CodeBlue:
A Wireless Sensor Infrastructure for Medical Monitoring

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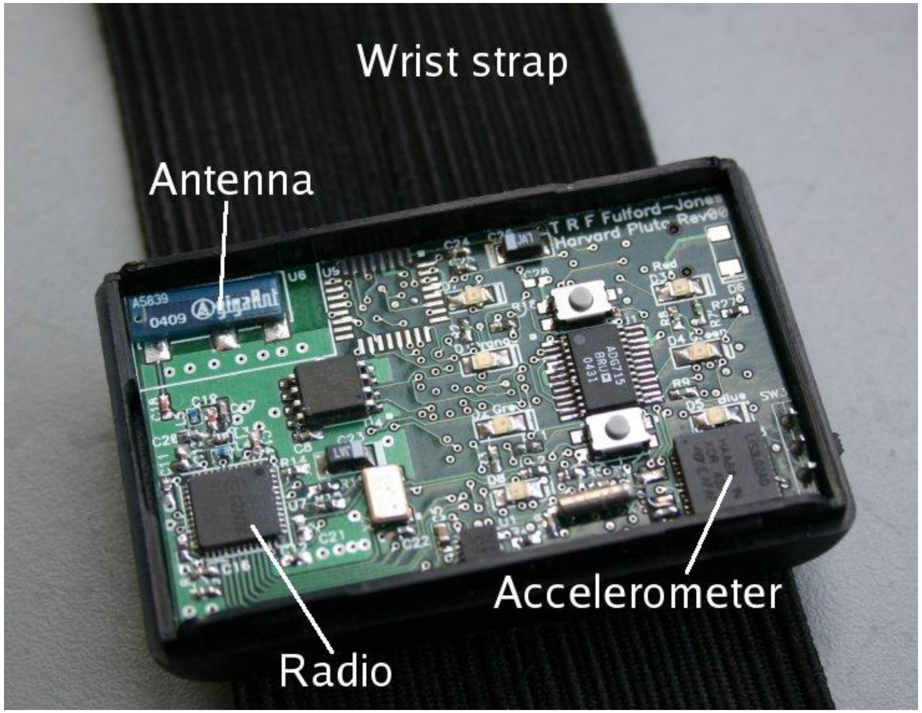
Introduction: Wireless Sensor Networks



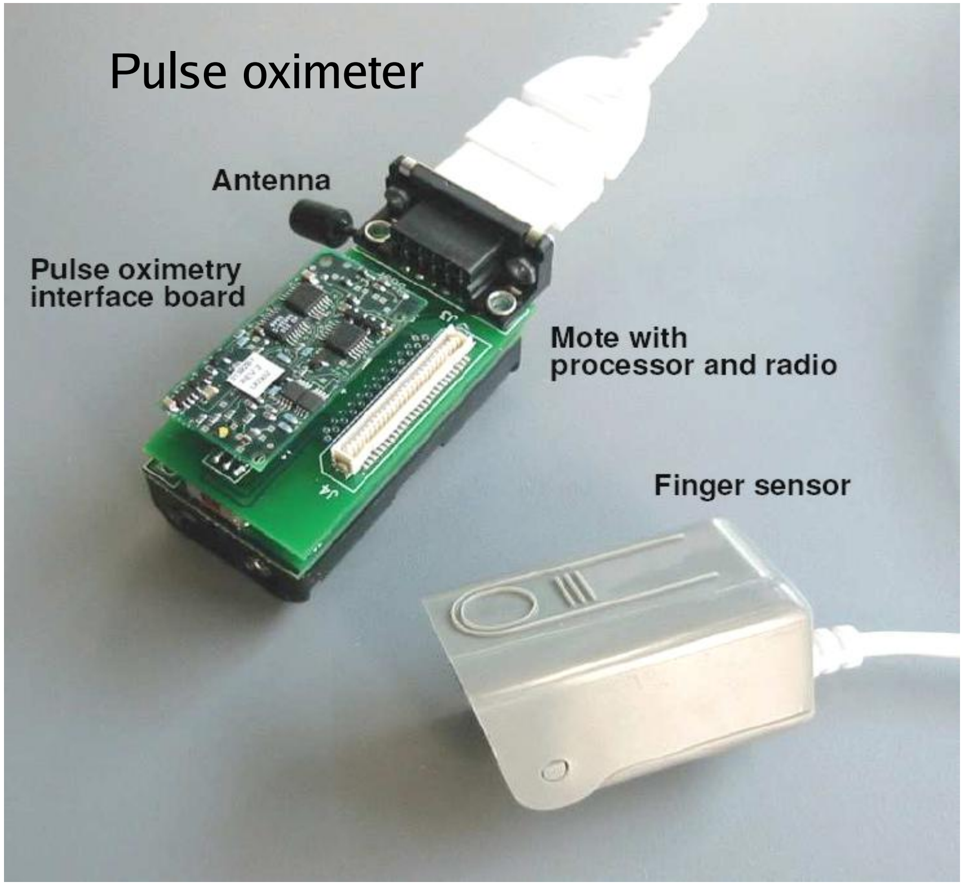
- Tiny, low-power, wireless sensors
- Minimal CPU, memory, and radio
  - 8 Mhz CPU, 10 KB RAM
  - 100 m radio range, 802.15.4/Zigbee
- Extremely low power
  - Battery lifetime of months to years

http://www.eecs.harvard.edu/~mdw/proj/codeblue

Potential Medical Applications

- Real-time, continuous patient monitoring
  - Pre-hospital, in-hospital, and ambulatory monitoring
  - Augment or replace wired telemetry systems
- Home monitoring for chronic and elderly patients
  - Collect periodic or continuous data and upload to physician
  - Allows long-term care and trend analysis
  - Reduce length of hospital stay
- Collection of long-term databases of clinical data
  - Correlation of biosensor readings with other patient information
  - Longitudinal studies across populations
  - Study effects of interventions and data mining

Some wireless sensors we have developed...



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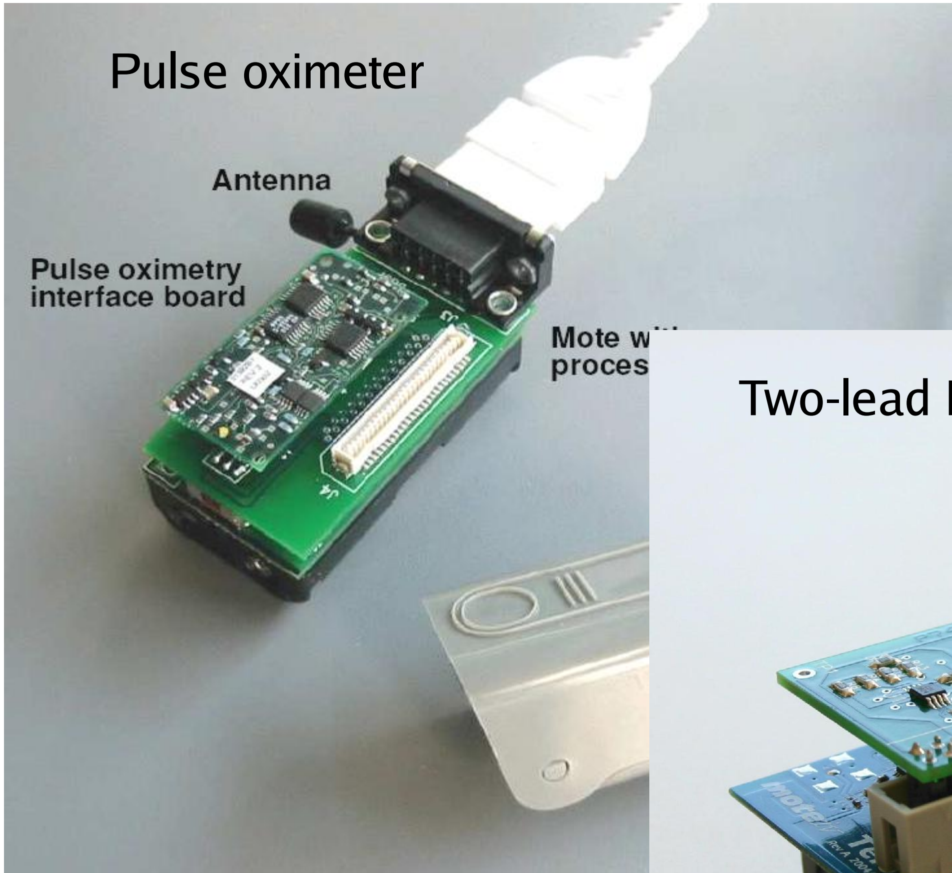

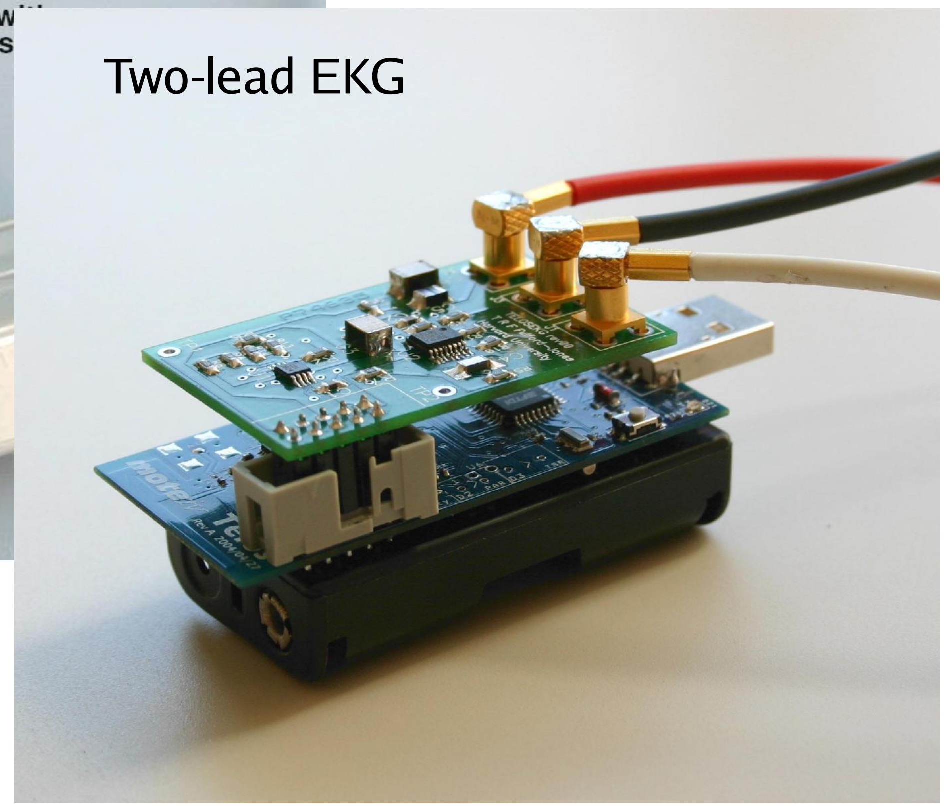

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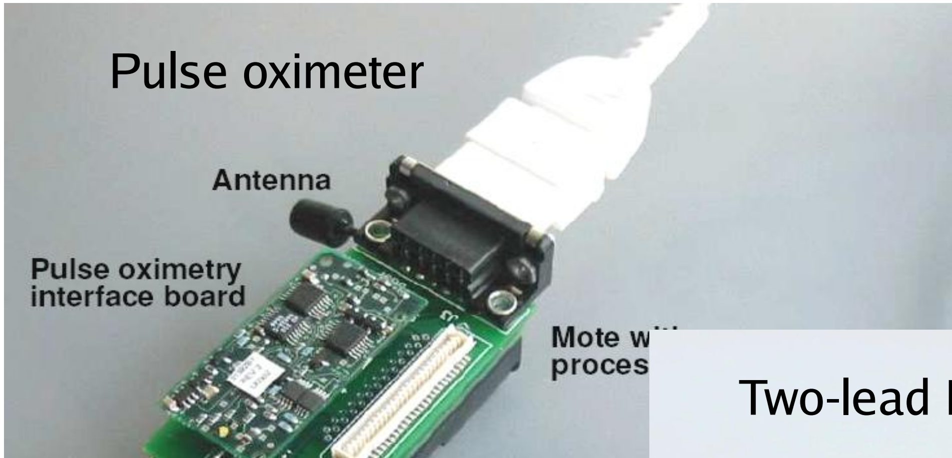

