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Building Blocks for Large-Scale Wireless Sensor Networks

An Infrastructure Perspective

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Information Society Technologies

Outline

- Motivation
- Large-Scale Networks
  - Sensor Andrew
- A Complete Sensor Network Protocol Stack
  - FireFly Hardware
  - Nano-RK
  - RT-Link
  - Voice over Sensor Networks
- Vision Sensors
- Concluding Remarks

Information Society

Motivation

Unfortunately, recent news speaks for itself…

2006 Report Card for Pennsylvania's Infrastructure

Each category was evaluated on the basis of condition and performance, capacity vs. need, and funding vs. need.

A= Exceptional
B= Good
C= Mediocre
D= Poor
F= Failing

Aviation	C+
Bridges	C
Dams	C-
Drinking Water	D+
Navigable Waterways	D-
Rail	B
Roads	D
Transit	D+
Wastewater	D-
Pennsylvania's Infrastructure GPA	D

Critical Infrastructures

- "Critical infrastructures are those physical and cyber-based systems essential to the minimum operations of the economy and government. … their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States." - *President William J. Clinton, 1998*
- They Include:
  - Transportation infrastructure
  - Water distribution and treatment
  - Power generation and distribution
  - Telecommunications infrastructure

The Need - Manageability

- The Federal Real Property Initiative – A Top 10 Critical issues along with Medicare and Social Security in 2003 by the Whitehouse
- Established by Executive Order, a Senior Real Property Officer was designated within each agency
- The US government also owns or manages one in every four acres of land in the United States *(According to its fiscal year 2003 financial statements)*

The Need – Privatization/Profit

- A wave of road privatization is about to hit the US. This will fundamentally change the way that a road is constructed, operated, marketed and maintained.
- The road will be operated like any other private business, and that will require active real-time technology to maximize efficiency, safety and profit.
- For similar reasons rail, some utilities, and other asset owners are also in this opportunity.
- According to the CATO Institute "With private operators responsible for maintenance as well as improvement of the highways, gasoline taxes and other government charges for roads could be phased out. New ideas and new technologies would be applied."

The Need – Maintenance/Safety

- In Jan 2006, a bridge collapsed onto I-70
- Interstate 70 was closed for several days.
    - The bridge had been recently inspected and given a rating of 4 out of 10.

- Extensive corrosion damage to the pre-stressing cables and reinforcing bars in the concrete beam is believed to have contributed to the failure.
- The extent of this damage was not detected during visual inspection. It will require modern sensing technologies to reduce this kind of accident.

The Need – Operations

- On August 14, 2003, a blackout, twice as large as any in US history, left 50M people without electrical power
- Affected 250 power plants, 62 Gigawatts of generating capacity and occurred in less than 8 min
- Started with a few plants seeing excessive demand
- "Before it was over, three people were dead. 1.5M people in Ohio had no running water for 2 days….Twelve airports closed in eight states/Canadian provinces.
- The estimated economic damage was $4.5-$10 billion."

[Mansueti 2004]

The Need - Assessment

- Most of infrastructure assessments are based on human visual inspection
- Problems:
  - Inspector training inconsistent
  - Some conditions go visually undetected
  - Actual usage unknown
  - History = numeric condition ratings & textual report
- Do we really know the true state of this infrastructure?

The Need - Environmental

- Major Undetected Pipe Leak in 2006
- The largest oil spill occurred on the tundra of Alaska's North Slope
- 270k gallons of thick crude oil spilled over two
- Oil escaped through a pinprick-size hole in a corroded 34-inch pipe
- Most of the oil seeped beneath the snow without attracting the attention of workers monitoring alarm systems.
- The spill went undetected for as long as five days …

New York Times, March 15, 2006 [Berringer 2006]:

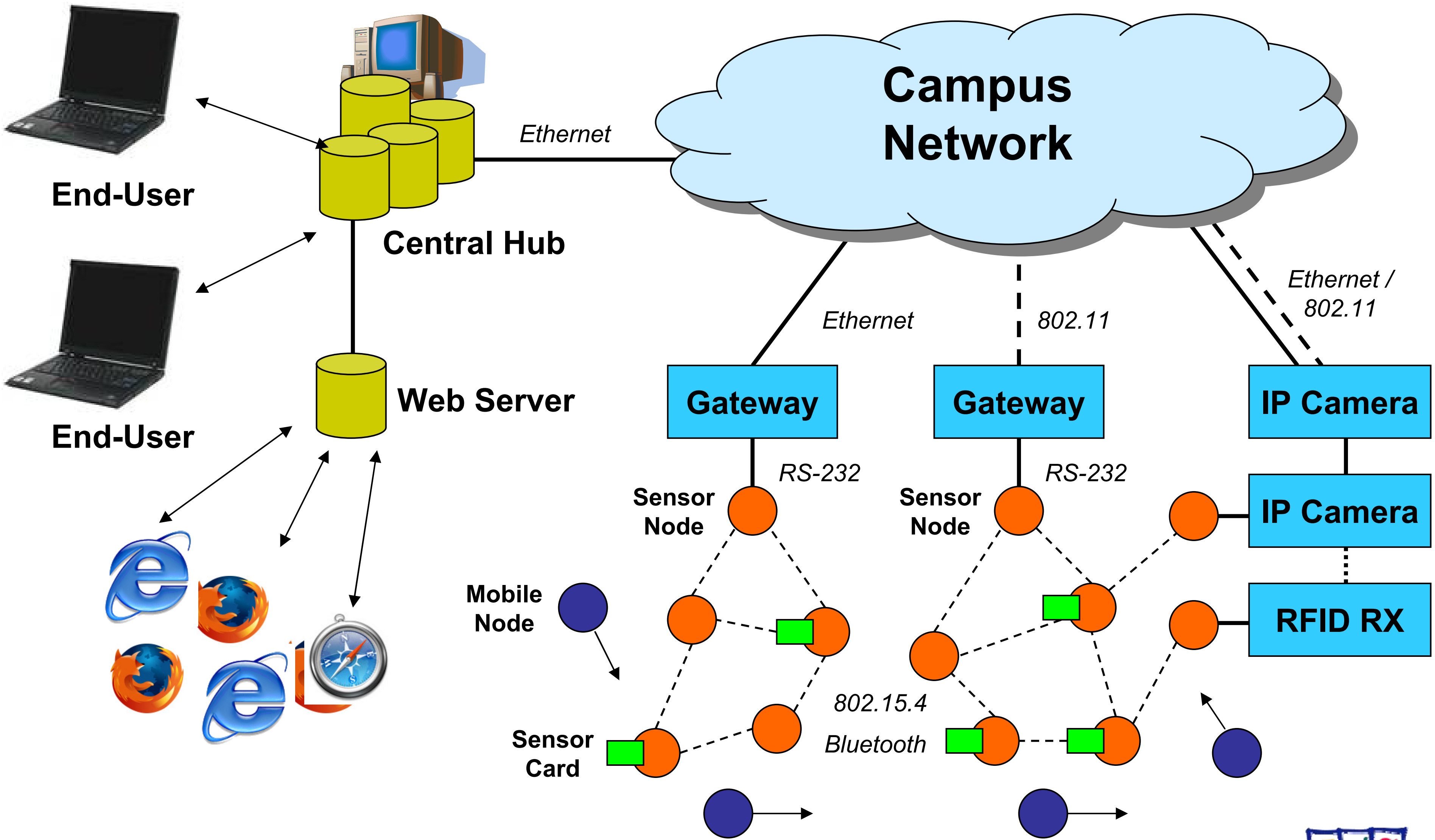
Sensor Andrew

A Living Laboratory for Infrastructure Sensing Technologies

Sensor Andrew

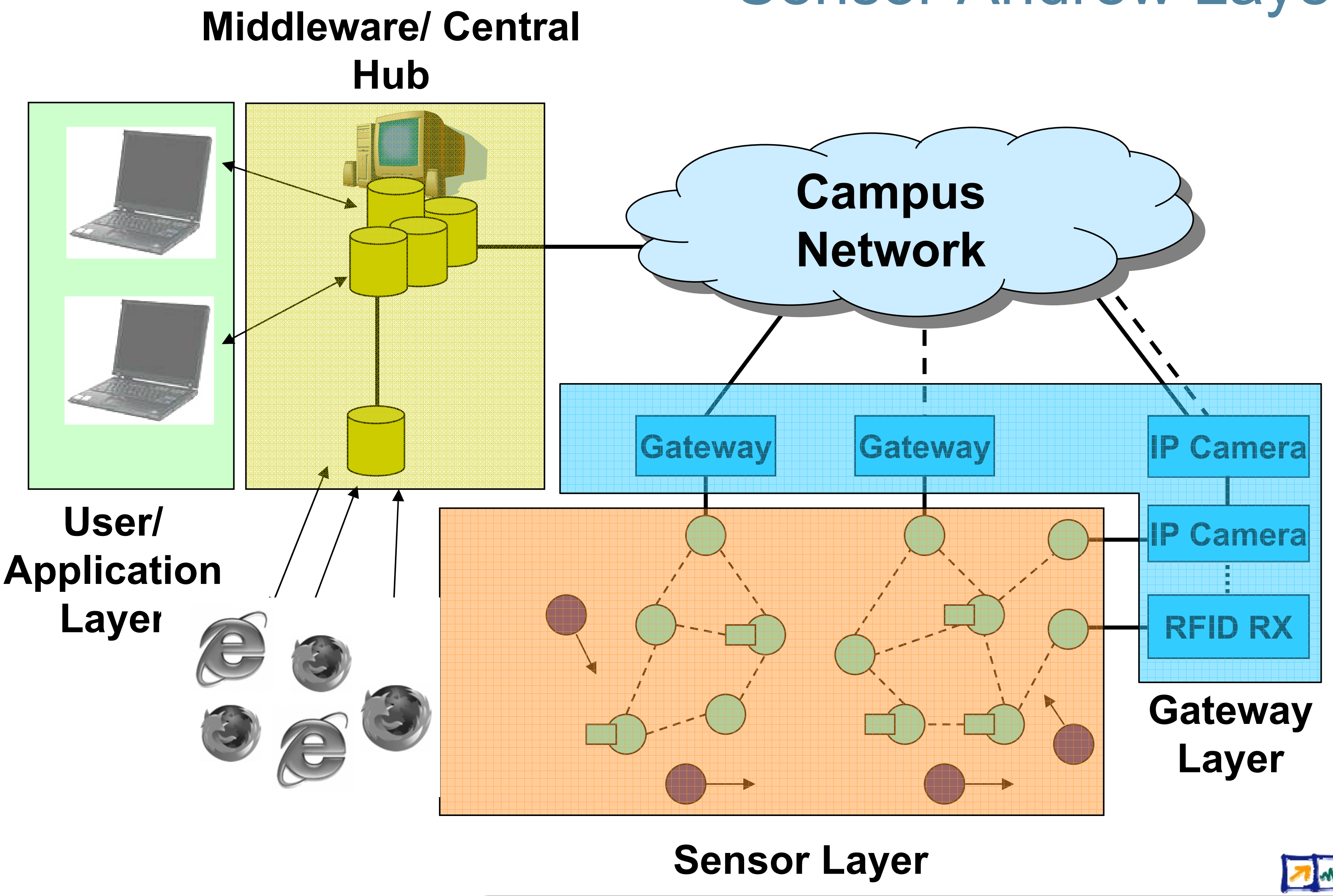
- **Campus-wide infrastructure for sensing *and* control**
- **Goals**
  - Ubiquitous large-scale monitoring and control
  - Easy to manage, configure & use
  - Scalable and extensible
  - Secure and private
  - Evolves
    - Evaluate different computational paradigms for sensor networks
    - Rapidly prototype applications at scale
    - Demonstrate utility, deployability and practical usage

