CodeBlue:
A Wireless Sensor Network for Medical Care and Disaster Response

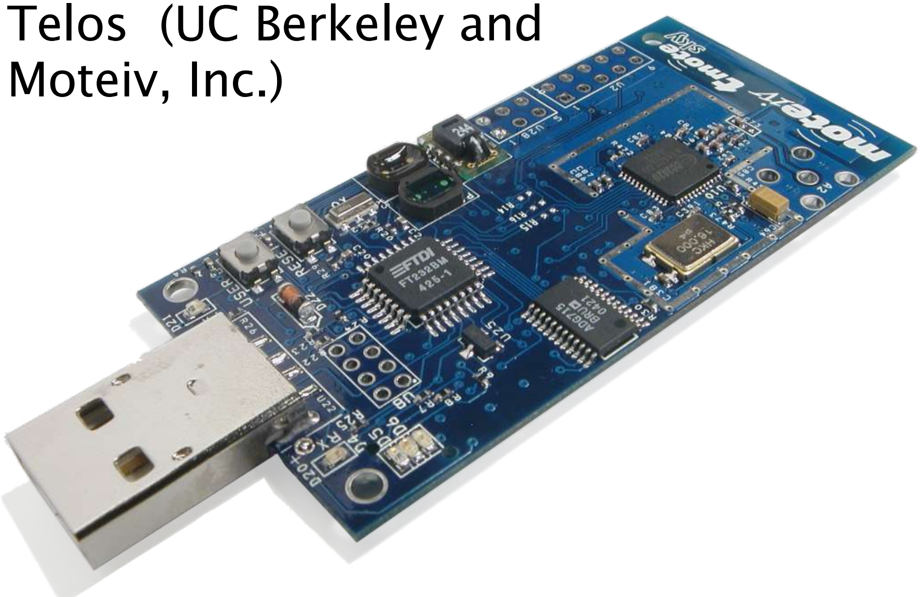
Matt Welsh

Harvard University

Division of Engineering and Applied Sciences

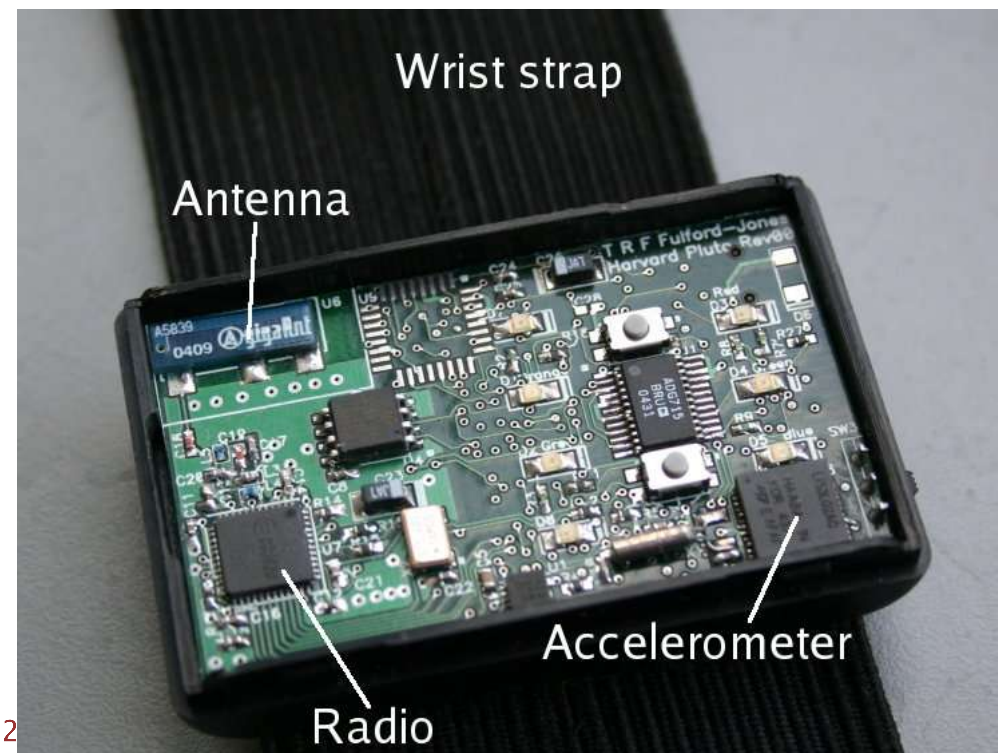
Introduction: Sensor Networks

Telos (UC Berkeley and Moteiv, Inc.)



- 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

Pluto mote (Harvard)