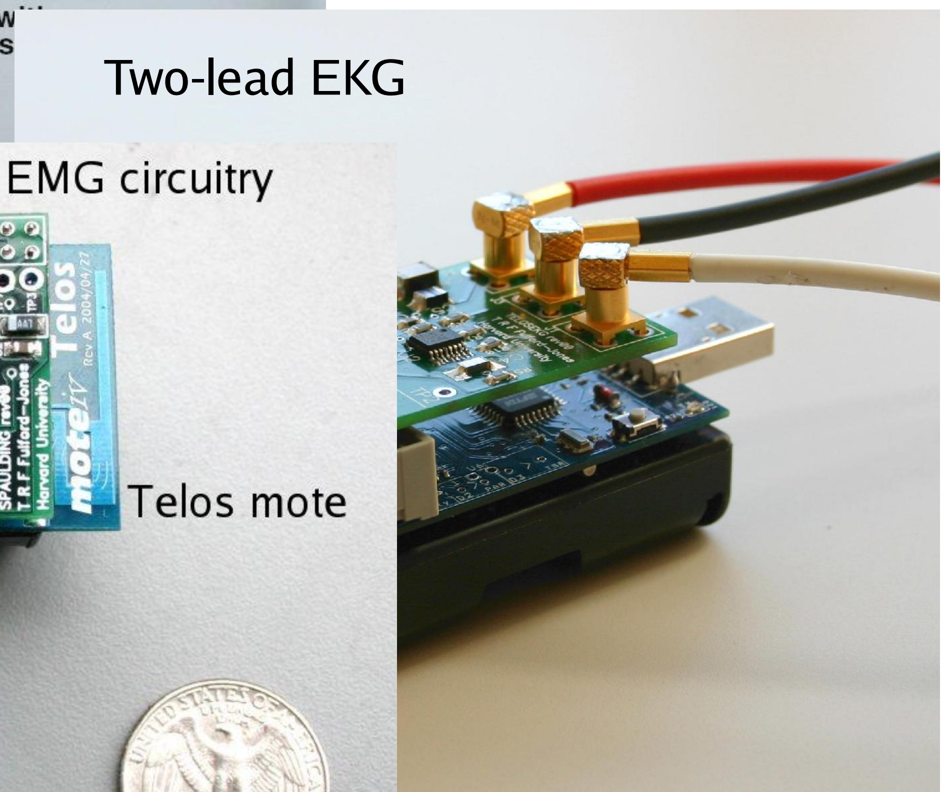

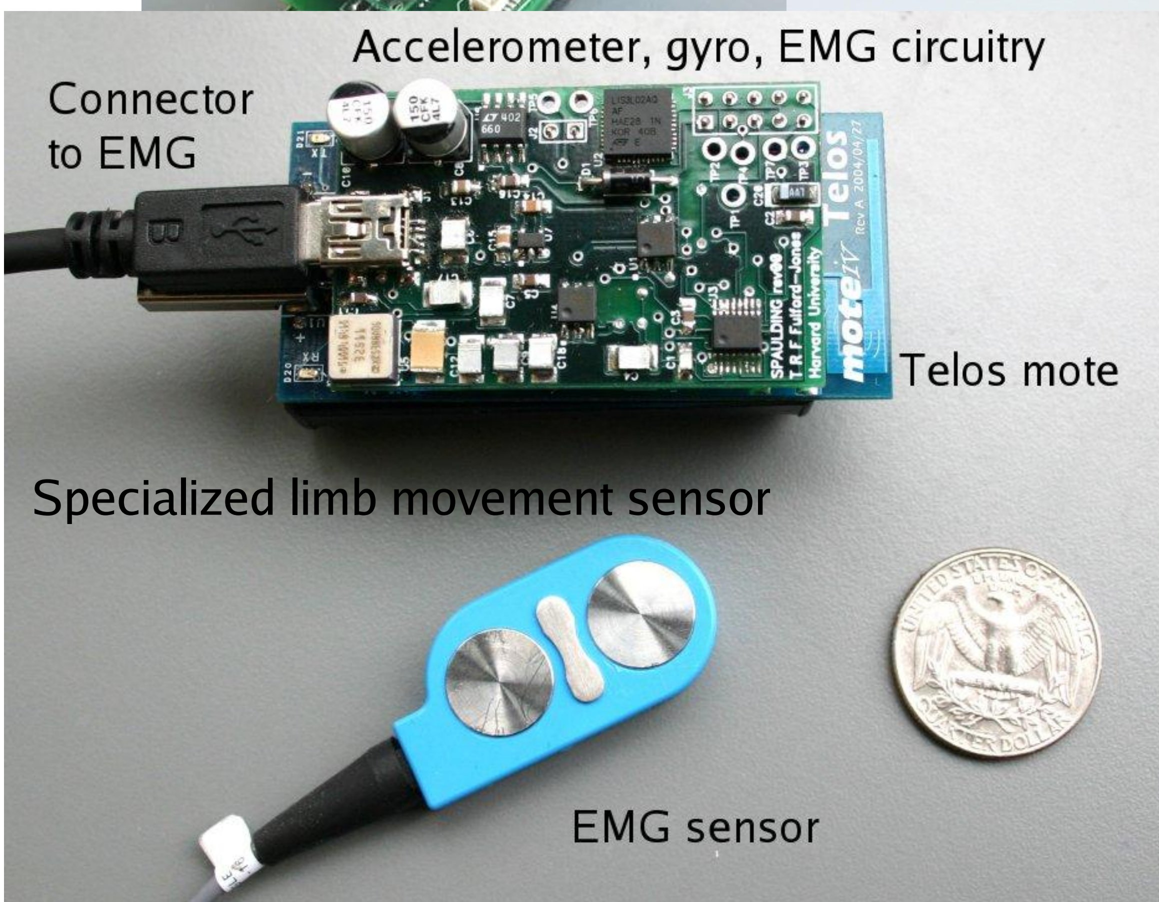

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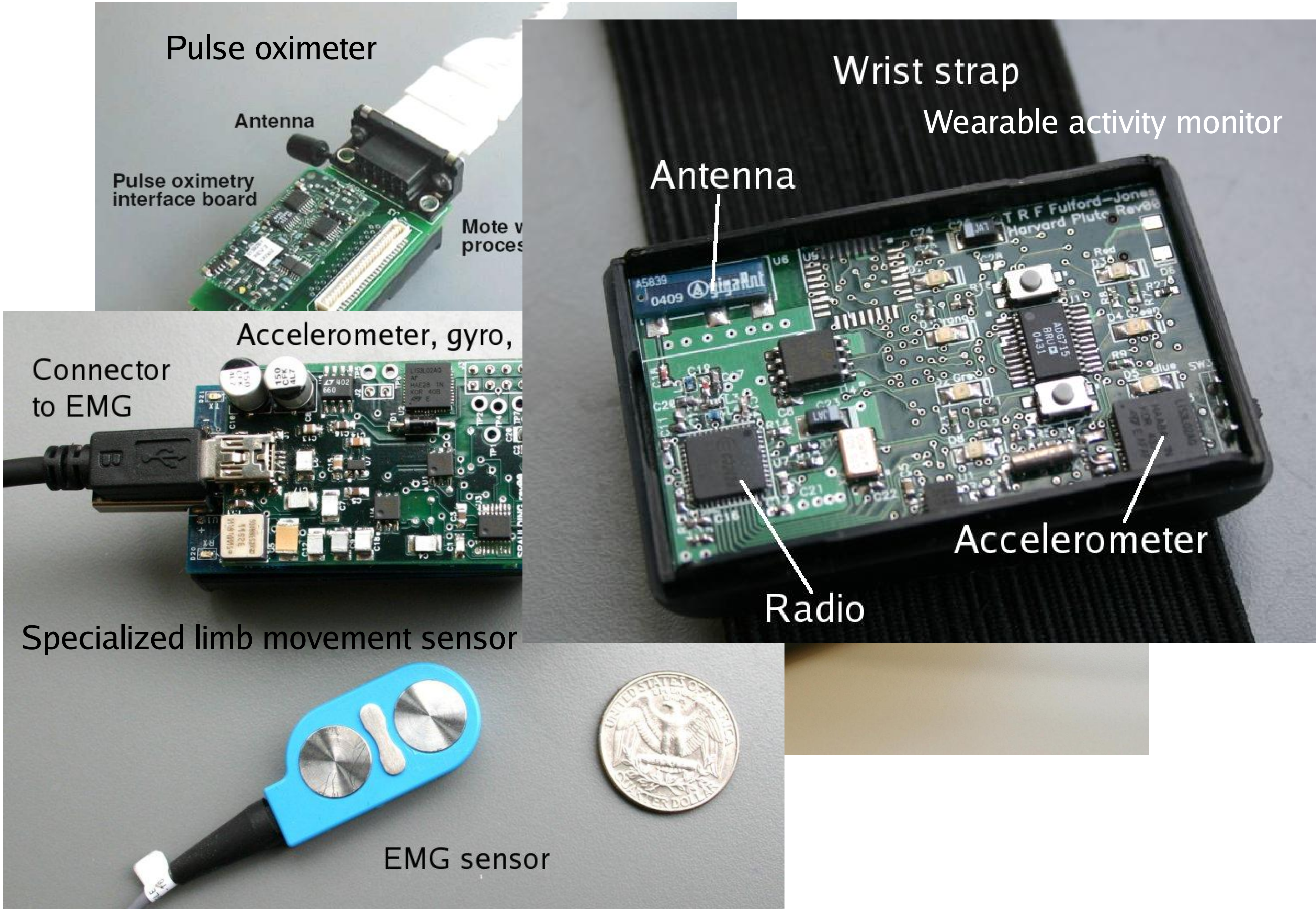

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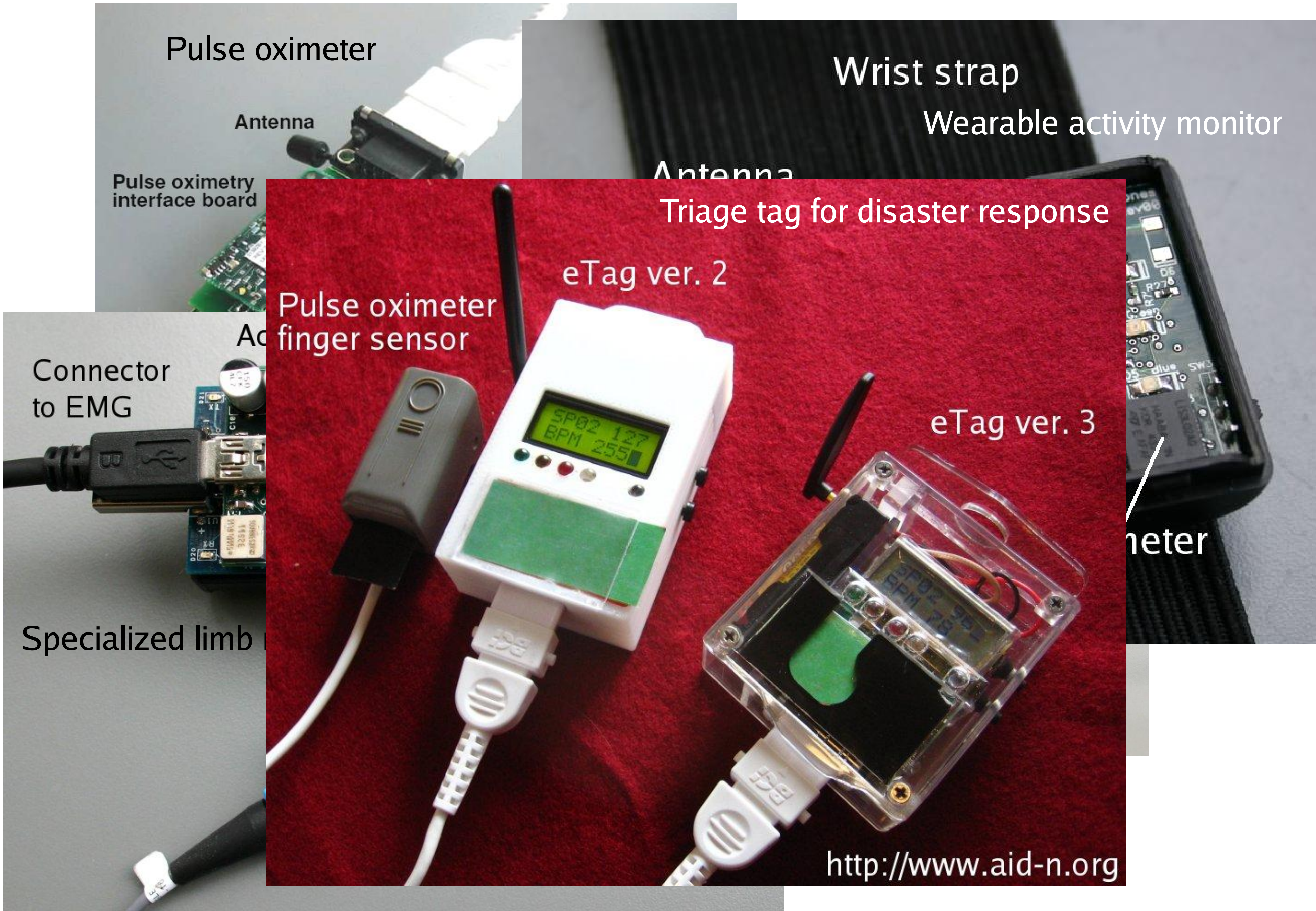
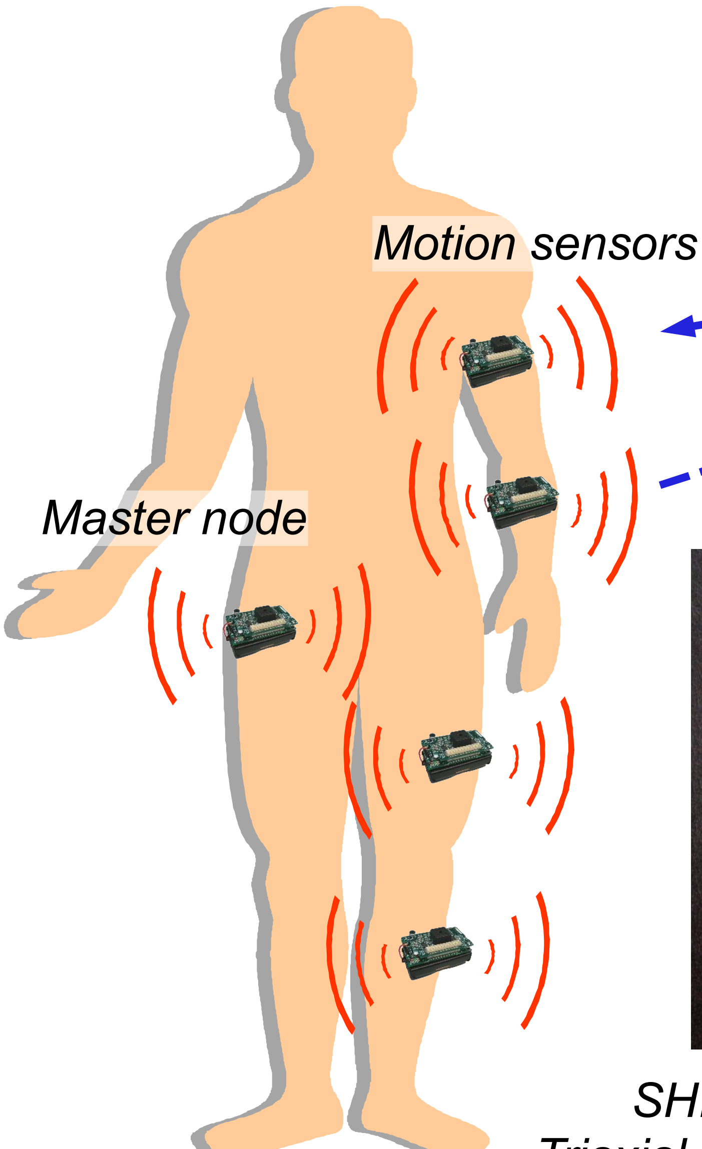
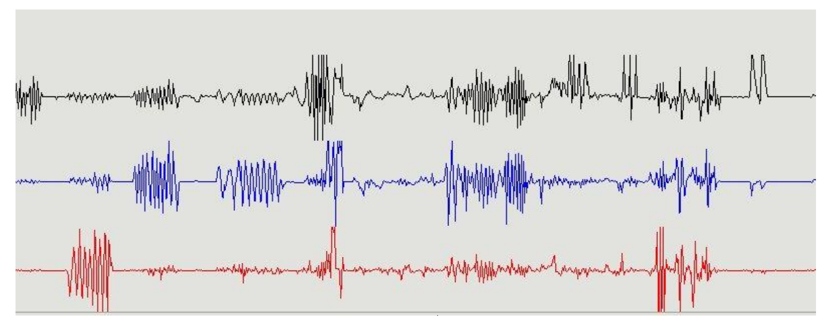


