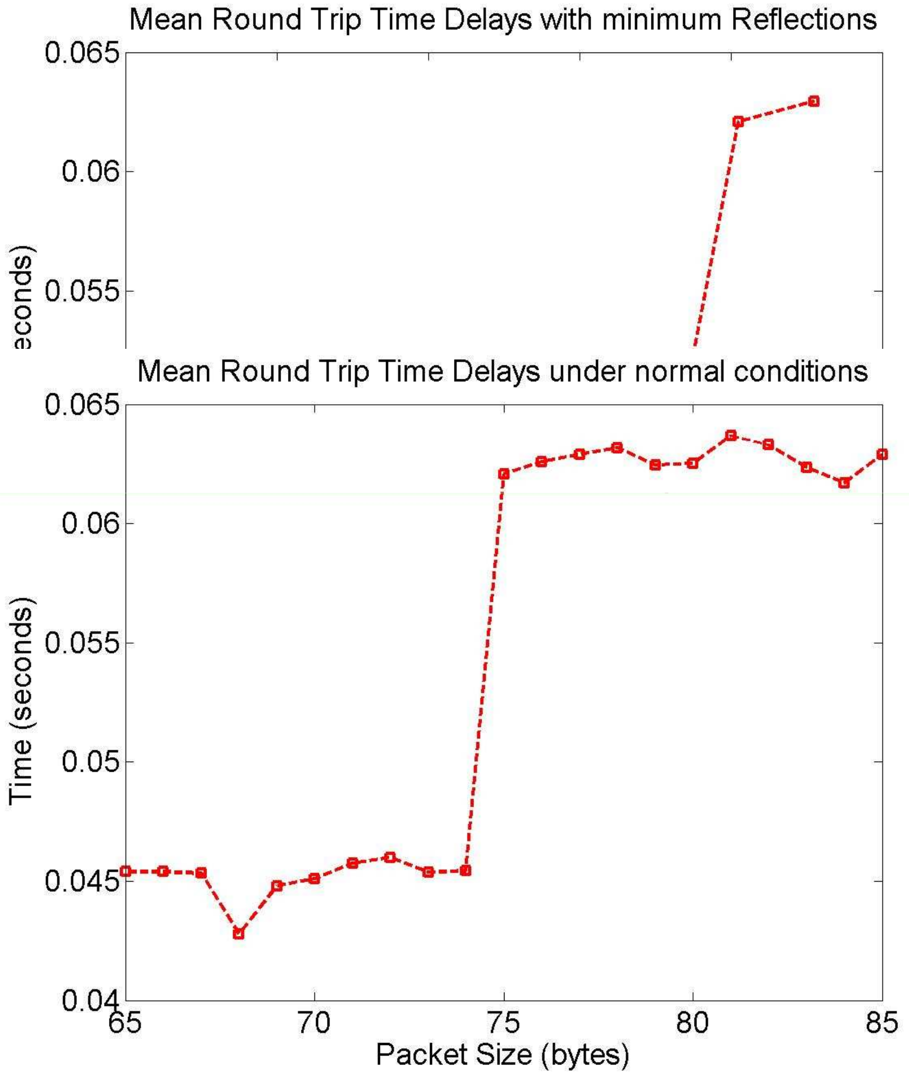

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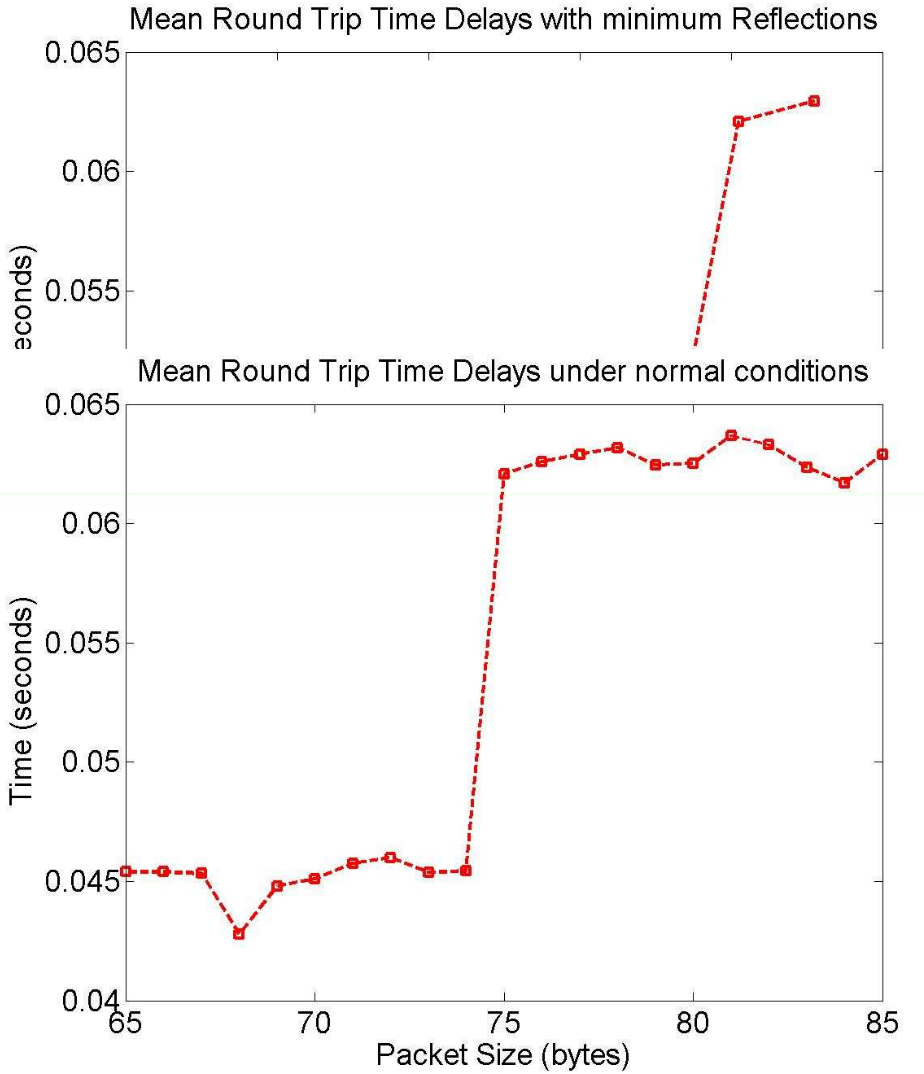
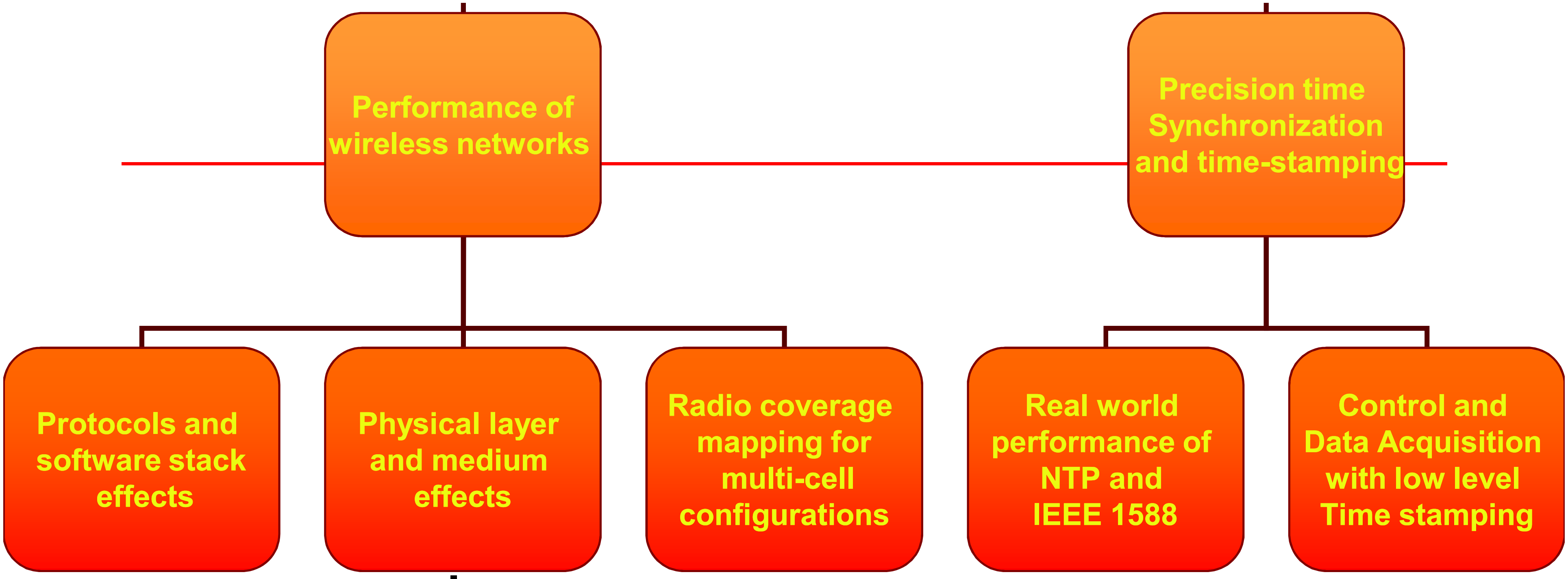


Data packets for control networks are typically sized around this value making this a serious effect to consider.



