Networking Infrastructure and Data Management for Cyber-Physical Systems

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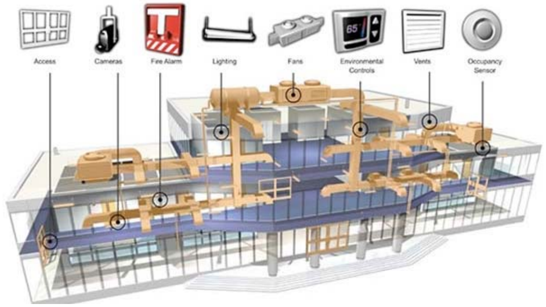
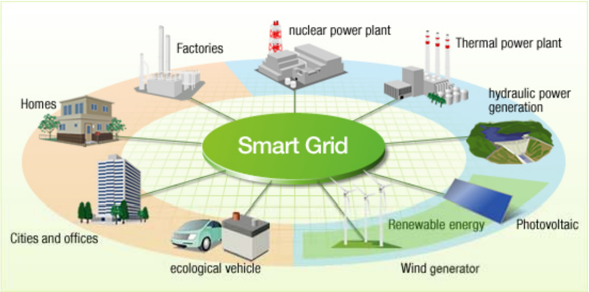
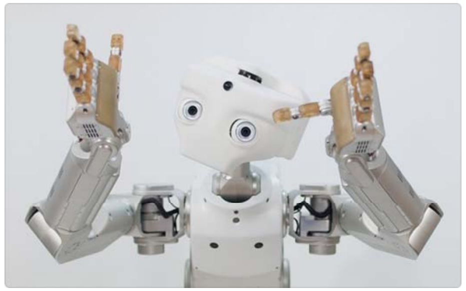
What is Cyber-Physical System (CPS)?

Cyber-physical system is a system featuring a tight combination of, and coordination between, the system's computational and physical elements.

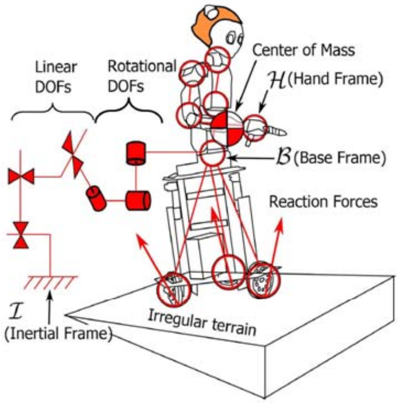


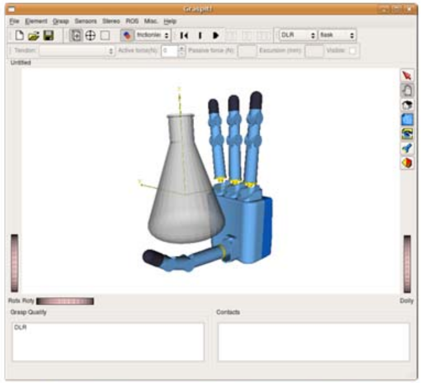




CPS Application – Cyberphysical Avatar

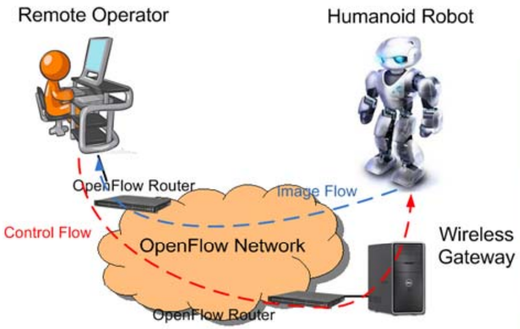
Dynamic Model and Control Structure Design

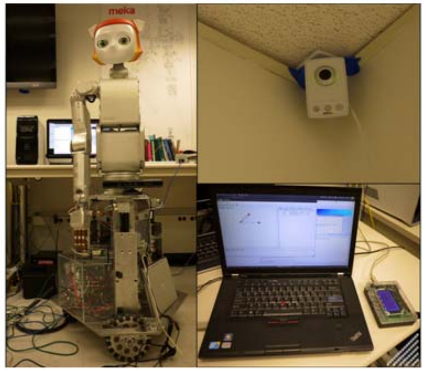

Linear DOFs
Rotational DOFs
Center of Mass
$\mathcal{H}$ (Hand Frame)
$\mathcal{B}$ (Base Frame)
Reaction Forces
$\mathcal{I}$ (Inertial Frame)
Irregular terrain



Skill Acquisition through Machine Learning

Real-time Avatar-Human Interaction

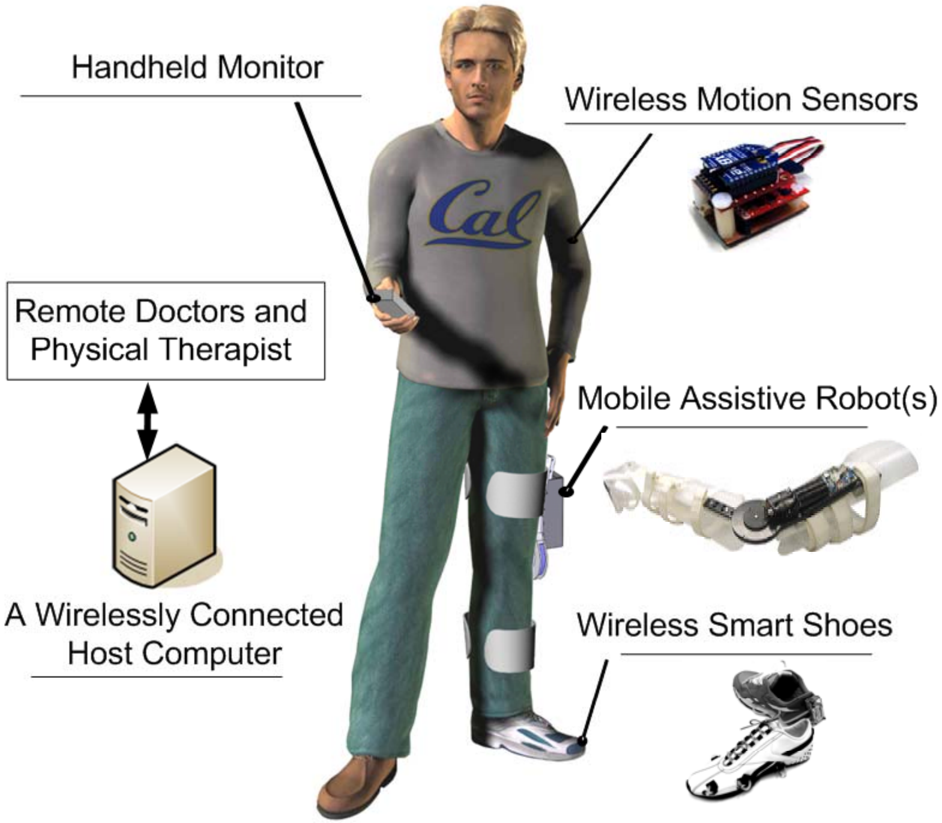




Prototype Testbed

Cyberphysical Avatar: A semi-autonomous robotic system (joint project with UT Human Centered Robotics Lab)

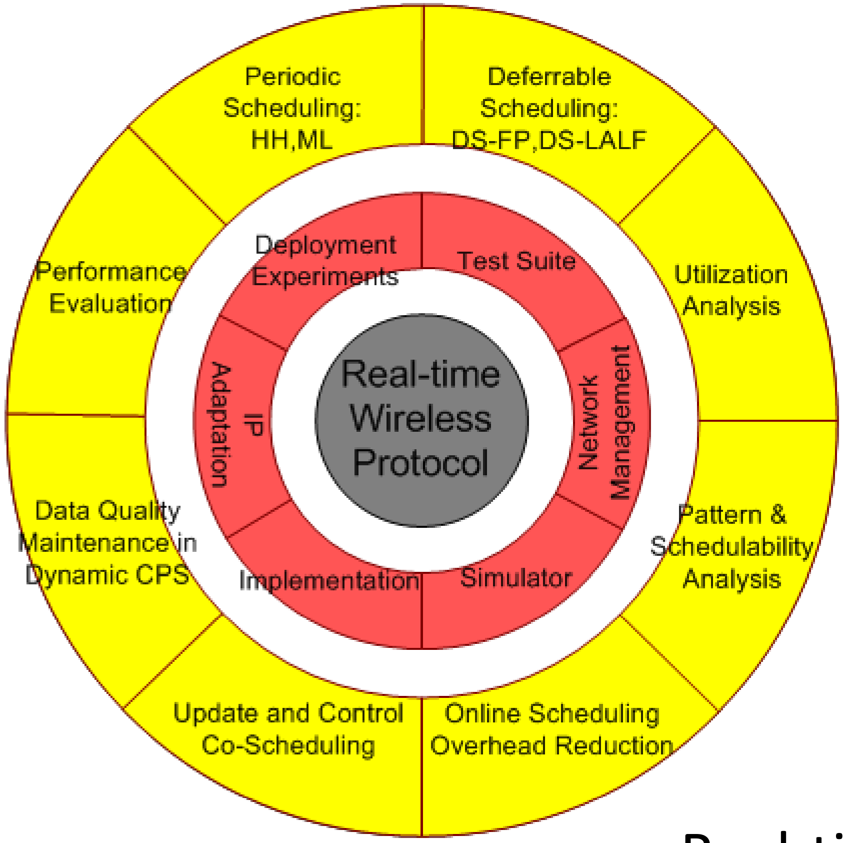
CPS Application – Network-based Mobile Gait Rehabilitation System


Handheld Monitor
Wireless Motion Sensors
Remote Doctors and Physical Therapist
Mobile Assistive Robot(s)
A Wirelessly Connected Host Computer
Wireless Smart Shoes
Cal

- Integrating heterogeneous sensors into real-time wireless platform
- Low-level motion control of rehabilitation device over wireless network
- Development of high-level decision making algorithm

Network-based Mobile Gait Rehabilitation System (joint project with Mechanical Systems Control Laboratory, UC Berkeley)

Research Overview



Real-time Wireless Protocol

Deployment Experiments

Test Suite

Network Management

Simulator

Implementation

IP Adaptation

Periodic Scheduling: HH,ML

Deferrable Scheduling: DS-FP,DS-LALF

Utilization Analysis

Pattern & Schedulability Analysis

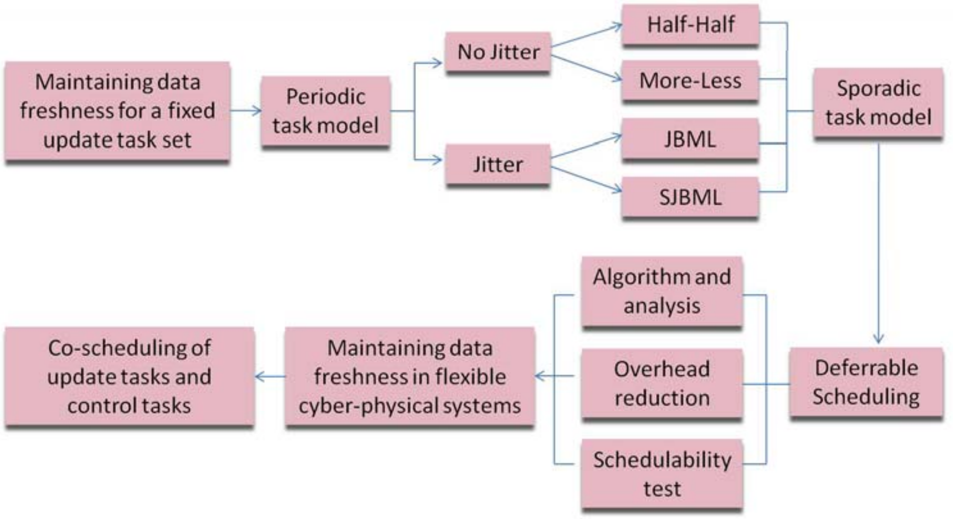
Online Scheduling Overhead Reduction

Update and Control Co-Scheduling

Data Quality Maintenance in Dynamic CPS

Performance Evaluation

Theoretical Framework for Real-time Data Management Techniques



Maintaining data freshness for a fixed update task set

Periodic task model

No Jitter

Jitter

Half-Half

More-Less

JBML

SJBML

Sporadic task model

Deferrable Scheduling

Algorithm and analysis

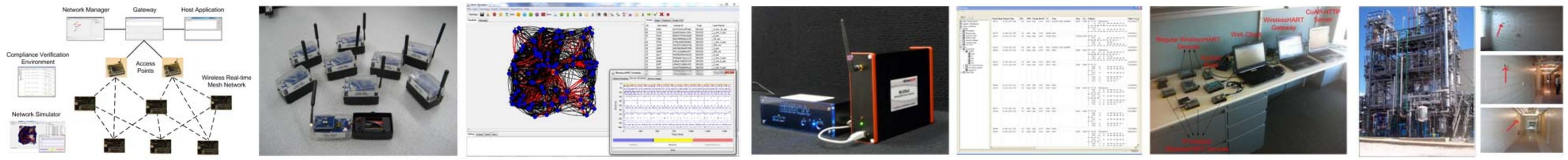
Overhead reduction

Schedulability test

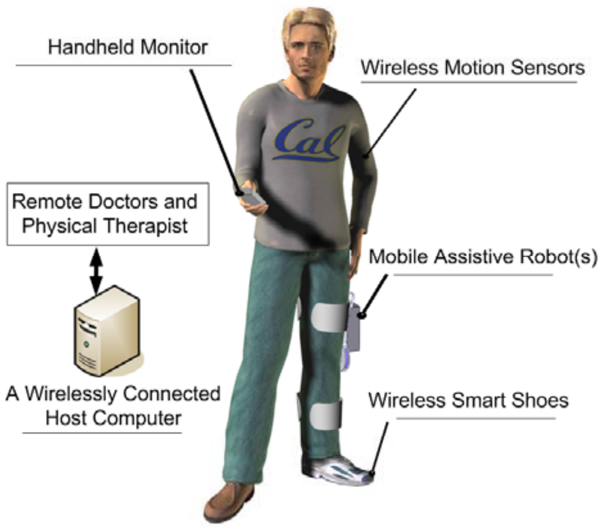
Maintaining data freshness in flexible cyber-physical systems

Co-scheduling of update tasks and control tasks

Real-time Wireless Communication Platform



Guiding Applications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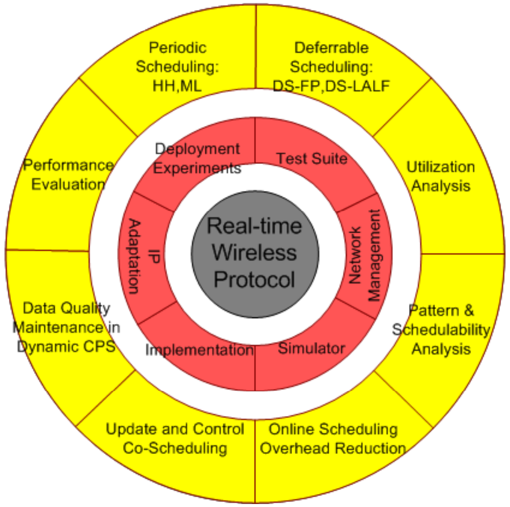
Network-based Rehabilitation System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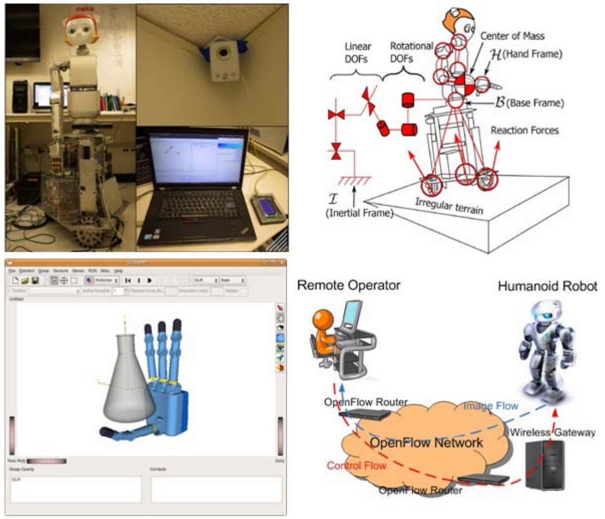
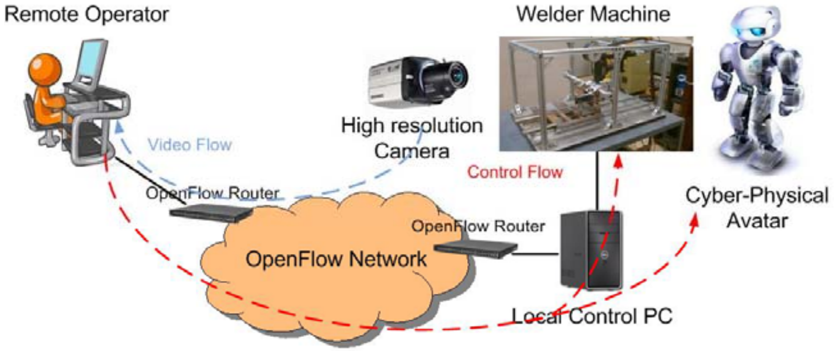