Applications: Parkinson's Disease and Stroke Rehabilitation Monitoring

with P. Bonato, Spaulding Rehabilitation Hospital



Data acquisition at laptop



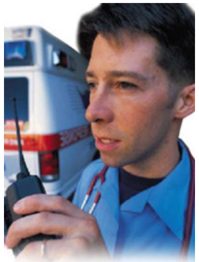
SHIMMER mote (Intel corp.)
Triaxial accelerometer and gyroscope

Feature extraction

↓

Classification (e.g., UPDRS scores)

The challenge

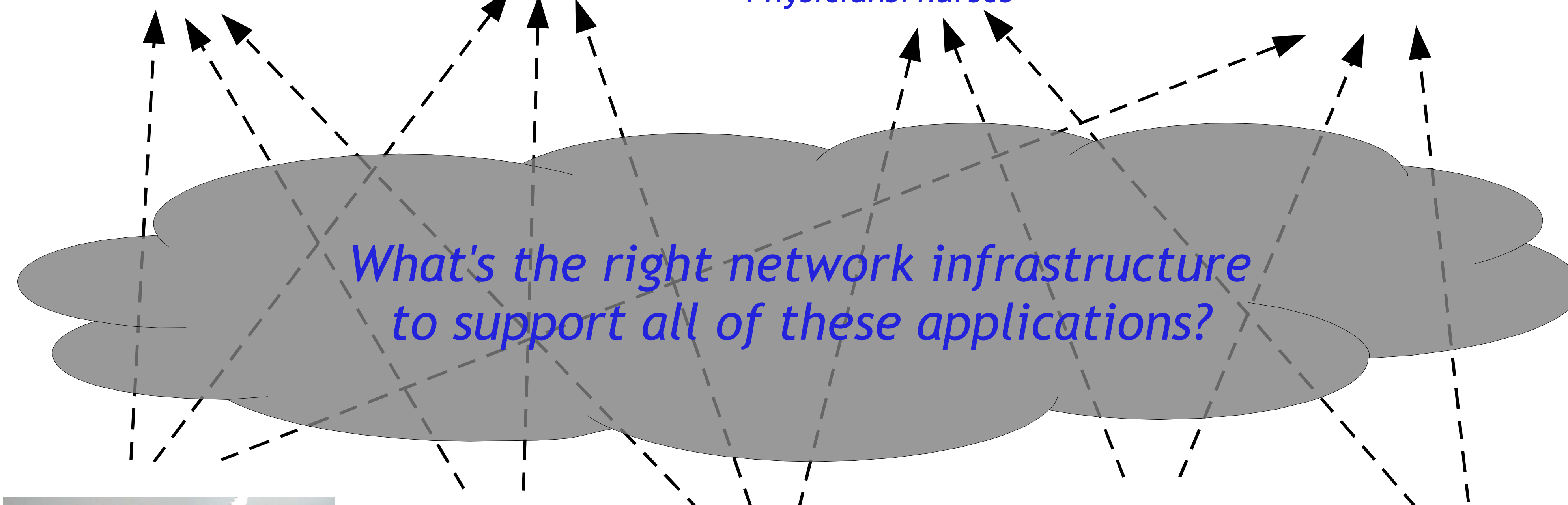


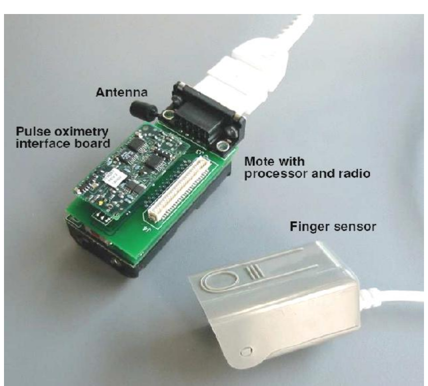
First responders

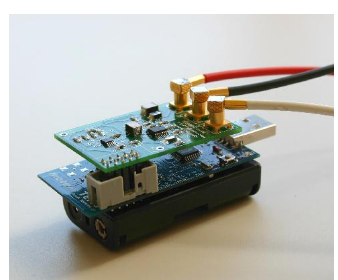
EMS / 911 Dispatch

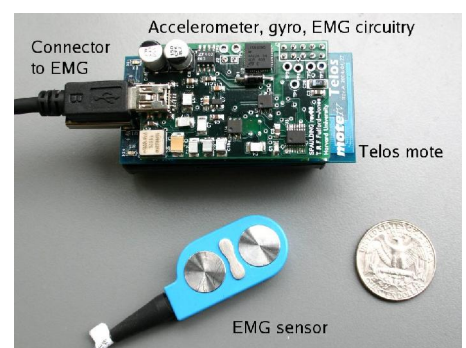
Physicians/nurses

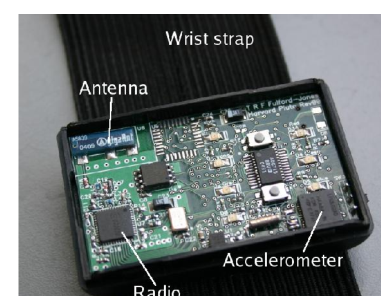
Hospital Information Systems



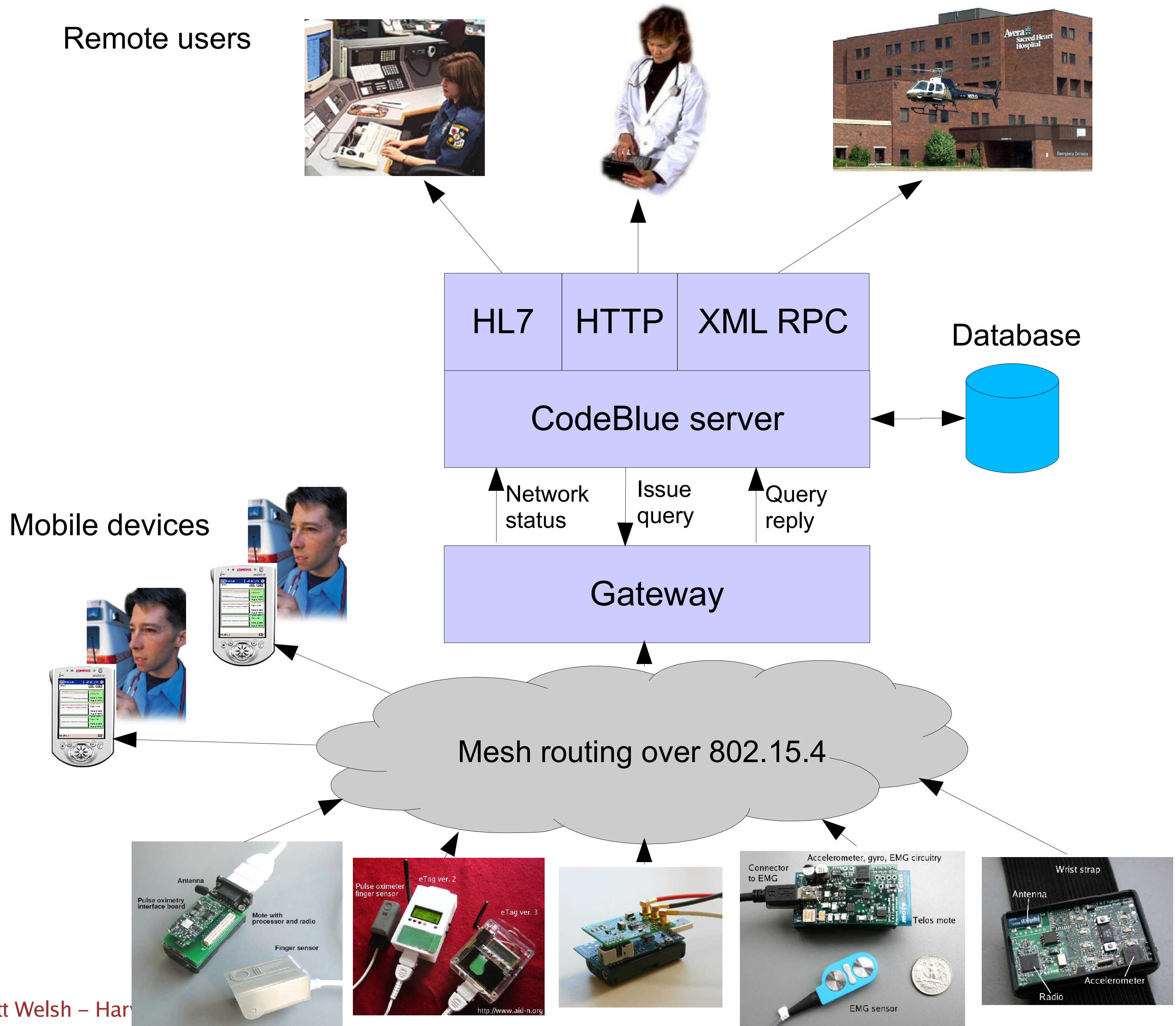








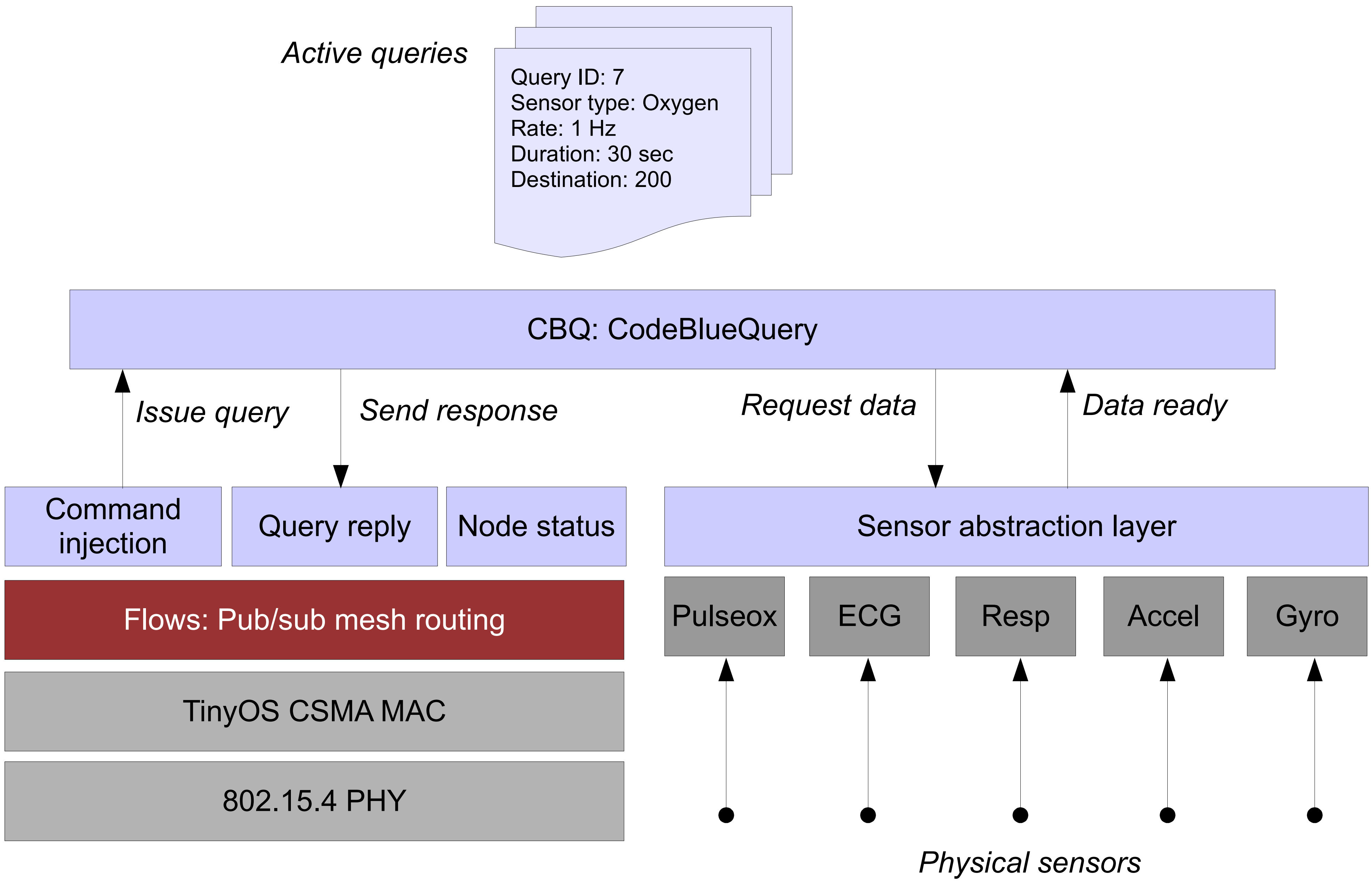
The Harvard CodeBlue Network Architecture



Sensor Network Limitations and Challenges

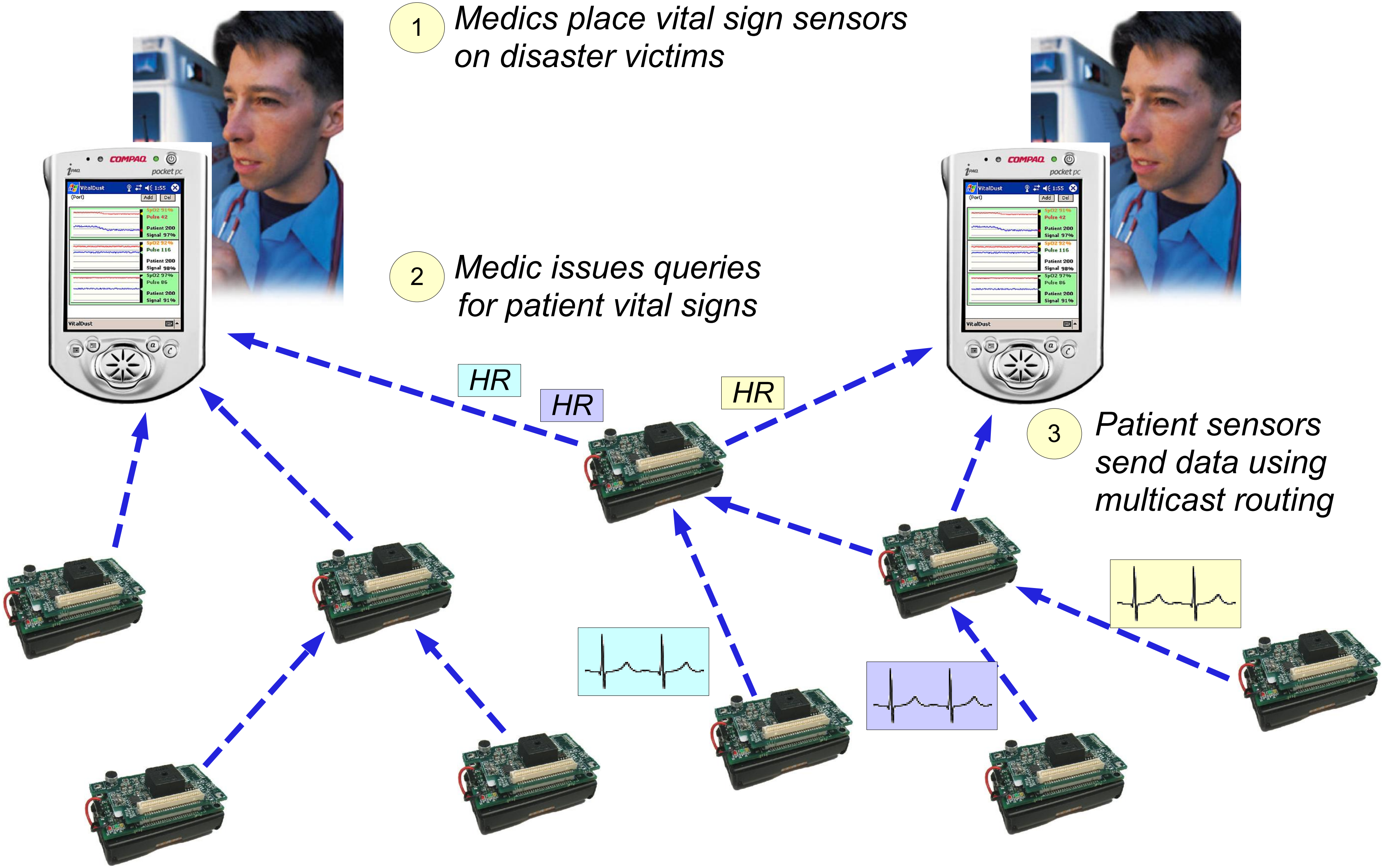
- The low power consumption of these devices implies very limited capabilities – well below that of a cell phone or PDA!
- Extremely limited radio bandwidth
  - Low-power, 802.15.4 radios – max PHY rate of 250 Kbps