Performance of wireless networks

- Protocols and software stack effects
- Physical layer and medium effects
- Radio coverage mapping for multi-cell configurations

Precision time Synchronization and time-stamping

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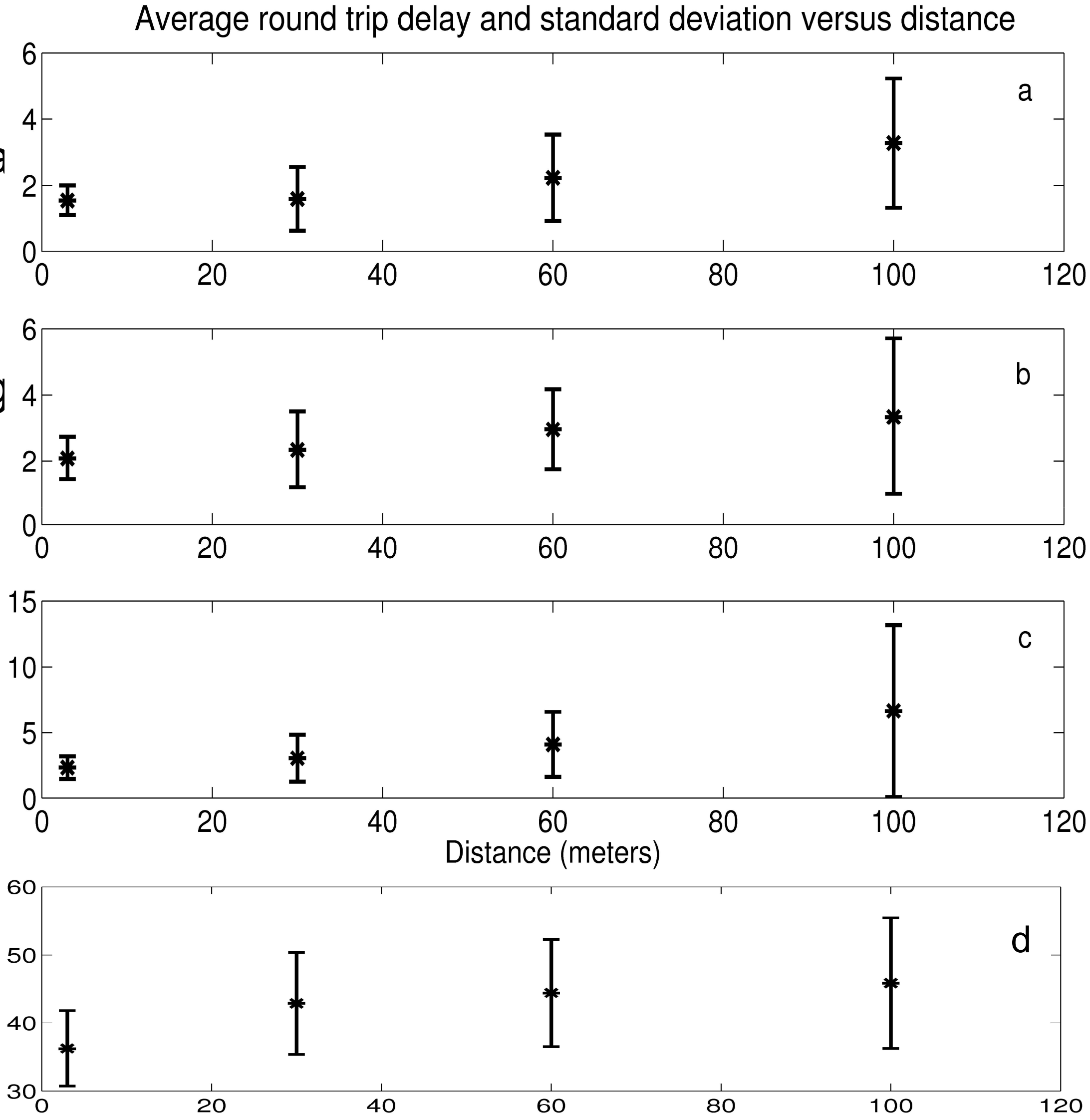
Performance with increasing distance
Performance under the influence of active radio interference
Performance with multipath reflections

Performance of wireless networks

Physical layer and medium effects

With radio communication, the physical channel quality is always a source of uncertainty.

Early in the course of our research we took up the task of documenting performance parameters with changing physical parameters. A set of results presented here shows the effect of distance and interference on network delays and jitter.


Average round trip delay and standard deviation versus distance

a) 802.11a
b) 802.11b
c) 802.11g
d) Bluetooth

Performance of wireless networks › **Physical layer and medium effects**

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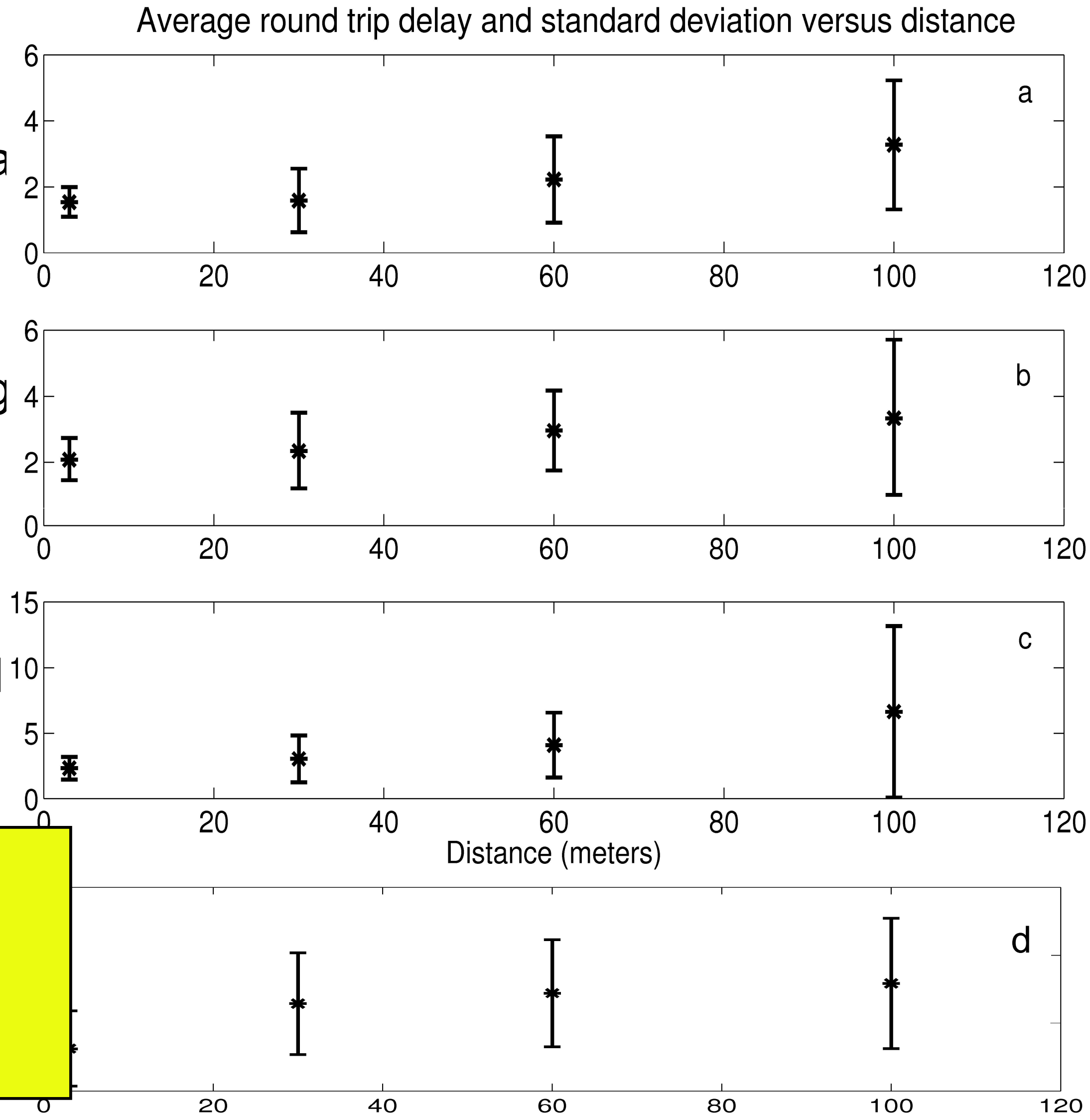

With increasing distance we see a steady increase in the standard deviation and the average delay.