Cyberphysical Avatar



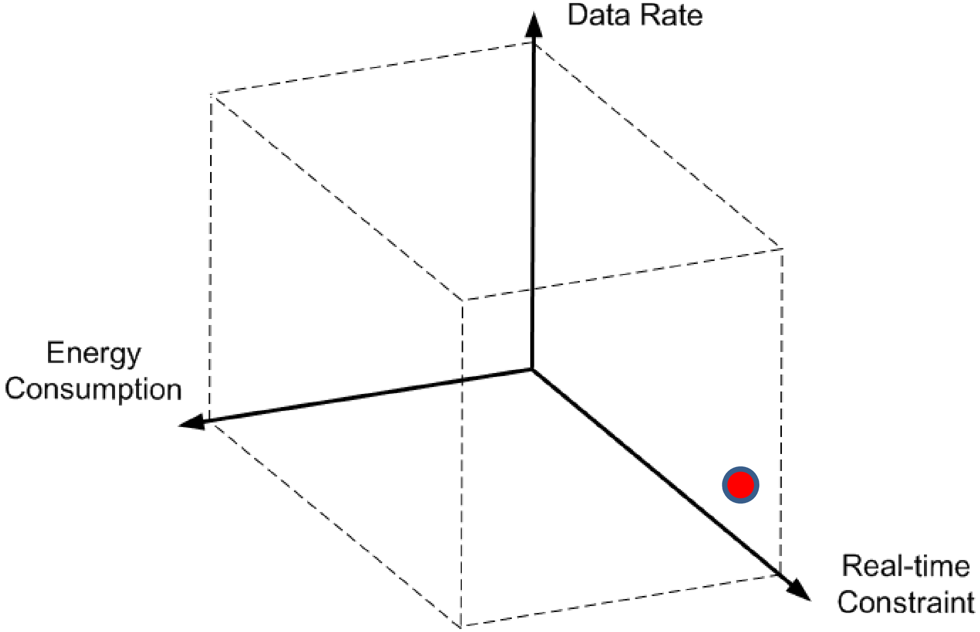
Remote and Real-time Welding System

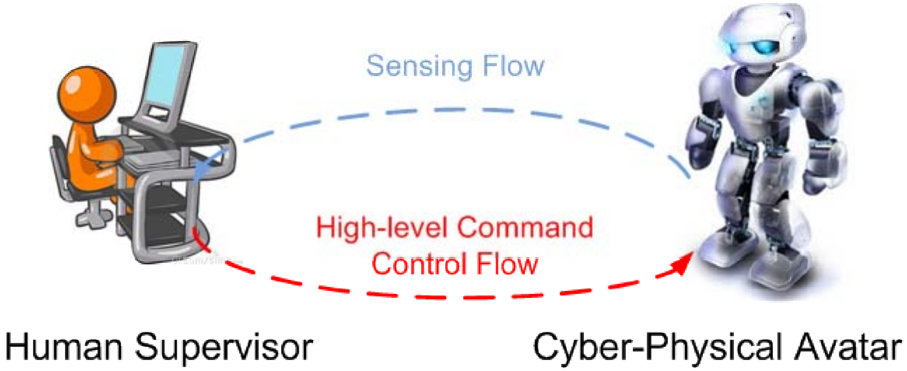
Outline

- Research Overview
- Reliable and Real-time Wireless Platform for CPS
  - Wireless real-time communication protocol
  - Network management techniques
  - System design and implementation
- Real-time Data Management in CPS
  - Model and assumptions
  - Algorithms and analysis
- Summary and Future Work

Wireless Reliable and Real-time Communication Platform

Design Space and Required Features





Low-power

- 802.15.4-based radio

Real-time

- TDMA Data Link Layer (DLL)
- Centralized management

Reliable

- Mesh networking
- Data link layer ACK
- Channel hopping mechanism

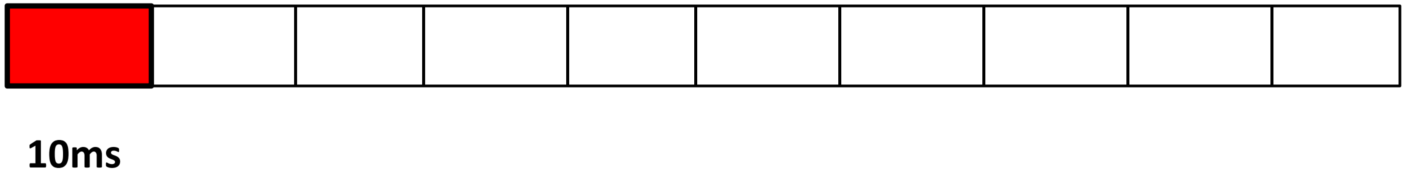
Secure

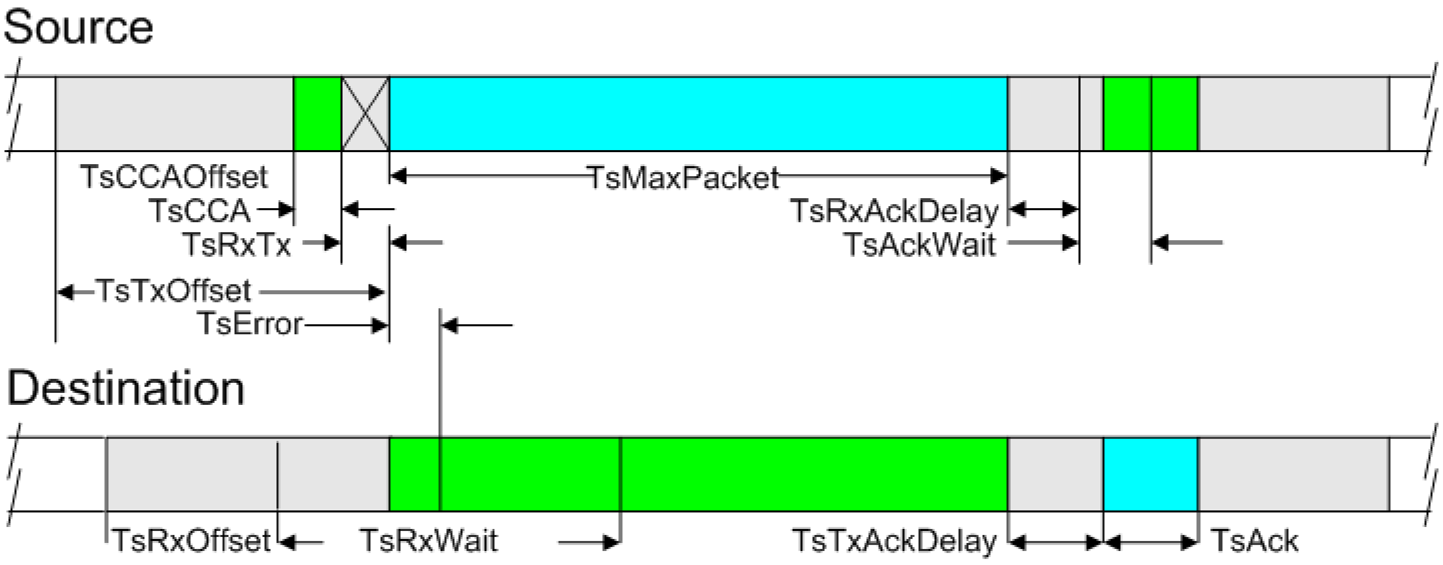
- Data integrity on DLL
- Data confidentiality on network layer (NL)

Overview of Our Real-time Protocol Stack

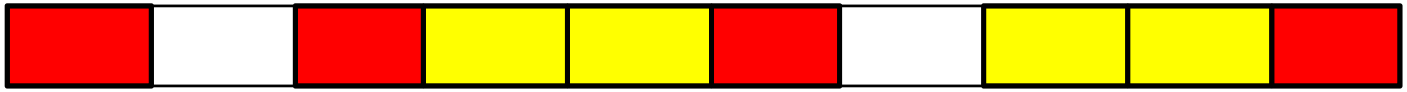
- TDMA-based Data Link Layer
  - Guarantee timely delivery
- Channel Hopping and Blacklisting
  - Spread communication in all active physical channels
  - Reduce interference to provide reliable communication
- Confidential and Secure Communication
  - Use both public and private keys to secure communication in both join process and normal operations

TDMA-based Data Link Layer





TDMA-based Data Link Layer



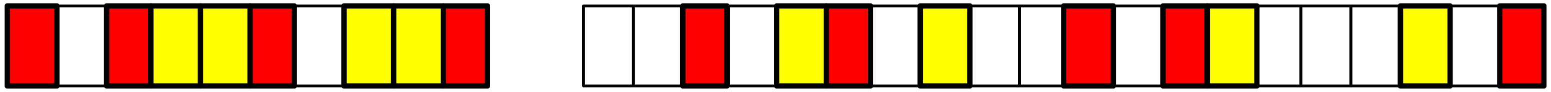
- Link: activity in a time slot
  - Neighbor
  - Send/Receive
  - Communication channel

□ Idle link

🟨 Send link

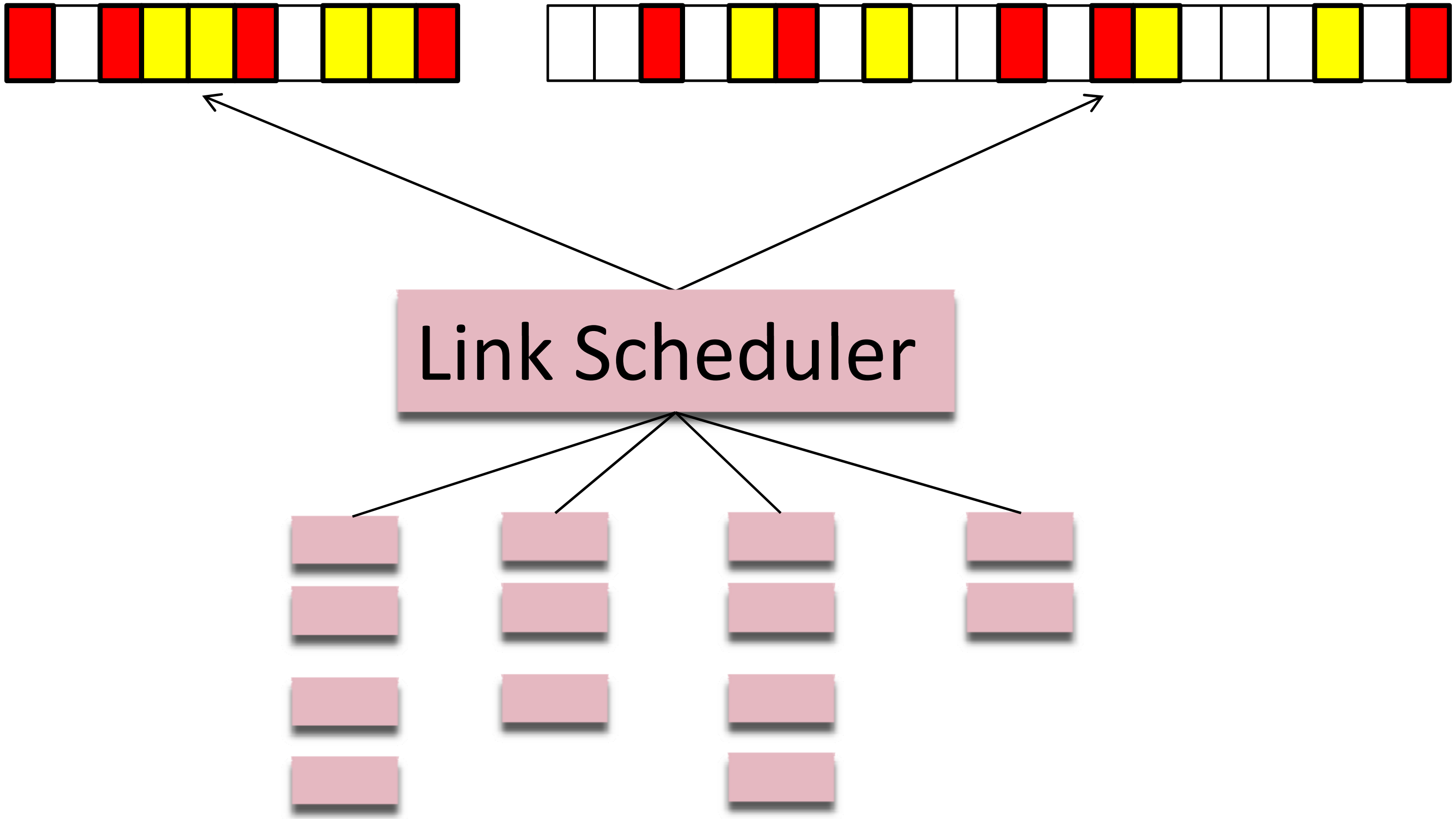
🟥 Receive link

TDMA-based Data Link Layer



- Superframe: a group of links
  - Repeat itself infinitely
  - A device can support several superframes

TDMA-based Data Link Layer



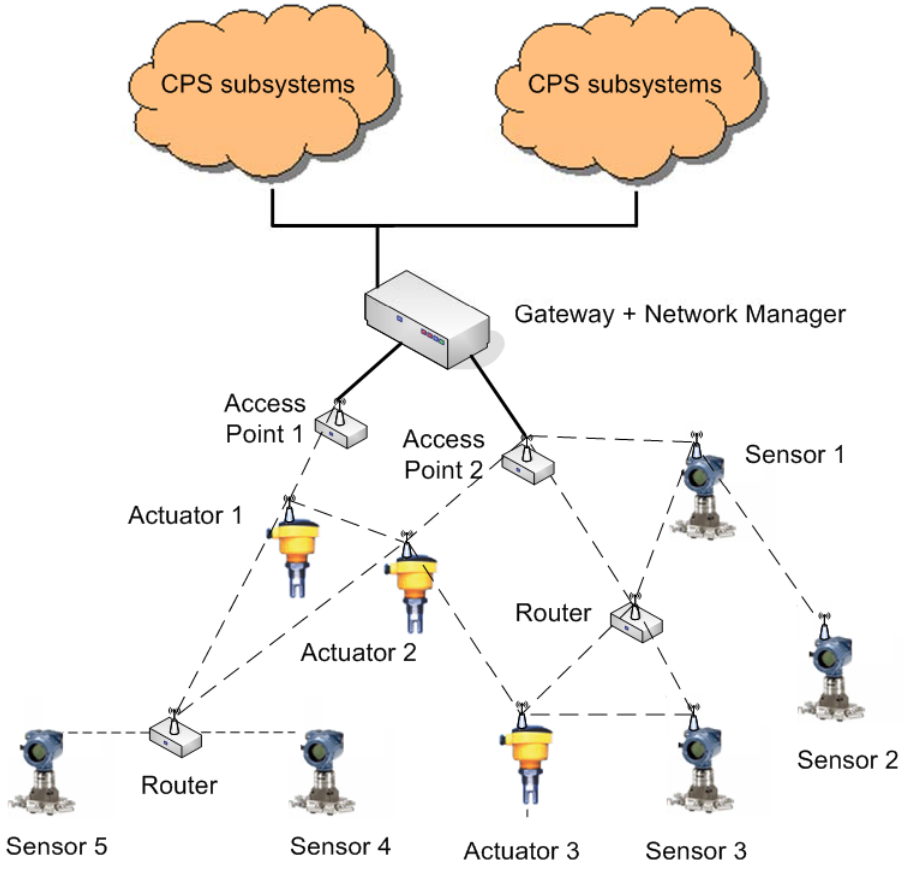
Priority queues for data link layer packets

How to Achieve Reliable and Real-time Services in CPS

- Network Manager
- Authenticating devices
- Forming the network
- Constructing routing graphs
- Scheduling DL transmissions