  - Drops to 100 Kbps when taking MAC overhead and framing into account
  - A small number of sensors can rapidly saturate the channel
- Device mobility
  - Both patient sensors and receiving devices are moving around
  - Need to maintain good connectivity – in elevators, stairwells, etc.
- Multihop, multicast communications
  - Cannot always assume fixed infrastructure – e.g., disaster response
  - Multiple patient sensors may be monitored by multiple end users
- Limited device capabilities
  - Low CPU power (10 MIPS), tiny memories (10 KB of RAM)
  - Cannot run sophisticated algorithms involving lots of computation or memory usage

CodeBlue Software Architecture



CodeBlue Mesh Routing

1. *Medics place vital sign sensors on disaster victims*
2. *Medic issues queries for patient vital signs*
3. *Patient sensors send data using multicast routing*
4. *Sensors locally filter, compress, or analyze data to reduce radio congestion*



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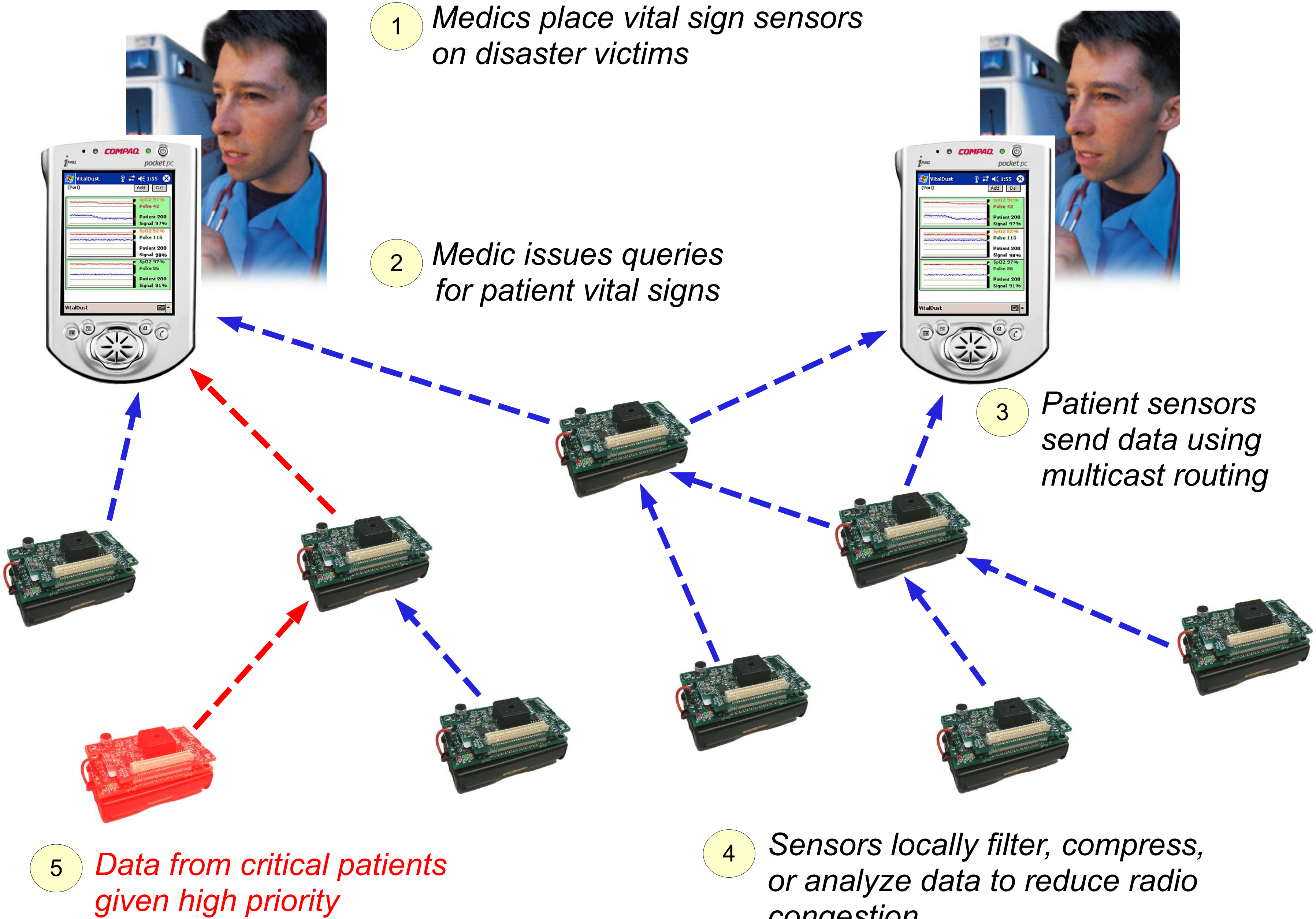
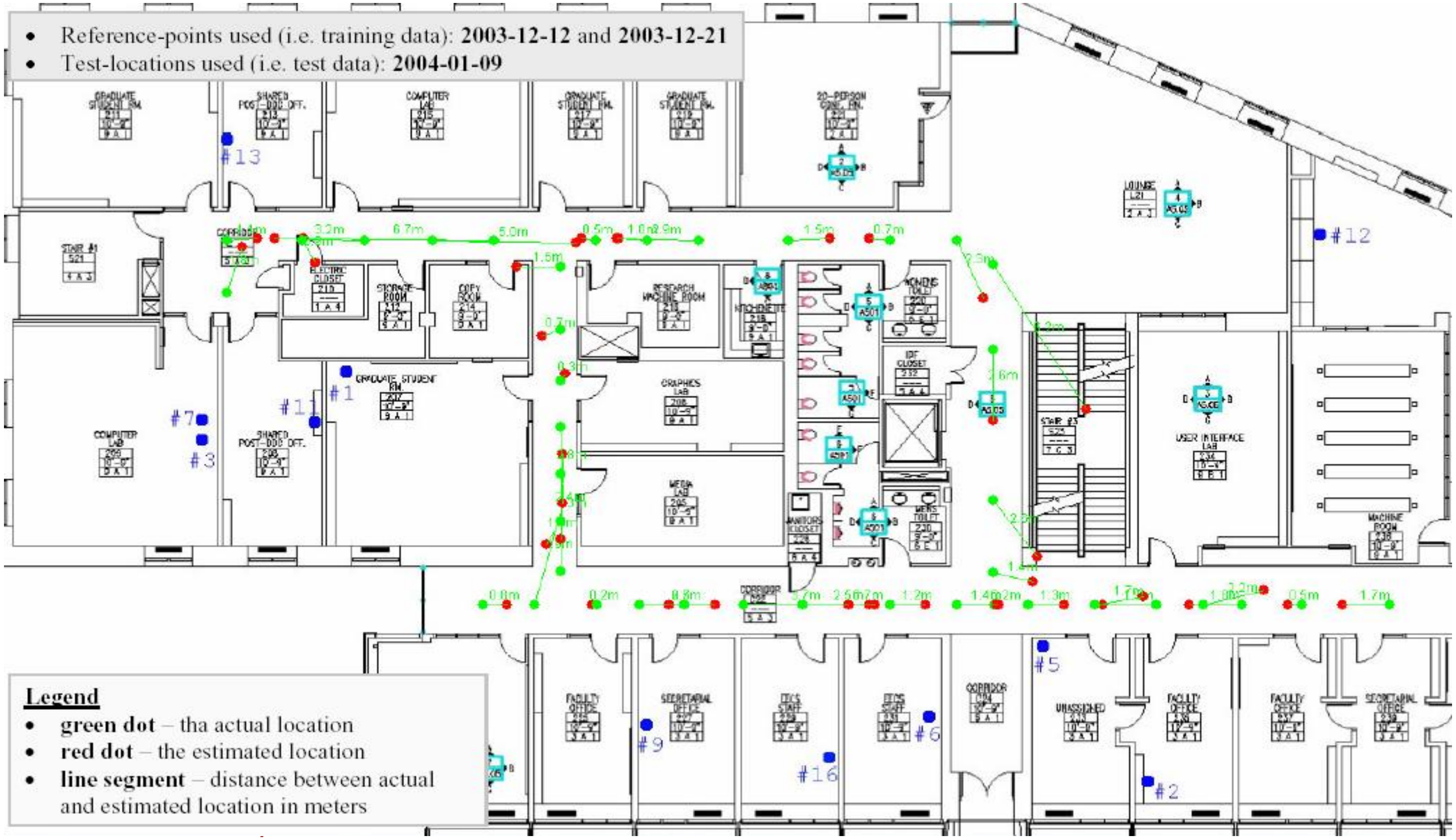