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

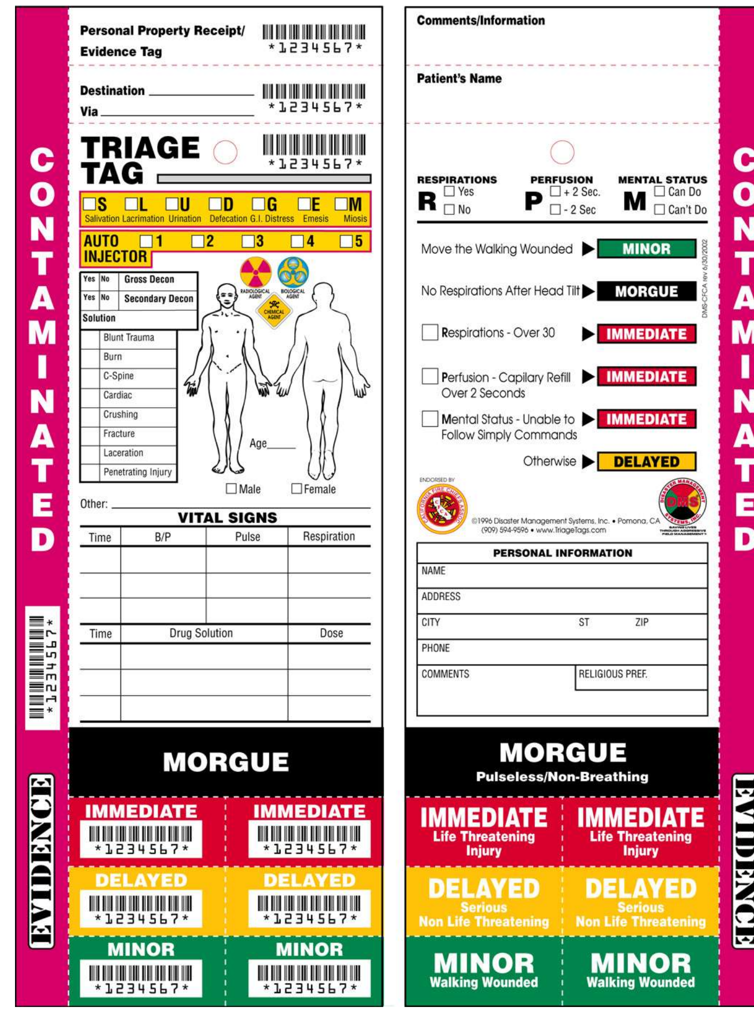
Disasters and Mass Casualty Events

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



CodeBlue Project Goals

Develop tiny, wearable, wireless sensors for medical care and disaster response

Scalable, robust wireless communication protocols

- Support large number of patients and first responders
- Reliable communication despite mobility, limited radio bandwidth

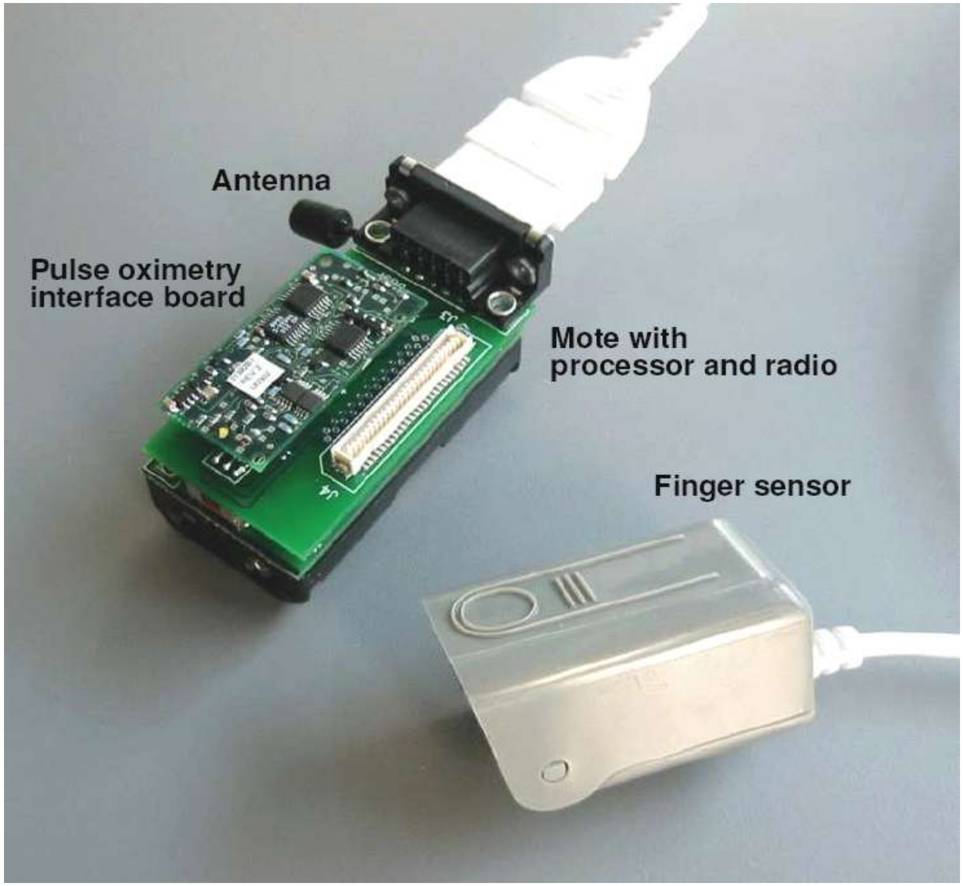
Integrate real-time sensor data into medical care

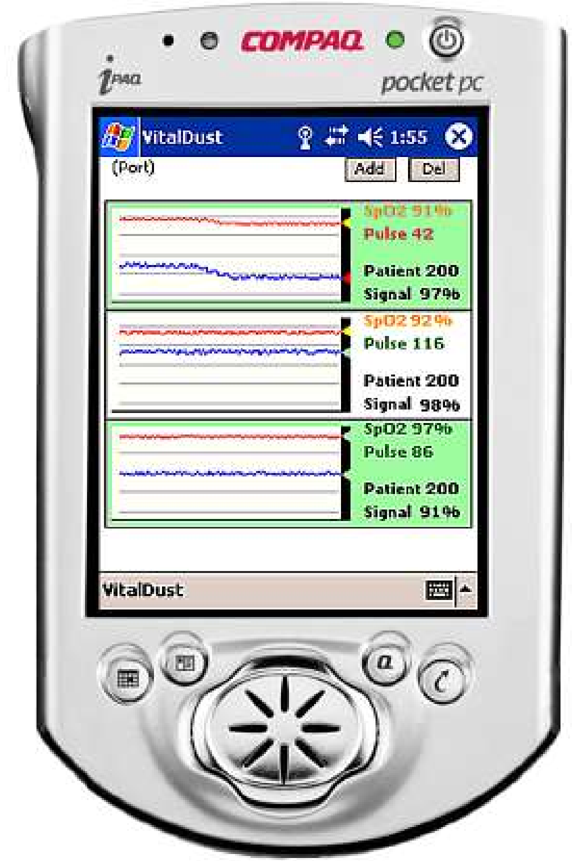
- Effective interfaces for querying sensor data
- Store in patient care records