- Gateway
- Collecting/caching sensor data
- Process queries from other systems

- Security Manager
- Manage key information

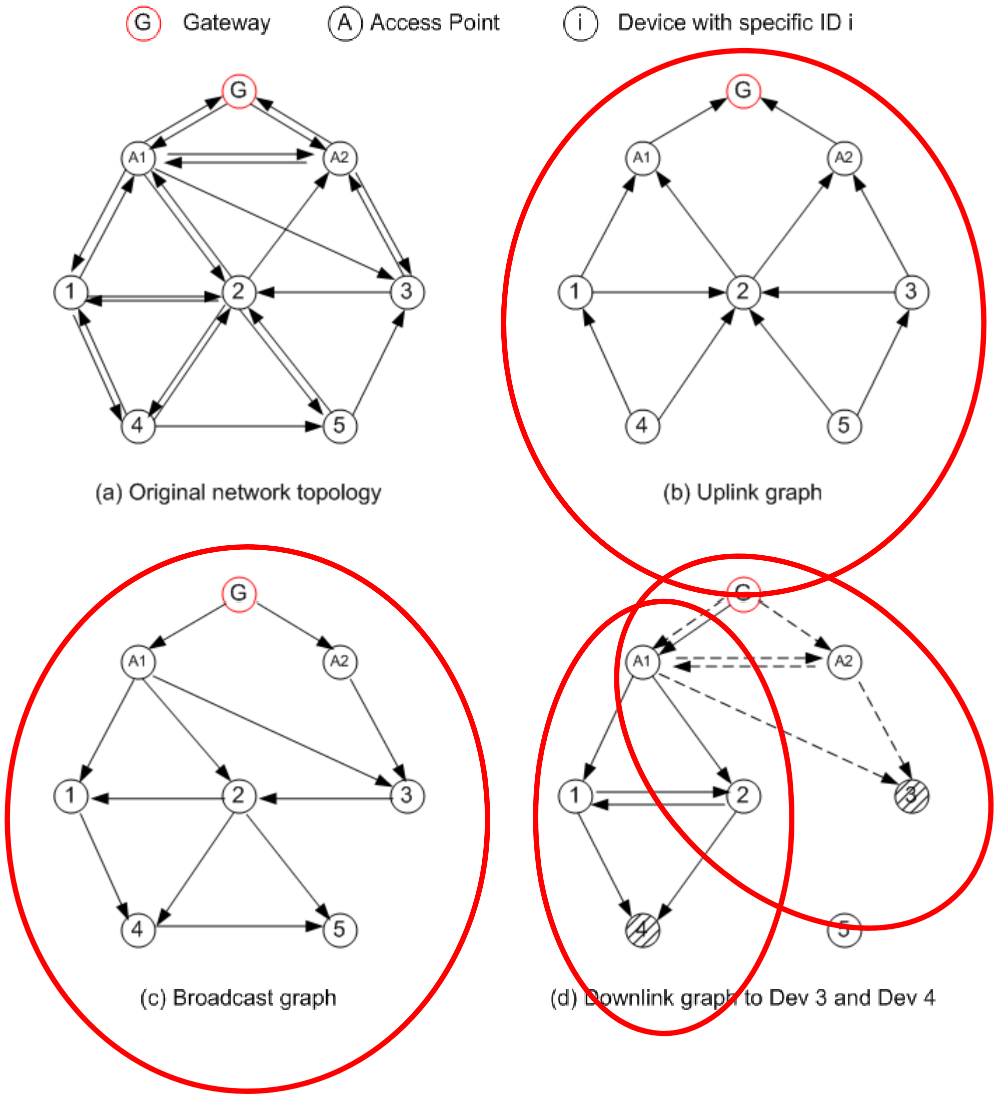


How to Achieve Reliable and Real-time Services in CPS

- Communication task definition
  - Need to solve two related sub-problems:
    1. communication graph design
    2. link scheduling

- Technical Objectives
  - Achieve reliable routing in wireless mesh networks
  - Achieve real-time communication by deterministic link and channel assignment
  - Evaluate their performance in real industrial environments

Communication Graph Design to Achieve Reliable Graph Routing



(a) Original network topology

(b) Uplink graph

(c) Broadcast graph

(d) Downlink graph to Dev 3 and Dev 4

To avoid forwarding loop:

1) Only one cycle of length 2 in G_v
2) Each DEV on the cycle has direct edges to v

Constructing Reliable Graphs

- Reliable Broadcast Graph and Uplink Graph
  - Grow the graph by greedily selecting the reliable node with minimum latency to the Gateway
- Standard Reliable Downlink Graph
  - Construct a completely new graph from GW to DEV v
  - Configuration in intermediate nodes cannot be reused
  - High configuration cost and poor scalability

Sequential Reliable Downlink Routing (SRDR)

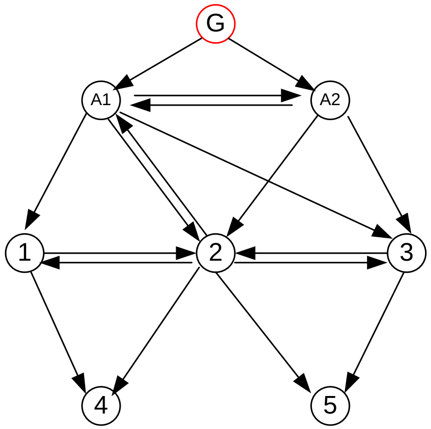
- Key Principles
  - Each node only keep a small local graph
  - Local graphs are reusable building blocks for constructing reliable downlink graph for multiple destinations

Low configuration cost

High Scalability

High Reliability

An Example of SRDR



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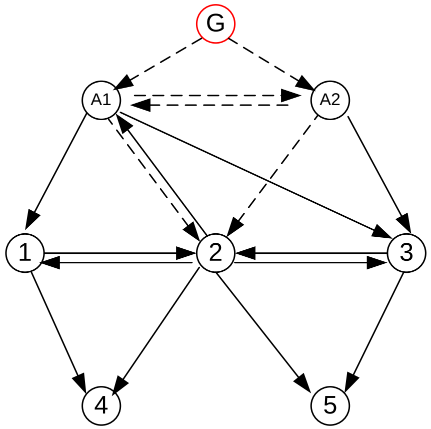
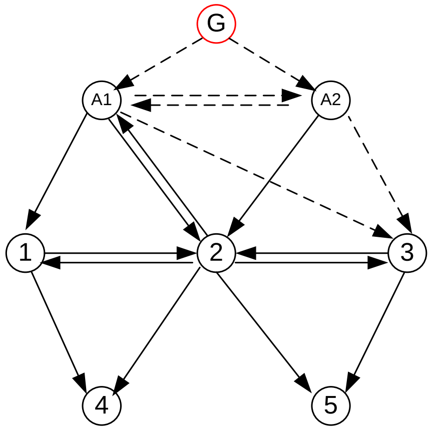
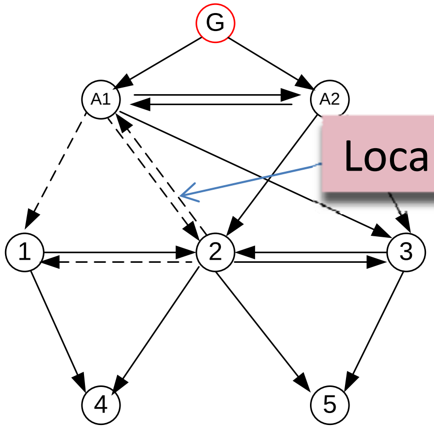


(b) Downlink graph: g2
Sequential route for Dev 2: g2

(b)

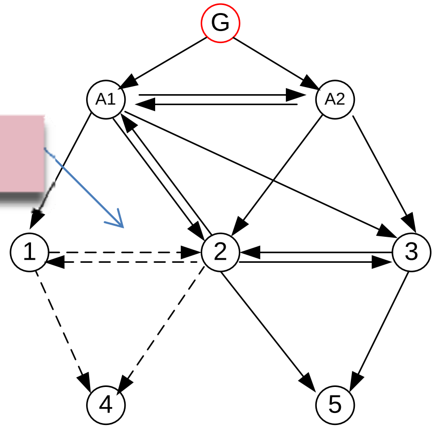


Avoid node failure at DEV2

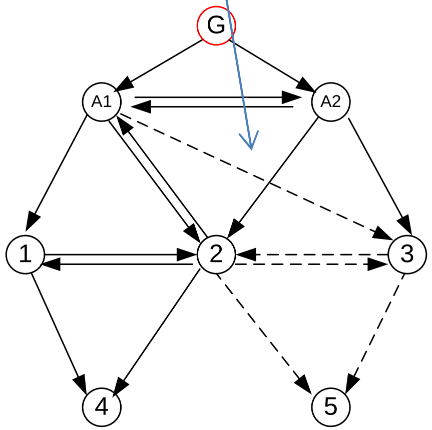


Local graph

(d) Downlink graph: g1
Sequential route for Dev 1: g2, g1

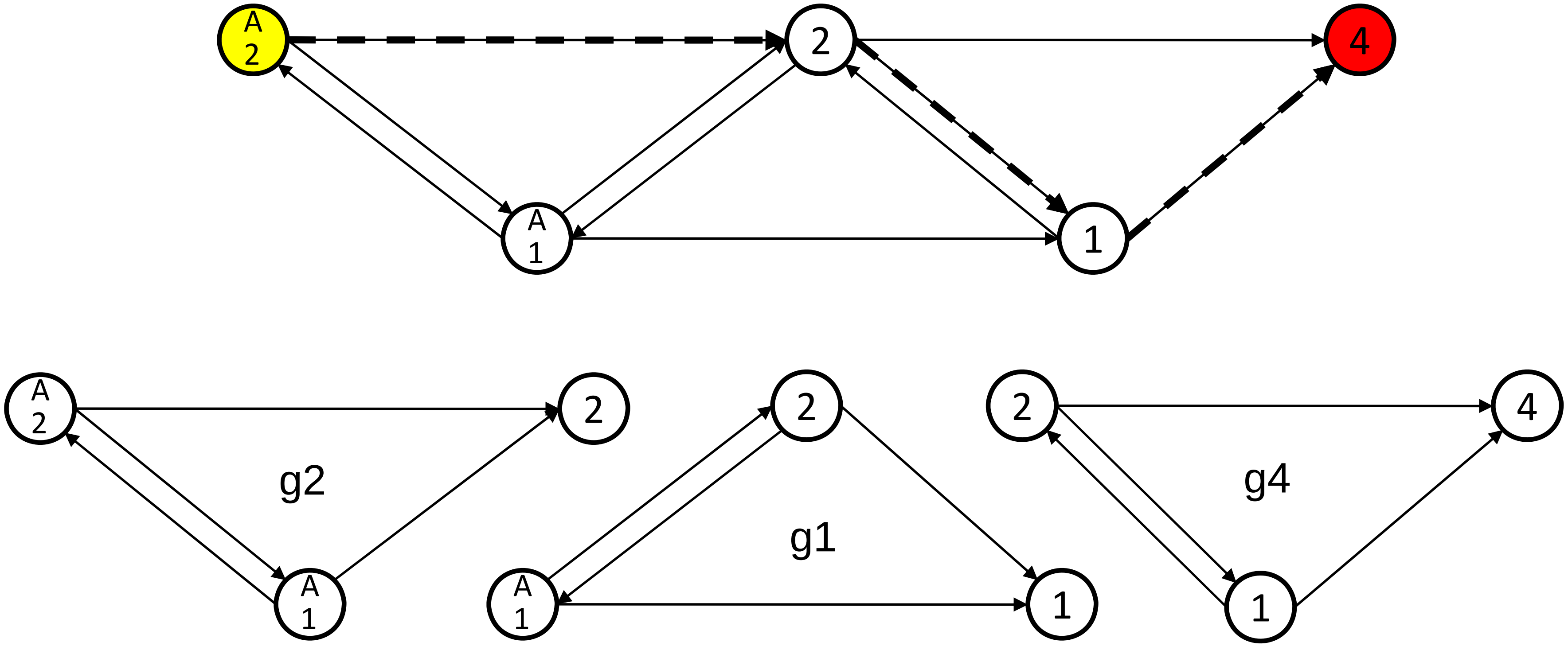


(e) Downlink graph: g4
Sequential route for Dev 4: g2, g1, g4



(f) Downlink graph: g5
Sequential route for Dev 5: g2, g5

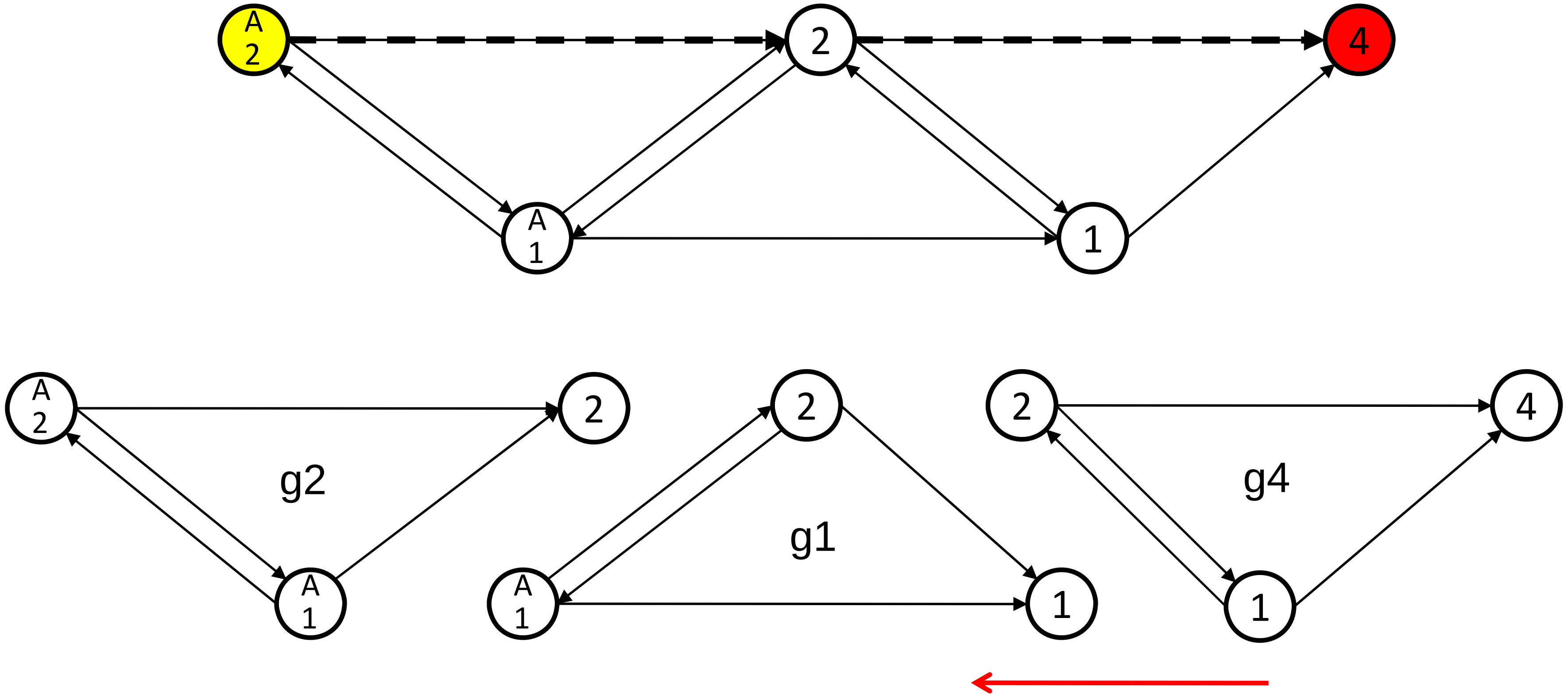
SRDR Extensions



Control	TTL	ASN Snippet	Graph ID	Dest Addr	Source Addr	Proxy Route	g2	g1	g4	Payload