MoteTrack: RF-Based Localization

- Collect RF signal "signatures" from various points in building
  - Use MoteLab testbed with 30 beacon nodes
  - Similar to RADAR scheme for 802.11 networks, with much higher density
- Nodes compute location by comparing to stored signatures
  - Centroid of weighted signature distance from known points
- Good results: 80th percentile error of *1 meter*



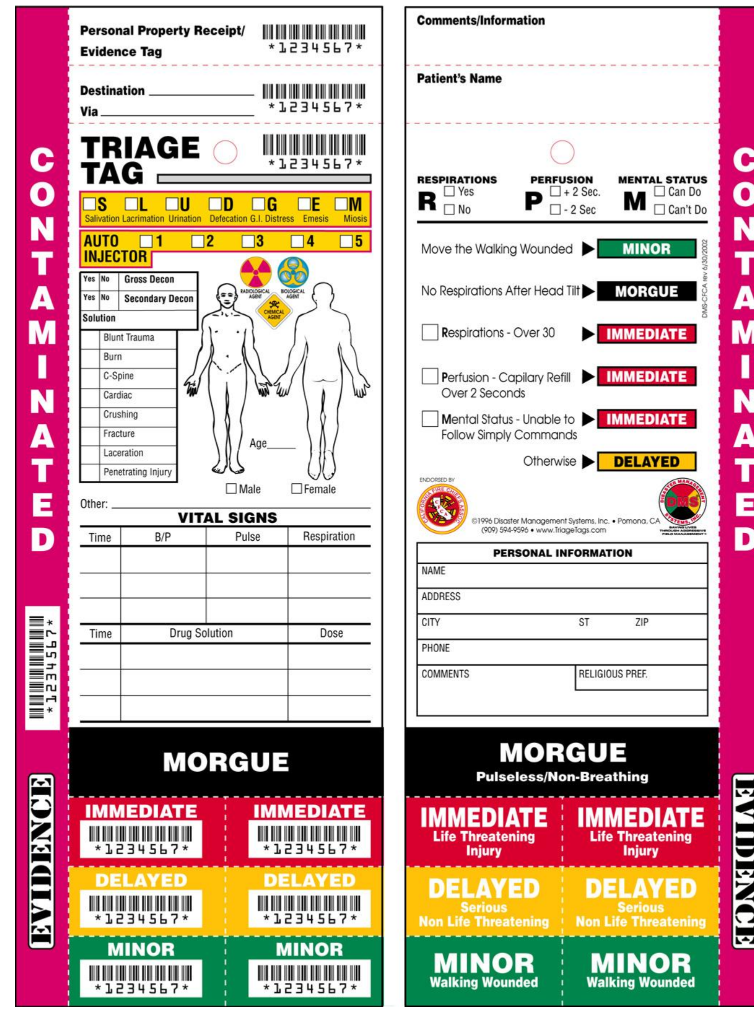
GUI for Real-Time Patient Tracking

Map showing location (MoteTrack)

Applications: Emergency medicine

- Large accidents, fires, terrorist attacks
  - Normal organized community support may be damaged or destroyed
  - Large numbers of patients, severe load on emergency personnel

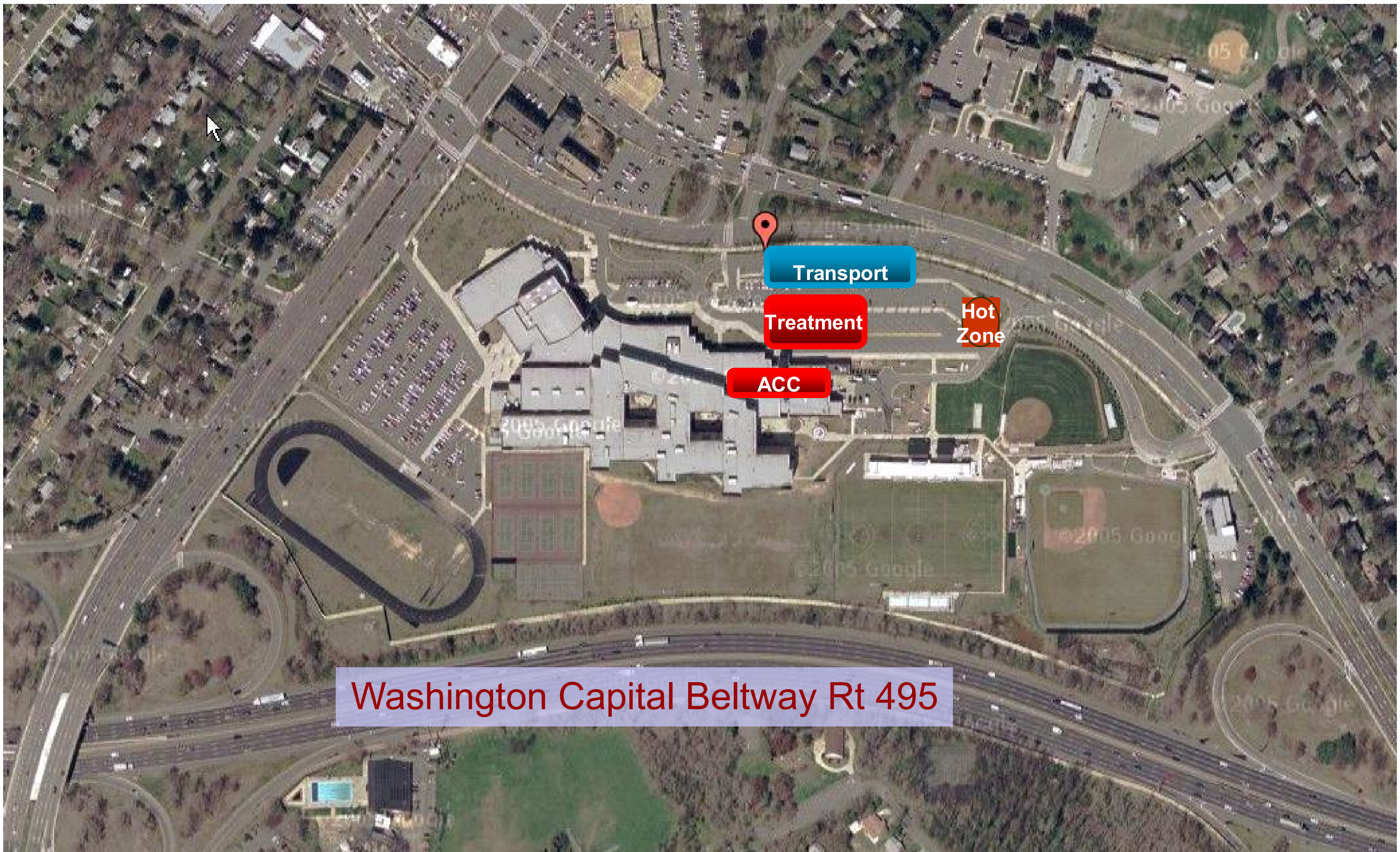
- Manual tracking of patient status is difficult
  - Current systems are paper, phone, radio based
  - No real-time updates on patient condition



DHS Disaster Drill, August 2006

DHS Disaster Drill, August 2006

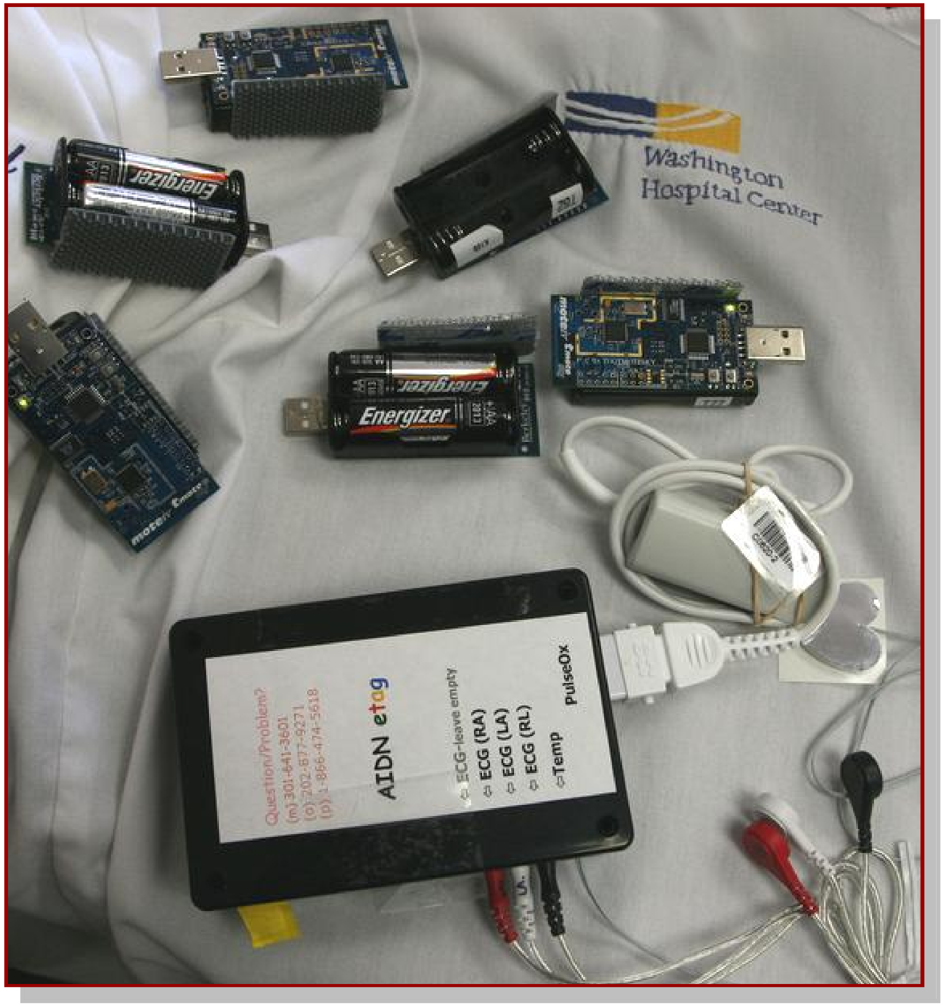
- Bus accident at junction of Washington Capital Beltway Rt 495
- Assumption: Hospitals within 15 mi radius reached surge capacity