Performance of wireless networks

Physical layer and medium effects

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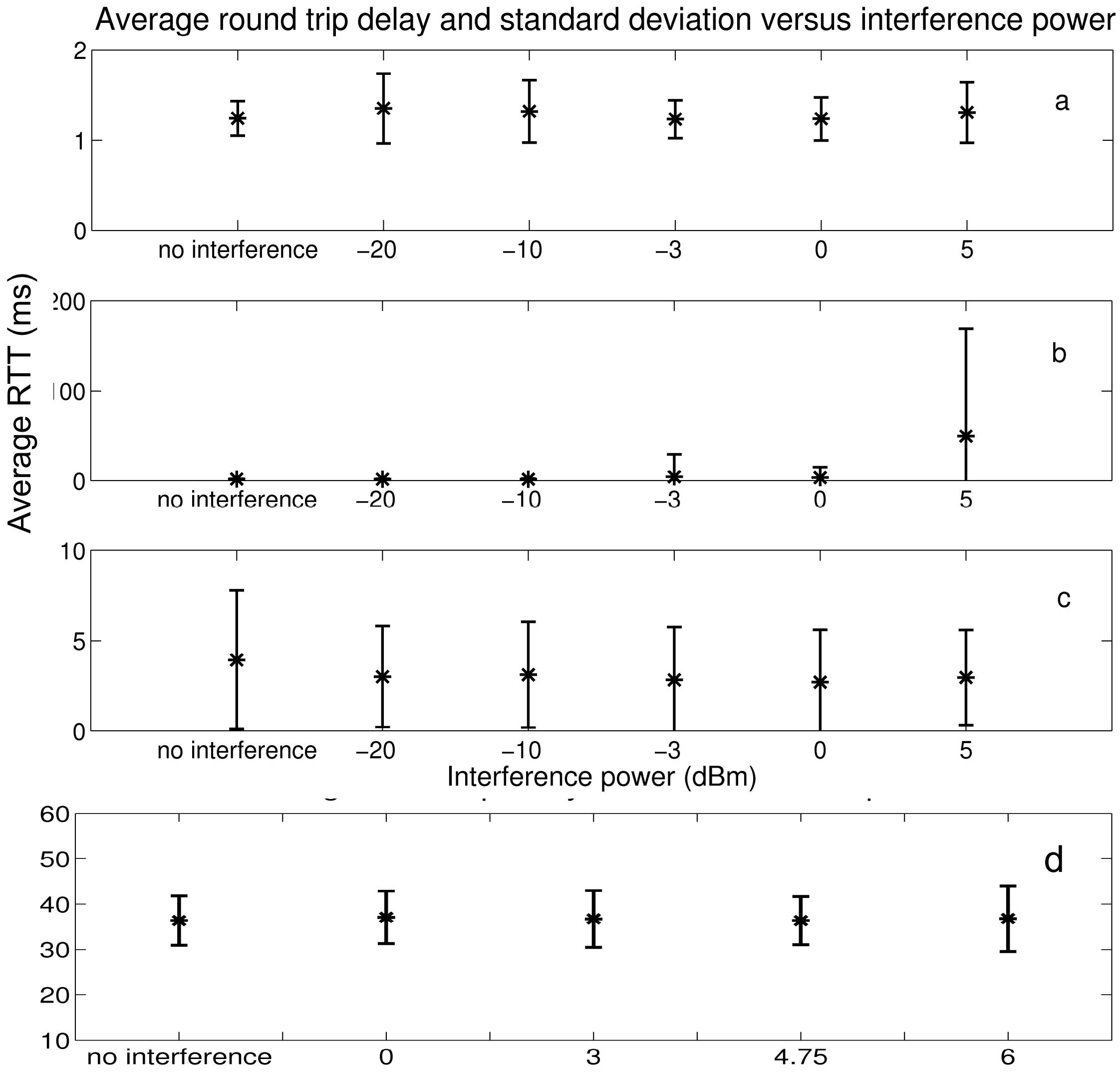

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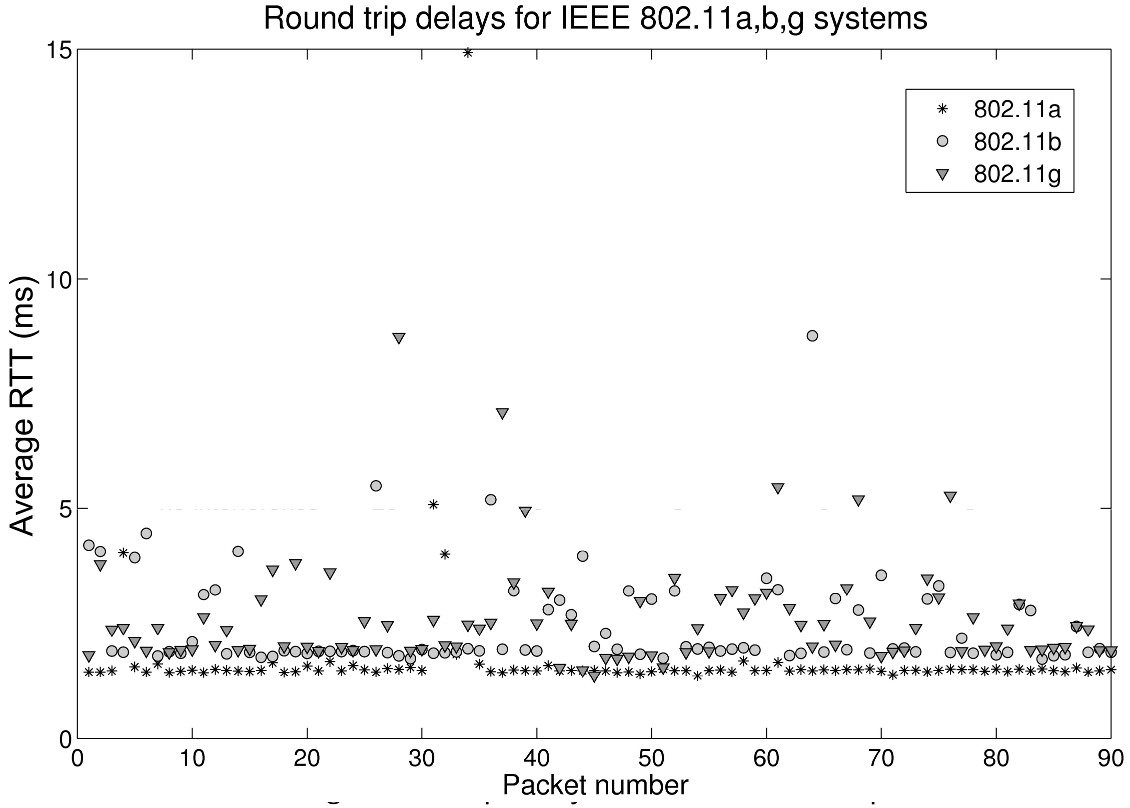

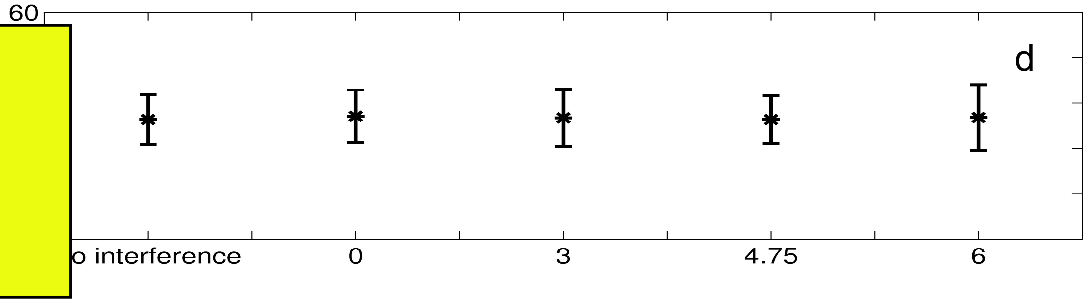

With increasing interference power the delays in communication are bursty and sporadic.

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Another significant factor affecting the physical channel is multipath interference. An experiment shown below measures Bluetooth latency under conditions where there were no reflections and then in a reflection rich environment.

Facilities and equipment courtesy:

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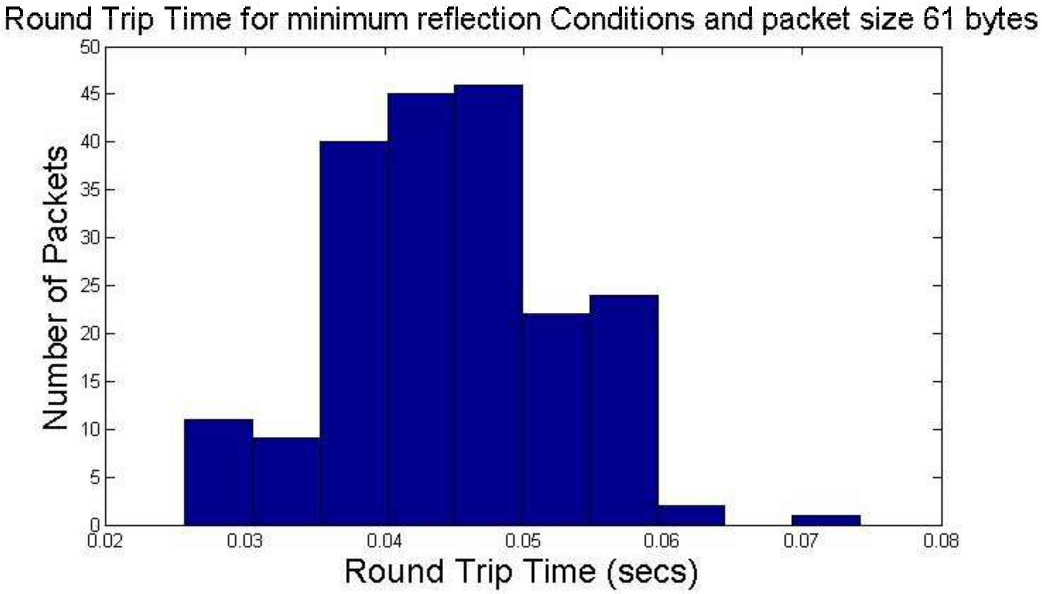
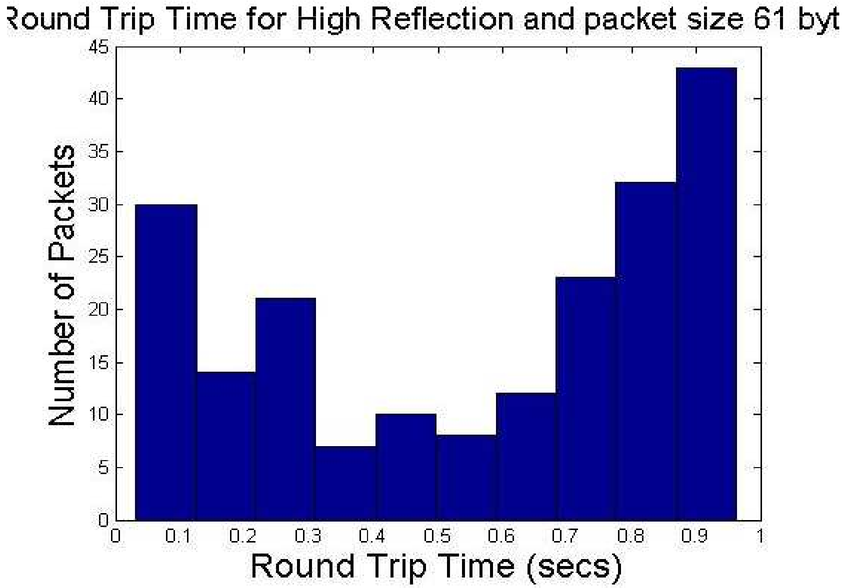
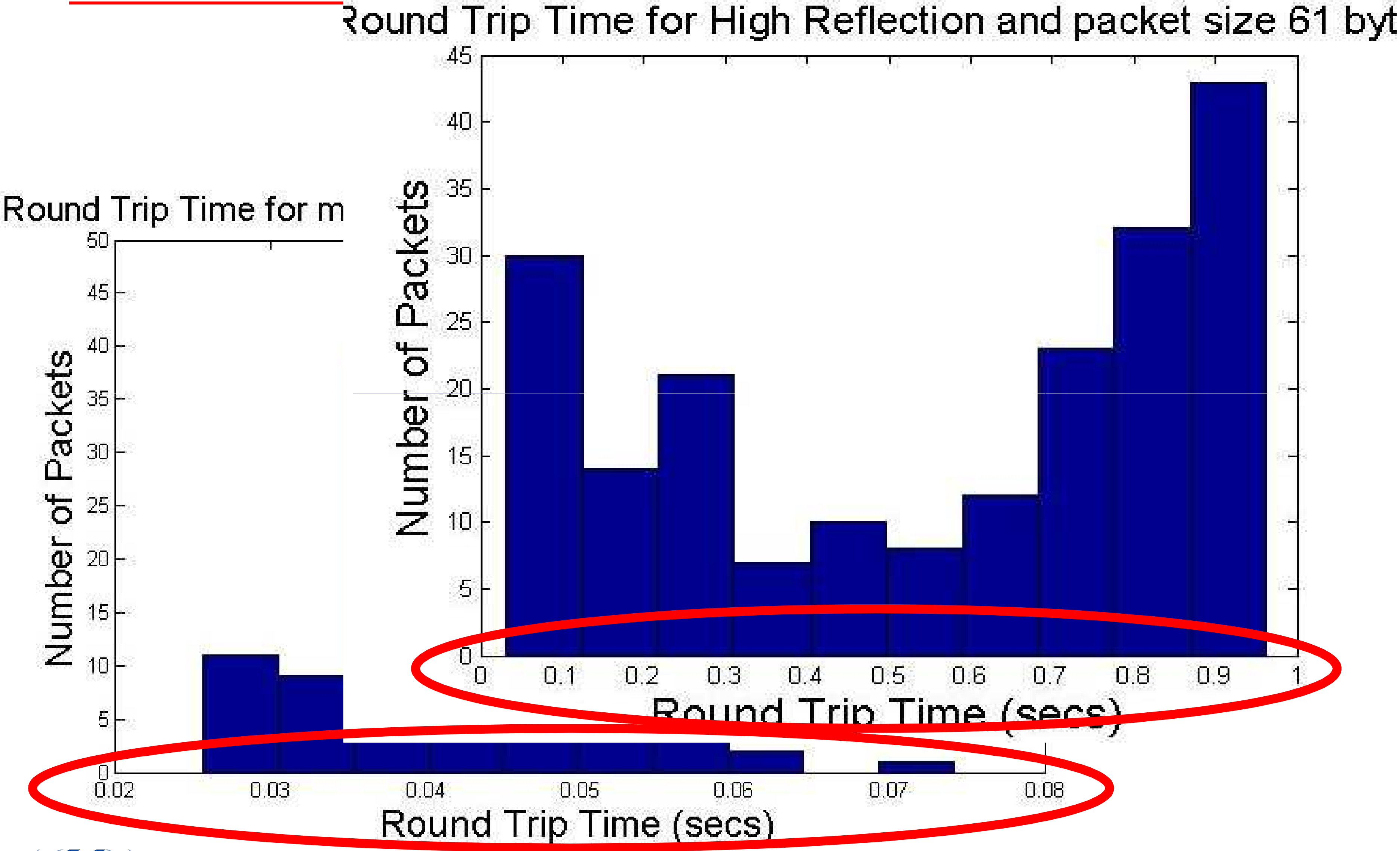
The histograms below show the delay spread for these two runs. The distance between the two devices was fixed at 2 meters (well within the rated distance) and there were no active interference sources (the test chambers provide a -200dB attenuation to the outside world).

The reflections in the second run of the experiment result in an order of magnitude increase in the delay times.






Round Trip Time for High Reflection and packet size 61 byt
Number of Packets
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Round Trip Time (secs)
Round Trip Time for m
Number of Packets
0
5
10
15
20
25
30
35
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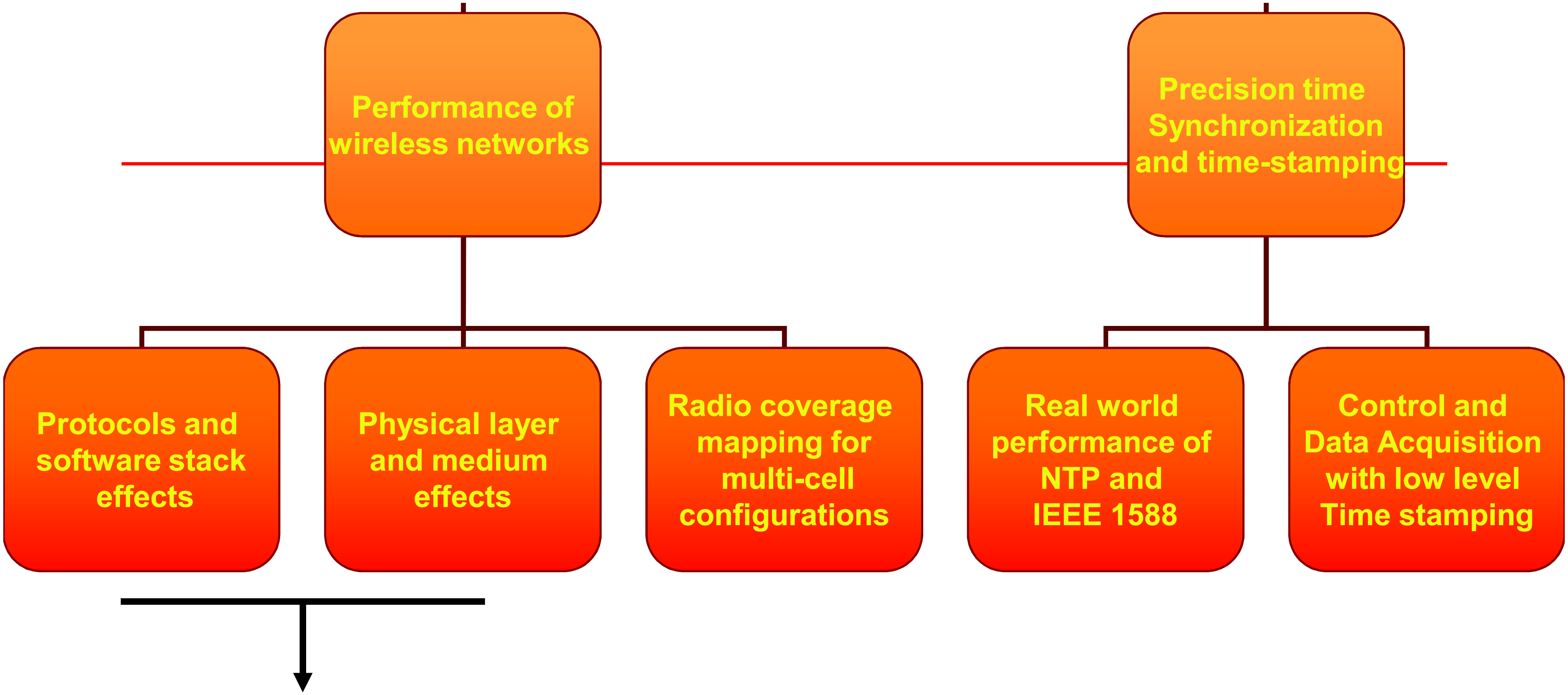
45
50
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Round Trip Time (secs)



Performance of wireless networks

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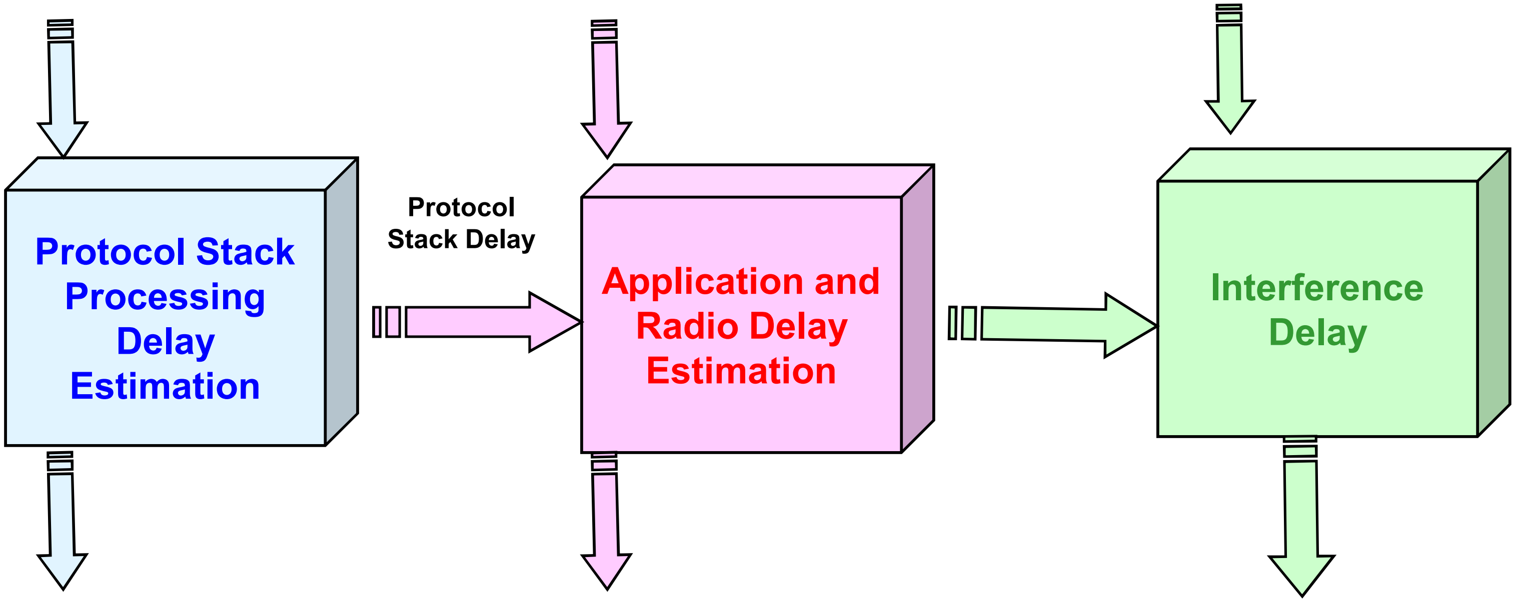
Network performance simulation