Extended Routing Information

SRDR Optimization



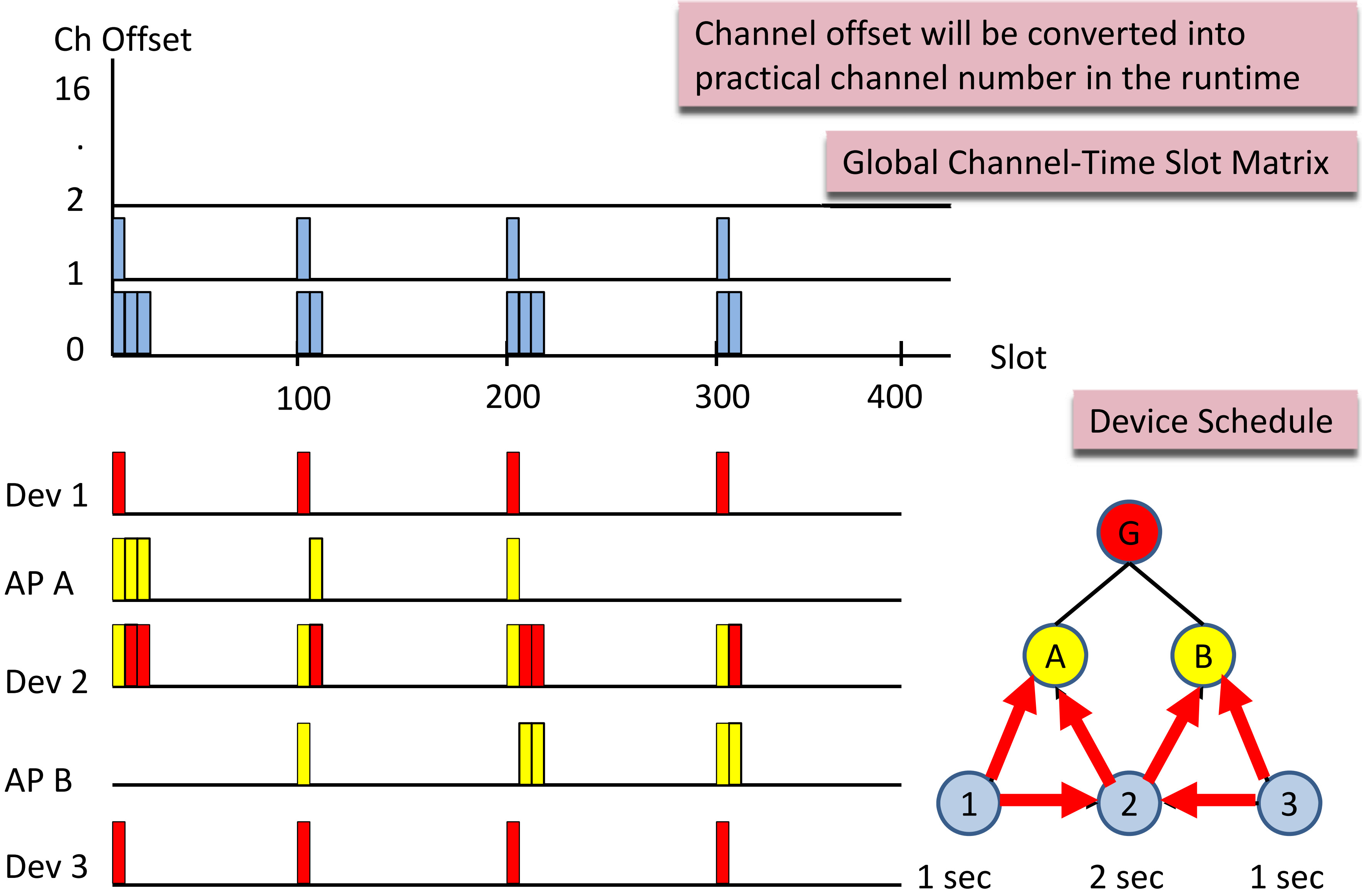
Control	TTL	ASN Snippet	Graph ID	Dest Addr	Source Addr	Proxy Route	g2	g1	g4		Payload

Extended Routing Information

Communication Link Scheduling

- The general scheduling problem is known to be NP-hardness [Saifullah et al. 2010]
- Key Principles:
  - Spread out the channel usage in the network
  - Apply Fastest Sample Rate First policy (FSRF)
  - Allocate the links iteratively from Src to Dest
  - Split traffic (bandwidth) among all successors

Example Schedule Construction Using the Key Principles

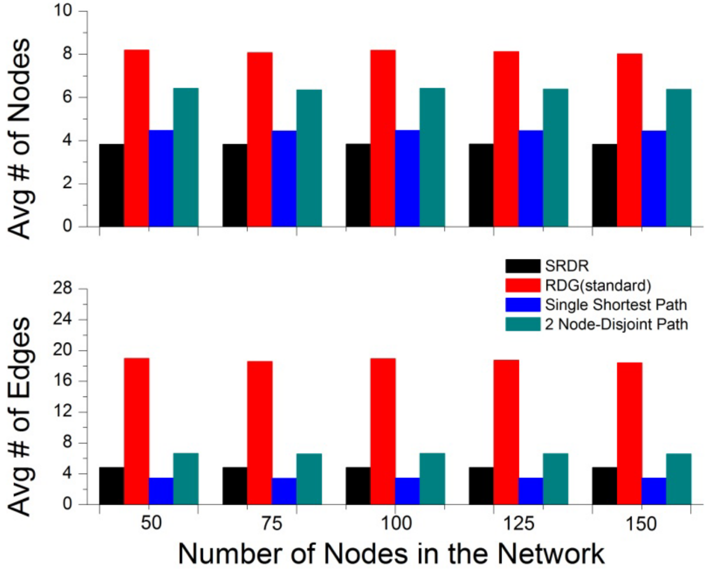


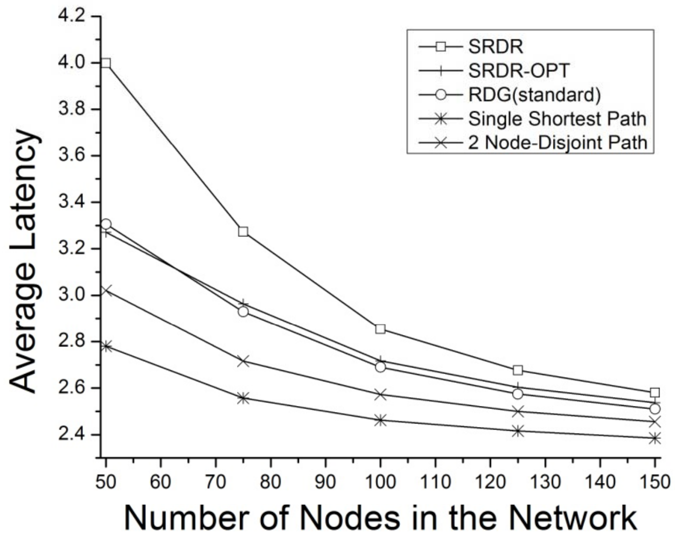
Channel offset will be converted into practical channel number in the runtime

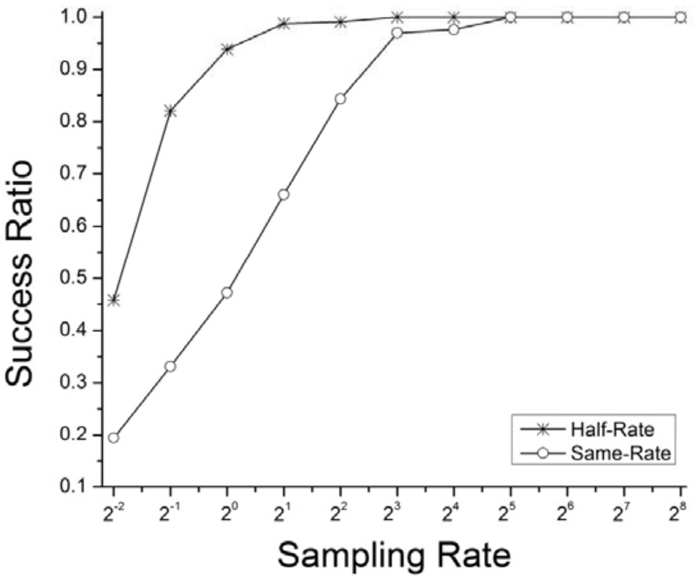
Global Channel-Time Slot Matrix

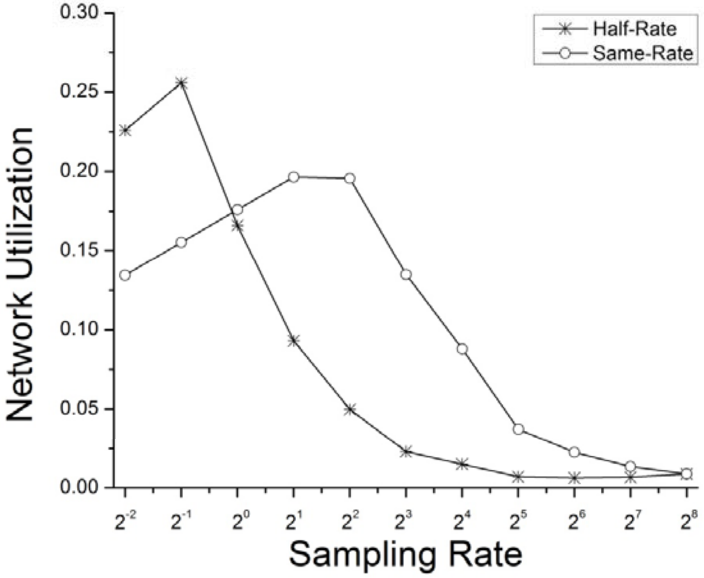
Device Schedule

Performance Evaluation

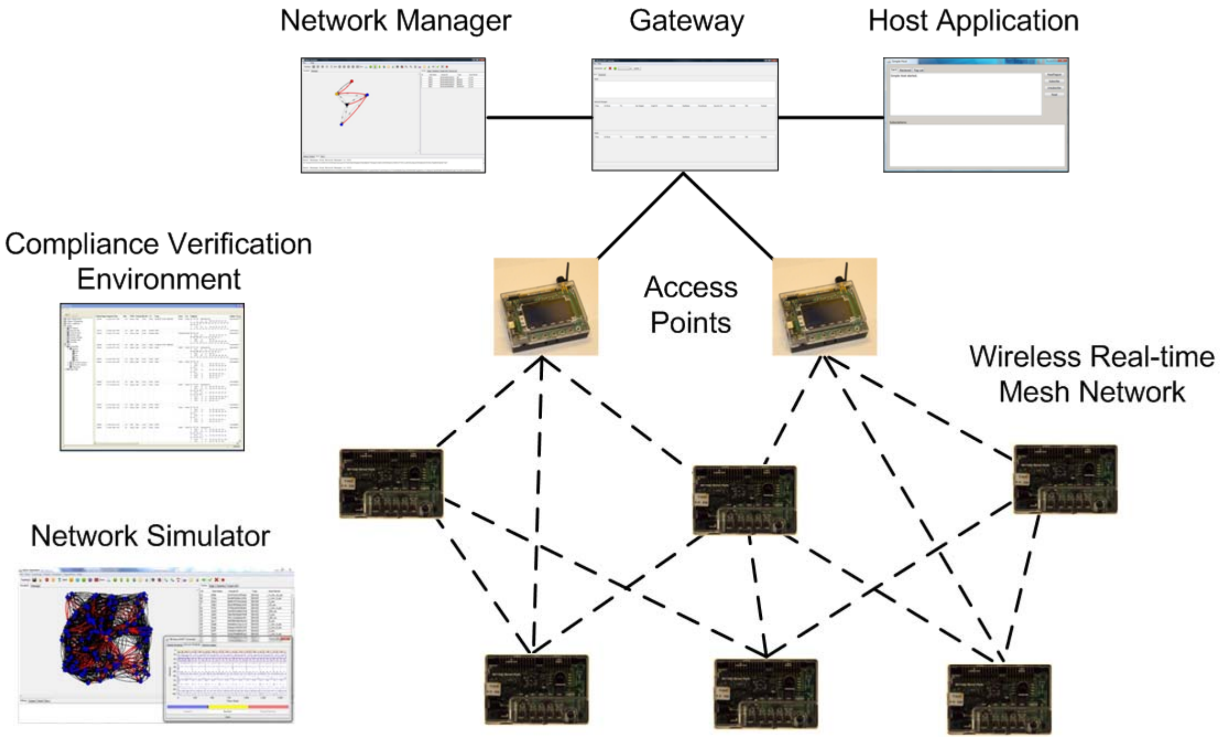






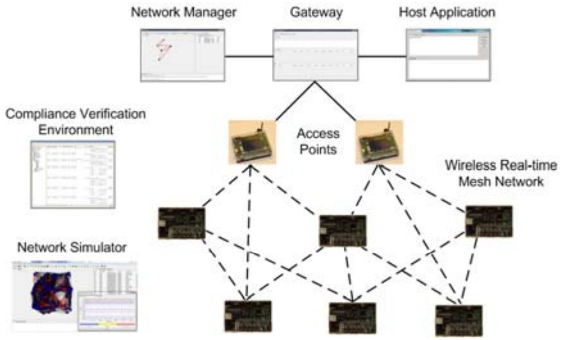


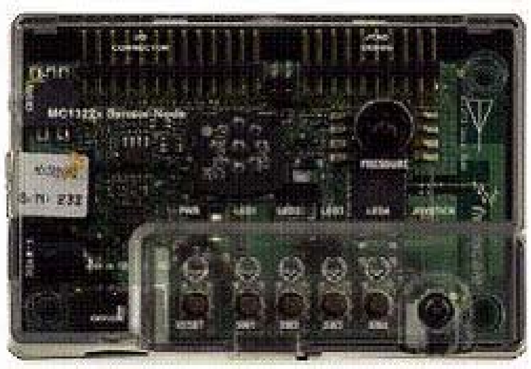
System Design, Implementation and Deployment



System Design, Implementation and Deployment

Hardware Platforms





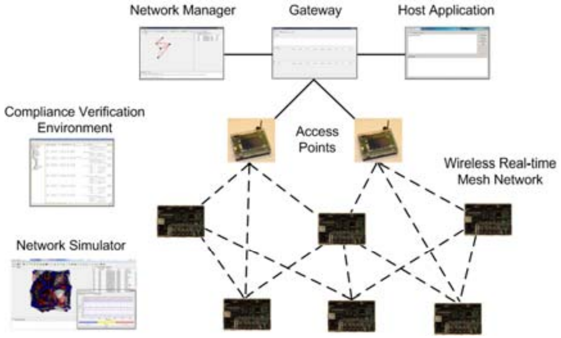
Freescale 1322x SRB Evaluation Board

Custom Designed Mother Board with Sensor Support

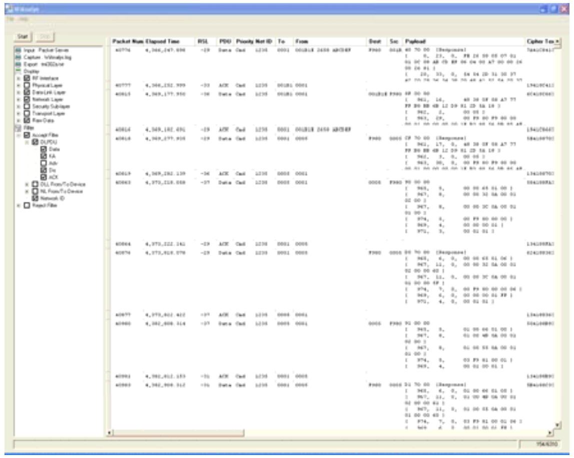
Custom Designed Board with EnergyMicro EFM32 MCU

System Design, Implementation and Deployment (Cont.)