Sensor Andrew



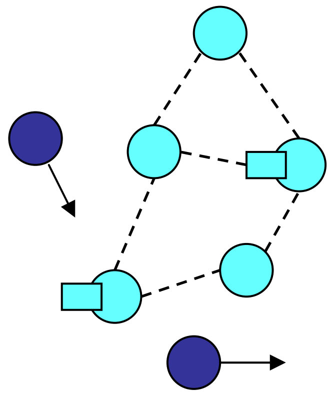
* Protocols listed are examples

Sensor Andrew Layers



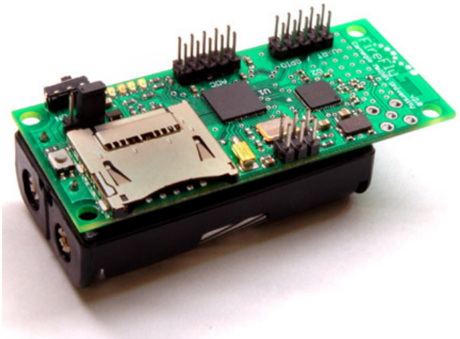
Current Application Families

- **Physical Infrastructure monitoring and control**
  - Stress on pipes + humidity monitoring, temperature control, energy control
  - Inventory tracking (RFID)
- **Access Control to Physical Areas**
  - Entry/exit point access control
- **Social Networking**
  - People tracking and notification with privacy constraints



Mobile node

Hardware



Time Synchronization

FireFly sensor nodes

Smart Camera Nodes

Line Voltage Control

eWatch

FireFly Hardware

D Cell Node

AA Cell Node

Development Node

Gateway Node

eWatch

Objective

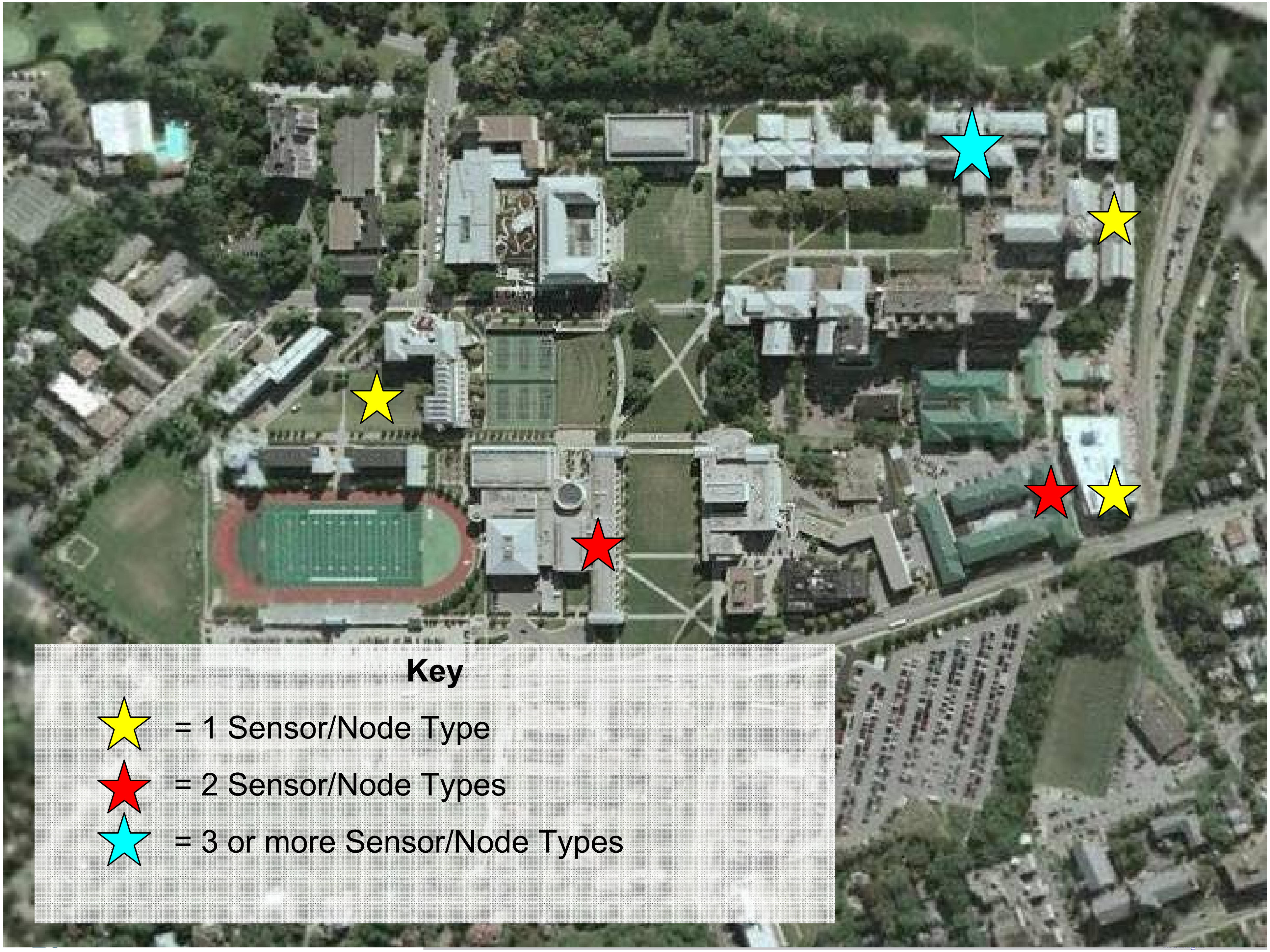
- Context-Aware Wearable Computing Platform
- Link to cellular phone (via Bluetooth) as gateway to outside world
- Experimental Platform for Learning of User State
- Experimental Platform for Power Management Schemes

Hardware / Sensors

- Acceleration, Tilt, Ambient Light, Temperature and Audio
- Tactile, Visual and Audio Notification
- Bluetooth, IR and 802.15.4 Communication
- ARM7 Processor
- 1MB Flash Storage
- Extensive Power Management Hardware
  - Frequency Scaling
  - Peripheral Power gating

Applications

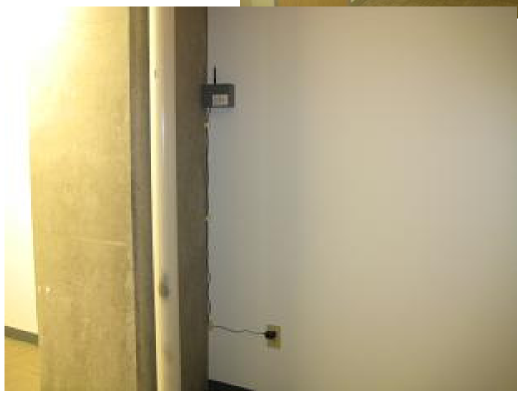
- Detect Accidents and call for help
- Context Aware Notification
  - Only interrupt for important calls / email
- Monitor Physical Activity
  - Monitor Daily Exercise
  - Help prevent RSI etc…
- Universal Remote Control
  - Interface with smart nodes in environment