Wireless Control Network Simulator



Device Measurement
- **Actual Device Pair**
- **1 Client 1 Server**
- **Ideal Conditions**

Application and Radio Parameters
- Node Number
- Node Distance
- Signal Power
- Application Data Requirements

Interference Parameters
- Coexistence Interference Source
- Interference Source Distance
- Interference Source Signal Power

or

- Interference Model File

Protocol Stack Processing Delay Estimation

Protocol Stack Delay

Application and Radio Delay Estimation

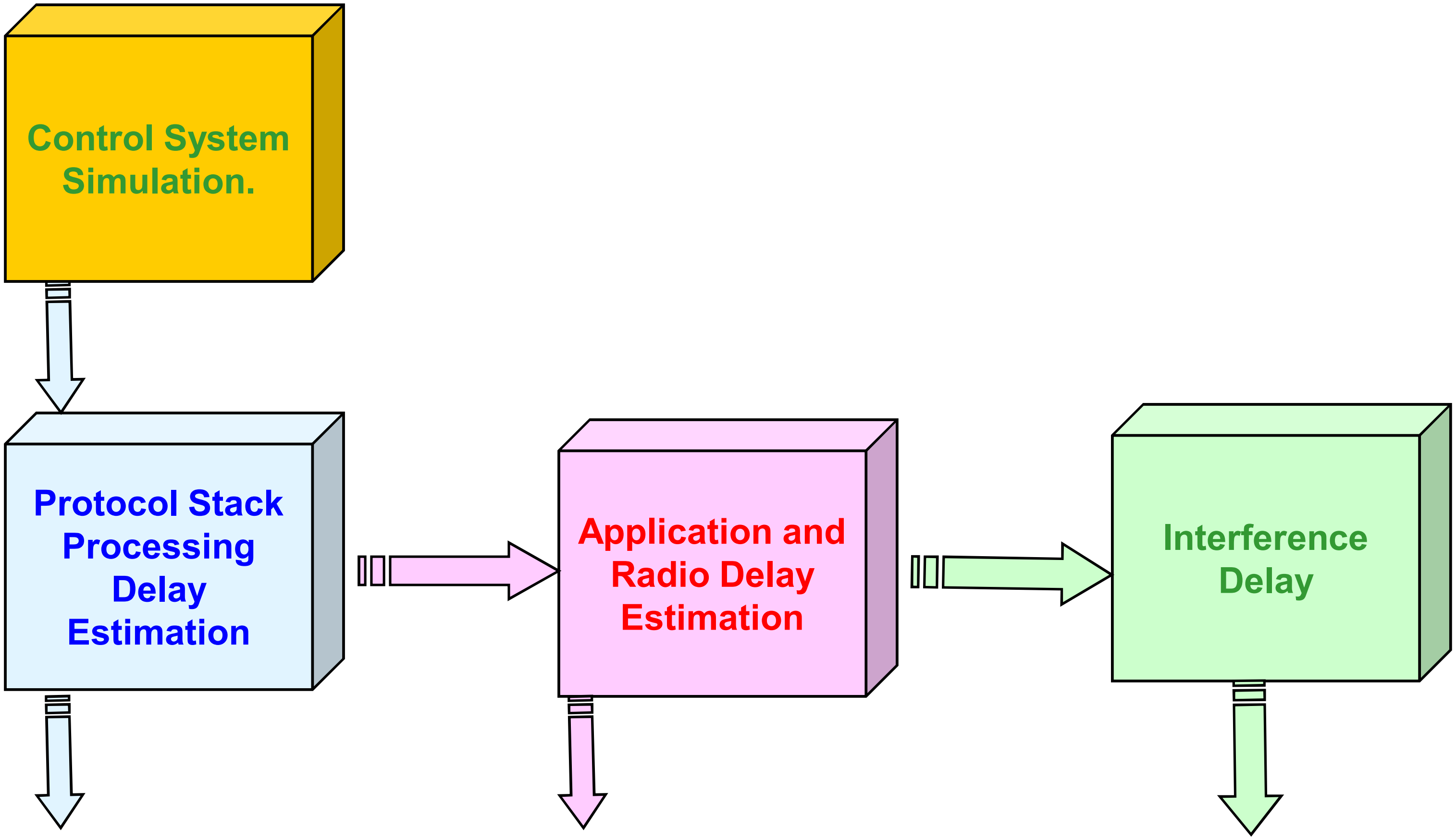
Interference Delay

- **Device Specific Wireless Protocol Stack Delay**

- **Delays due to arbitration**
- **Link Management dynamics.**

- **Delay with Interference**
- **Delay Output Graph**
- **Delay output file**

Wireless Control Network Simulator



Control System Simulation.

Protocol Stack Processing Delay Estimation

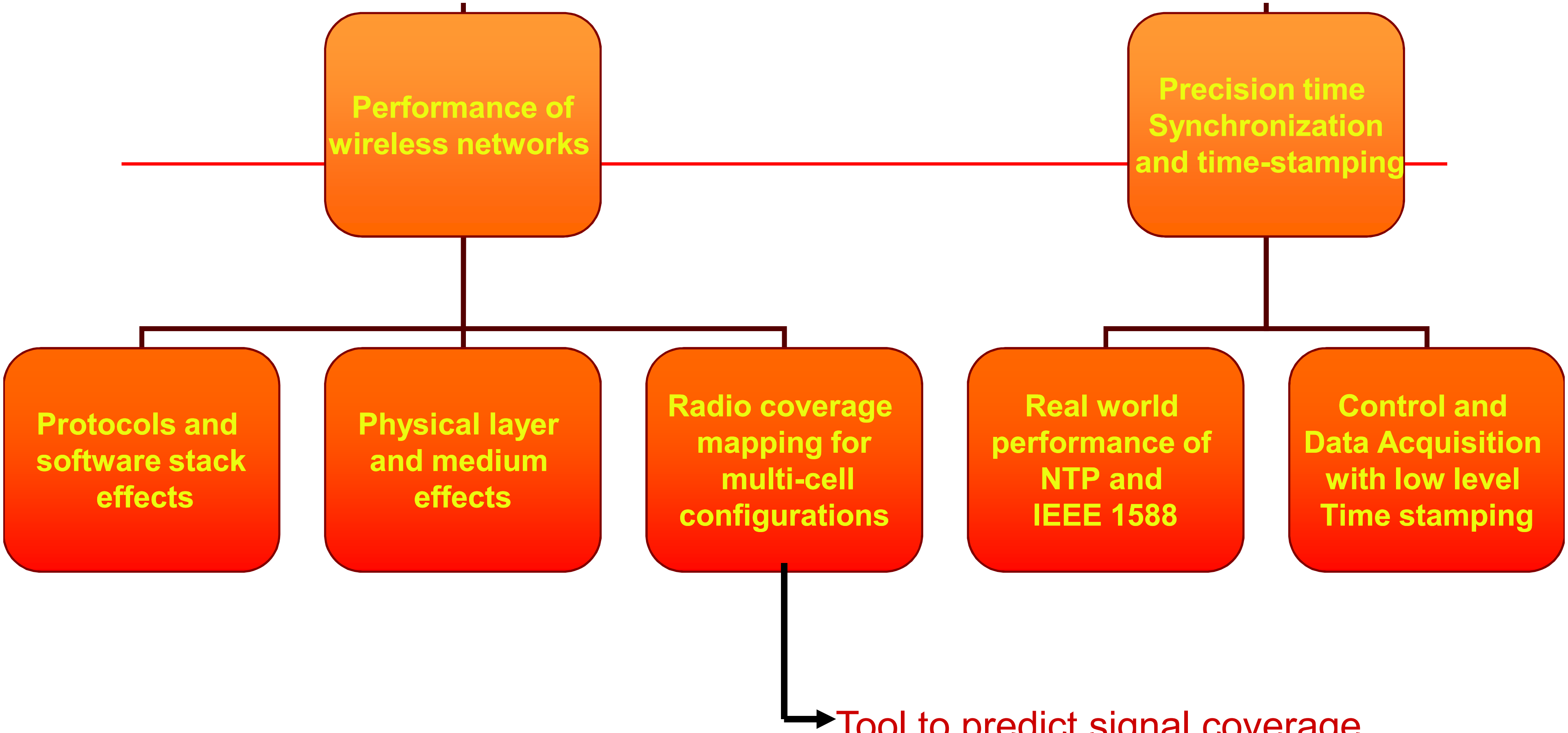
Application and Radio Delay Estimation

Interference Delay

- Sampling Rate
- System Bandwidth
- Min RPI

- Optimal Sampling rate.
- Ideal packet size.
- Packet prioritization and determinism improvement algorithms.