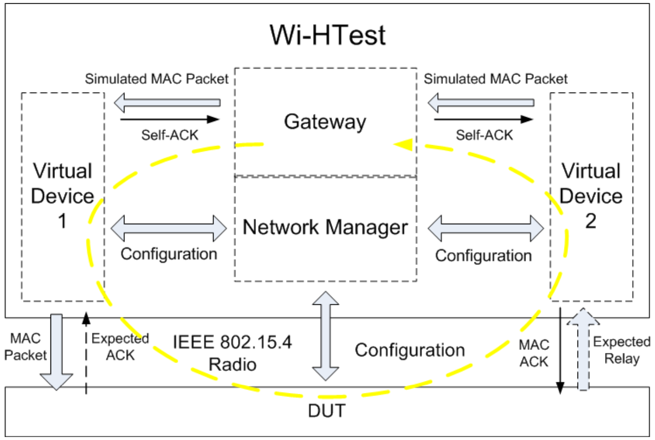
Compliance Testing Suite



Testing Engine



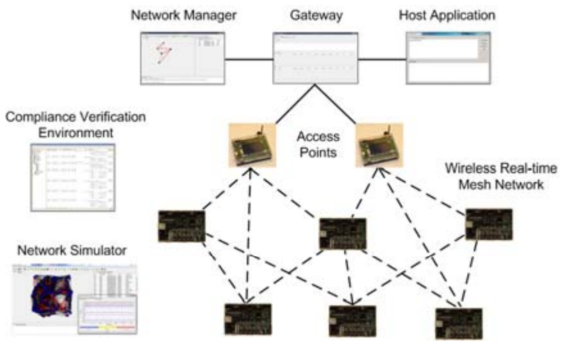
16-Channel Sniffer

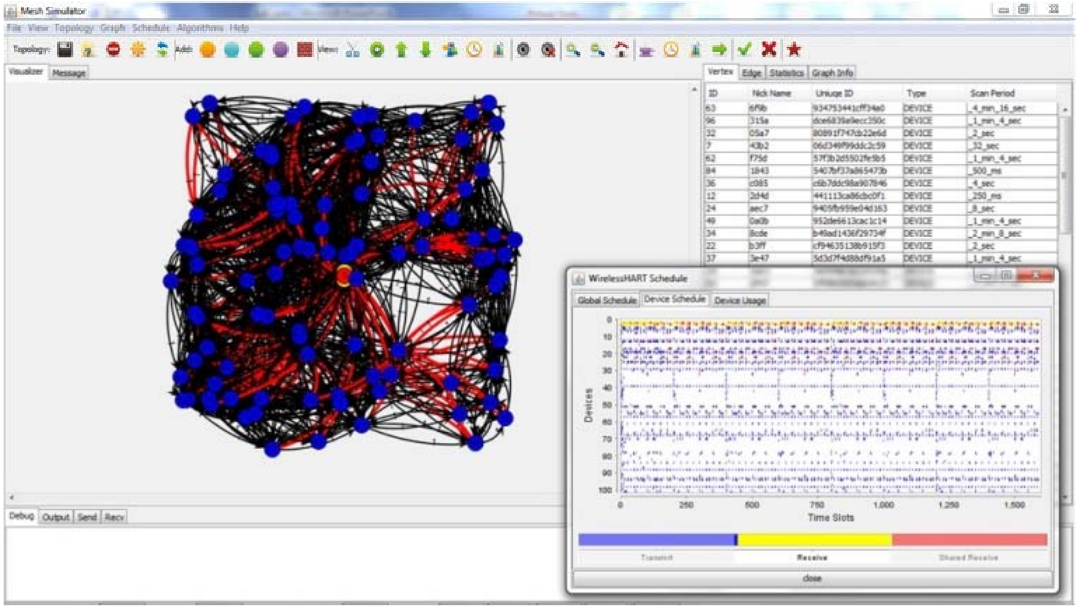


Virtual Network Approach

System Design, Implementation and Deployment (Cont.)

Network Manager and Simulator





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62	f75d	57f3b2d5502fe5b5	DEVICE	_1_min_4_sec
84	1843	5407bf37a865473b	DEVICE	_500_ms
36	c085	c6b7ddc98a907846	DEVICE	_4_sec
12	2d4d	441113ca86cbc0f1	DEVICE	_250_ms
24	aec7	9405fb959e04d163	DEVICE	_8_sec
49	0a0b	952de6613cac1c14	DEVICE	_1_min_4_sec
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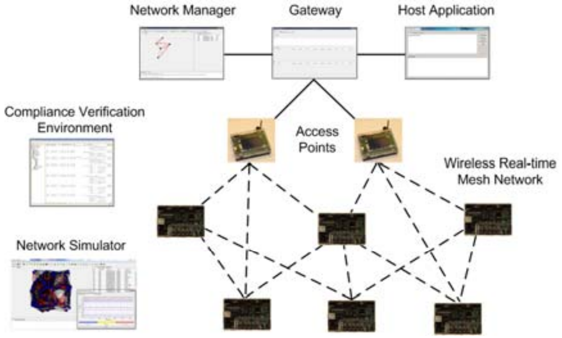
Simulating a real-time wireless network with 100 devices:

- reliable broadcast graph
- device communication schedule

System Design, Implementation and Deployment (Cont.)



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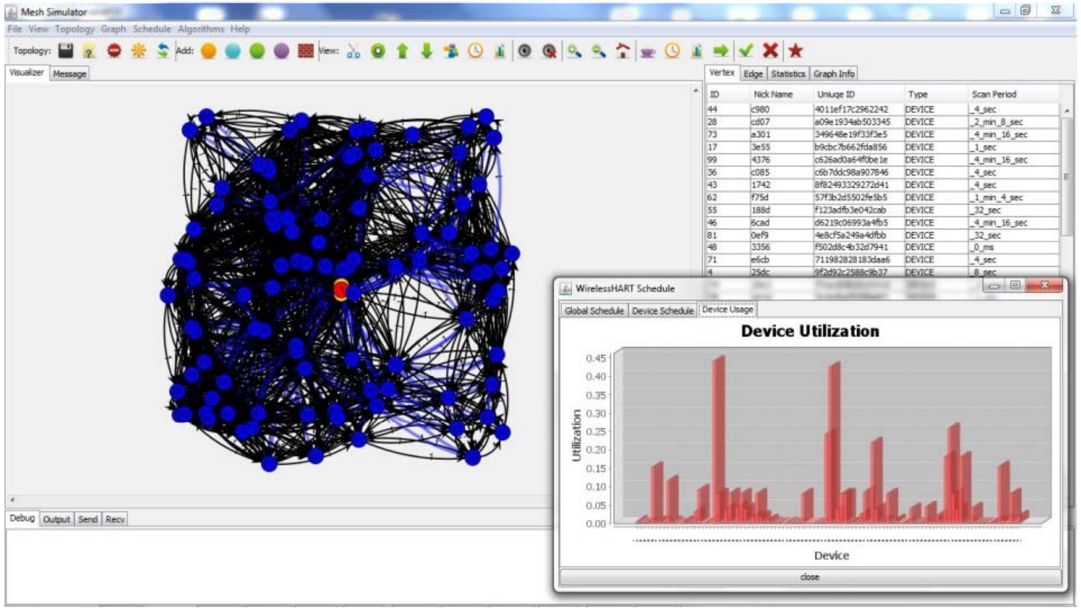

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17	3e55	b9cbc7b662fda856	DEVICE	_1_sec
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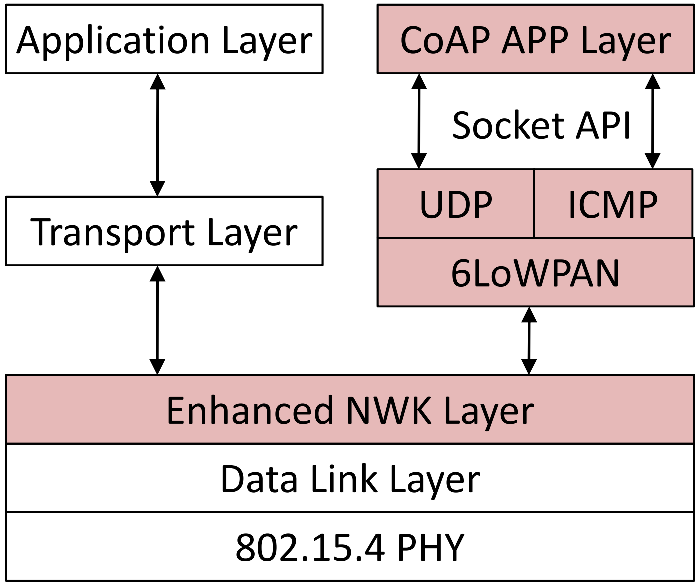
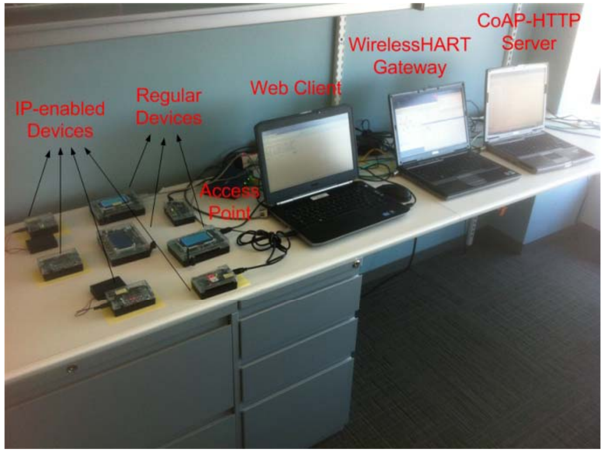
48	3356	f502d8c4b32d7941	DEVICE	_0_ms
71	e6cb	711982828183daa6	DEVICE	_4_sec
4	25dc	9f2d92c2588c9b37	DEVICE	_8_sec

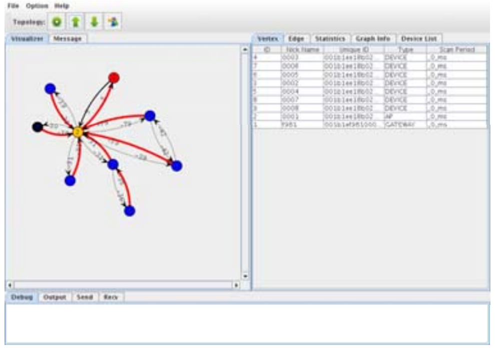
Simulating a real-time wireless network with 100 devices:

- reliable uplink graph
- device bandwidth utilization

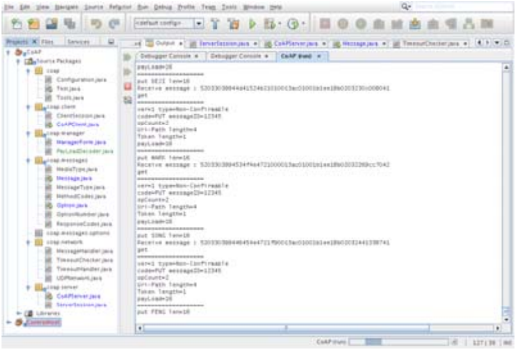
System Design, Implementation and Deployment (Cont.)







Network Topology



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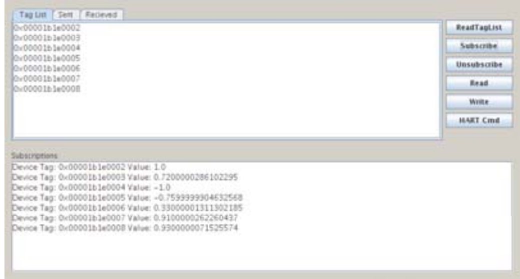
payLoad=[illegible]
====================
put DEJI len=[illegible]
Receive message : [illegible]
get
====================
ver=1 type=Non-Confirmable
code=PUT messageID=12345
opCount=2
Uri-Path length=4
Token length=1
payLoad=[illegible]
====================
put MARK len=[illegible]
Receive message : [illegible]
get
====================
ver=1 type=Non-Confirmable
code=PUT messageID=12345
opCount=2
Uri-Path length=4
Token length=1
payLoad=[illegible]
====================
put SONG len=[illegible]
Receive message : [illegible]
get
====================
ver=1 type=Non-Confirmable
code=PUT messageID=12345
opCount=2
Uri-Path length=4
Token length=1
payLoad=[illegible]
====================
put FENG len=[illegible]
```

CoAP-HTTP Server

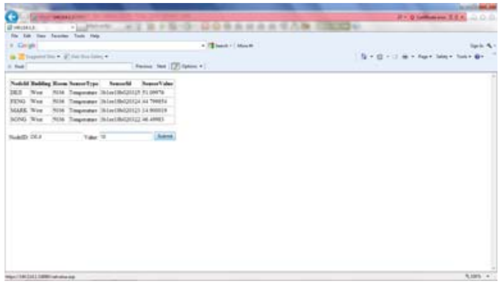


```
0x00001b1e0002
0x00001b1e0003
0x00001b1e0004
0x00001b1e0005
0x00001b1e0006
0x00001b1e0007
0x00001b1e0008
```

Subscriptions