Key
= 1 Sensor/Node Type
= 2 Sensor/Node Types
= 3 or more Sensor/Node Types

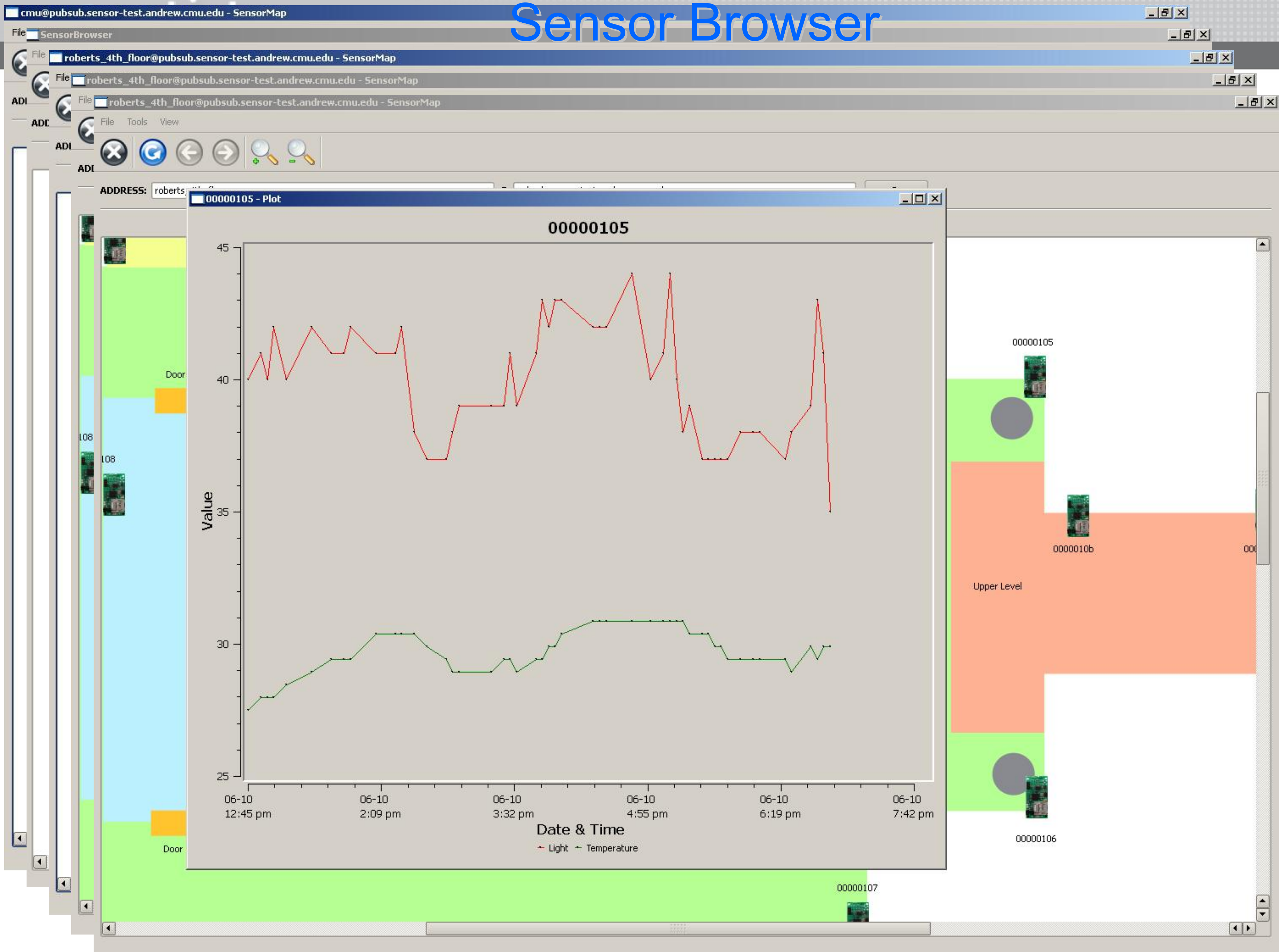
Wean Hall Deployment

Roberts Engineering Hall

CIC Deployment



Sensor Browser



Information Society

nano-RK

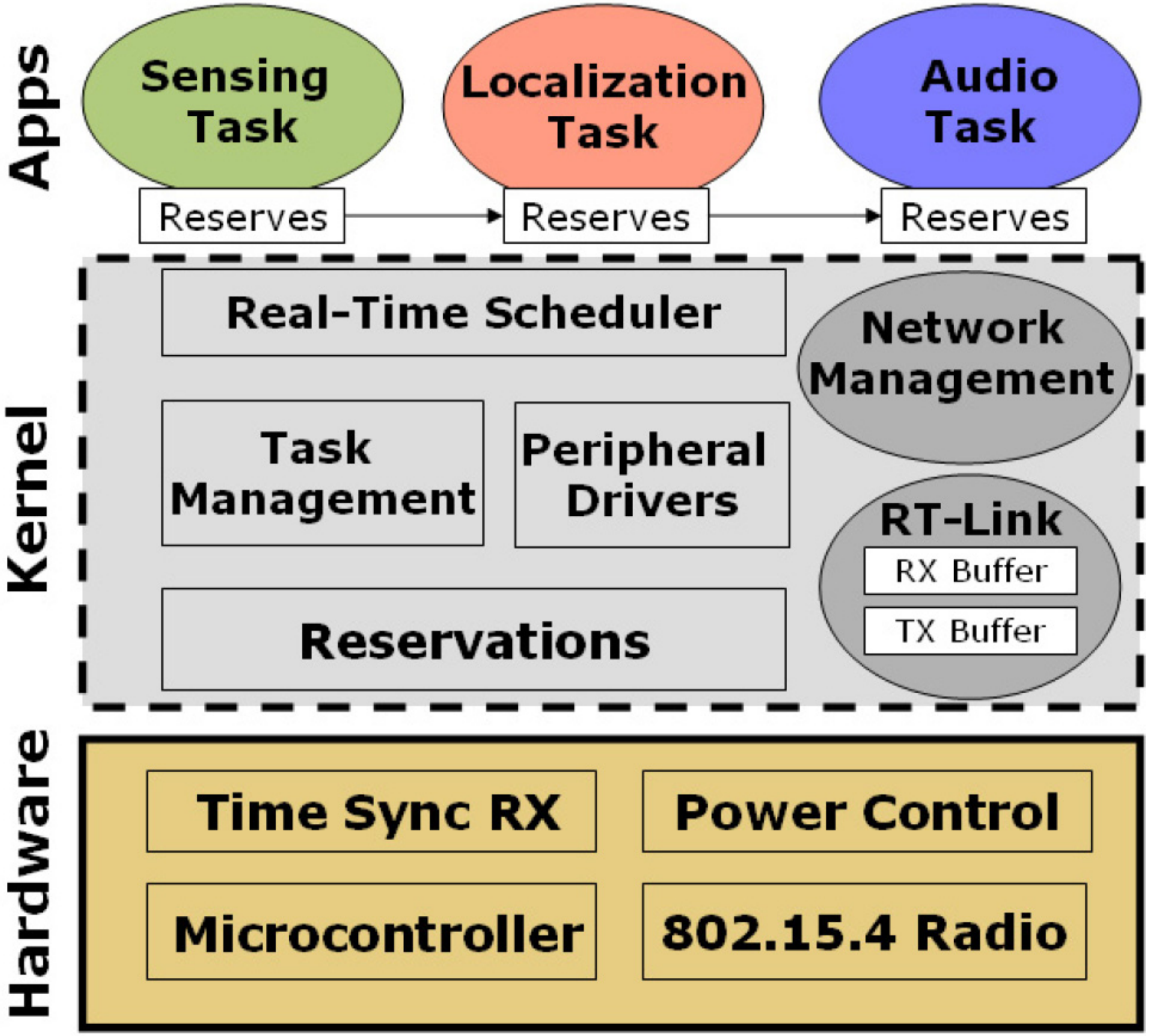
Nano-RK RTOS

- **Real-Time Preemptive Multitasking**
  - **Priority-driven: mapped from reservations**
  - **Interleaved processing and Communications**
- **Resource Reservations ("Resource Kernel") per task**
  - **CPU cycles, Network packets, Sensor / Actuator accesses**

  → Virtual Energy Reservation (aggregated across components)
- **Energy-Efficient Time Management**
  - **TDMA: go to sleep whenever possible (predictable and analyzable)**
  - **POSIX Style time Representation**
  - **Variable Tick Timer enables waking up only when necessary**
- **Fault Handling**
  - **Canary Stack Check, Reserve Violation, Unexpected Restarts, Low Voltage**

Nano-RK

www.nano-rk.org
www.ece.cmu.edu/~firefly



NanoRK Motivation

Why Priority-based scheduling?

	Period	Execution Time
Network Radio	Sporadic	10ms
Audio Sensor	200 hz	10us
Light Sensor	166 hz	10us
Smart Camera	1 hz	300ms
Global Positioning	5 hz	10ms

Time-triggered task interleaving can become daunting…

Furthermore, what if a new sensor is added or a period changes?

NanoRK Resources

Component	Resource
Context Swap Time	45 mS
Mutex Structure Overhead	5 Bytes per Resource
Stack Size Per Task	32→128 bytes (64 bytes by default)
OS Struct Overhead	50 bytes Per Task
Network Overhead	164 bytes
Total Typical Configuration: (8 tasks, 8 mutexes, 4 16 byte network buffers)	**2KB RAM, 10KB ROM**

Current Hardware Platform:

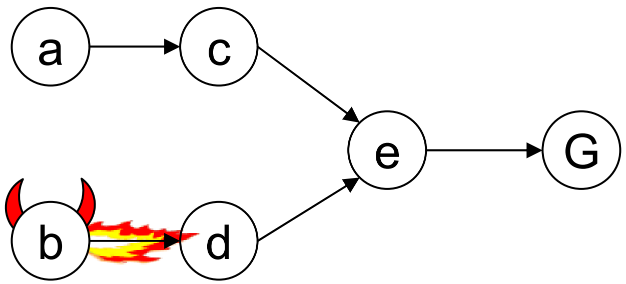
Atmega1281 with Chipcon CC2420 802.15.4 transceiver

NanoRK Reservations

- **CPU**
  - **Each Task can be given a budget of how long it is allowed to execute per a given period**
- **Network**
  - **Per Task Budget on Network Usage**
  - **Transmit and Receive Packets and/or Bytes**
- **Sensors / Actuators**
  - **Number of System Calls to a particular peripheral per a given period**

Virtual Energy Reservations

- **{CPU, Network, Sensors}**
  - **Together comprise the total energy usage of the node**
- **Static Offline Budget Enforcement**
  - **It is possible to calculate a node lifetime given a certain energy budget**

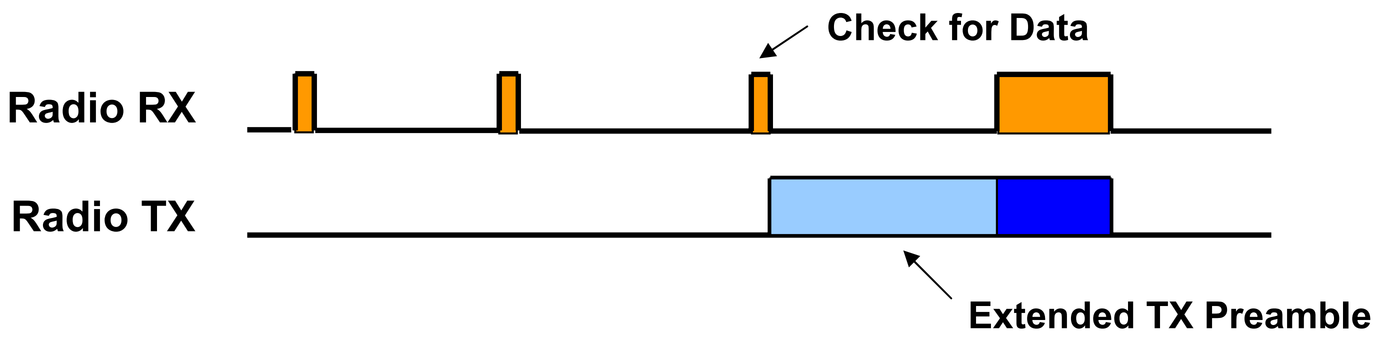


Node	Reserve [TX, RX]	TX Rate	Lifetime w/ out Reserve	Lifetime w/ Reserve
a	[1,2]	1	8 years	8 years
b	X	300	3.5 days	3.5 days
c	[1,2]	1	5 years	5 years
d	[1,2]	1	3.9 days	5 years
e	[1,2]	1	4 days	2.9 years