- Failure Modes.
- Recovery strategies.
- Fault tolerance/ Robustness



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Tool to predict signal coverage
A-priori co-channel interference detection
Wireless system health monitoring

Performance of wireless networks

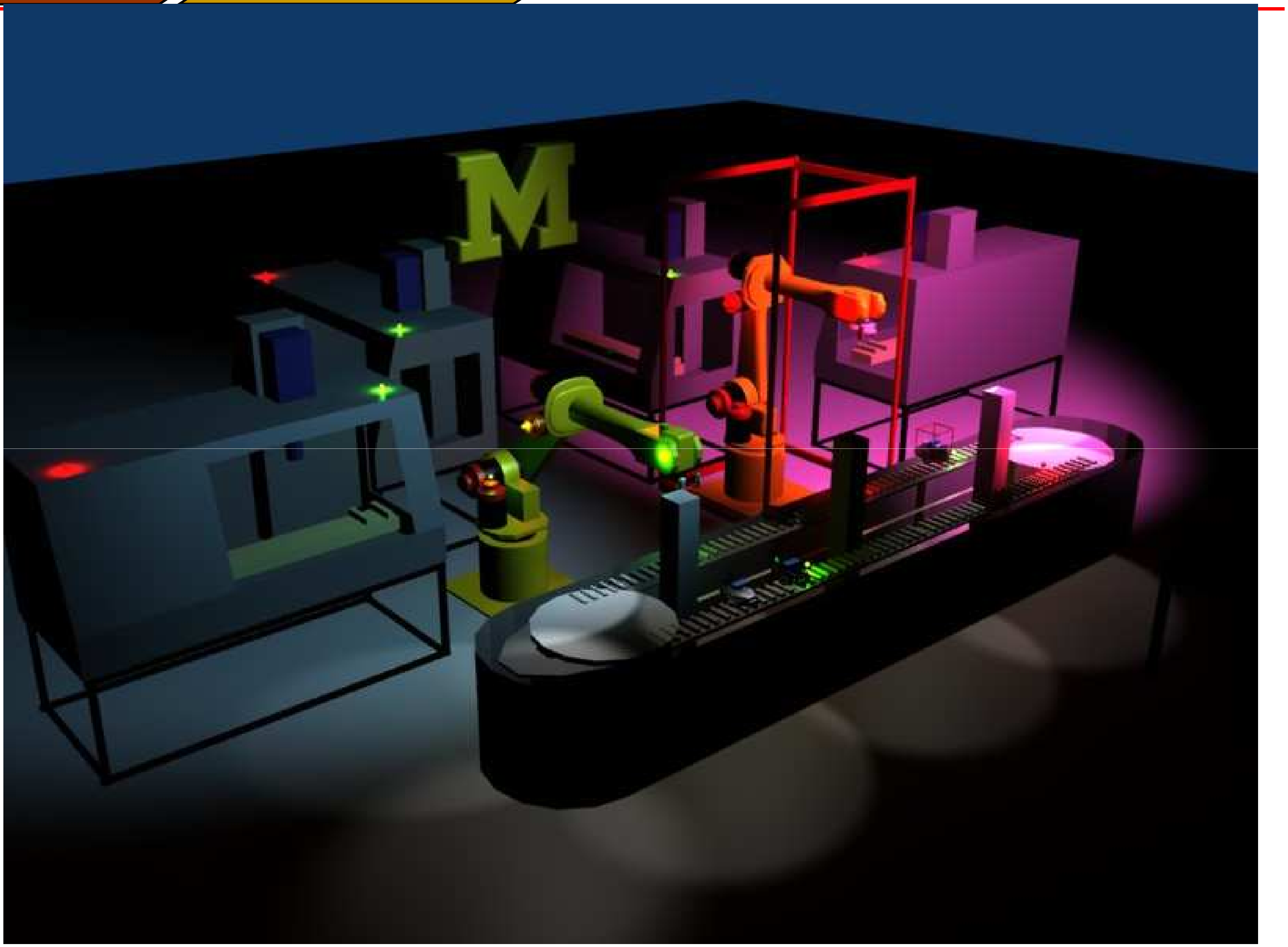
Radio coverage mapping

Inputs from industry suggest that implementation of wireless will first be at a production cell level. Inter-cell interference is therefore an important factor and requires layout planning ahead of installation.

To support this we are developing a simulation tool capable of predicting radio coverage over a wireless cell. Overlaying spatial representation of radio coverage over the existing cell geometry.

Using data from our performance measurement exercise we can look for trouble spots in the form of weak fields, shadow zones, interference and leakage outside the cell.

We can also overlay coverage maps of non-conventional radio feeders like the leaky coax cable or directional patch antenna.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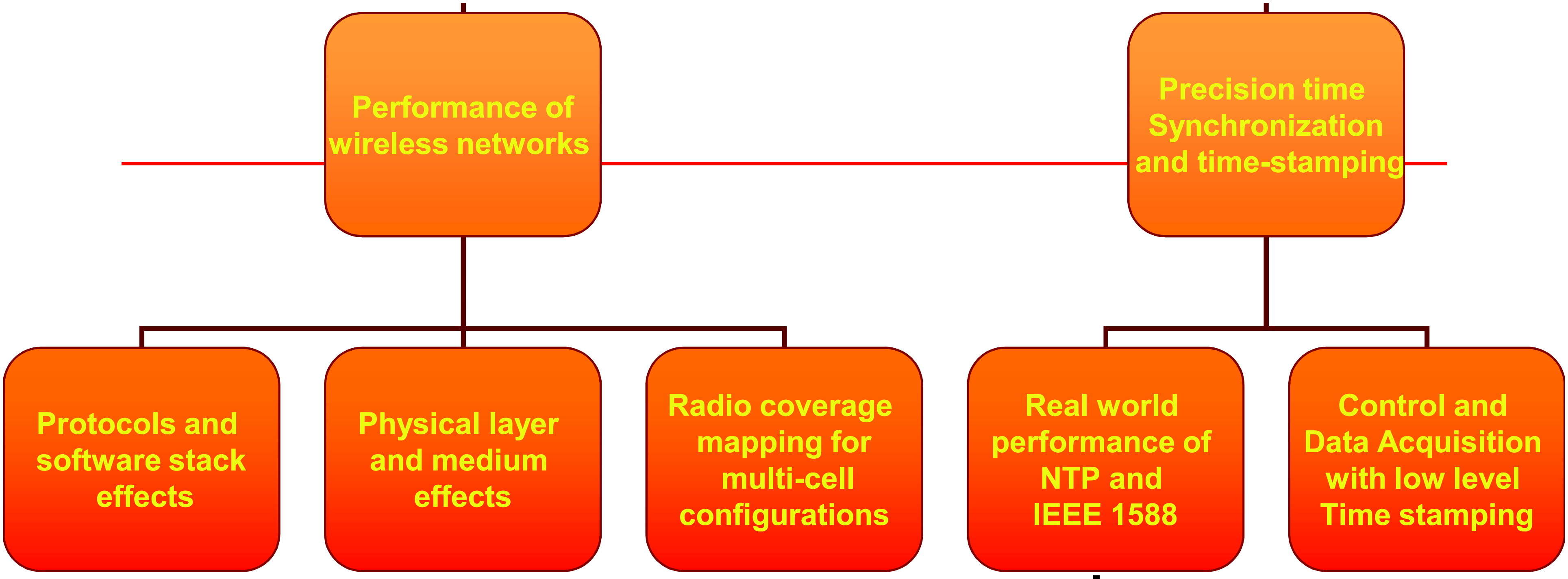

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Time synchronization performance in industrial networks

Determining timing accuracy for distributed process control

Precision time Synchronization

NTP and IEEE 1588

Two nodes can be precisely synchronized in time to one another over the network.

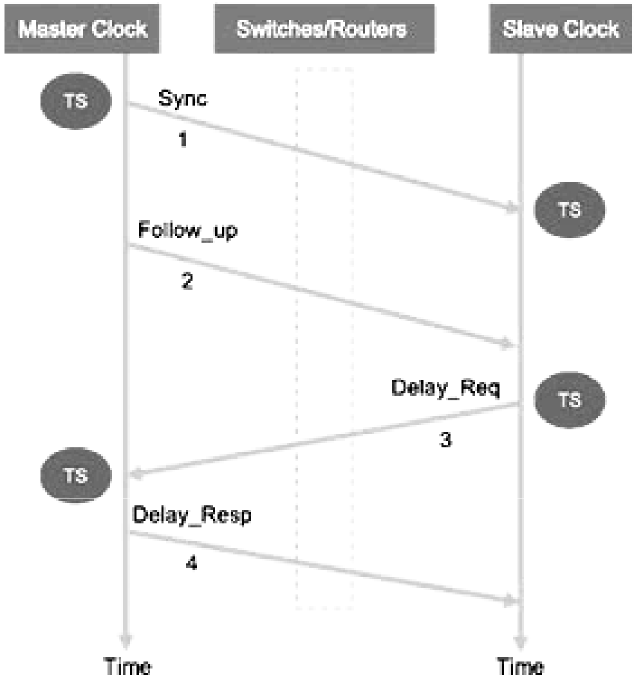
This can be done once a real time model of transmission delays over a network is produced.

Two prevalent techniques for this are NTP and IEEE 1588.

NTP implements this algorithm as a software daemon running on top the operating system.

IEEE 1588 mandates the use of dedicated firmware to perform this function.

1588 is amenable to being grafted onto field-bus sensors and actuators.