Explore a range of clinical applications

- Trauma care and intensive care monitoring
- Motion analysis studies in stroke and Parkinson's Disease

Mote-based pulse oximeter

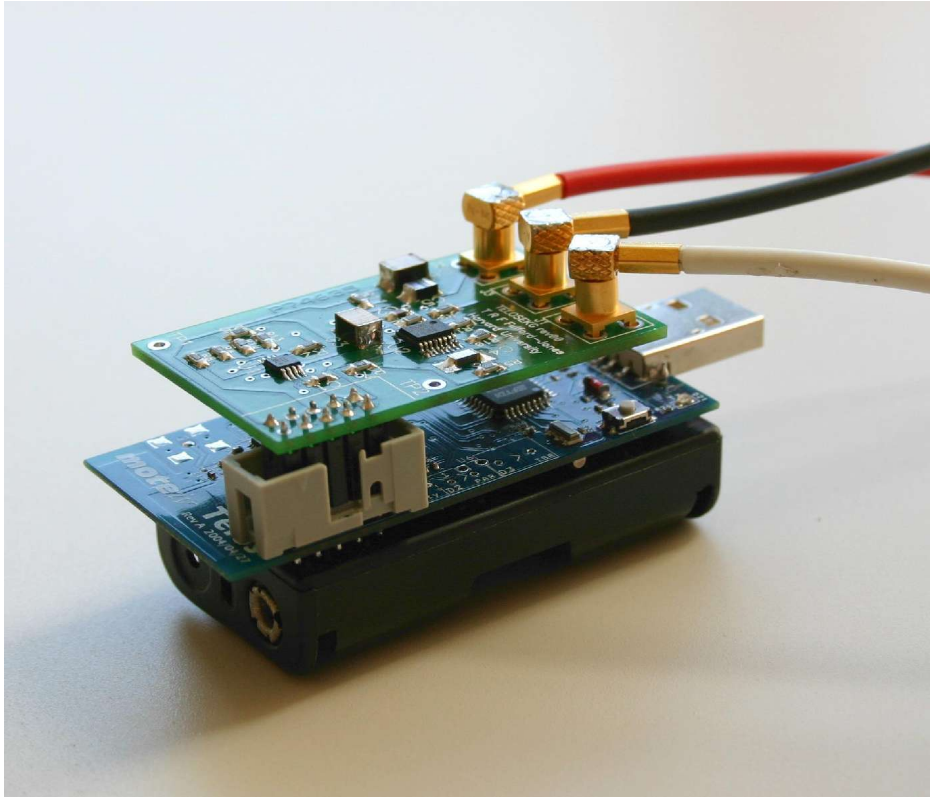


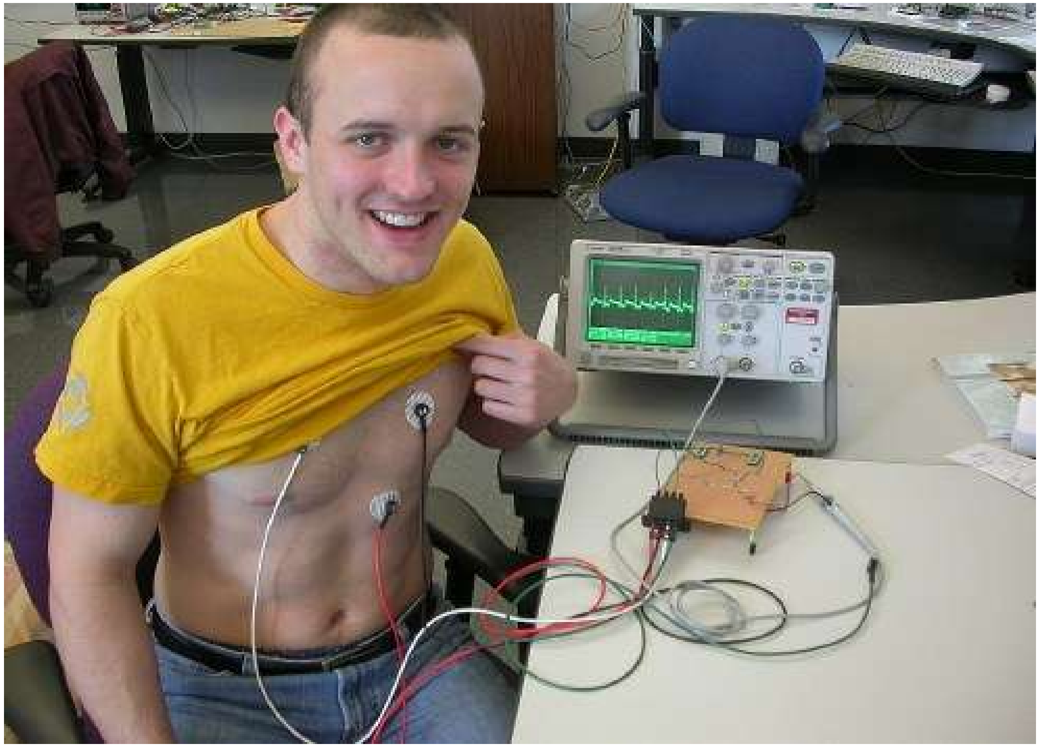


Measures heart rate and blood oxygen saturation

- Standard vital sign measure based on transmission of light (red and near-infrared) through finger or earlobe
- Widely used metrics for overall patient well-being
- Integration with *iRevive*, PDA-based patient care record system for EMTs