RT-Link

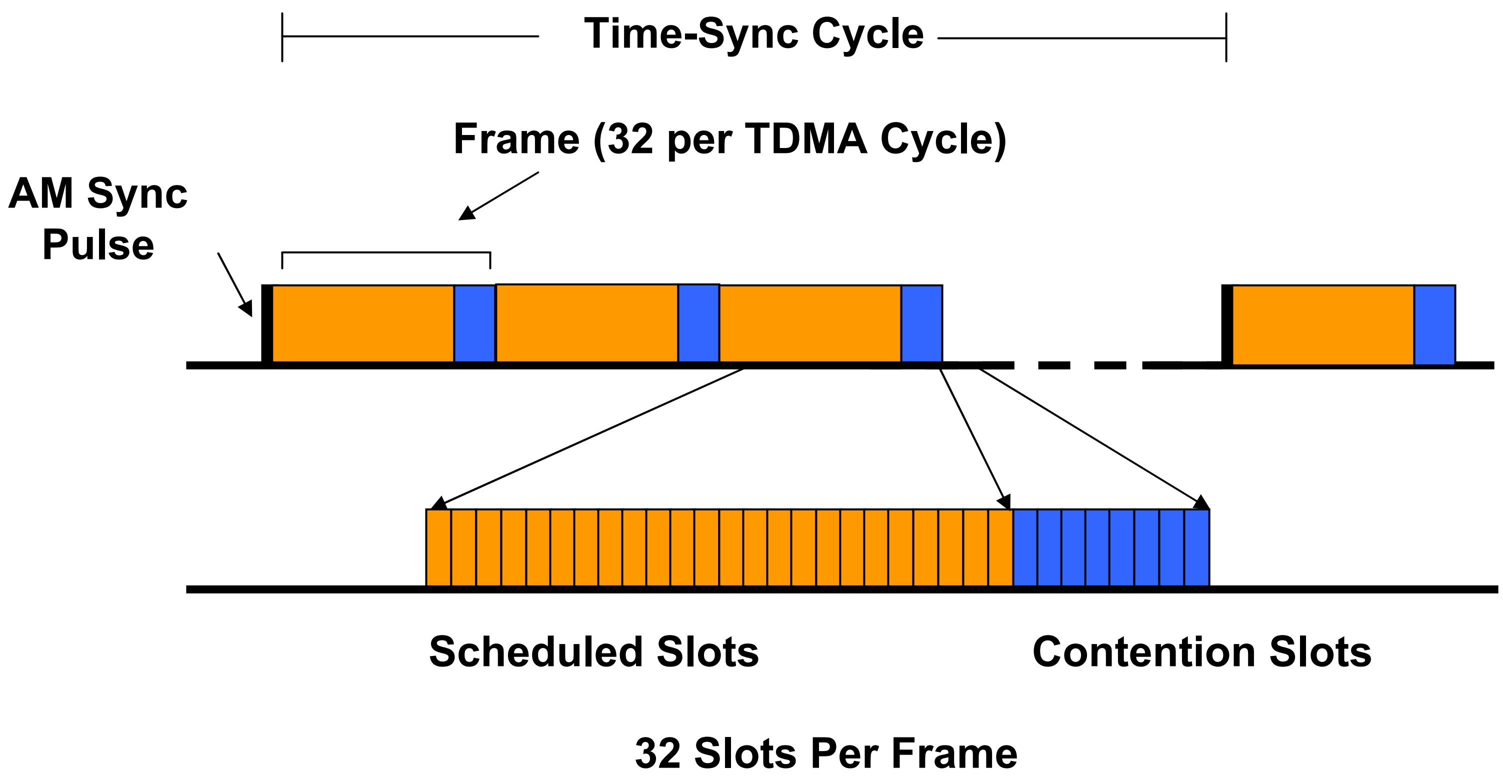
Current CSMA-based approaches

- **Low-Power Listen Carrier Sense Multiple Access (LPL-CSMA) schemes**



Tradeoff: Check Faster or Listen Longer?

TDMA-Based Approach (RT-Link)



NanoRK Network Stack

- **Zerocopy Buffering Mechanism**
  - **TX and RX buffers are in application space**
  - **Kernel Manages network data through pointer manipulation into application space**
- *Port* **Abstraction**
  - **A port allows applications to direct their data to individual tasks on each node**
- **Network Task**
  - **Handles Forwarding Packets, Routing, etc.**

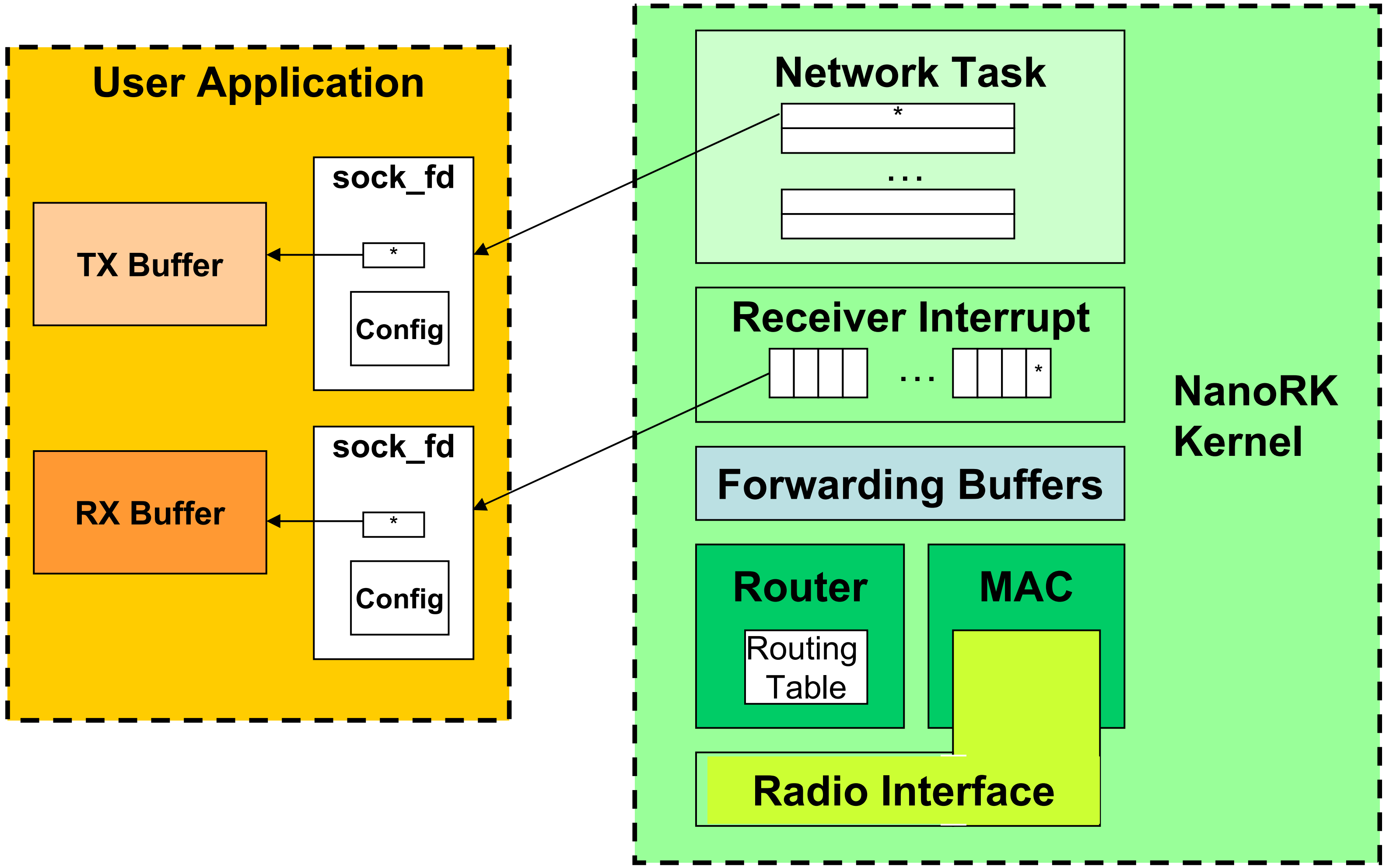
Network Stack

NanoRK Network Stack

- **CSMA MAC Support**
  - **Low Power Listen (LPL) MAC support**
- **TDMA MAC Support**
  - ***RT-Link:* Globally Time Synchronized MAC protocol**
- **Ad-Hoc Routing Support**
  - **Tasks can access low level routing table**
  - **Ex: An AODV or DSR *TASK* can be responsible for establishing and managing routes**