```
Device Tag: 0x00001b1e0002 Value: 1.0
Device Tag: 0x00001b1e0003 Value: 0.7200000286102295
Device Tag: 0x00001b1e0004 Value: -1.0
Device Tag: 0x00001b1e0005 Value: -0.7599999904632568
Device Tag: 0x00001b1e0006 Value: 0.33000001311302185
Device Tag: 0x00001b1e0007 Value: 0.9100000262260437
Device Tag: 0x00001b1e0008 Value: 0.9300000071525574
```

Intra-system Service

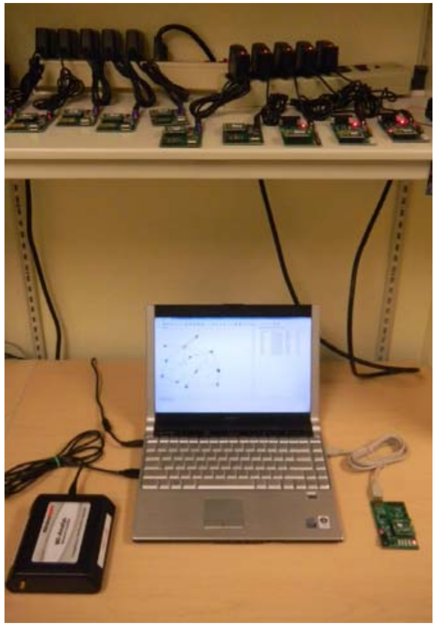


NodeId	Building	Room	SensorType	SensorId	SensorValue
DEJI	[illegible]	[illegible]	Temperature	[illegible]	[illegible]
FENG	[illegible]	[illegible]	Temperature	[illegible]	[illegible]
MARK	[illegible]	[illegible]	Temperature	[illegible]	[illegible]
SONG	[illegible]	[illegible]	Temperature	[illegible]	[illegible]

NodeID: [illegible] Value: [illegible] Submit

Web Service

System Design, Implementation and Deployment (Cont.)

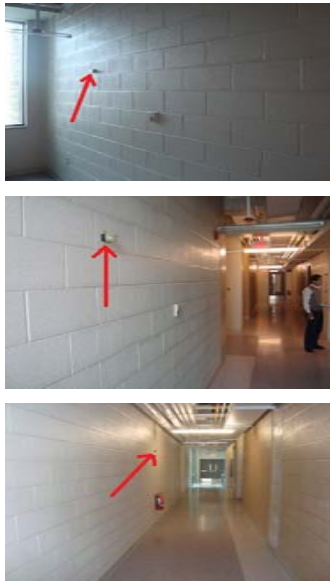


10 Device Testbed

Exec. Assist.
Faculty
Discussion
Coffee
Visitor 2
Visitor
Admin
Tech.
Tech
Mech
ECE Lab
IDF
Copy
Post Doc 2
Elec
Recept/ Exec. Assist.
Future
Tech 2
Workstation Lab
CS Lab
Res. 2

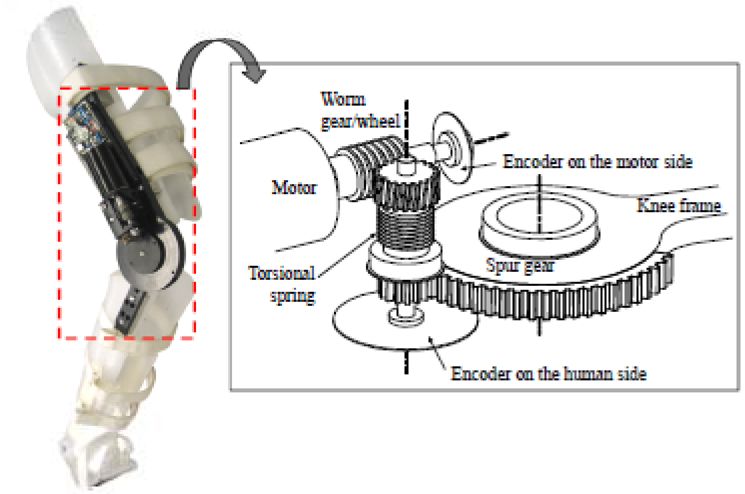
UT Austin ACES 5th floor

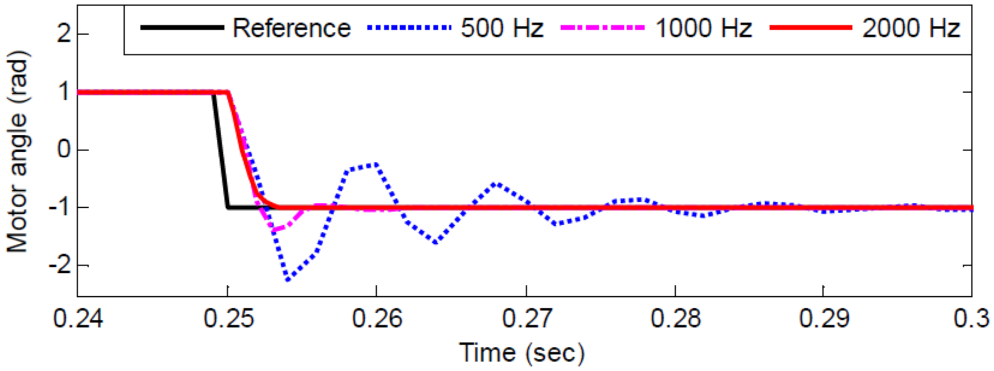
UT Pickle Research Center



UWO Power House

Higher Sampling Rate Required in Network-based Rehabilitation System

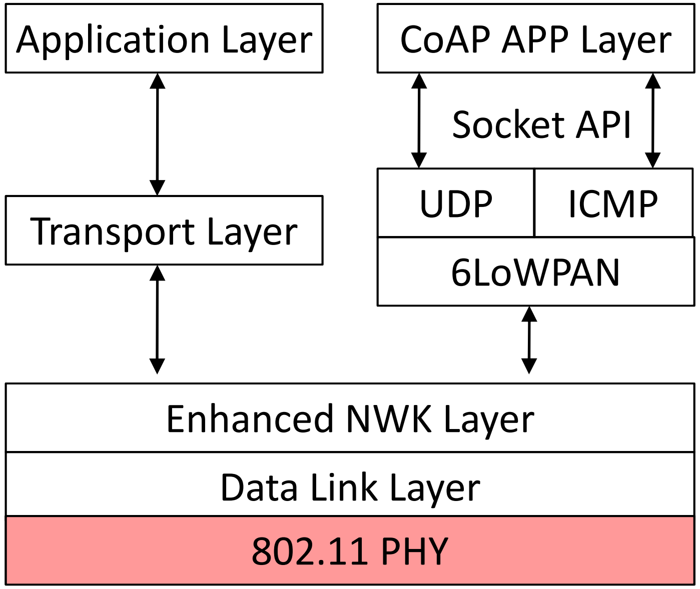




- Challenges
  - Mechanic modules need high frequency and low jitter control
  - A platform for a wide range of wireless control applications: a good balance among sampling rate, energy consumption and real-time performance

High-speed Real-time Wireless Control

- Real-time Wi-Fi to support high speed control
  - Replacing 802.15.4 PHY with 802.11 PHY
  - Network-wide synchronization and power saving



Application Layer

Transport Layer

CoAP APP Layer

Socket API

UDP

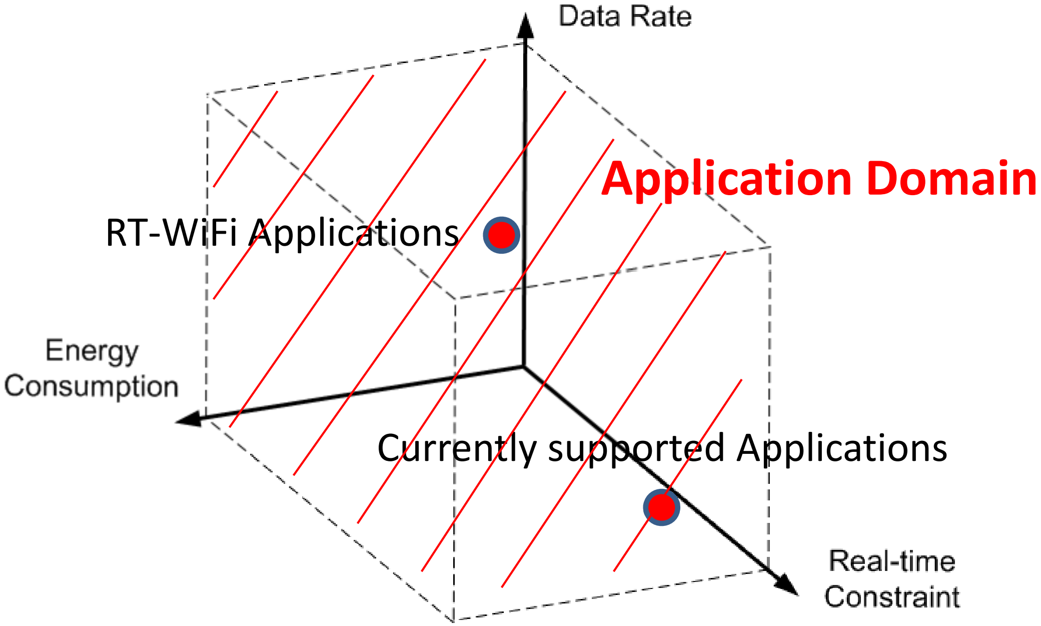
ICMP

6LoWPAN

Enhanced NWK Layer

Data Link Layer

802.11 PHY



Data Rate

Application Domain

RT-WiFi Applications

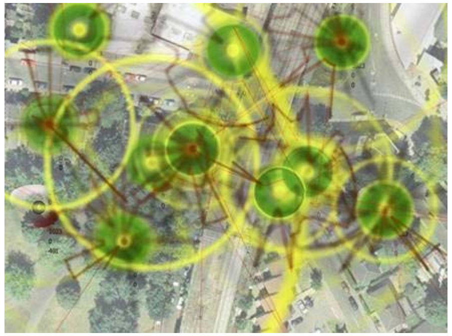
Energy Consumption

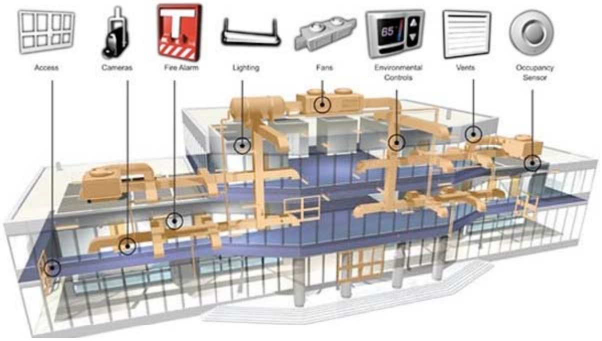
Currently supported Applications

Real-time Constraint

Real-time Data Management in CPS

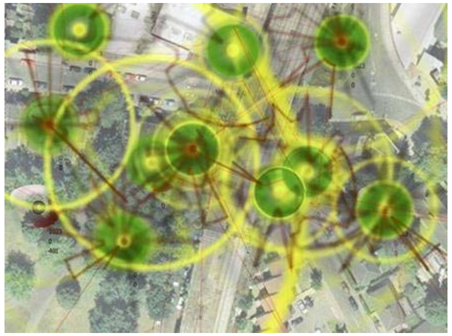
Maintaining Data Quality in CPS is Key

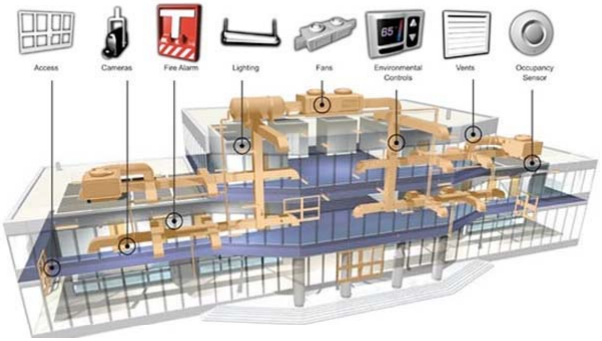




- CPS are in essential sensing and control systems
- Data quality is the key to the success of sensing and control applications
- Sensor data have time semantics, and their quality degrade with time

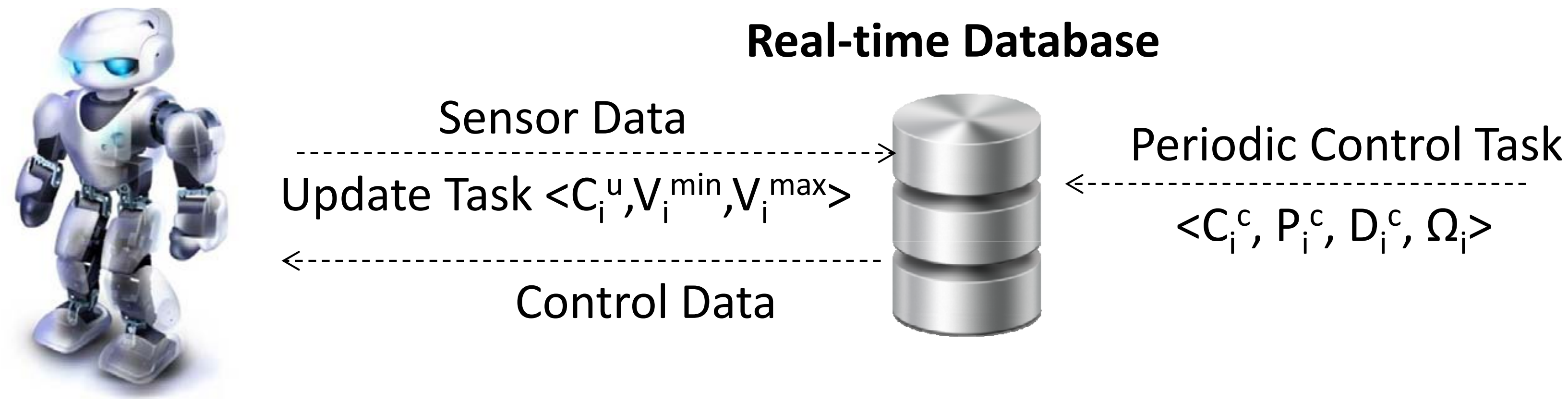
Maintaining Data Quality in CPS is Key





- Need to enable tradeoff between data quality and sampling rate
  - High sampling rate -> high network traffic & CPU workload
  - More power consumption & shorter network lifetime
  - Reduce sampling rate but maintain data and control quality
- Will exploit concept of validity interval to make the tradeoff

Task Model



Real-time Database

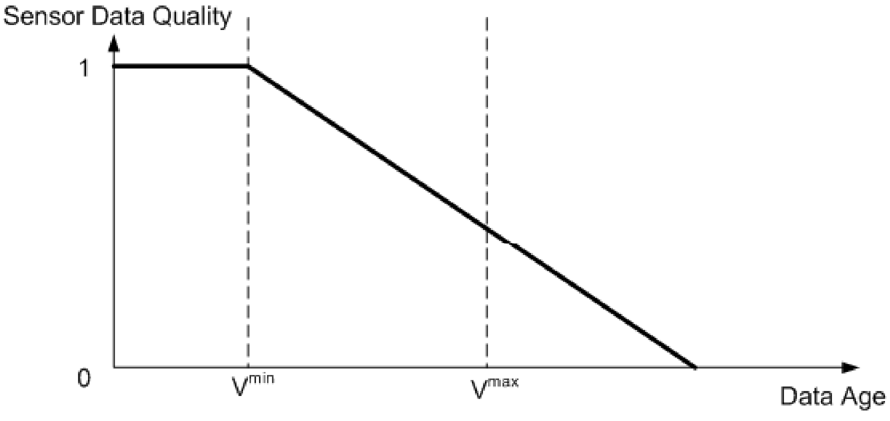
Sensor Data

Update Task $<C_i^u, V_i^{min}, V_i^{max}>$

Control Data

Periodic Control Task

$<C_i^c, P_i^c, D_i^c, \Omega_i>$



- A task is an abstraction of resource consumer; a task can be a computing task (consuming CPU cycles) or a communication task (consuming network bandwidth)

- Validity intervals quantify the quality of sensor data

- Control data quality is a function of sensor data quality

Task Model

- Sensor update task set $T^u = \{\tau_i^u\}_{i=1}^n$