Mote-based two-lead EKG



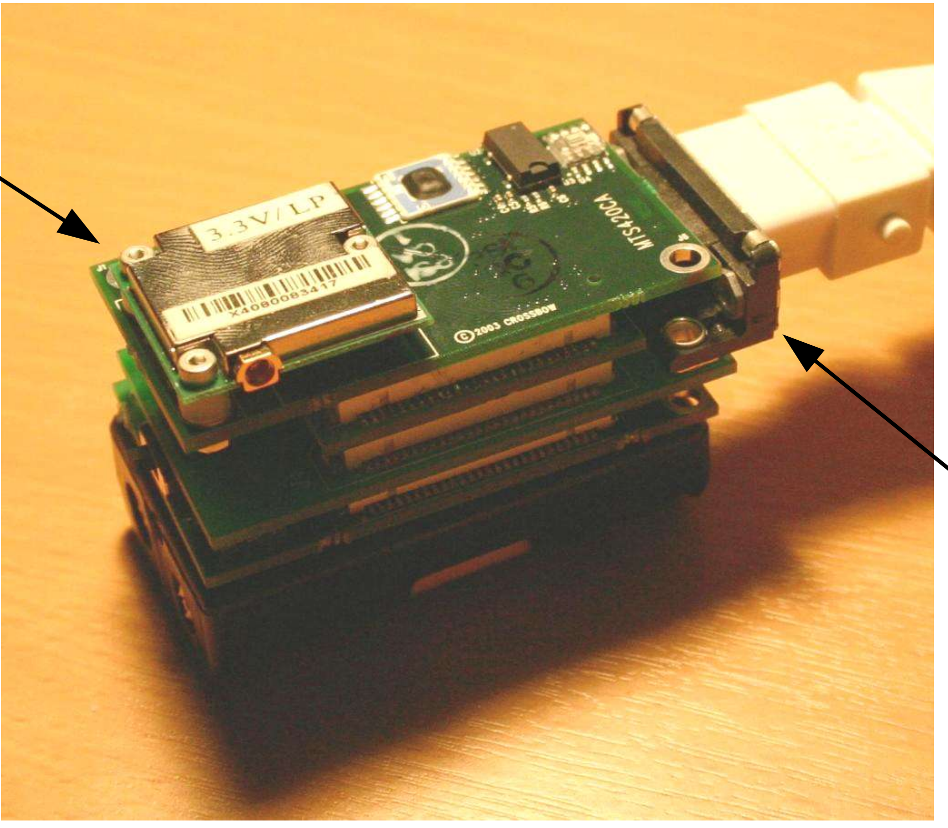


EKG based on Telos mote platform

- Samples EKG signal 12 bits @ 120 Hz
- Lossless compression using delta encoding – transmit at 4 Hz
- Signal is clinically relevant compared with commercial EKG

Integrated GPS and Vital Sign Sensor
with 10Blade, Inc.