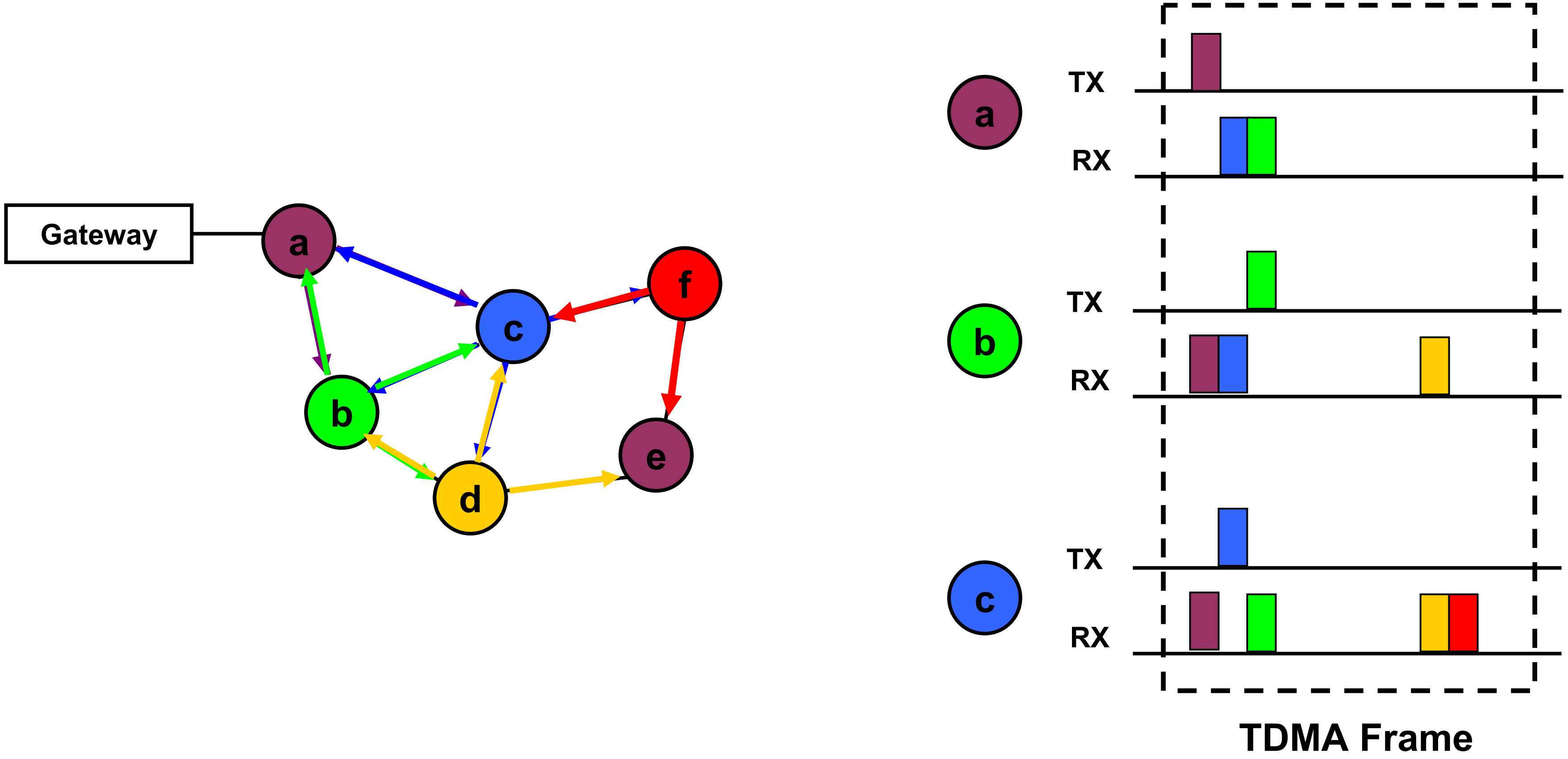
Network Stack

Detailed NanoRK Network Stack

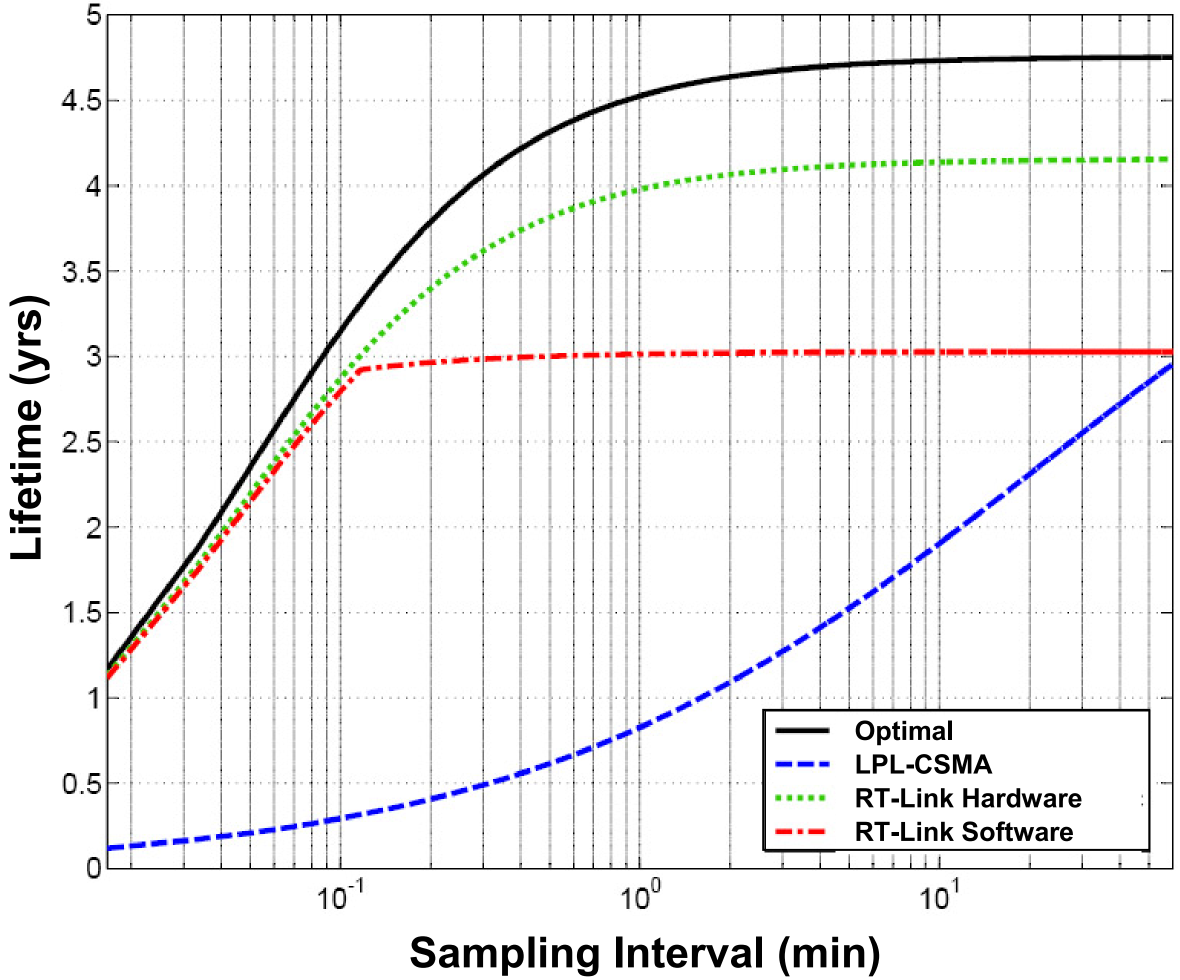


RT-Link Graph Coloring

- Color Topology Graph to Avoid Collisions
- Each Color represents a TDMA slot

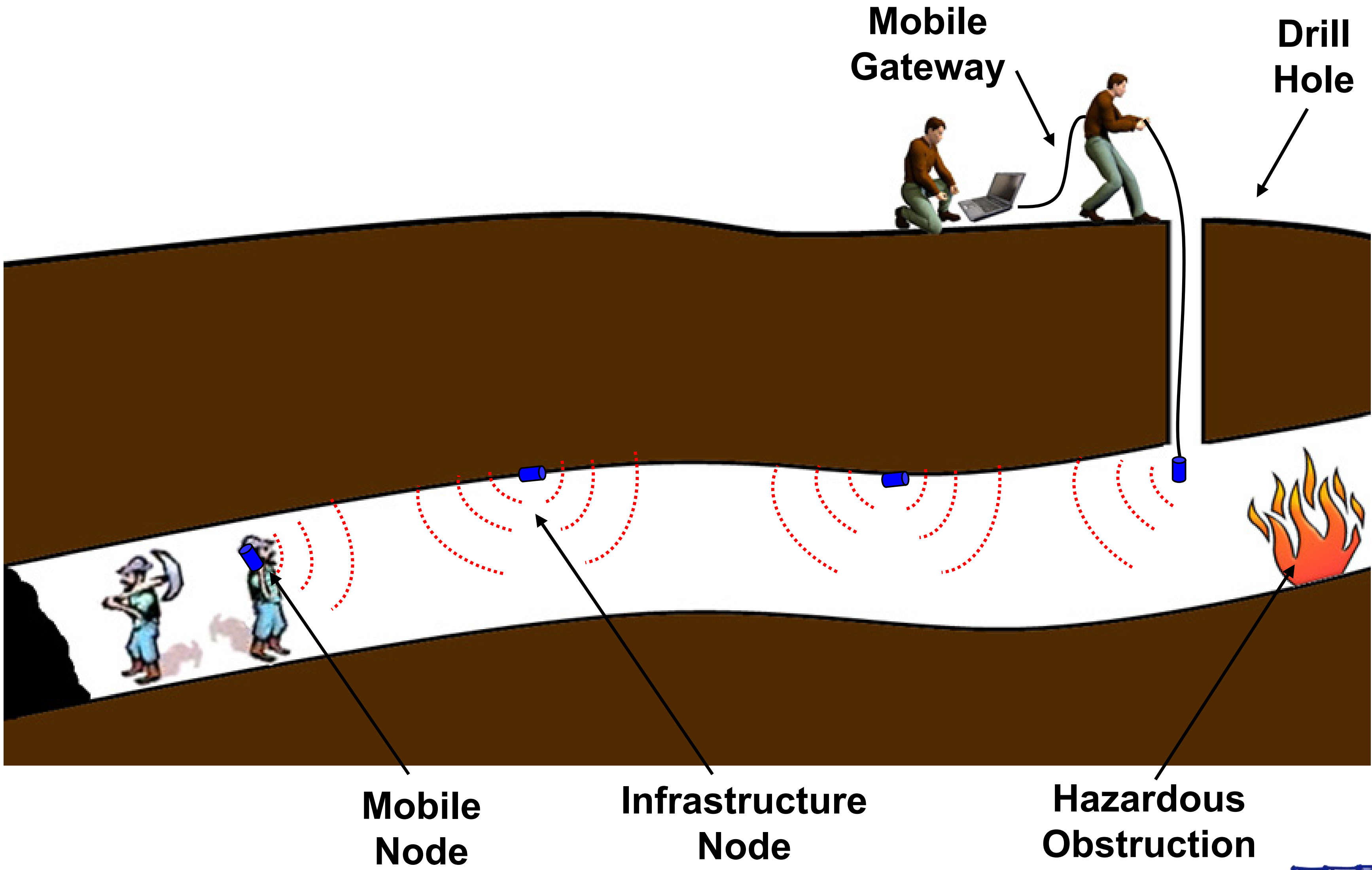


Lifetime Given Periodic Sampling



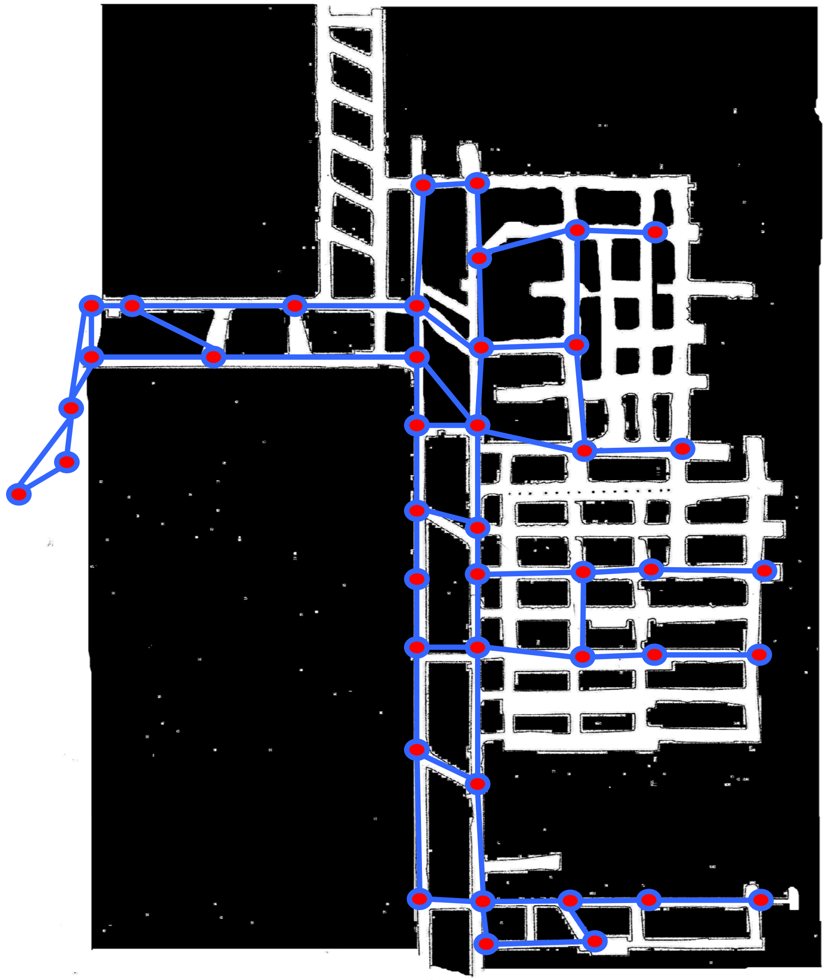
Voice over Sensor Networks

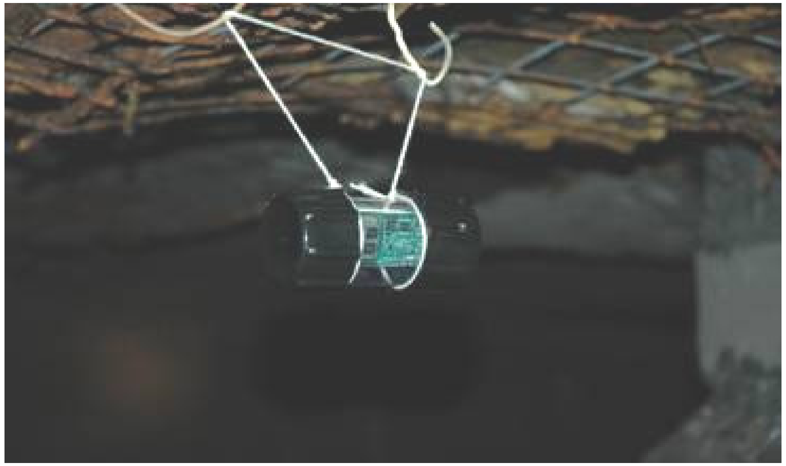
How Can a Sensor Network Help?