  - τ_i^u is a 4-tuple: $\tau_i^u = (C_i^u, V_i^{min}, V_i^{max}, Q_i^u(t))$.
  - $Q_i^u(t)$ is application-dependent.
- Control task set $T^c = \{\tau_i^c\}_{i=1}^m$
  - τ_i^c is a 5-tuple: $\tau_i^c = (C_i^c, D_i^c, P_i^c, \Omega_i, Q_i^c(t))$
  - Ω_i is the update tasks that τ_i^c will access and $Q_i^c(t)$ is application-dependent

Symbol	Meaning
$\tau_i^{u(c)}$	Update/Control Task i
$C_i^{u(c)}$	WCET for $\tau_i^{u(c)}$
$Q_i^{u(c)}(t)$	Quality function for $\tau_i^{u(c)}$
$V_i^{min\ (max)}$	Min(max) validity interval
D_i^c (P_i^c)	Deadline (Period) of τ_i^c

Goal: Maintain the control data quality above threshold while Minimizing update workload

Task Model

Symbol	Meaning
$\tau_i^{u(c)}$	Update/Control Task i
$C_i^{u(c)}$	WCET for $\tau_i^{u(c)}$
$Q_i^{u(c)}(t)$	Quality function for $\tau_i^{u(c)}$
$V_i^{min\ (max)}$	Min(max) validity interval
$D_i^c\ (P_i^c)$	Deadline (Period) of τ_i^c

- Sensor update task set $T^u = \{\tau_i^u\}_{i=1}^n$
  - τ_i^u is a 4-tuple: $\tau_i^u = (C_i^u, V_i^{min}, V_i^{max}, Q_i^u(t))$.
  - $Q_i^u(t)$ is application-dependent.
- Control task set $T^c = \{\tau_i^c\}_{i=1}^m$
  - τ_i^c is a 5-tuple: $\tau_i^c = (C_i^c, D_i^c, P_i^c, \Omega_i, Q_i^c(t))$
  - Ω_i is the update tasks that τ_i^c will access and $Q_i^c(t)$ is application-dependent
- Simplifying Assumptions
  - No control task in the system for now
  - $V_i^{min} = 0$ and $V_i = V_i^{max}$

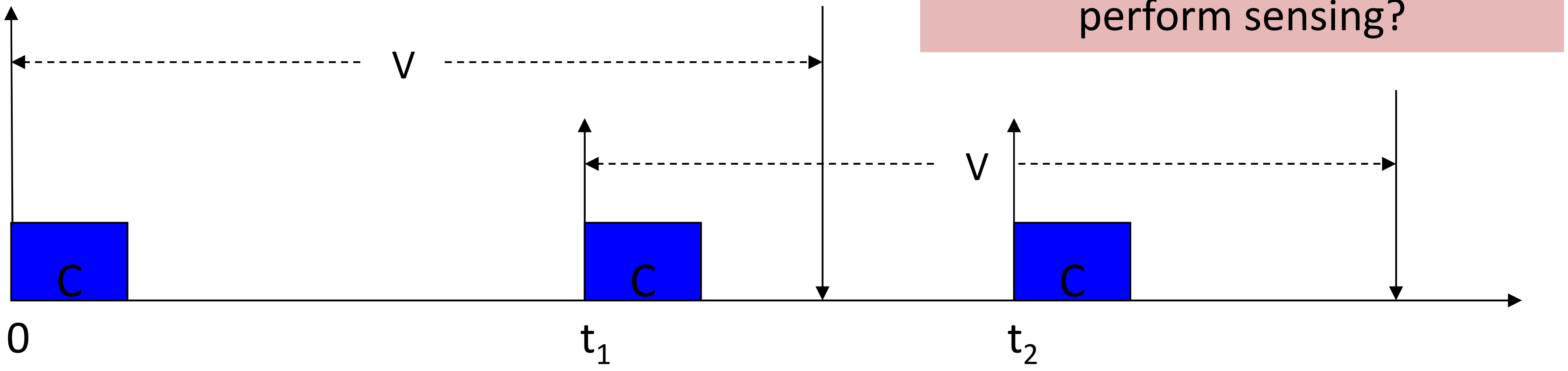
Validity Constraint: An update job must finish before its previous job's validity interval expires

Goal: Guaranteeing validity constraint while minimizing the update workload.

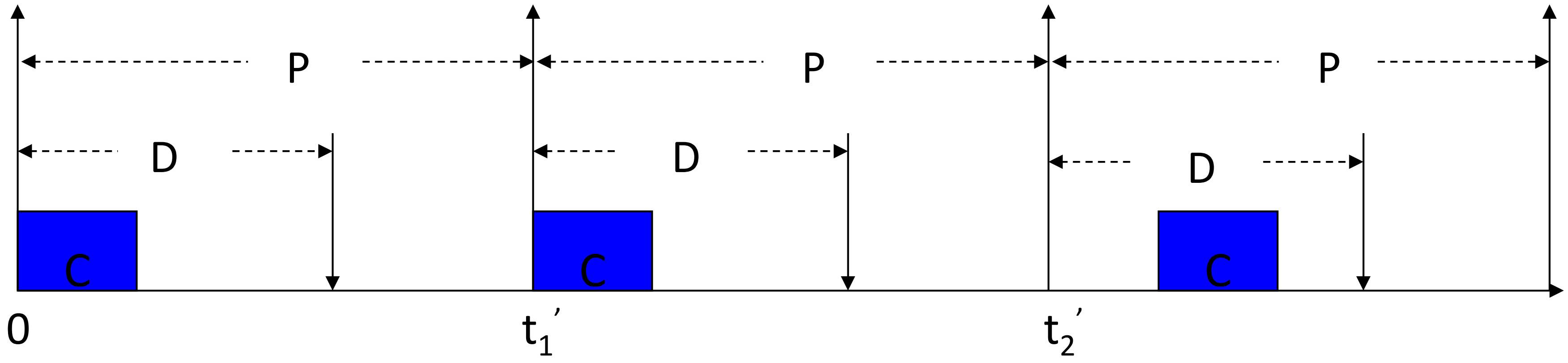
From Validity Interval Model to Periodic Task Model

How to pick the time point to perform sensing?

Validity Interval Task Model

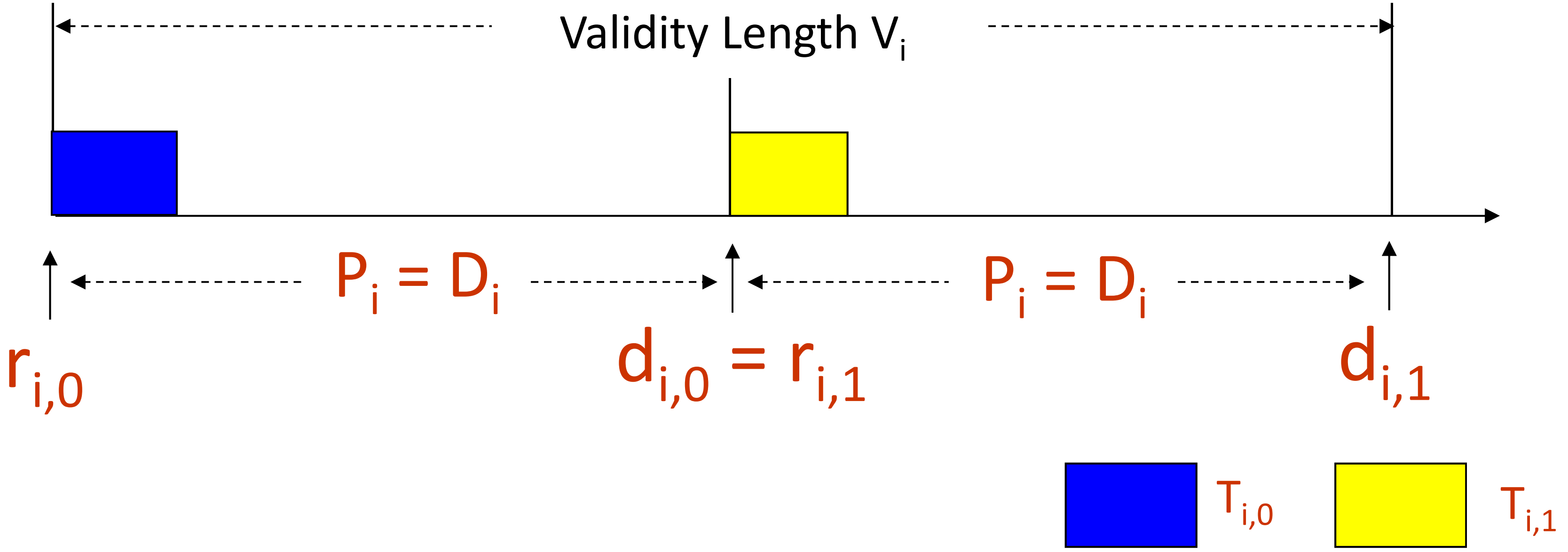


Periodic Task Model



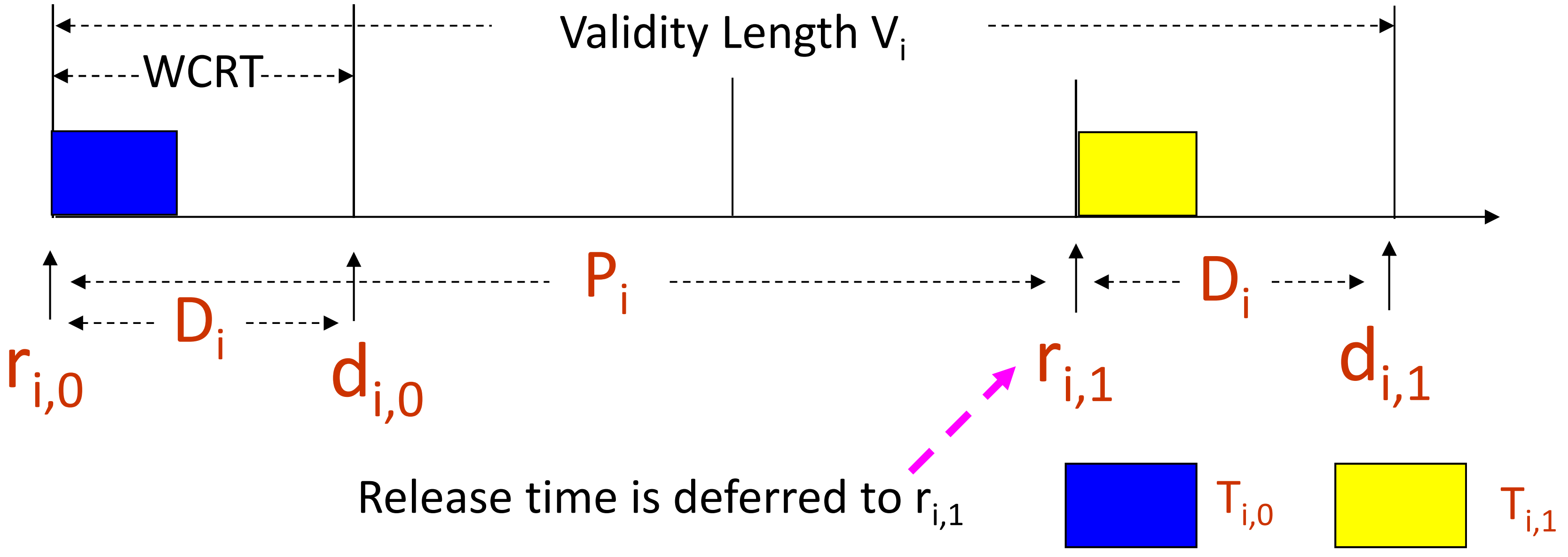
Maintaining Update Data Freshness
- Baseline Scheduling Techniques

- HH (Half-Half) Algorithm
  - Period (P_i) and relative deadline (D_i) of an update task i are each set to be one-half of the data validity length (V_i).



Maintaining Update Data Freshness - Baseline Scheduling Techniques

- ML (More-Less) Algorithm
  - Relative deadline (D_i) of an update task i is set to be its worst-case response time (WCRT). Period $P_i = V_i - D_i$



Deferrable Scheduling with Fixed Priority (DS-FP)
- From Periodic to Sporadic Task Model

Principles

- Adopts the sporadic task model.
- Defers the sampling time of the update job as late as possible to increases the distance of two consecutive jobs.

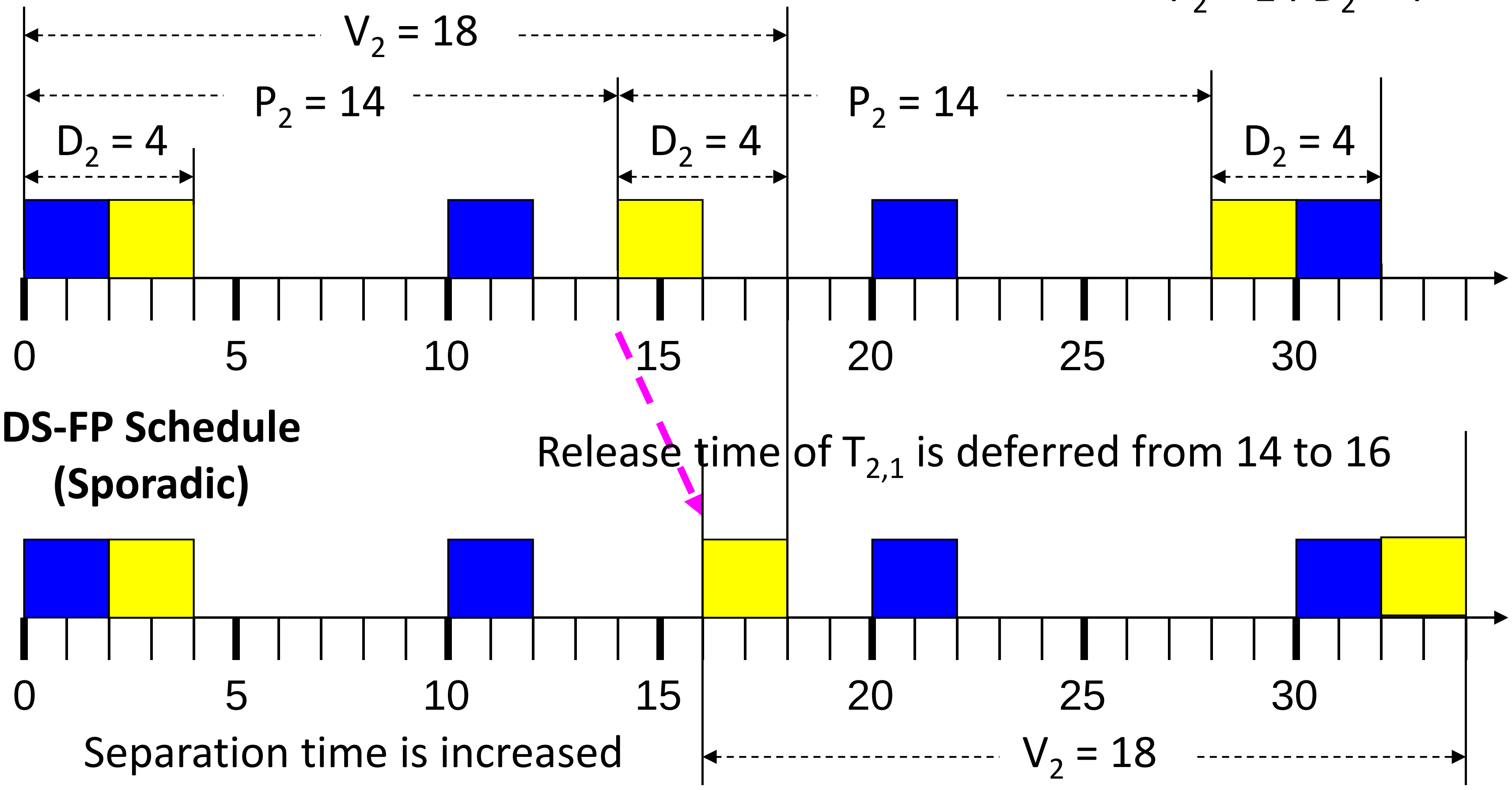
Deferrable Scheduling with Fixed Priority (DS-FP) - From Periodic to Sporadic Task Model

🟦 T_1: { C_1= 2, V_1= 12 } 🟨 T_2: { C_2= 2, V_2= 18 }

ML Schedule (Periodic)

P_1 = 10 D_1 = 2

P_2 = 14 D_2 = 4



DS-FP Schedule (Sporadic)

Release time of $T_{2,1}$ is deferred from 14 to 16

Separation time is increased

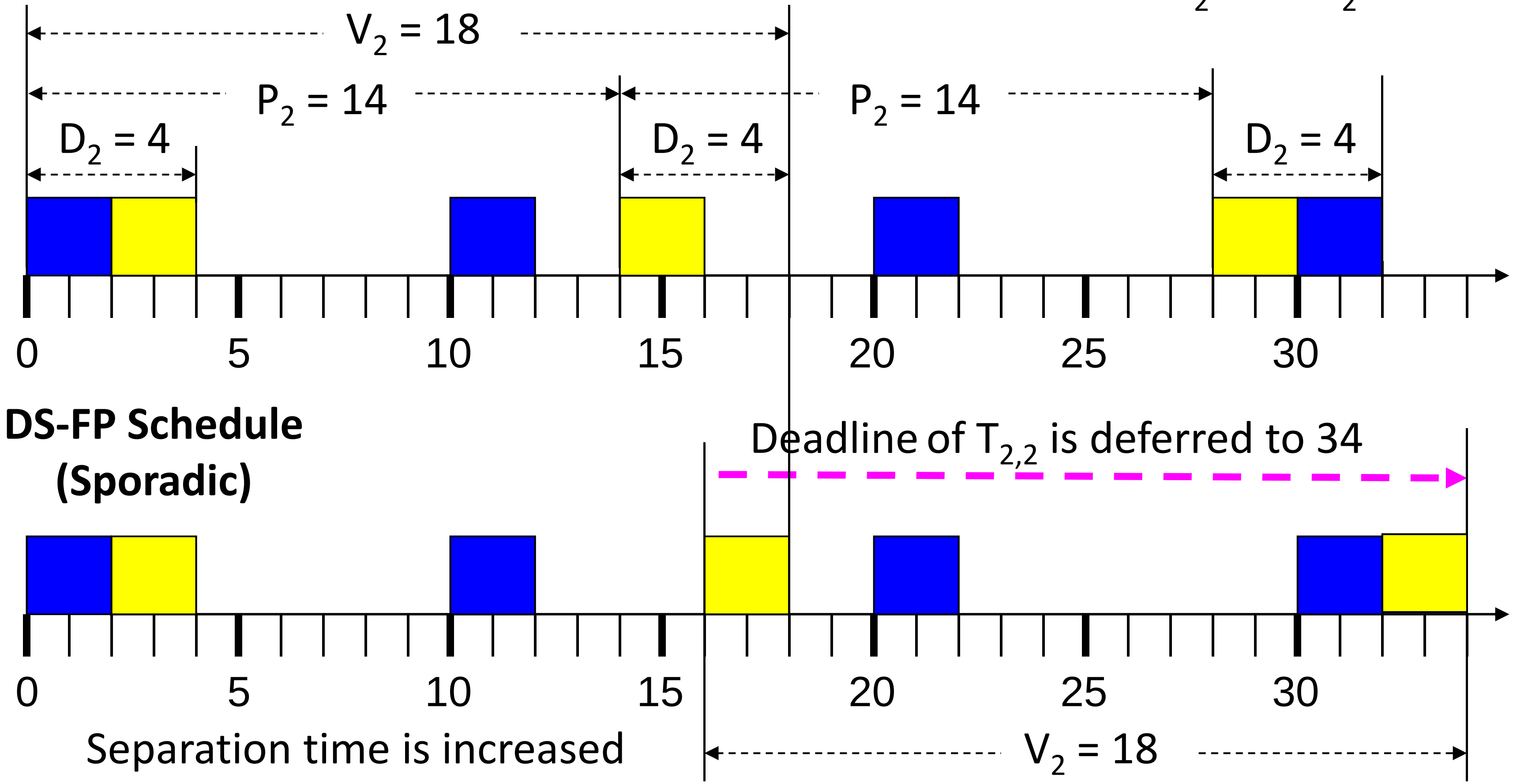
Deferrable Scheduling with Fixed Priority (DS-FP) - From Periodic to Sporadic Task Model

🟦 T_1: { C_1= 2, V_1= 12 } 🟨 T_2: { C_2= 2, V_2= 18 }

ML Schedule (Periodic)

P_1 = 10 D_1 = 2

P_2 = 14 D_2 = 4



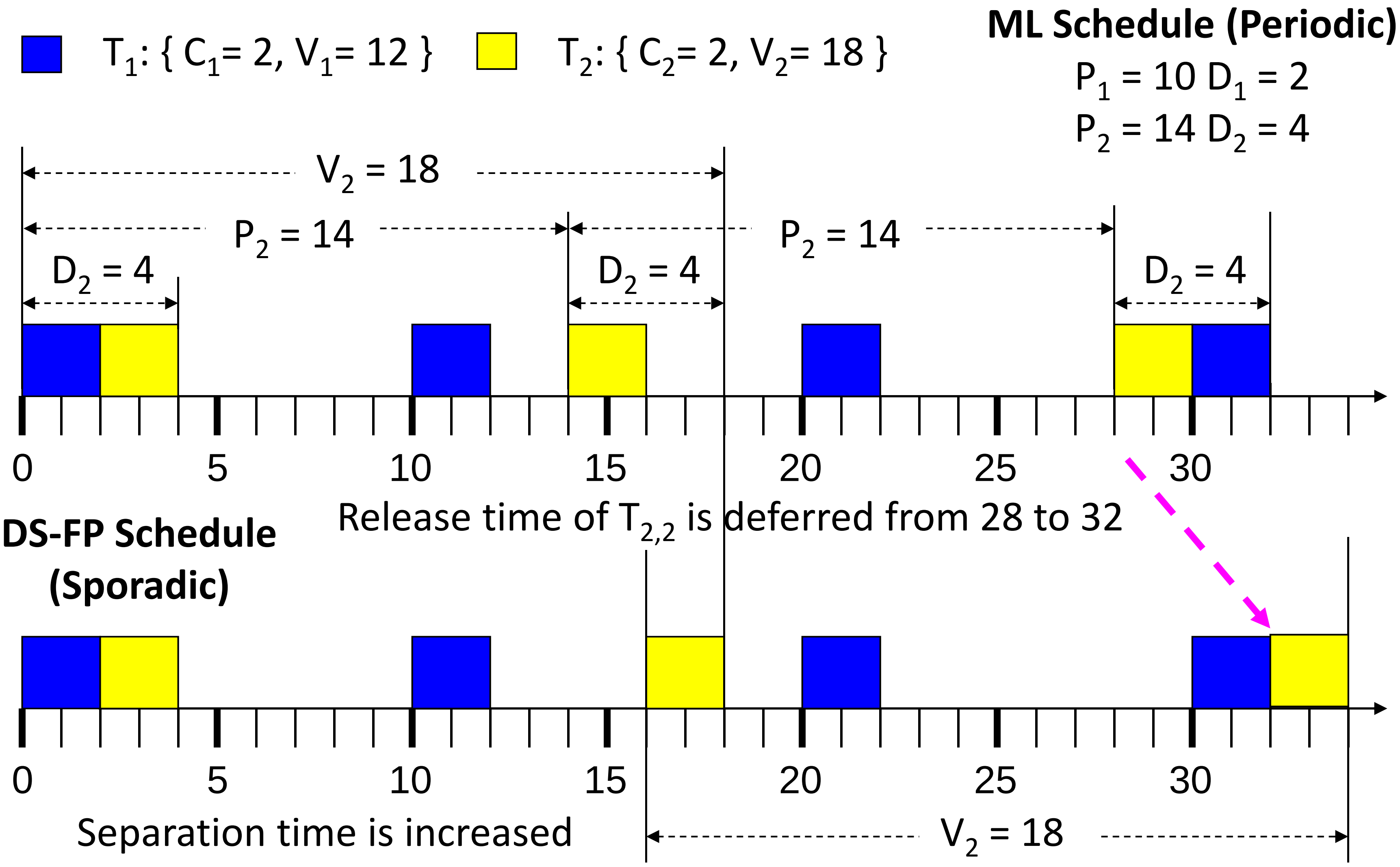
DS-FP Schedule (Sporadic)

Deadline of $T_{2,2}$ is deferred to 34

Separation time is increased

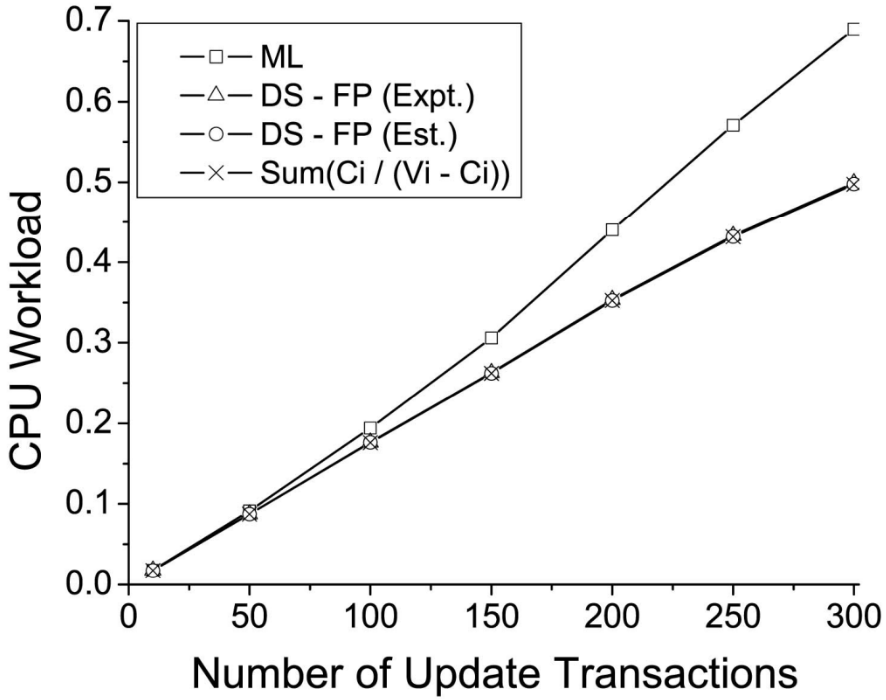
Deferrable Scheduling with Fixed Priority (DS-FP) - From Periodic to Sporadic Task Model