Applications: Inpatient Monitoring

Electronic Triage Tag, version 2

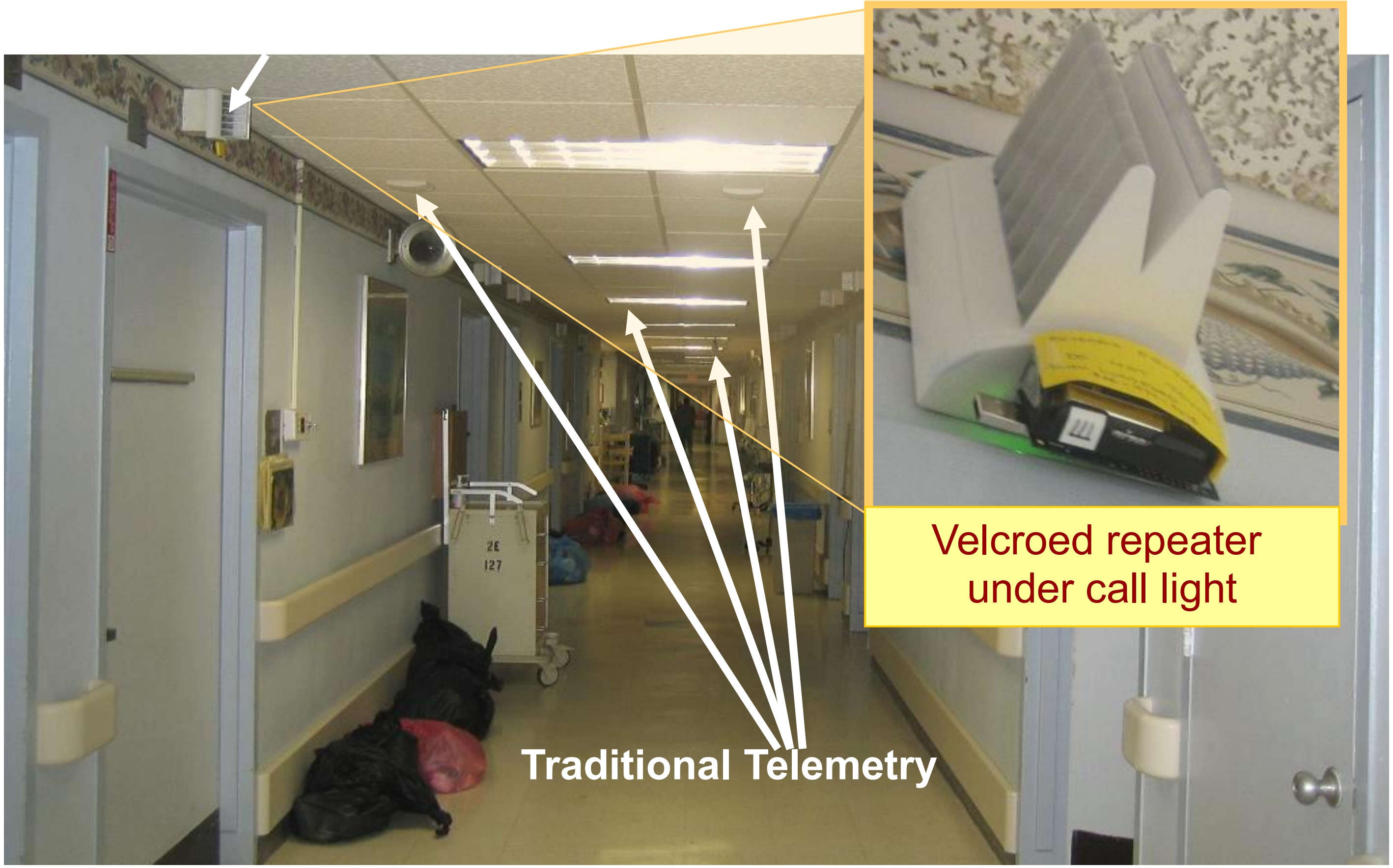
- 250kbps 2.4GHz IEEE 802.15.4
- 10 K RAM, 48K Flash
- Sampling Rates
  - Pulse Oximetry: 1 Hz
  - EKG: 250 Hz
  - Temperature: 1Hz
- Battery life: 2.5 days on 2 AA batteries



Washington Hospital Burn Unit, Feb 2007

Monitoring patients for one week 24 hours per day in a burn center introduces new hurdles

- Departmental approvals needed
  - IT department: wireless interference
  - Clinical engineering: device safety
- Network noise
  - Wireless devices
  - Equipment
  - Doors
  - Walls, hallways
- Sensor noise
  - Moving patients
  - Physiologic artifacts
- Installation of Repeaters



Current Status

- First prototype of CodeBlue protocol framework is complete
  - TinyADMR for multicast routing
  - MoteTrack for indoor localization
  - Java-based GUI for real-time visualization
  - Web services interface for application integration
- Range of medical sensors based on motes
  - Pulse oximeter, EKG, accelerometer/gyro/EMG board
  - Pluto custom mote for wearable applications
- Disaster drill completed in collaboration with JHU AID-N project
- Pilot at Washington Hospital Burn Unit in Feb 2007
- Deployment at Beth Israel Deaconess ED in coming months
- Ongoing collaboration with Spaulding Rehabilitation Hospital

Some Lessons and Take Away Points...

- New wireless sensor technologies have tremendous potential to impact many aspects of healthcare.
  - But, there is still a large gap between the existing technology and the needs of medical practitioners.
  - We aim to close this gap by developing a robust and flexible **sensor network infrastructure** to tie wireless sensors into a range of medical applications.
- Medical monitoring raises new challenges for wireless sensors
  - Hardware platforms, data fidelity, bandwidth requirements, fault tolerance, and security
  - Prior work in mobile ad hoc networking focuses on simulations, as well as very different application requirements (i.e., Web browsing)
  - Should re-examine the fundamental assumptions behind this work for medical use
- Need more real world experience deploying, testing, and evaluating these sensors in real clinical settings.
  - Our disaster drill and hospital tests have been promising, but shed light on many open technology and policy questions
  - Need a better path towards new technology adoption in healthcare to enable innovation

Acknowledgments

- This work is supported by grants from the National Science Foundation, National Institutes of Health, and US Army

- We are also supported by industrial sponsors:
  - Intel Corporation
  - Microsoft
  - Sun Microsystems
  - Siemens

- The CodeBlue hardware deisgns and software are available for download:

http://www.eecs.harvard.edu/~mdw/proj/codeblue

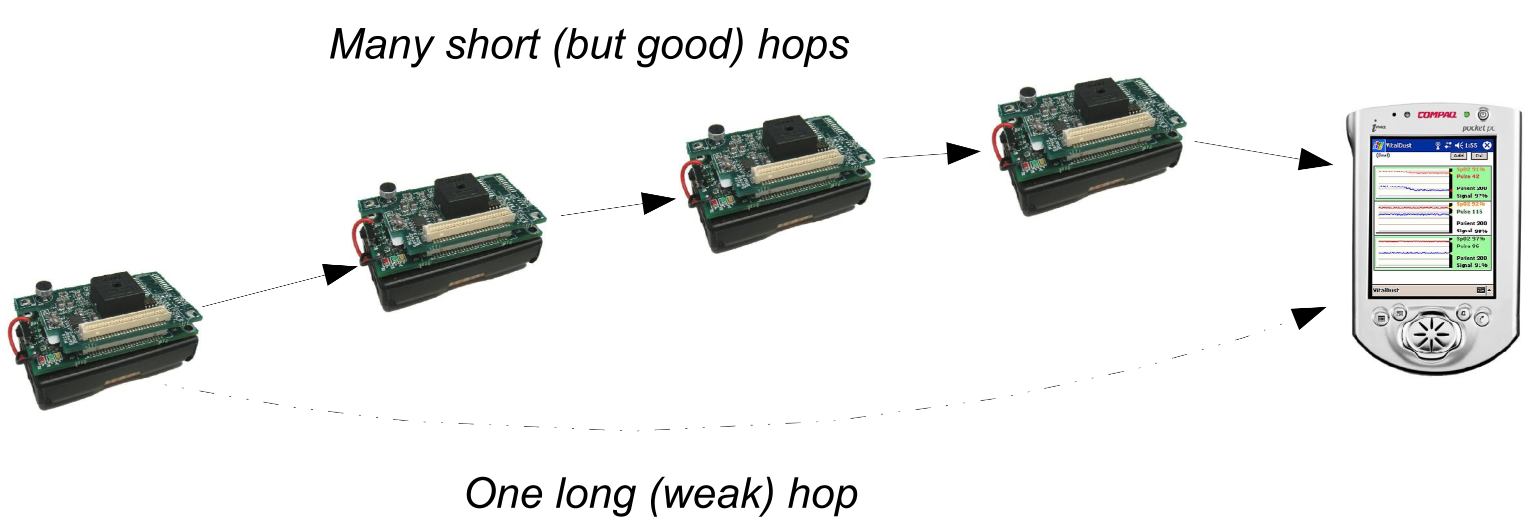
mdw@eecs.harvard.edu

CodeBlue Mesh Routing Protocol

- CodeBlue requires an *ad hoc* multicast routing protocol
  - *Ad hoc*: No need for fixed infrastructure, forms routes “on demand”
  - Multicast: Data from each sensor can be received by multiple end-user devices
- Ad hoc routing has been extensively studied in wireless environments
  - AODV, CSR, DSDV, ODMRP, ADMR, ...
  - Much of this work done in simulation assuming perfect radio links
  - Implementations primarily focus on laptops or PDAs with 802.11 radios
- What's new here?
  - Very limited radio bandwidth: protocol overhead is a big deal
  - Real radios with lossy, asymmetric links
  - Nodes have very small memory (< 10KB) and limited computational power

Our first protocol: TinyADMR

- Based on *Adaptive Demand-driven Multicast Routing (ADMR)*
  - [Jetcheva and Johnson, Proc. MobiHoc 2001]
  - Mature, well-designed multicast protocol for wireless networks
- We implemented the protocol on motes using TinyOS
  - Lots of changes required to get ADMR to work well on this platform
- Route selection metric:
  - Minimum-hopcount path performs poorly (selects short routes with bad links)



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- Route selection metric:
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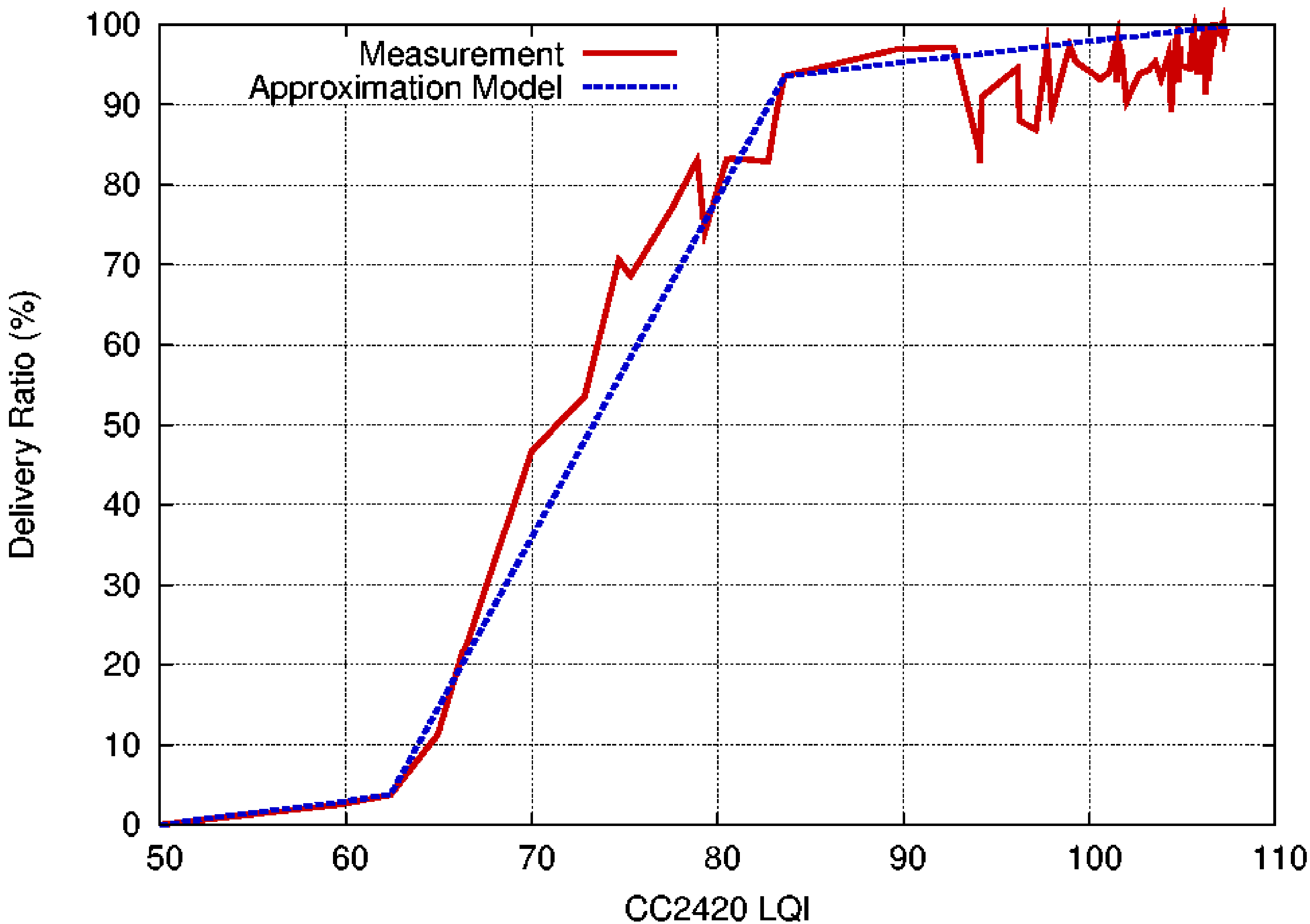
- Link asymmetry:
  - Node A can hear Node B does not imply that Node B can hear Node A
- Memory constraints:
  - ADMR keeps several tables with state about active paths and network neighbors
  - In a large network this state will rapidly consume available memory