NIOSH Research Coal Mine

near Pittsburgh

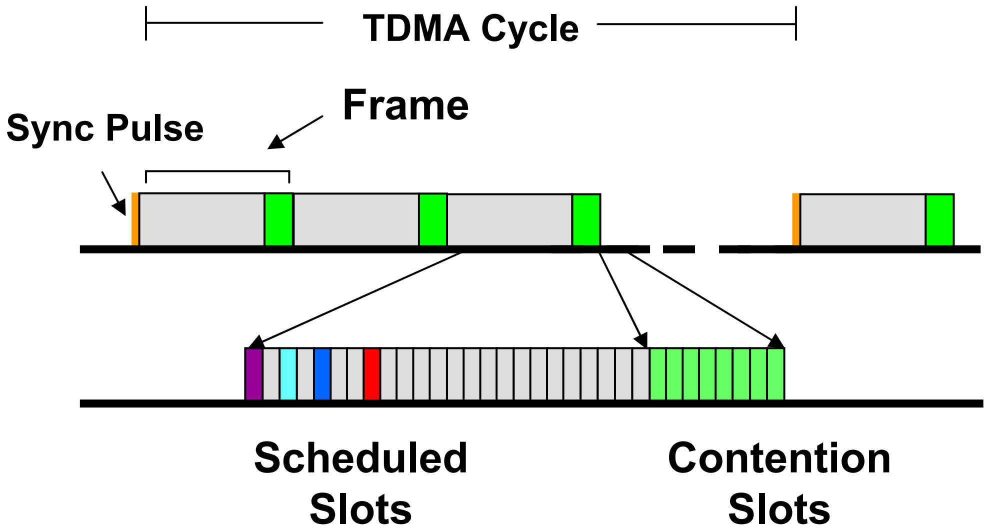


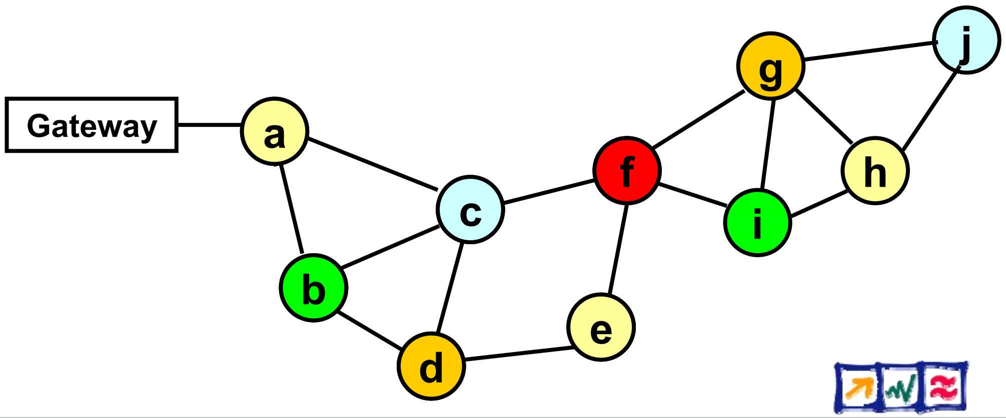


NIOSH: National Institute for Occupational Safety and Health

RT-Link TDMA Link Layer

- Fine-Grained Global Time Synchronization
- Collision-Free Energy-Efficient Communication





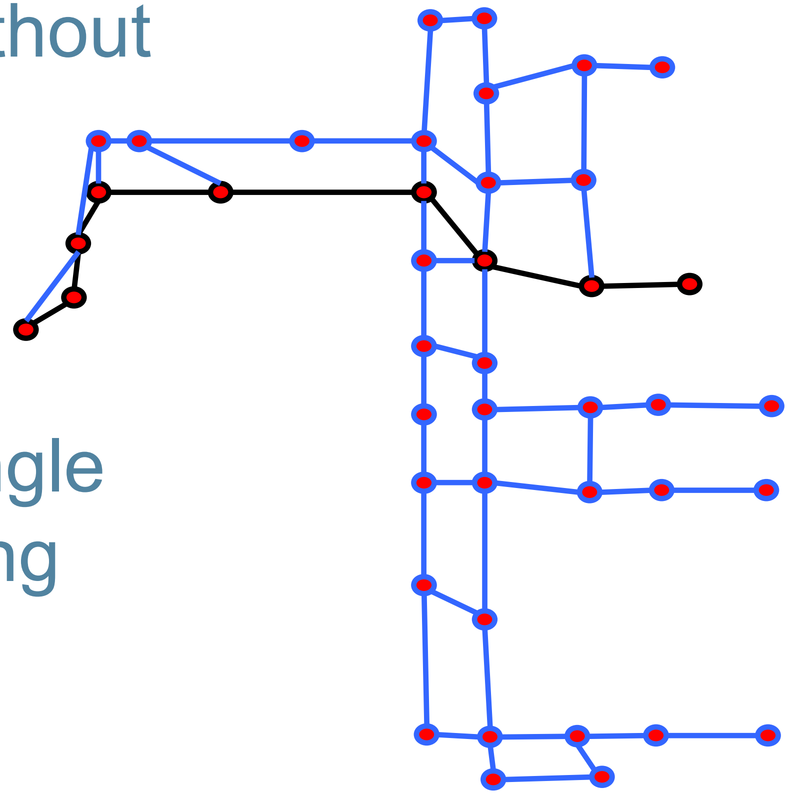
Information Society

Coal Mining Applications

- **Periodic Sensing Task**
  - **Every TDMA cycle (~6 seconds) sensor values are sent**
- **Location Task**
  - **Infrastructure Nodes Report List of Mobile Nodes in Range**
  - **RSSI values available if finer grained location required**
- **Audio Task**
  - **Sample Audio every 250*ms* (Nano-RK Driver)**
  - **ADPCM Compress Buffer (45*ms* per byte)**

Voice Scheduling Challenges

- Schedule Voice Along With Lower-Rate Sensor Data without Interference
- Balance Upstream / Downstream Voice Latency
- On-Demand Gateway to Single Mobile Node Voice Streaming

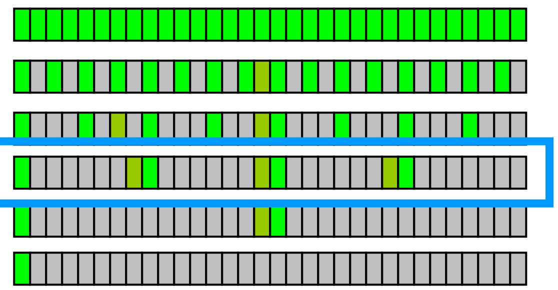


RT-Link Multi-Rate Support

Rate Index	Slot Interval	Max. Goodput (kbps)
0	-	0
1	1	149.3
2	2	74.6
3	4	37.3
4	8	18.6
5	16	9.3
6	32	4.6

Unused Slot

Active Slot

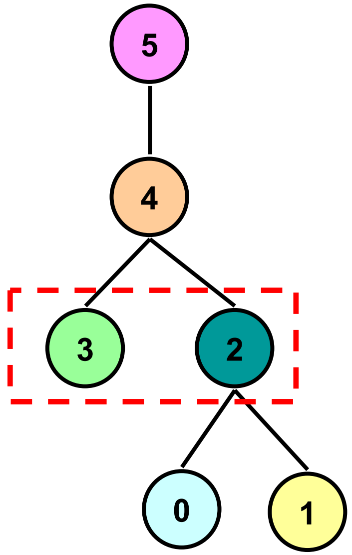


TDMA Frame

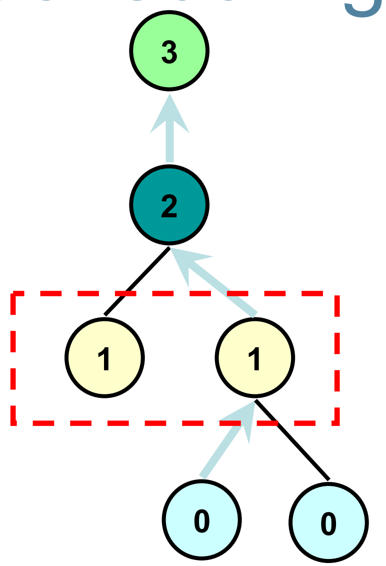
RT-Link Rate	Raw Audio 32Kbps	ADPCM-1 16Kbps	GSM-1 13Kbps	ADPCM-2 12Kbps	ADPCM-3 8Kbps	GSM-2 7Kbps	Avg. Hop Delay	Voice Reliability
1	4	9	11	12	18	21	6ms	Single
2	2	4	5	6	9	10	12ms	Single
3	1	2	2	3	4	5	24ms	Single
4	1	2	2	2	4	4	24ms	Double
5	0	0	0	0	4	4	48ms	Double

Voice Codecs: Concurrent Streaming

Point-to-Gateway Scheduling



Typical D-2 Coloring (Tree)

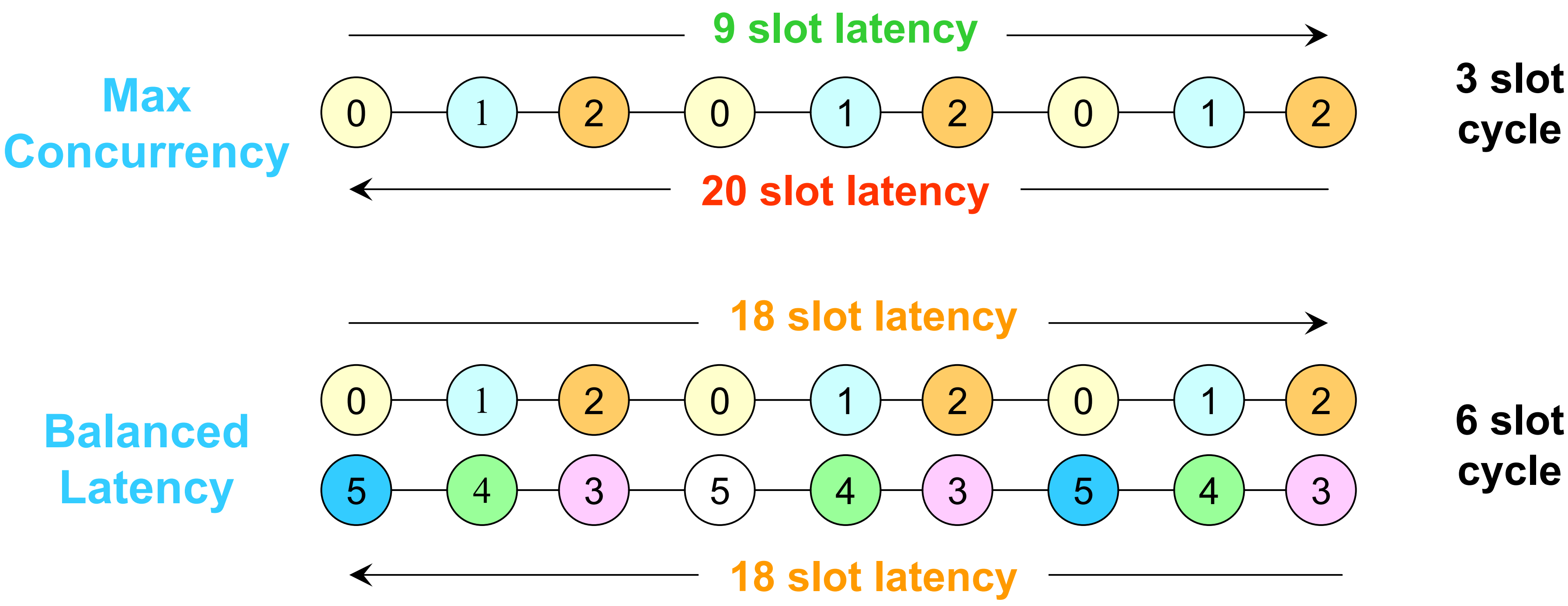


Simplified Voice Schedule (Equivalent to a Chain)