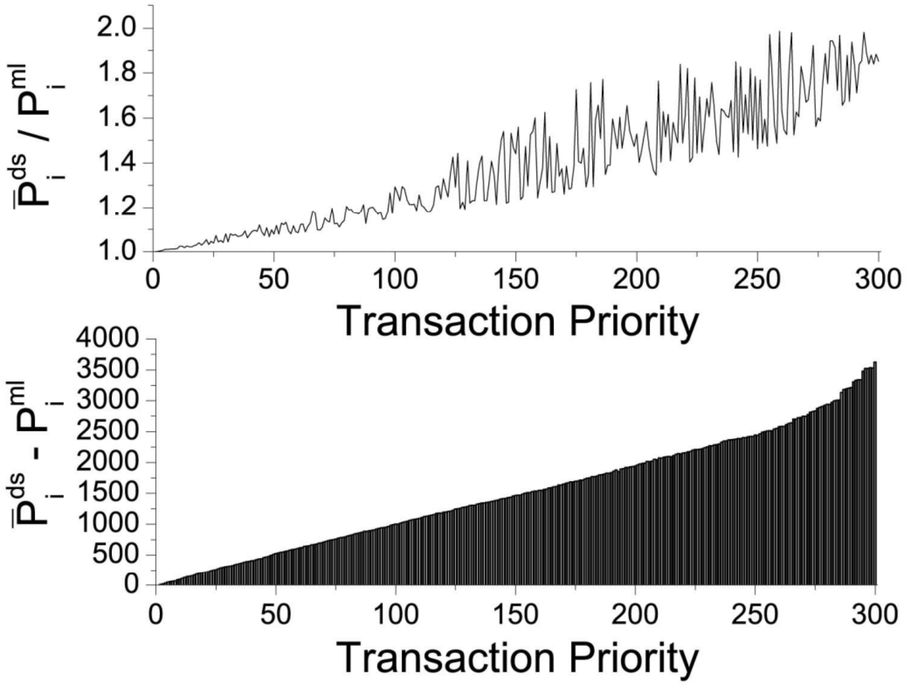
🟦 T_1: { C_1= 2, V_1= 12 } 🟨 T_2: { C_2= 2, V_2= 18 }



ML Schedule (Periodic)
$P_1 = 10$ $D_1 = 2$
$P_2 = 14$ $D_2 = 4$
$V_2 = 18$
$P_2 = 14$
$P_2 = 14$
$D_2 = 4$
$D_2 = 4$
$D_2 = 4$
0
5
10
15
20
25
30
Release time of $T_{2,2}$ is deferred from 28 to 32
DS-FP Schedule (Sporadic)
0
5
10
15
20
25
30
Separation time is increased
$V_2 = 18$

Deferrable Scheduling with Fixed priority (DS-FP)





DS-FP significantly reduces the CPU workload incurred by update trans.

Lower priority tasks have larger relative avg. sampling periods

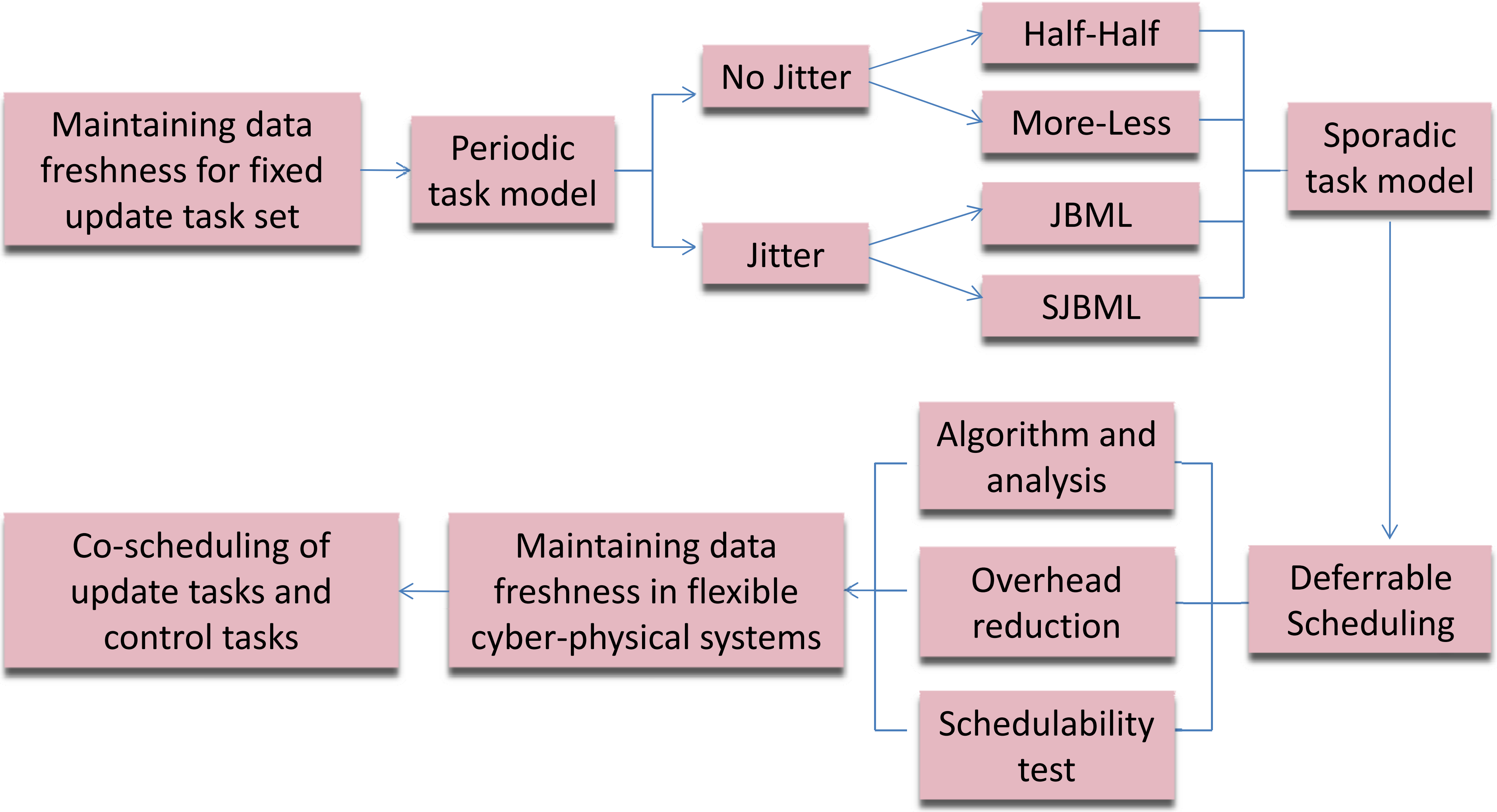
Deferrable Scheduling with Fixed priority (DS-FP)

- Comparison of DS-FP and ML
  - THEOREM. Given a synchronous update transaction set T with known C_i and V_i ,if for all i, $f_{i,0}^{ml} \leq V_i / 2$, then T is schedulable with DS-FP.

- Necessary and Sufficient Schedulability Test
  - THEOREM. Given an update task set T, if it can be scheduled by DS-FP in the bounded time interval $[0, V_m – C_m + \prod_{i=1}^{m} (V_i – C_i + 1) - 1]$, then the schedule has a repeating pattern that must occur at least once in the bounded time interval $[V_m – C_m, V_m – C_m + \prod_{i=1}^{m} (V_i – C_i + 1) - 1]$.

- Overhead Reduction Algorithms
  - DS with Hyperperiod by Schedule Construction (DESH-SC)
  - DS with Hyperperiod by Schedule Adjustment (DESH-SA)

CPS Real-time Data Management Research Roadmap



Maintaining data freshness for fixed update task set

Periodic task model

No Jitter

Jitter

Half-Half

More-Less

JBML

SJBML

Sporadic task model

Deferrable Scheduling

Algorithm and analysis

Overhead reduction

Schedulability test

Maintaining data freshness in flexible cyber-physical systems

Co-scheduling of update tasks and control tasks

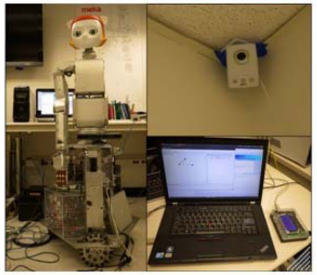
Research Summary

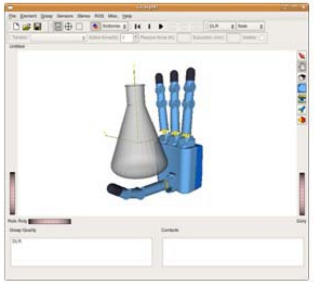
- Reliable and real-time wireless platform for CPS
  - Wireless real-time communication protocol
  - Network management techniques
  - System design and implementation
- Theoretical framework for real-time data management in CPS
  - Models and assumptions
  - Algorithms and schedulability analysis

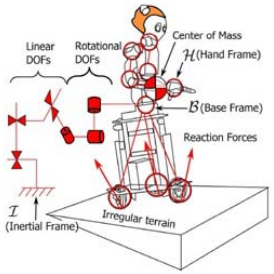
Ongoing and Future Work

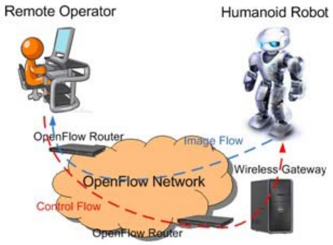
- I believe that the next Internet resolution will be about the delivery of physical services in addition to information services over long distances.

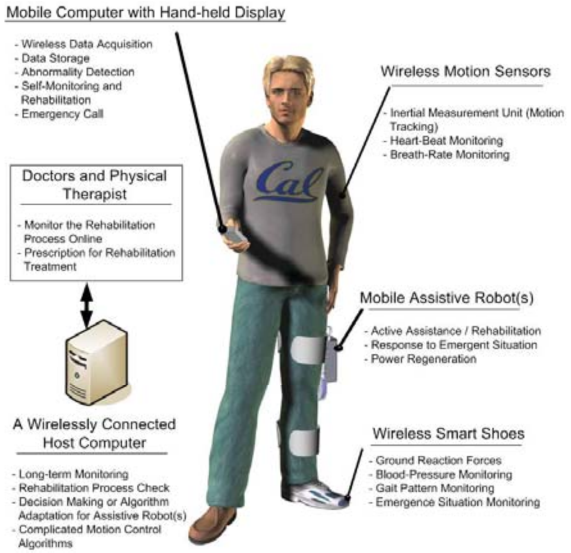
- The economic and social impact will be enormous.











Mobile Computer with Hand-held Display

- Wireless Data Acquisition
- Data Storage
- Abnormality Detection
- Self-Monitoring and Rehabilitation
- Emergency Call

Doctors and Physical Therapist

- Monitor the Rehabilitation Process Online
- Prescription for Rehabilitation Treatment

A Wirelessly Connected Host Computer

- Long-term Monitoring
- Rehabilitation Process Check
- Decision Making or Algorithm Adaptation for Assistive Robot(s)
- Complicated Motion Control Algorithms

Wireless Motion Sensors

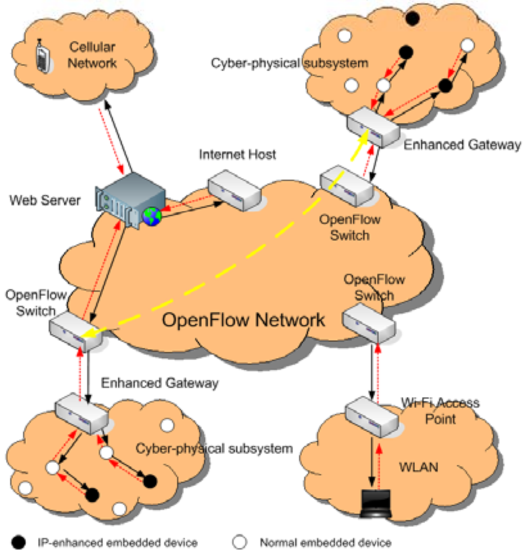
- Inertial Measurement Unit (Motion Tracking)
- Heart-Beat Monitoring
- Breath-Rate Monitoring

Mobile Assistive Robot(s)

- Active Assistance / Rehabilitation
- Response to Emergent Situation
- Power Regeneration

Wireless Smart Shoes

- Ground Reaction Forces
- Blood-Pressure Monitoring
- Gait Pattern Monitoring
- Emergence Situation Monitoring



Thanks and Questions?