GPS Receiver

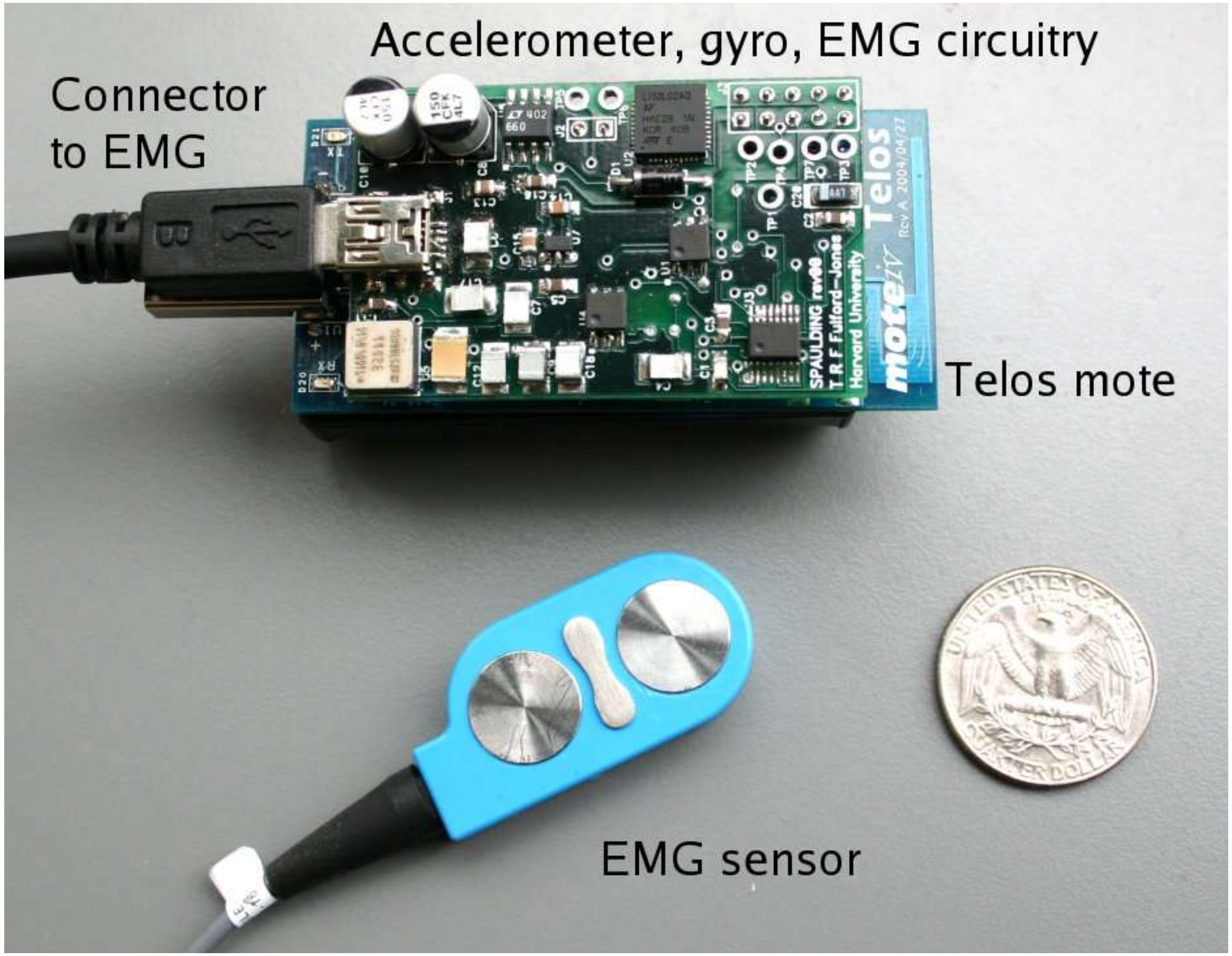


Pulse oximeter

Combined GPS and vital sign monitor for patient tracking

- Army STTR project with S. Moulton, Boston Medical Center/10Blade
- Relay patient status and location to trauma center

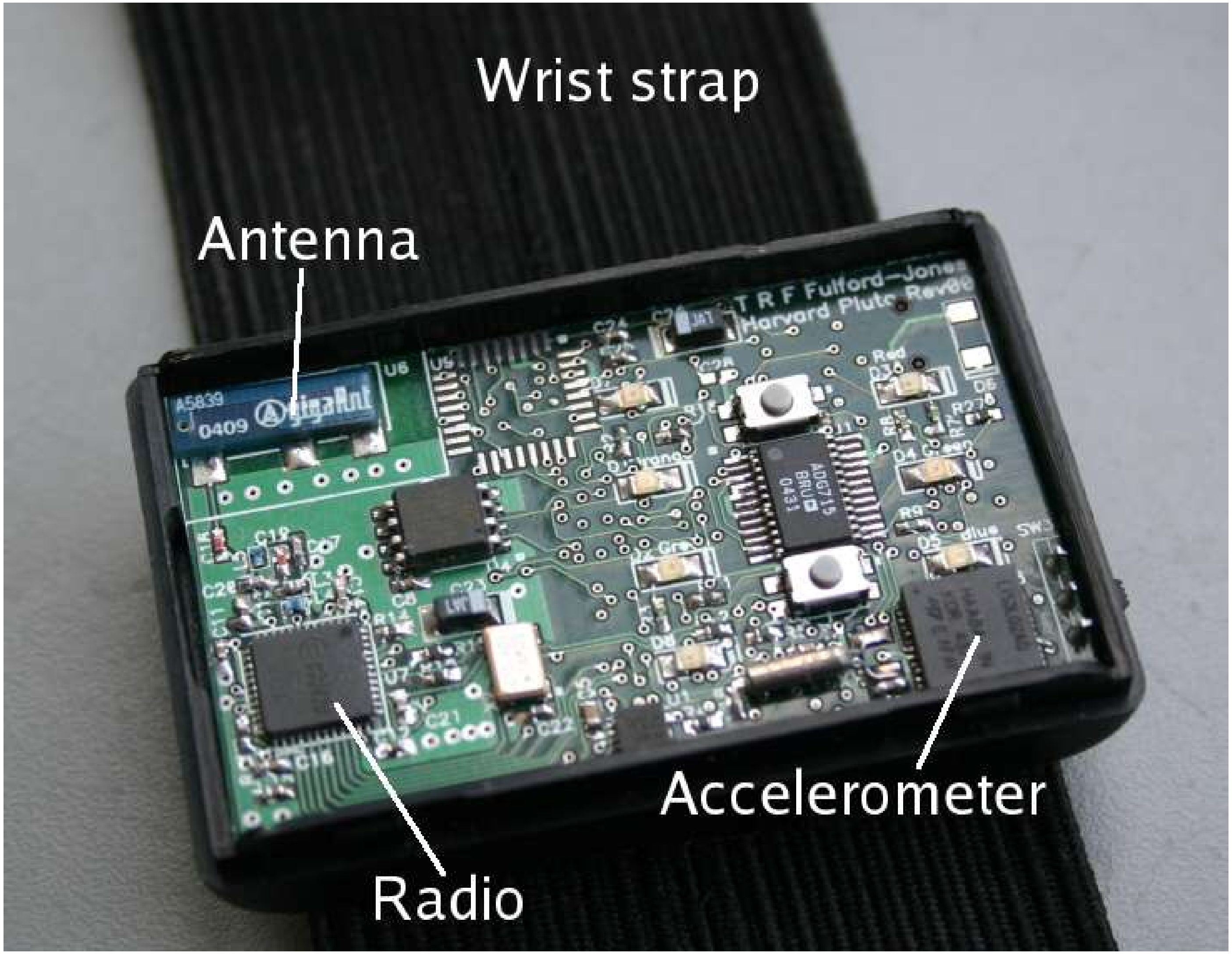
Motion Capture and EMG Sensors



Special-purpose sensors to capture limb motion and muscle activity

- To be used in stroke and Parkinson's Disease studies
- (with P. Bonato, Spaulding Rehabilitation Hospital)