- Schedule to Support a Single Flow to the Gateway
- Nodes at Each Depth Can Share Slots for a Single 2-way Voice Stream in the System

Balanced Latency

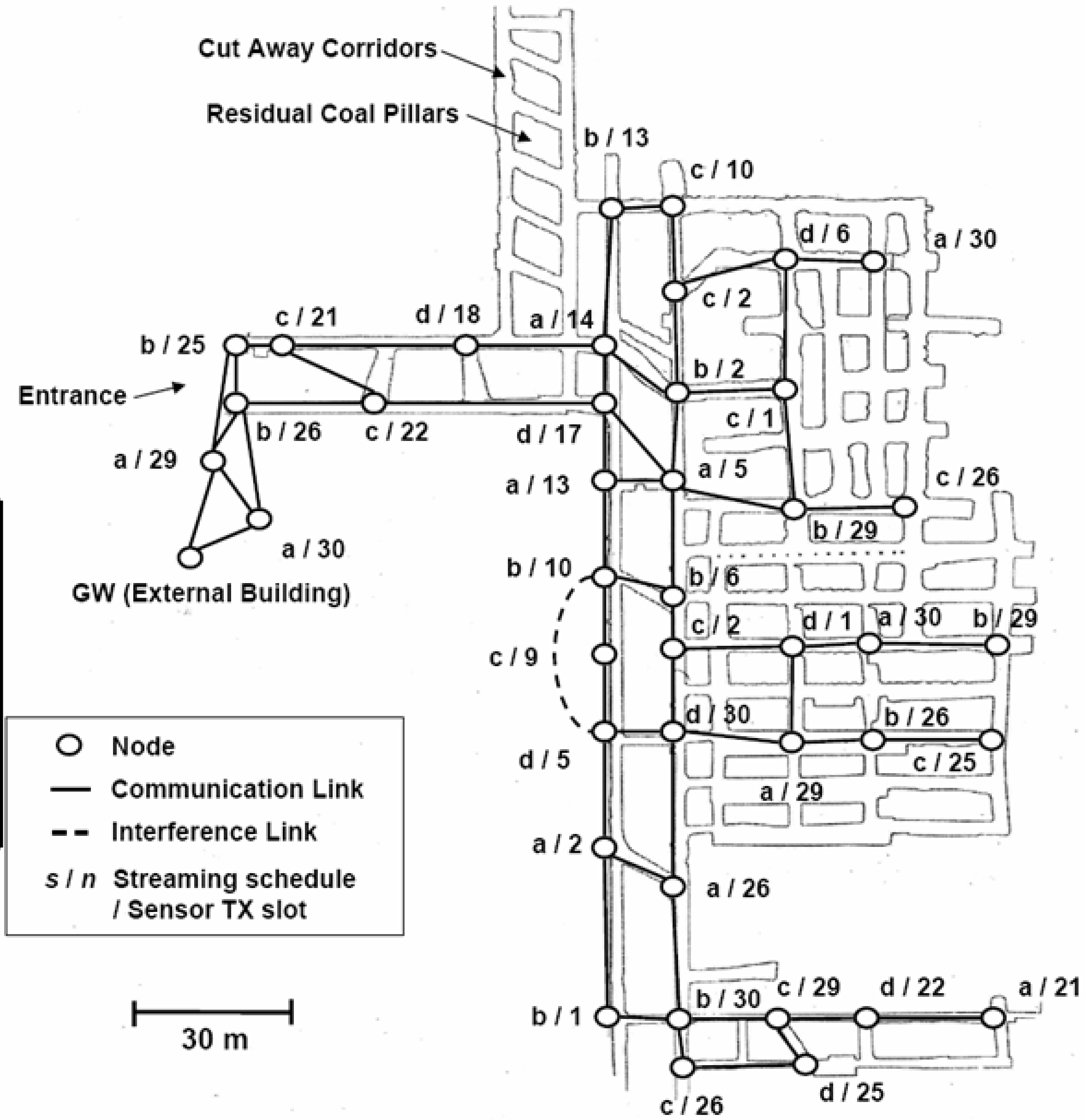
- Minimum Delay and Balanced Latency is more important than Maximizing Concurrency



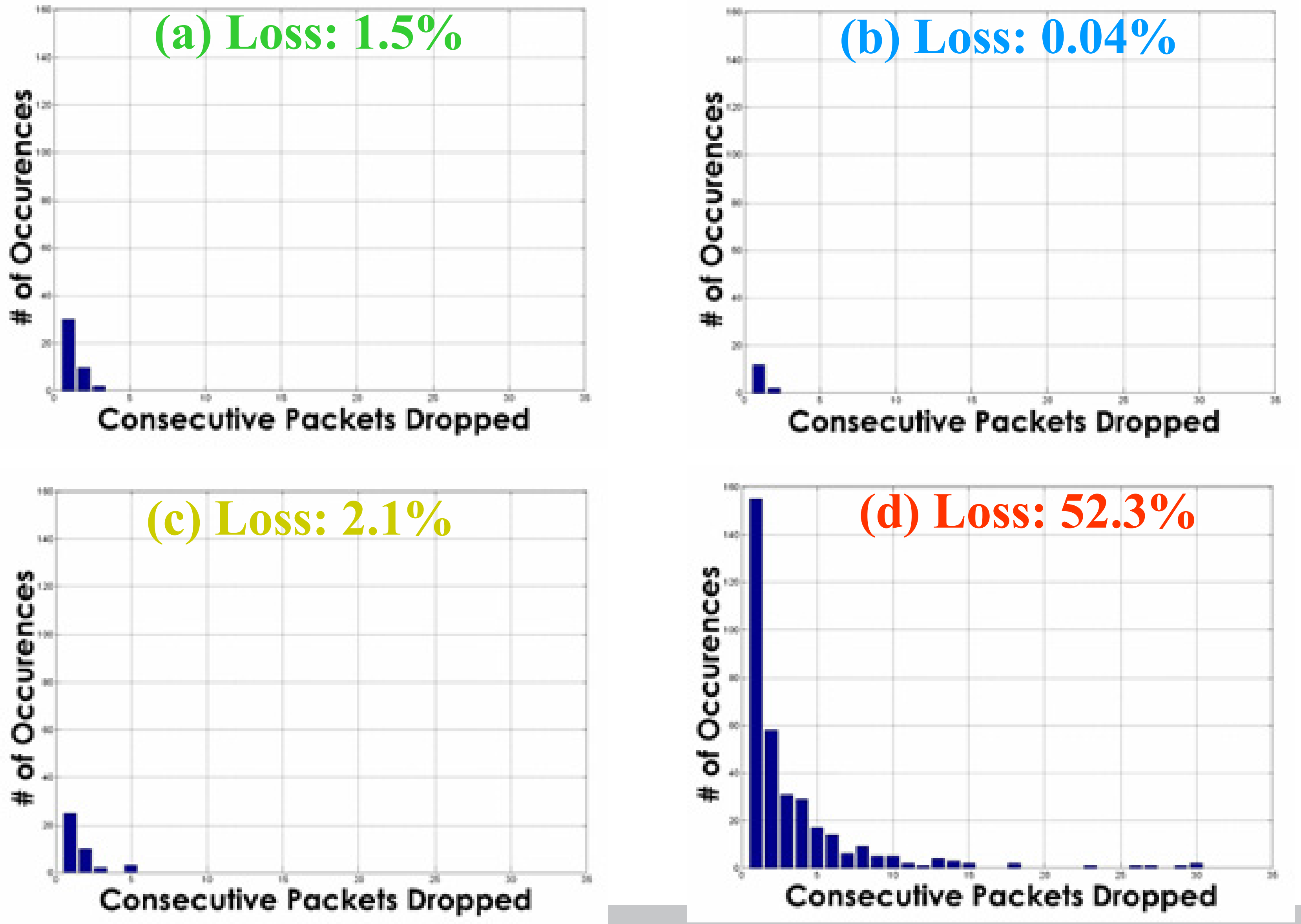
Example Schedule

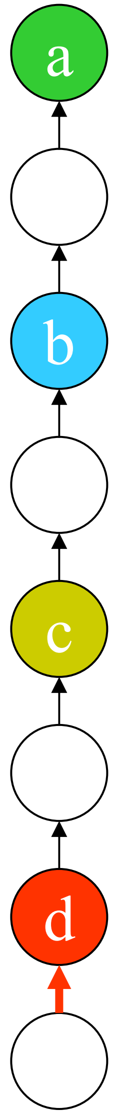
- Schedule Applied to NIOSH Experimental Coal Mine Topology

	TX Slots	RX Slots
a	0, 8, 16, 24	3, 11, 19, 27
b	3, 11, 19, 27	7, 15, 23, 31
c	7, 15, 23, 31	4, 12, 20, 28
d	4, 12, 20, 28	0, 8, 16, 24



Packet Loss Distributions





Power Consumption and Node Lifetime

Operation	Power	Time	Energy
4-bit ADPCM	21 *mW*	43 *ms*	903 *nJ*
2-bit ADPCM	21 *mW*	37 *ms*	777 *nJ*
ADC Sampling	21 *mW*	3 *ms*	6.3 *nJ*
RX Packet	59.1 *mW*	4 *ms*	236 *mJ*
TX Packet	52.1 *mW*	4 *ms*	208 *mJ*
Misc. CPU	21 *mW*	1 *ms*	21 *mJ*

Battery	Sensing	Streaming
2 x AA	1.45 years	16 days
2 x D	8.8* years	97 days
4 x D	17.6* years	194 days

**: longer than battery shelf-life*

Visual Sensor Networks

Current Video Surveillance Systems

- Human operators do most (if not all) recognition of objects on the screen
- System designed for archival and labor-intensive search
    - Timestamps are often the only automatic keys

Distributed Surveillance Applications

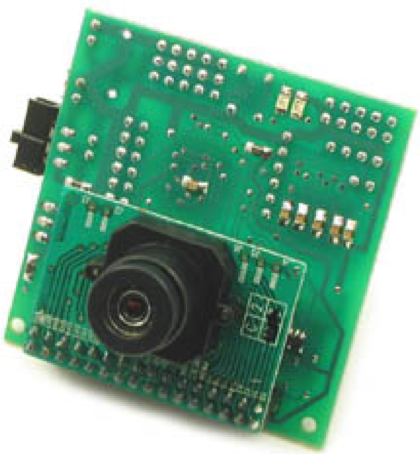
- Surveillance and event monitoring are critical for security and safety
  - Public infrastructure monitoring
  - Energy control
  - Campus and building security
    - Fire alarms
    - Intruder alerts
  - Hazardous material leakage
  - …

- Huge and growing industry worldwide
  - In the US, buildings consume more than 50% of the energy used
- Challenges:
  - Too many false alarms
  - Manual monitoring is too monotonous to be effective in practice
  - Wired installations are very expensive
  - Security and privacy concerns
  - Physical (sensing and actuation) and cyber (computing, networking and display) components
    - Complexity and heterogeneity of dynamic networks

Embedded Vision Processor

Objective

- Develop a Low Cost Embedded Vision Processor
- Exports High Level information to another processing board
  - Where is the brightest spot on the image?
  - What part of the image changed?