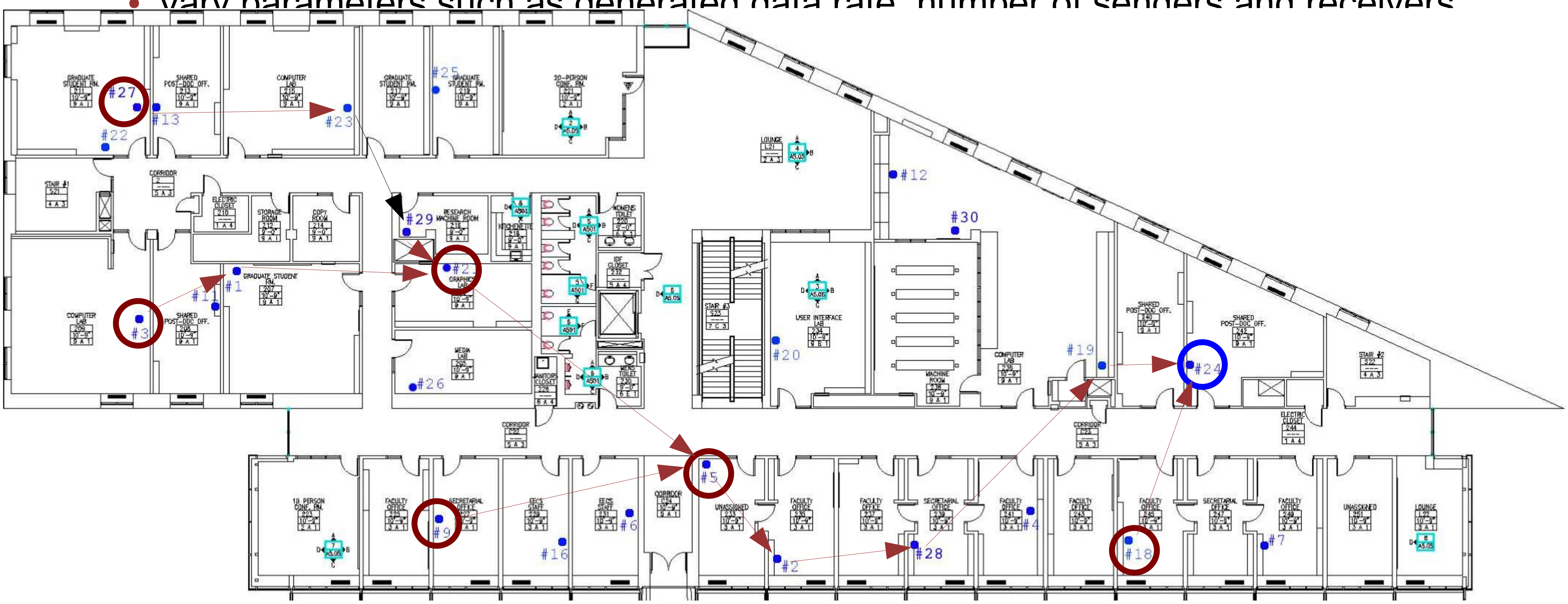
TinyADMR Route Selection

- We make use of CC2420 Link Quality Indicator (LQI) metric:
    - *Indicates ability of radio to decode start symbol of packet*
  - LQI is highly correlated with packet delivery ratio
  - Can be measured with a single packet reception (no probing traffic required)



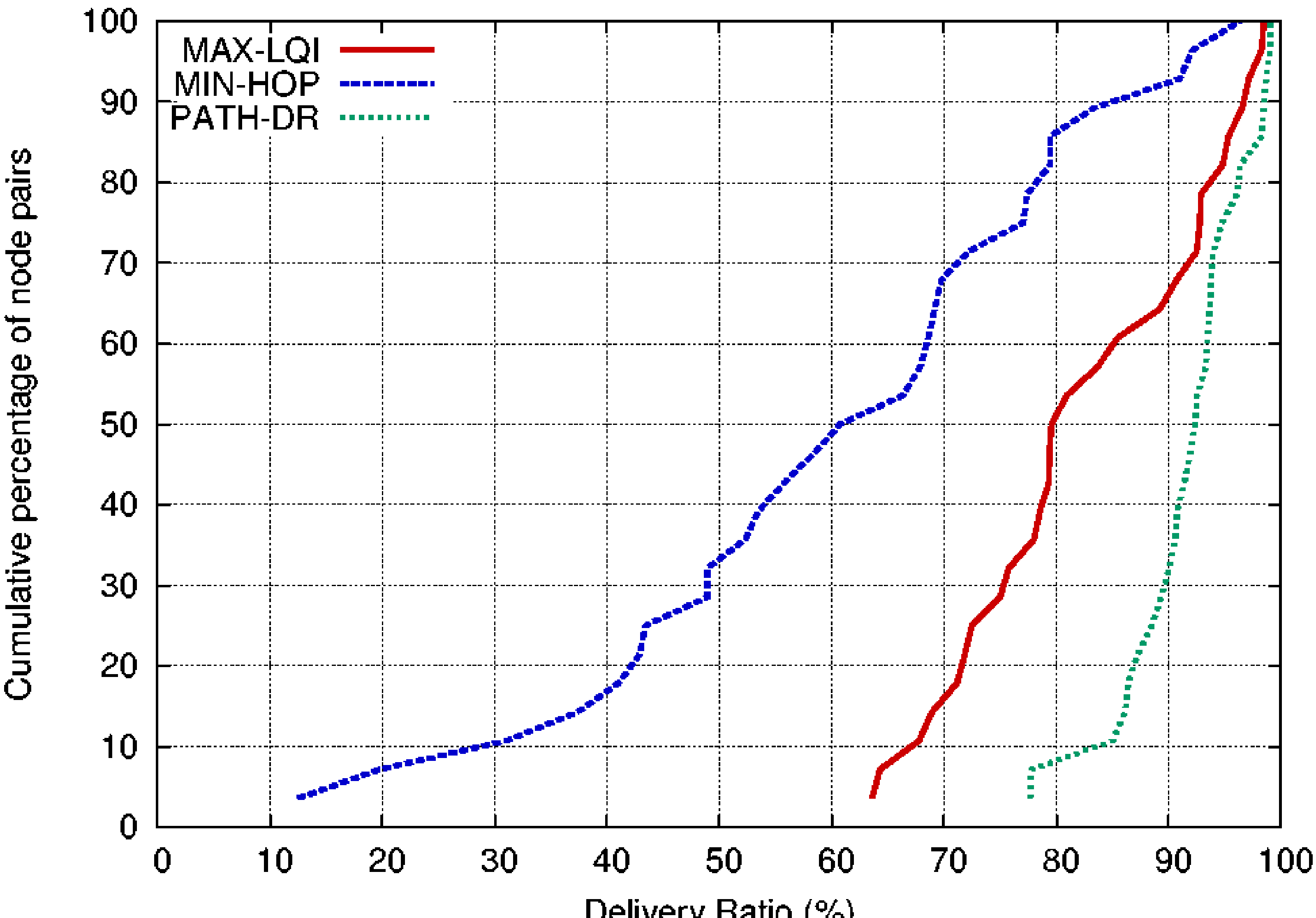
Evaluation Methodology

- Testbed of 30 MicaZ nodes distributed throughout our building
  - Reprogram and debug via web interface at motelab.eecs.harvard.edu
  - Now upgraded to 190 Tmote Sky motes
- Set up certain nodes as “virtual patients” and others as “virtual doctors”
  - Vary parameters such as generated data rate, number of senders and receivers

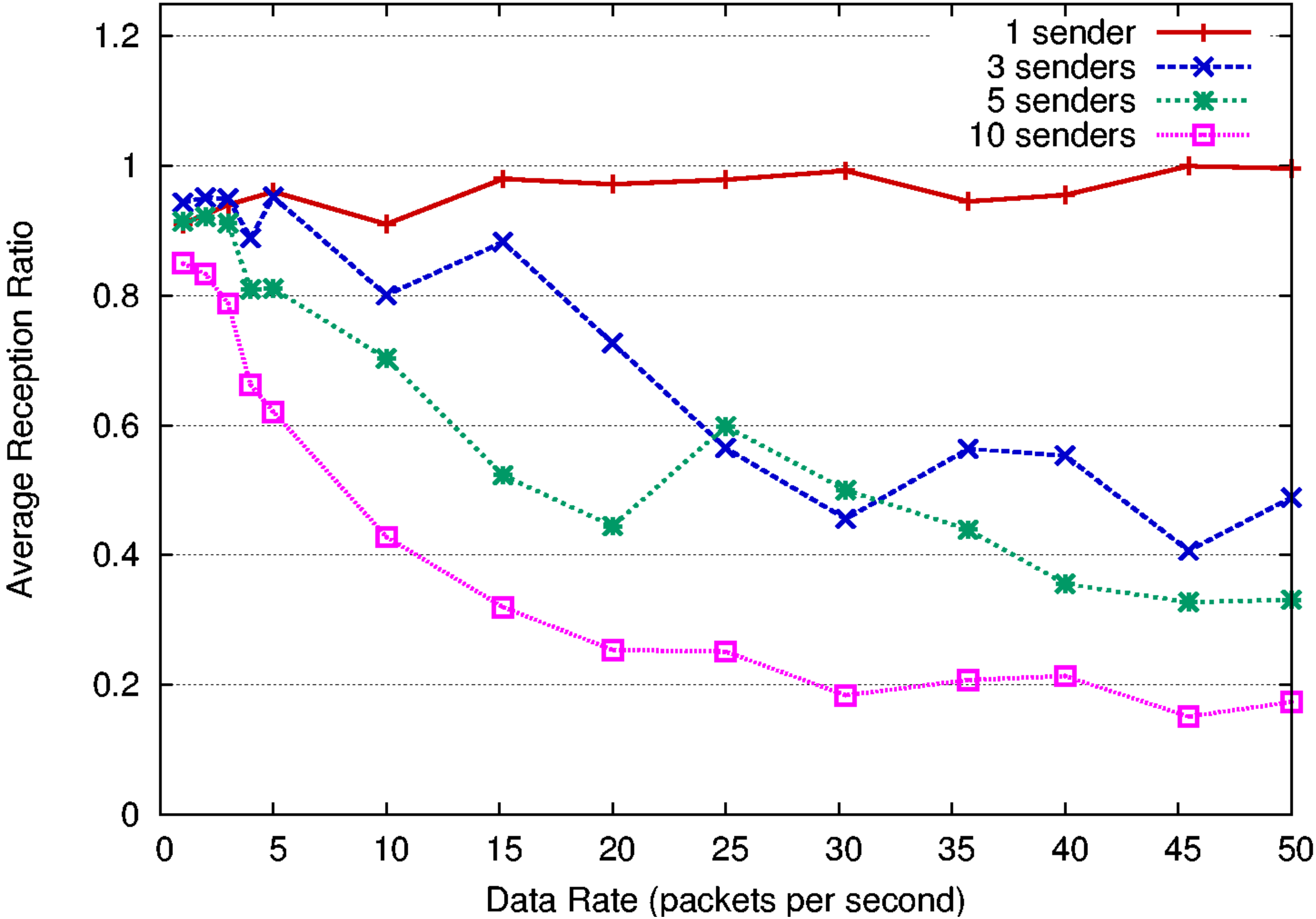


Effect of LQI Based Route Selection

- Comparison to other route selection metrics
  - MIN-HOP: Lowest hopcount path
  - MAX-LQI: Path with worst LQI rating per link
  - PATH-DR: Estimated path delivery ratio from LQI model