The Harvard Pluto Mote



Tiny, wearable mote design

- Slim rechargeable battery
- Integrated 3-axis accelerometer (motion and physical activity monitoring)

Sensor Network Challenges

Low computational power

- Current mote processors run at < 10 MIPS
- Not enough horsepower to do real signal processing
- 10 KB of memory not enough to store significant data

Poor communication bandwidth

- 802.15.4 advertises bandwidth of 250 Kbps
- But, raw overhead available to applications ~ 80 Kbps (at best!)
    - *Overhead due to CSMA backoff, noise floor detection, start symbol, etc.*

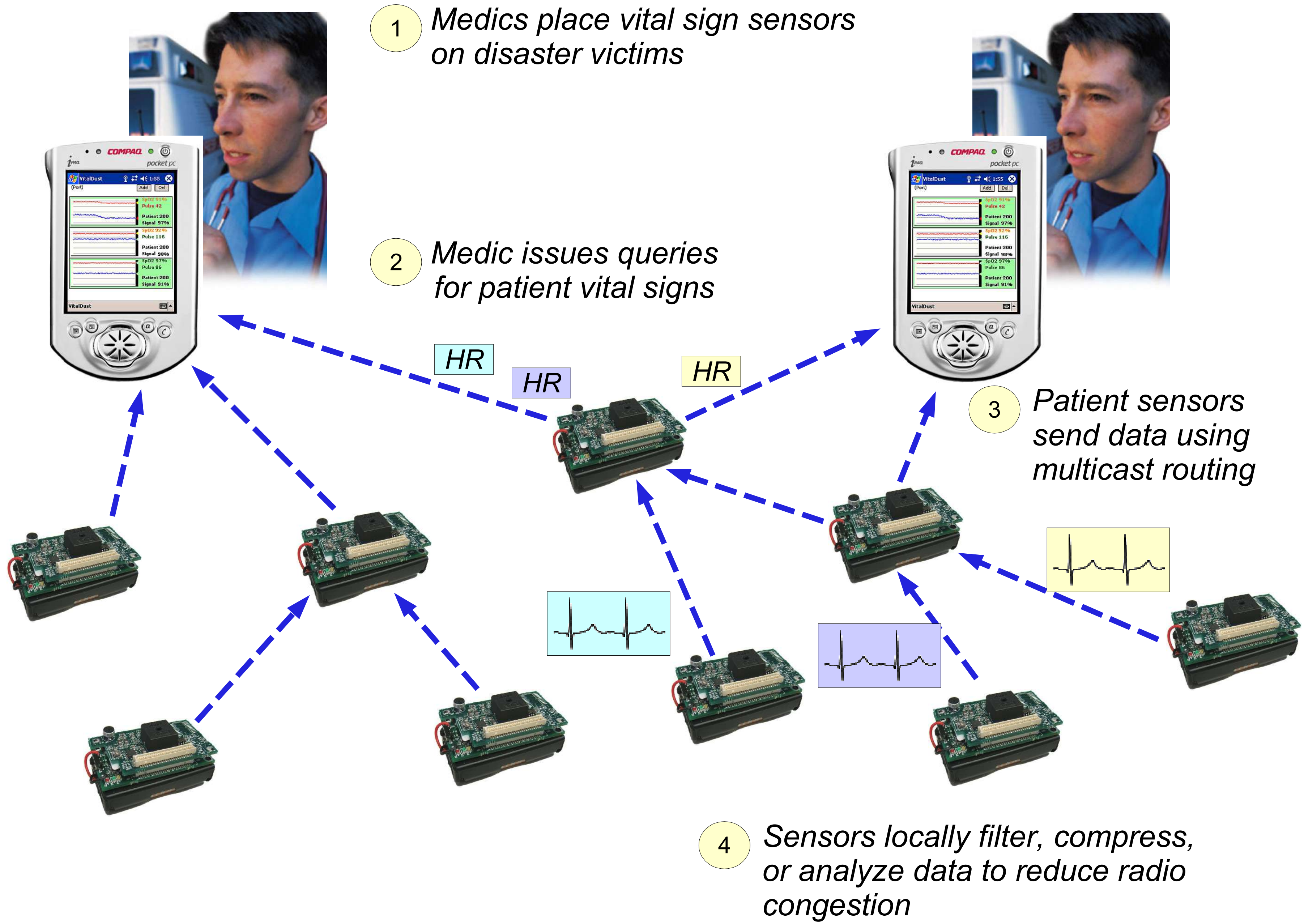
Radio congestion

- Even a small number of devices can saturate the radio channel

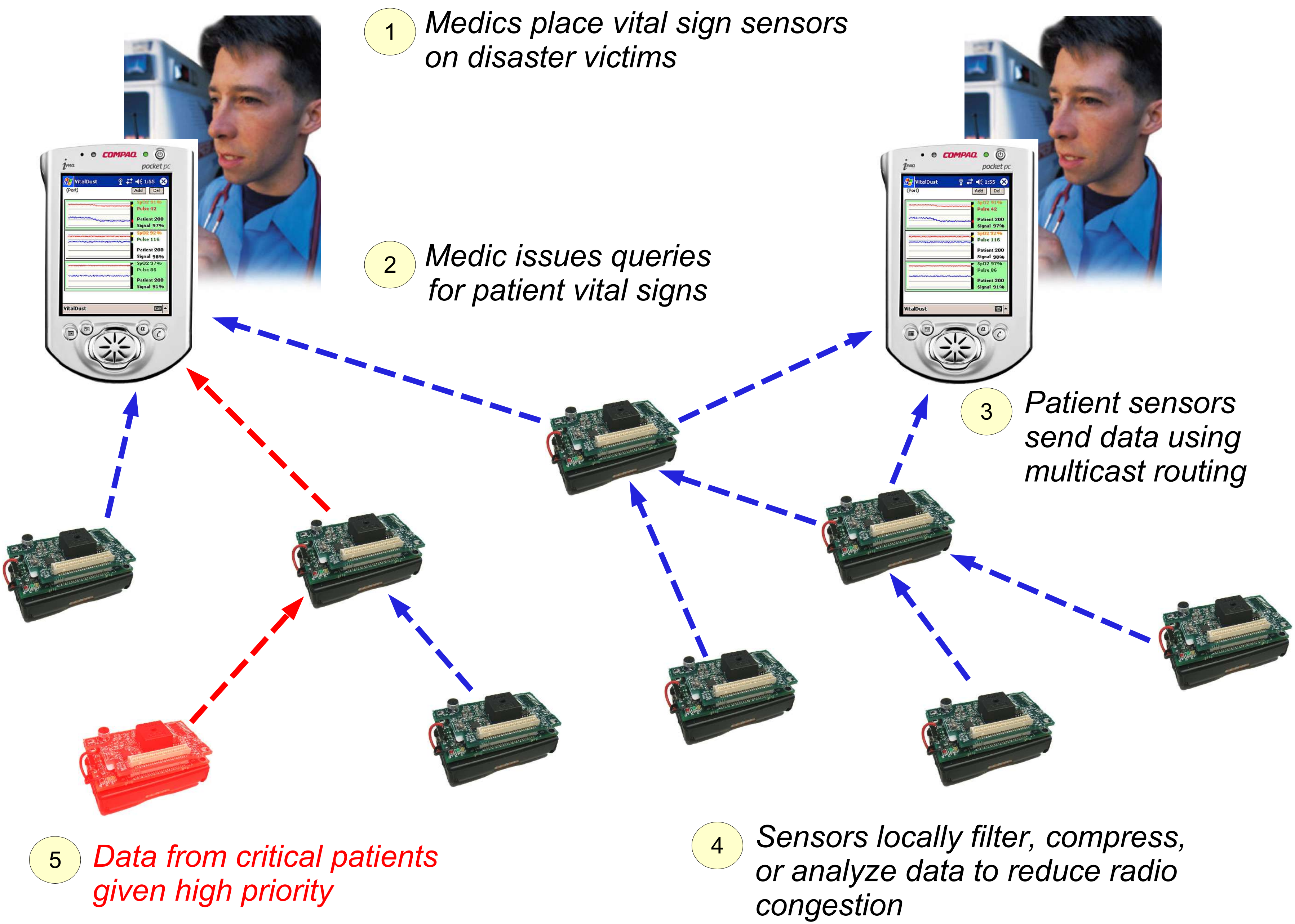
Limited energy budget

- 2 AA batteries can last about 5-6 days at full power
- Thin rechargeable batteries about 5 *hours*
- Must use *low duty cycle operation* to extend lifetime