Current Capabilities

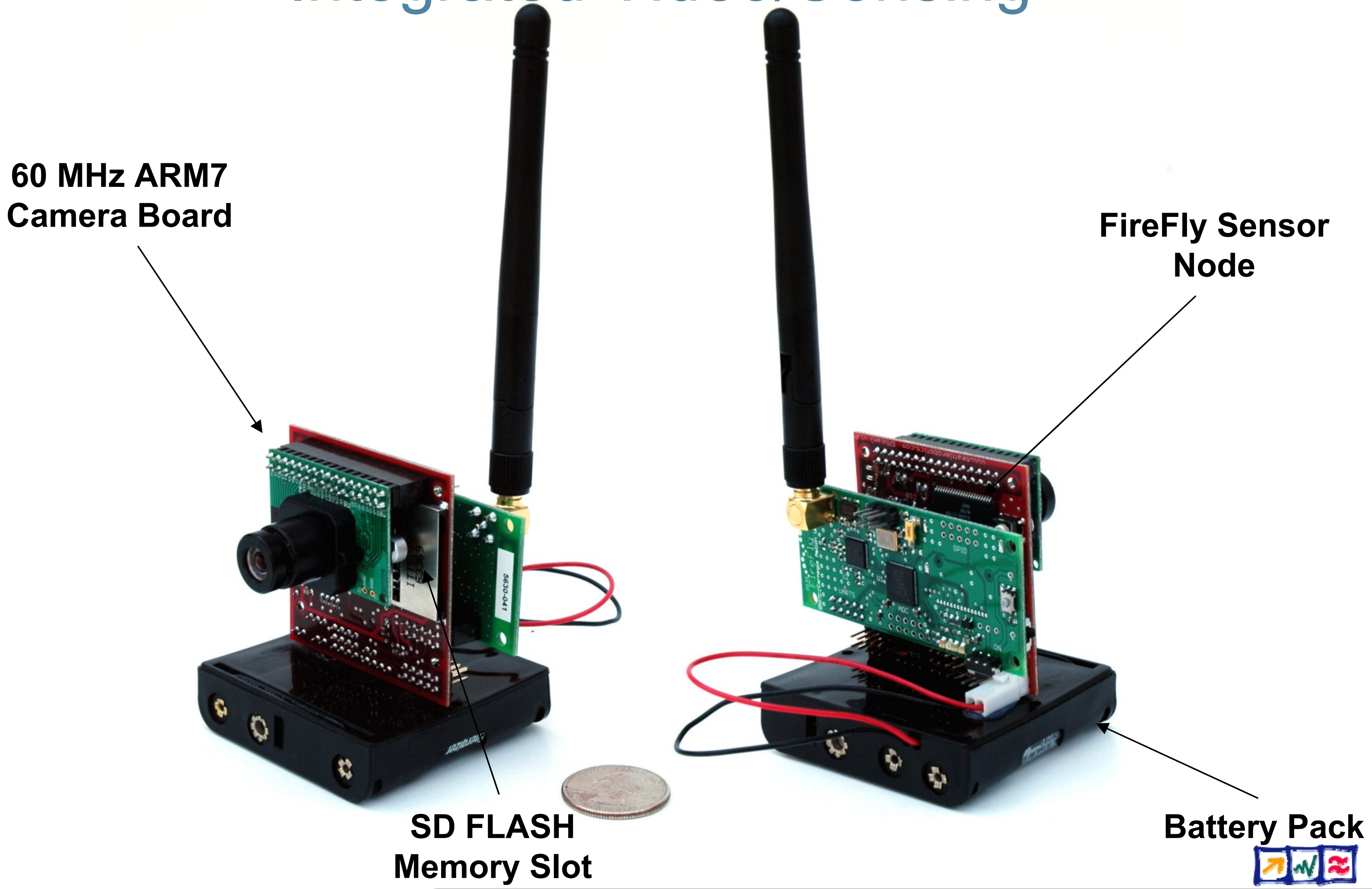
- 320 x 240 RGB CMOS Camera
- 60 Mhz ARM7 processor
- 50 Frames Per Second Color Tracking

Applications

- Sensor Networks
  - Intelligently select when to send images
  - Down Sample and Compress Images for Low Bandwidth Transmission
- Mobile Robotics
  - Horizon Tracking (UAV)

* Based on the “CMUcam and CMUcam2” www.cs.cmu.edu/~cmucam

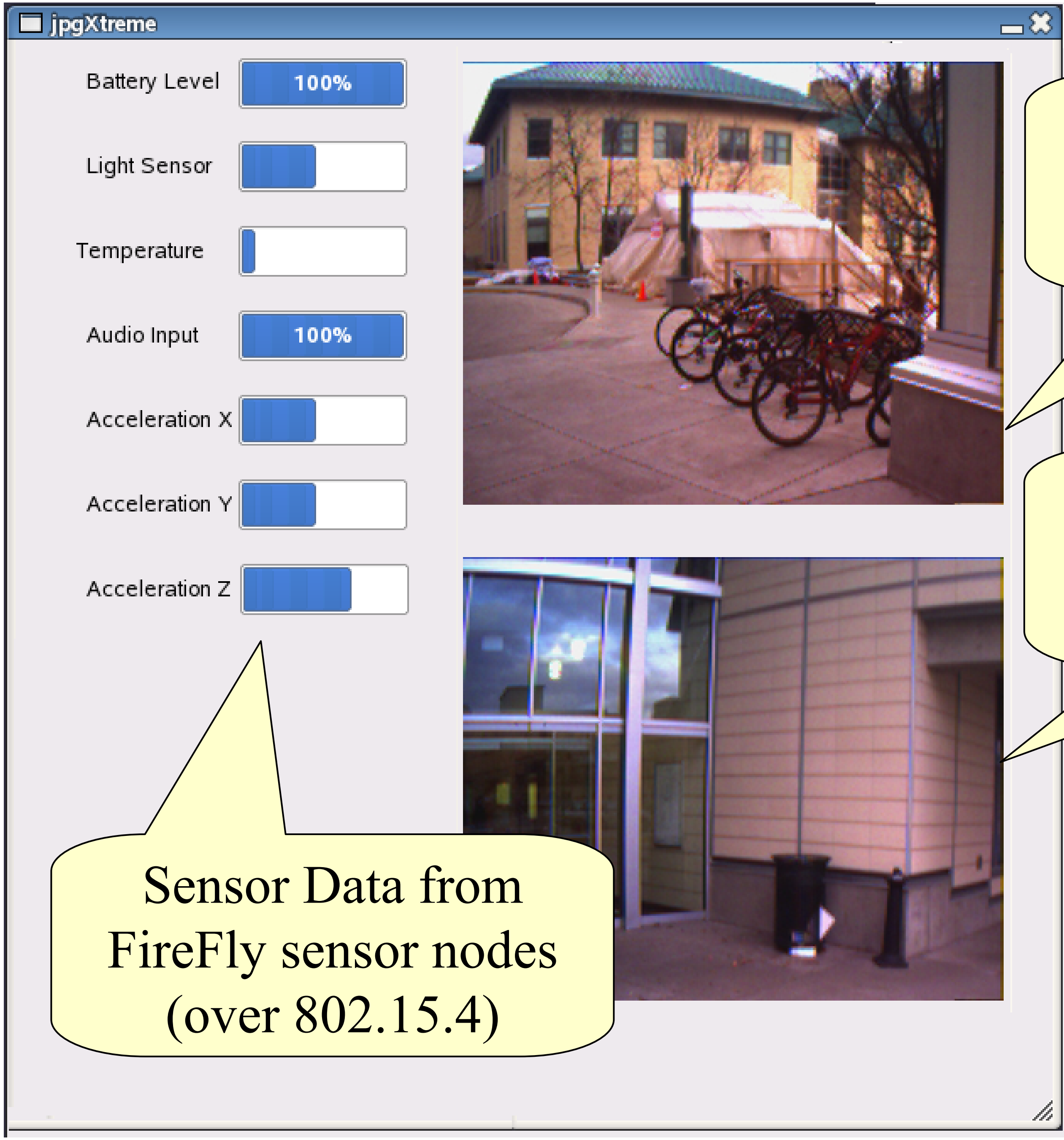
Integrated Video/Sensing



FireFly DSPcam v3

- VGA Color Camera
  - 640x480 images at 30Hz frame rate
  - DMA Frame Capture
- Analog Devices Blackfin DSP Media Processor
  - 600MHz, 32MB RAM and 4MB Flash
- Networking
  - 10/100Mbps Ethernet
  - 802.11 b/g
  - 802.15.4 FireFly Interface
- µClinux Operating System
  - Supports most Linux utilities
- GNU Development Environment
  - Open-source with GCC compiler
  - DMA CMOS Camera Driver

Real-Time Video + Sensor Data



View from FireFly DSPcam A (through 802.15.4)

View from FireFly DSPcam B (through 802.15.4)

Sensor Data from FireFly sensor nodes (over 802.15.4)

JPEG compression performed locally on FireFly DSPcam's

Concluding Remarks

- Sensor networks will have a large societal and economic impact on a wide range of infrastructure and other emerging applications
- Resource management in the form of energy management and timing coordination play a vital role in sensor networks
- Complete protocol stacks from hardware all the way to interesting applications are beginning to be deployed
  - Sensor Andrew and FireFly at Carnegie Mellon are examples
  - These networks must be self-configuring and self-healing
- Visual networks will add significant new dimensions in the future
  - Friendlier to humans, perception/recognition, privacy/security