NTP accuracy ~ 100 μs

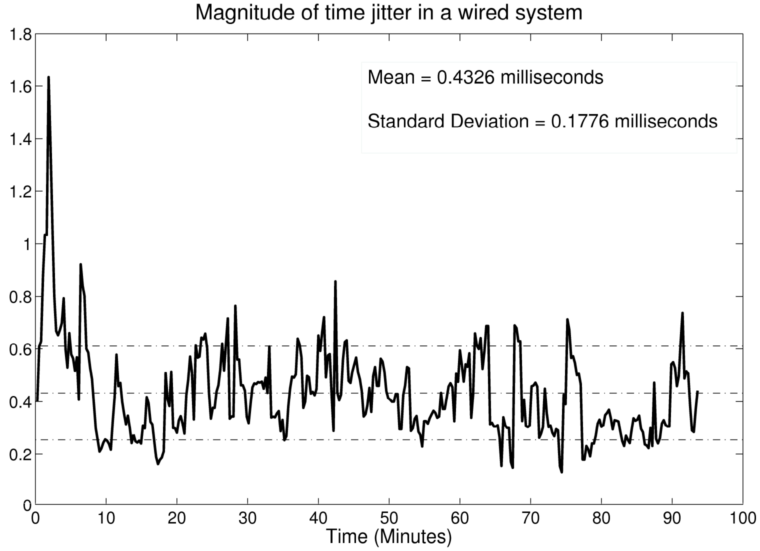
1588 accuracy ~ <1 μs

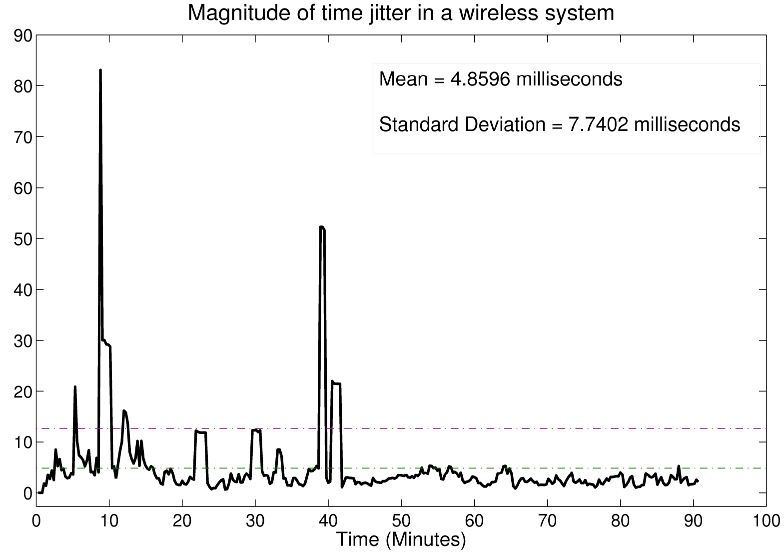
New result

Further investigation is required to understand time synchronization accuracy over wireless networks.

Initial experiments with NTP show a large increase in the jitter as estimated by the time synchronization algorithm. This reflects the degree of uncertainty in the system.

Looking at 1588 synchronization over wireless will allow us to justify the need for low level time synchronization.





- Performance of wireless networks
  - Protocols and software stack effects
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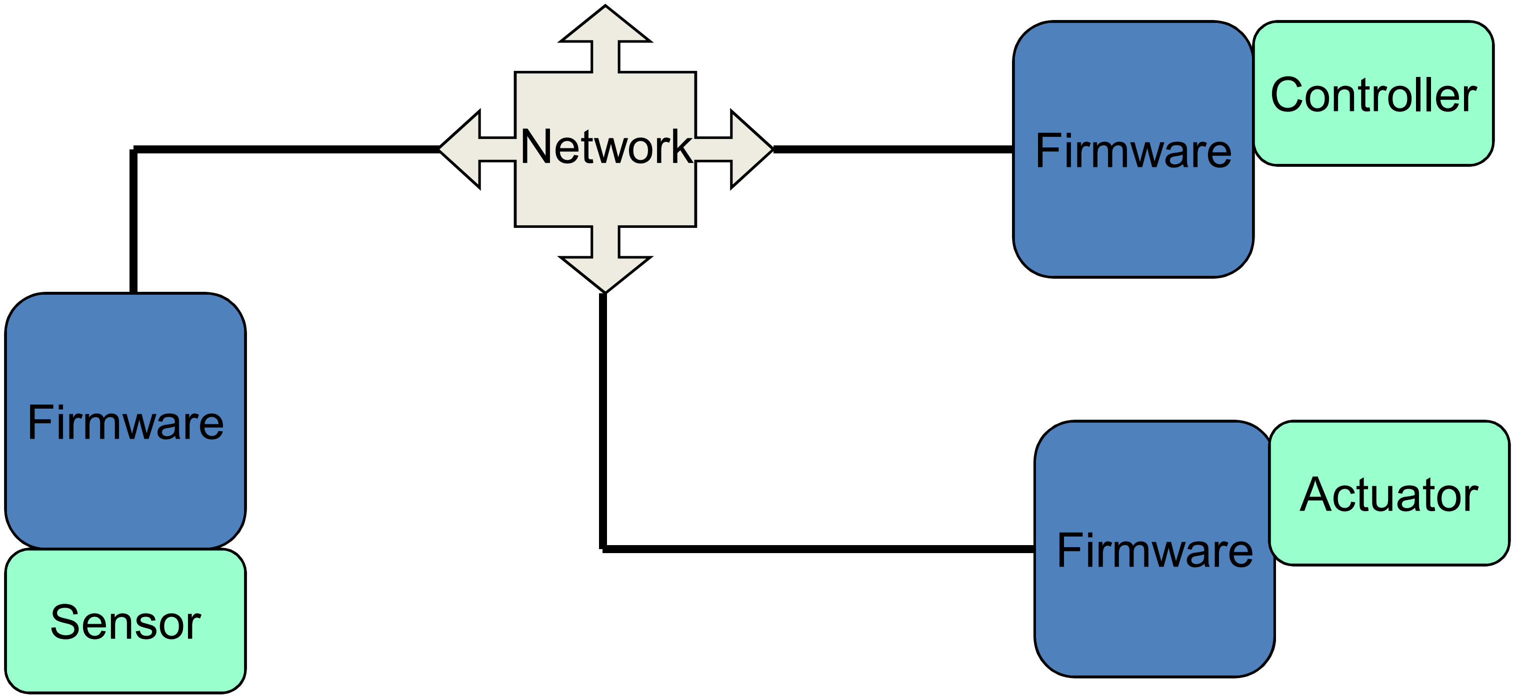
- Precision time Synchronization and time-stamping
  - Real world performance of NTP and IEEE 1588
  - Control and Data Acquisition with low level Time stamping
    - Designing controllers capable of utilizing time stamped data
    - Designing hardware with 1588 derived time stamps
    - Best practices for time stamping

Once two nodes are synchronized, time stamping data at the source ensures that even with unknown delays in the transmission, information about when the event occurred is conserved in a global time frame.



Precision time Synchronization → **Low level time stamping**

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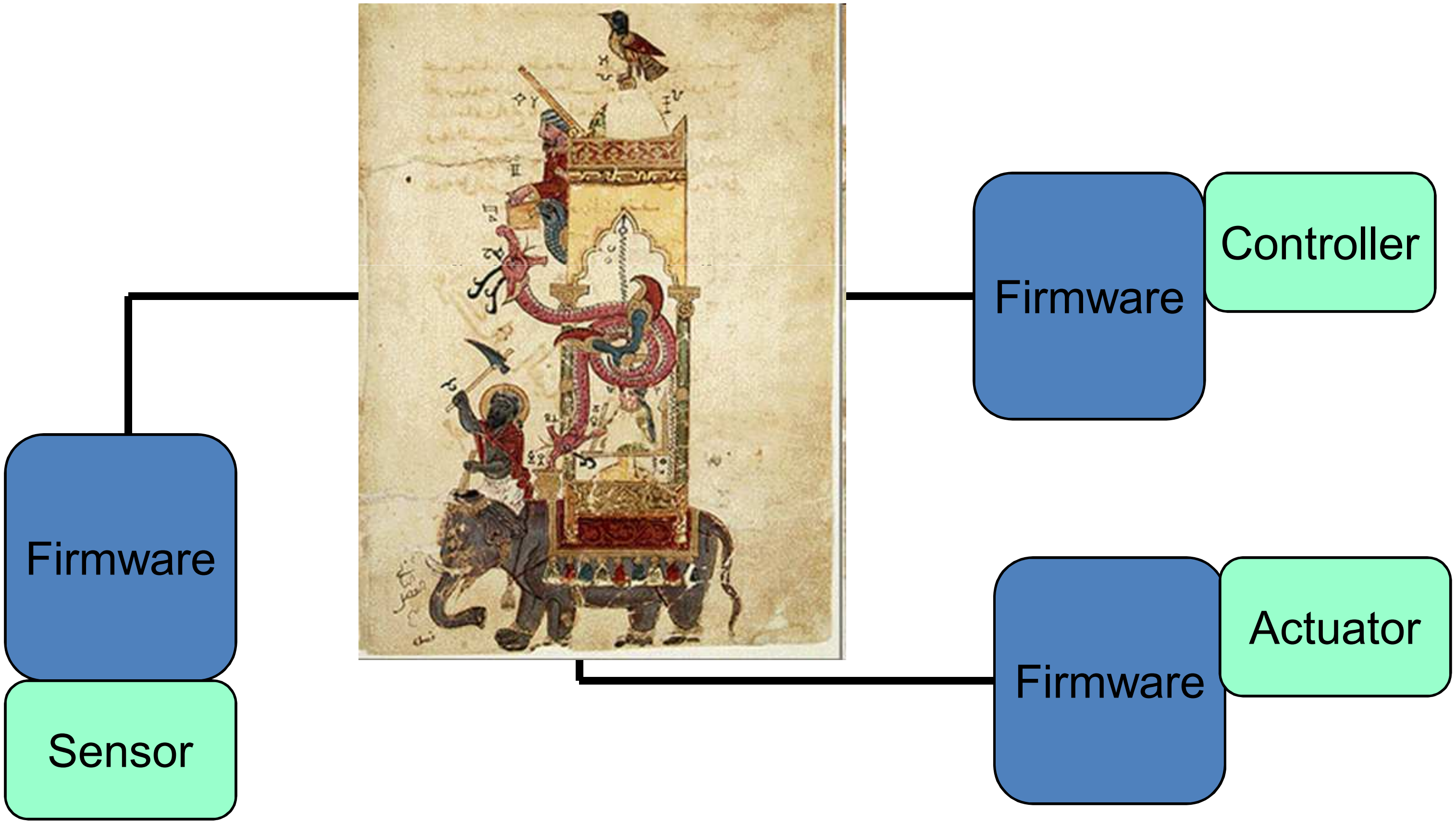