Effect of increasing data rate and number of senders



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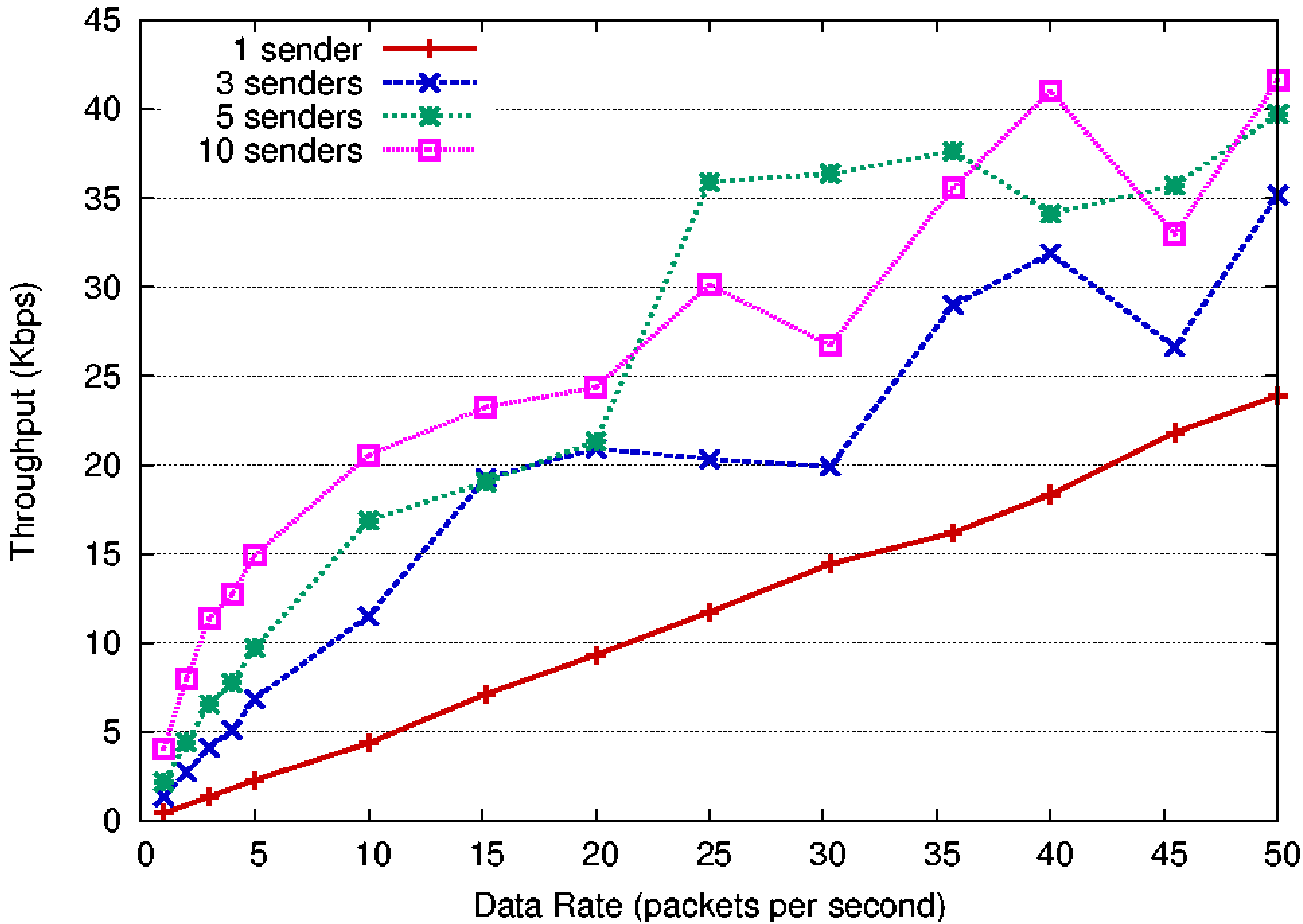
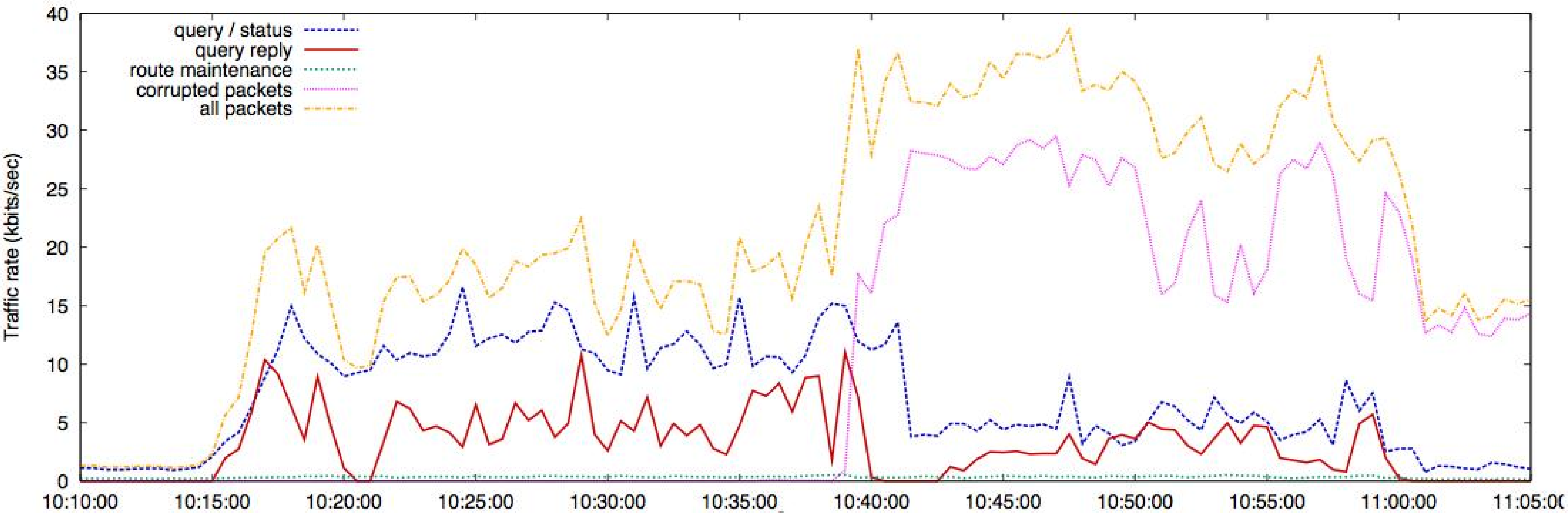


Rethinking multicast

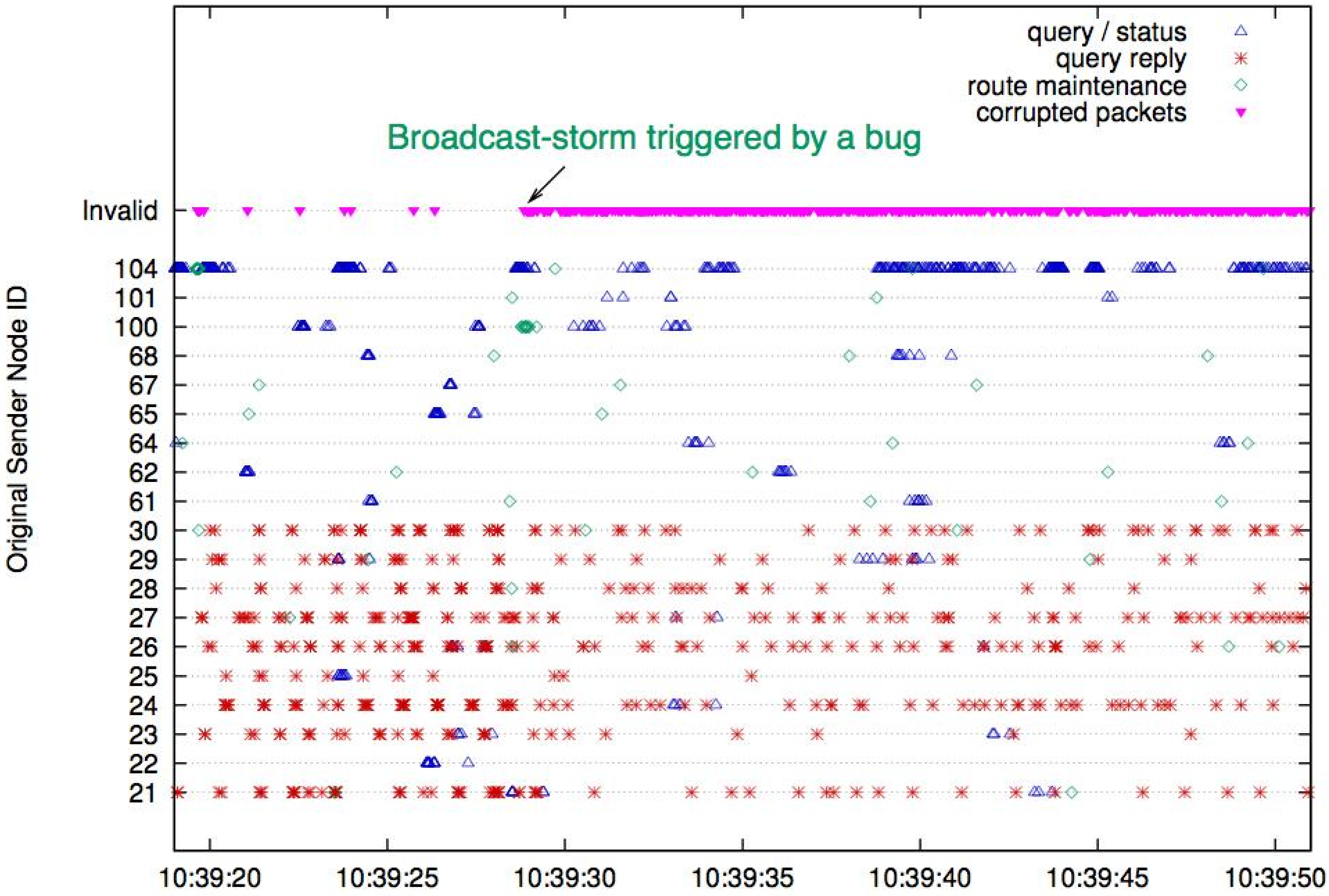
- Multicast routing is fundamentally based on **broadcast** packets
  - Problem: Cannot take advantage of MAC-level ACKs and retransmission
  - 802.15.4 MAC does not support multicast natively
- Original idea: “Best effort” transmission is adequate
  - As long as link to next hop is good – hence the focus on path selection metrics
- Problem: This assumption breaks down under moderate-heavy load
  - TinyOS MAC does not appear to work well with high radio contention
  - Problems with CCA and hidden terminals
- Current direction: Go back to unicast spanning trees
  - Current MAC seems to **require** hop-by-hop ACK and retransmission to ensure good delivery ratios.
  - Form a spanning tree for each receiving device
  - Implies multiple transmissions for multi-destination packets (heavier load)
  - We are currently investigating the break-even point.

Disaster Drill Evaluation

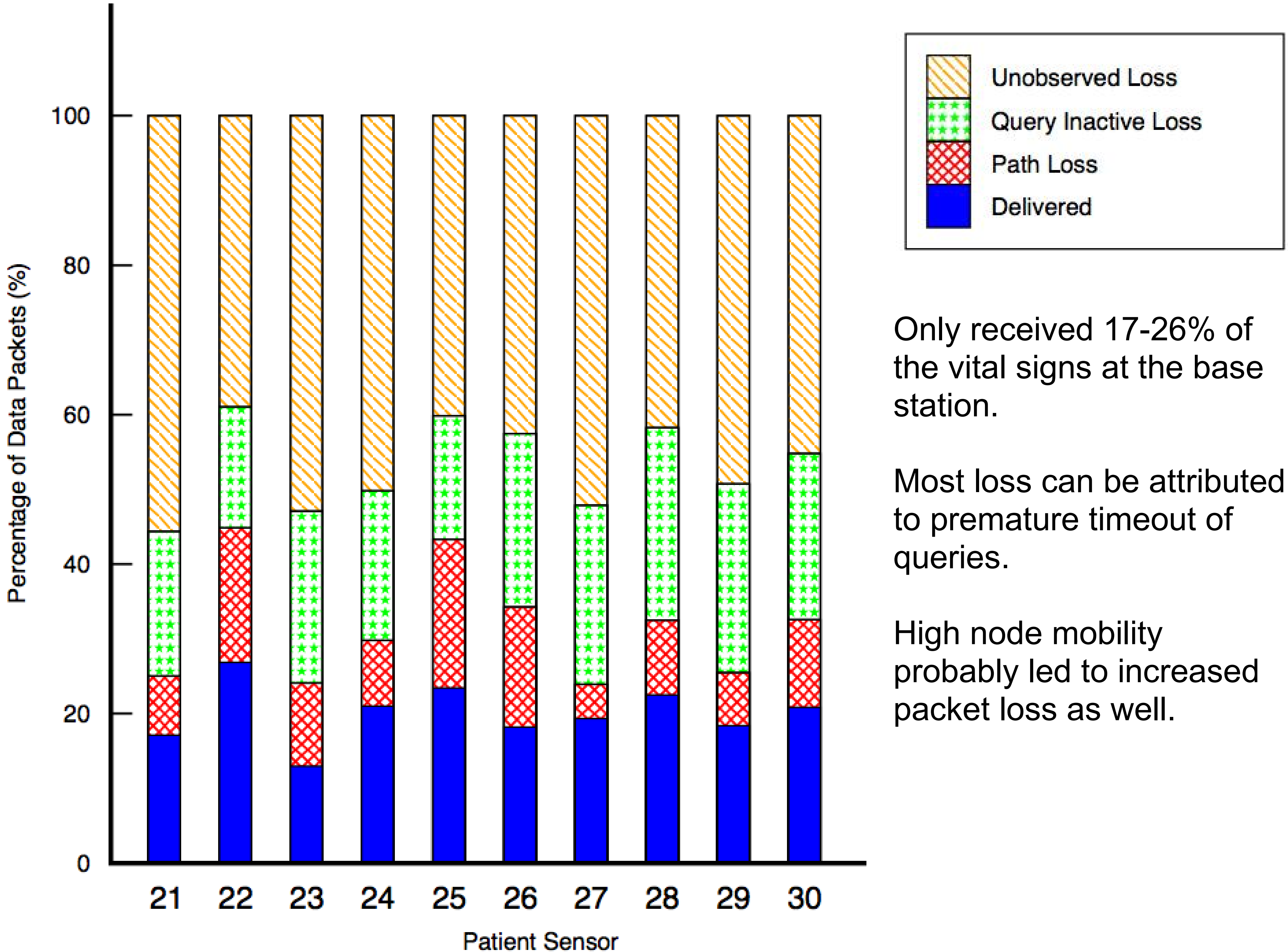
- How well did the system work "in the field?"
  - Deployed six packet sniffers along with the network to record traces of all packets
  - Merged traces to obtain global picture of the network's operation



Disaster Drill: Network flooding bug!



Disaster Drill Query Yield



Only received 17-26% of the vital signs at the base station.

Most loss can be attributed to premature timeout of queries.

High node mobility probably led to increased packet loss as well.