Firmware

Controller

Firmware

Sensor

Firmware

Actuator

Precision time Synchronization
Low level time stamping

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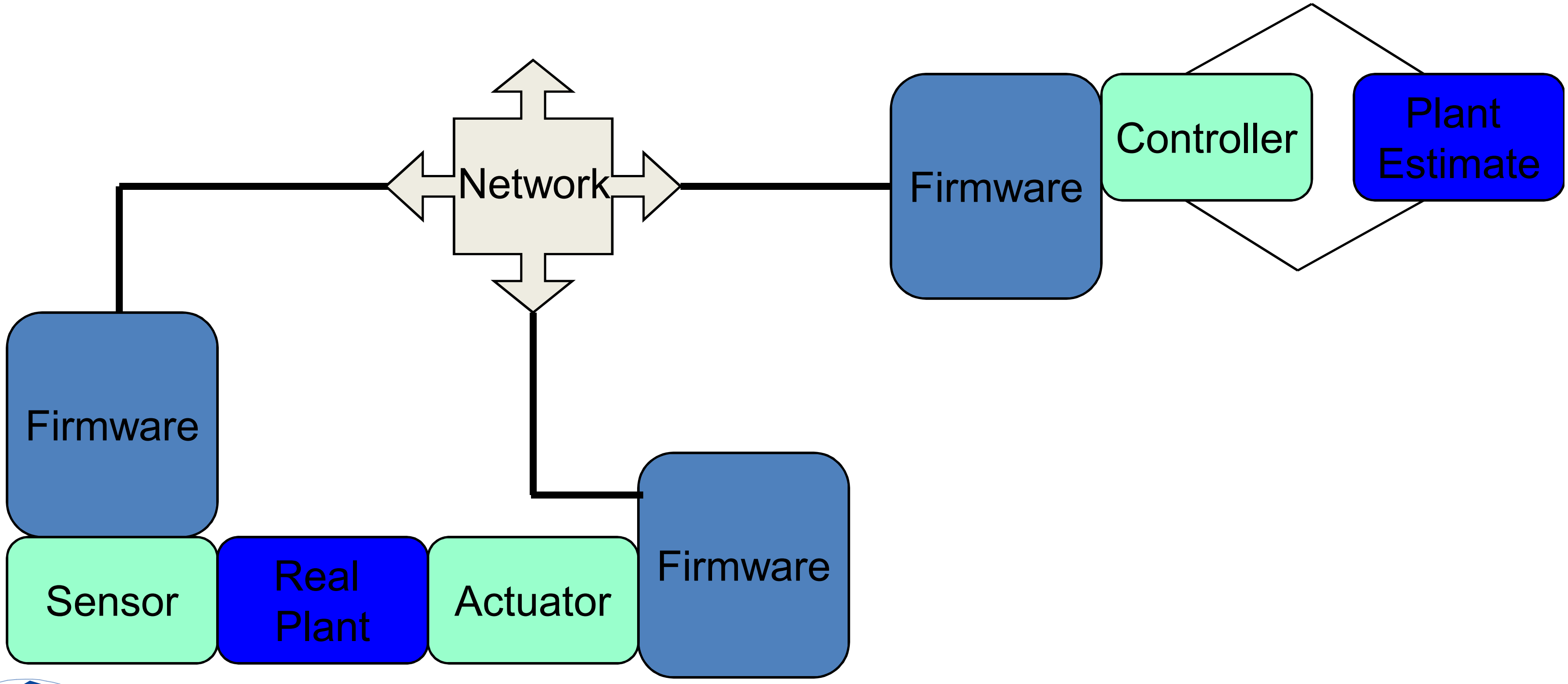


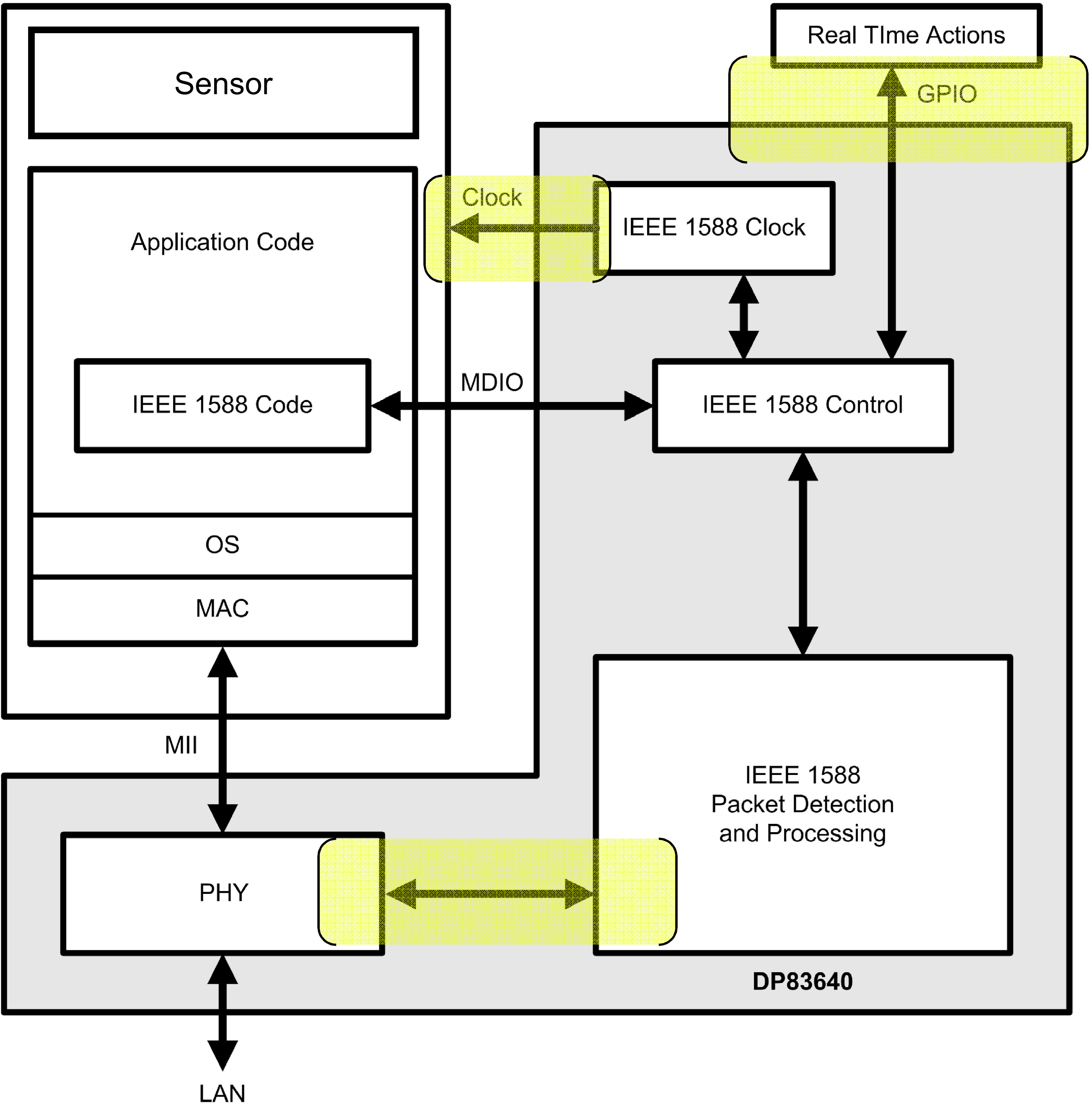
Precision time Synchronization

RX/TX packet parser injection

1588 Event Triggering

1588 Event Timestamping

1588 regulated scalable clock



Take aways

- *As expected with microwave transmissions in closed spaces, multi-path propagation effects dominate system performance.*
- *There are algorithm improvements that in simulation show appreciable improvement.*
- *We can predict failure conditions in the physical medium banking on our catalog of device tests.*
- *We have to study the protocol stack from a timing perspective.*
- *With precise time synchronization and time stamping, control is not wholly dependent on real-time network transmission.*

Milestones and Future Plans

September 2008	Device testing at Ford AMTD
November 2008	Development work on Wireless Network Simulator begun.
February 2009	Completed comprehensive catalog of test results
March 2009	Design approval for 1588 test-bed
April 2009	Performance evaluation of wireless protocol stack begun
April 2009	1588 test-bed Phase II completed
Summer 2009	First release of the Wireless Network Simulator 1588 test-bed phase III
Fall 2009	Wireless cell layout tool 1588 test-bed phase IV

References

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7. Time Synchronization in Semiconductor Manufacturing. *Proceedings of the IEEE 1588 Conference*, October 2007
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Thank You

Questions?