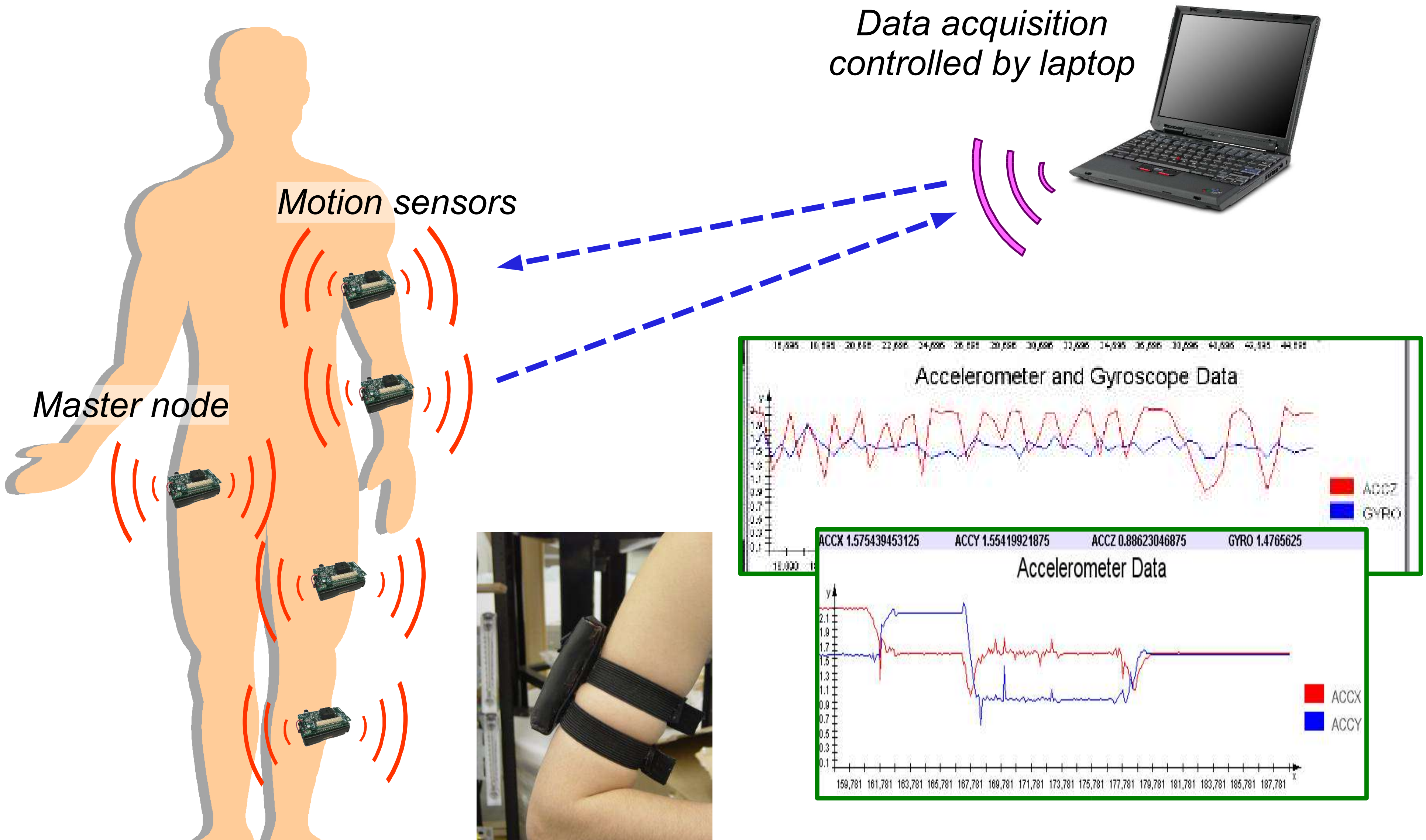
The CodeBlue Network Infrastructure



The CodeBlue Network Infrastructure

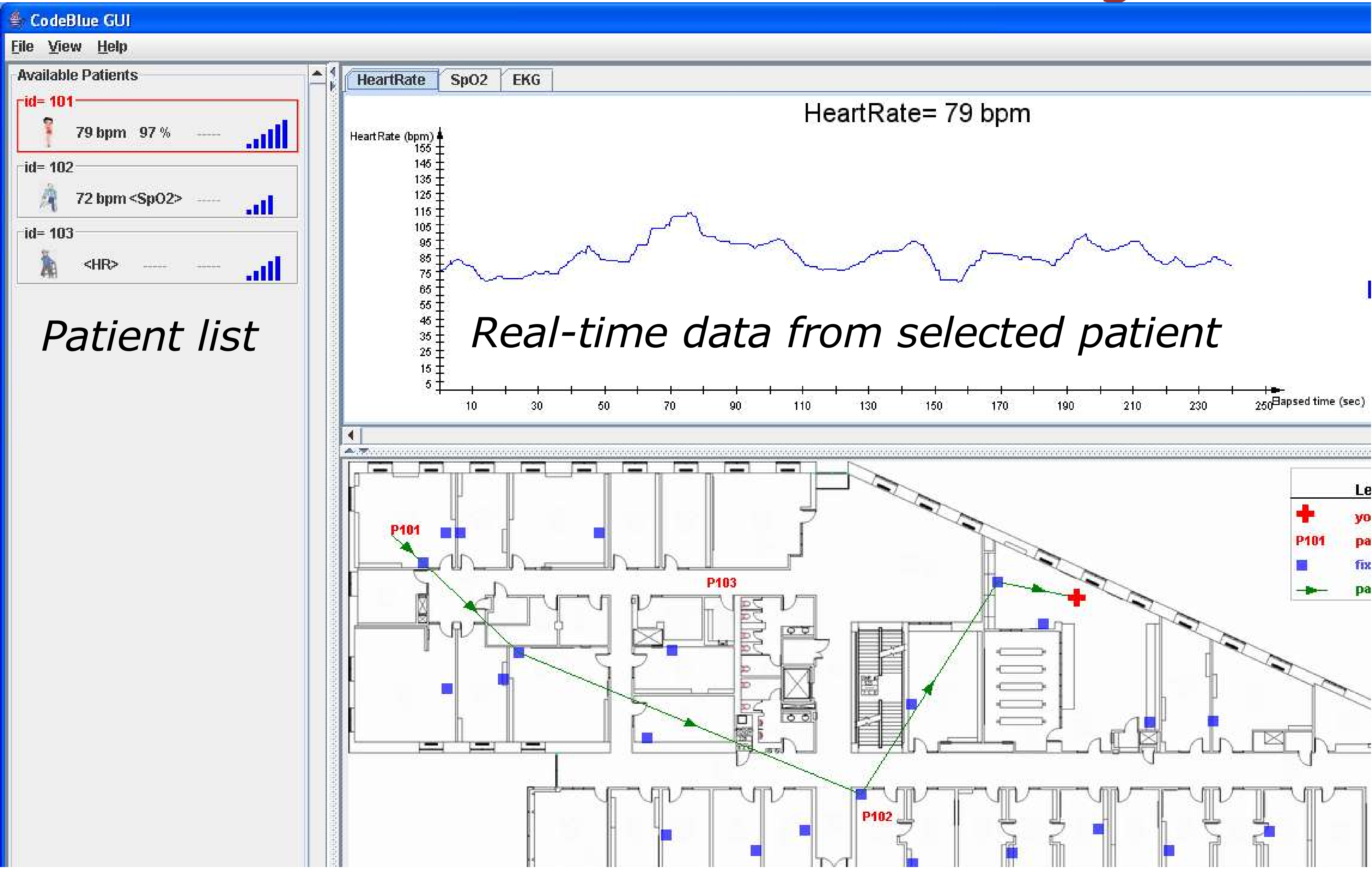


CodeBlue use in Clinical Settings



Wearable mote with armband

GUI for Real-Time Patient Tracking



Patient list

Real-time data from selected patient

Map showing location and routing path

CodeBlue Architecture

Suite of services and protocols for wireless medical devices

- Protocols providing discovery, routing, filtering, and security services
- Runs across a range of devices, from motes to PDAs to PCs

Mesh networking using publish/subscribe data model

- Sensor nodes publish vital signs, location, identity
- Rescue/medical personnel subscribe to data of interest
- Devices cooperate to route data from publishers to subscribers
- In-network filtering and aggregation of data to limit bandwidth and information overload

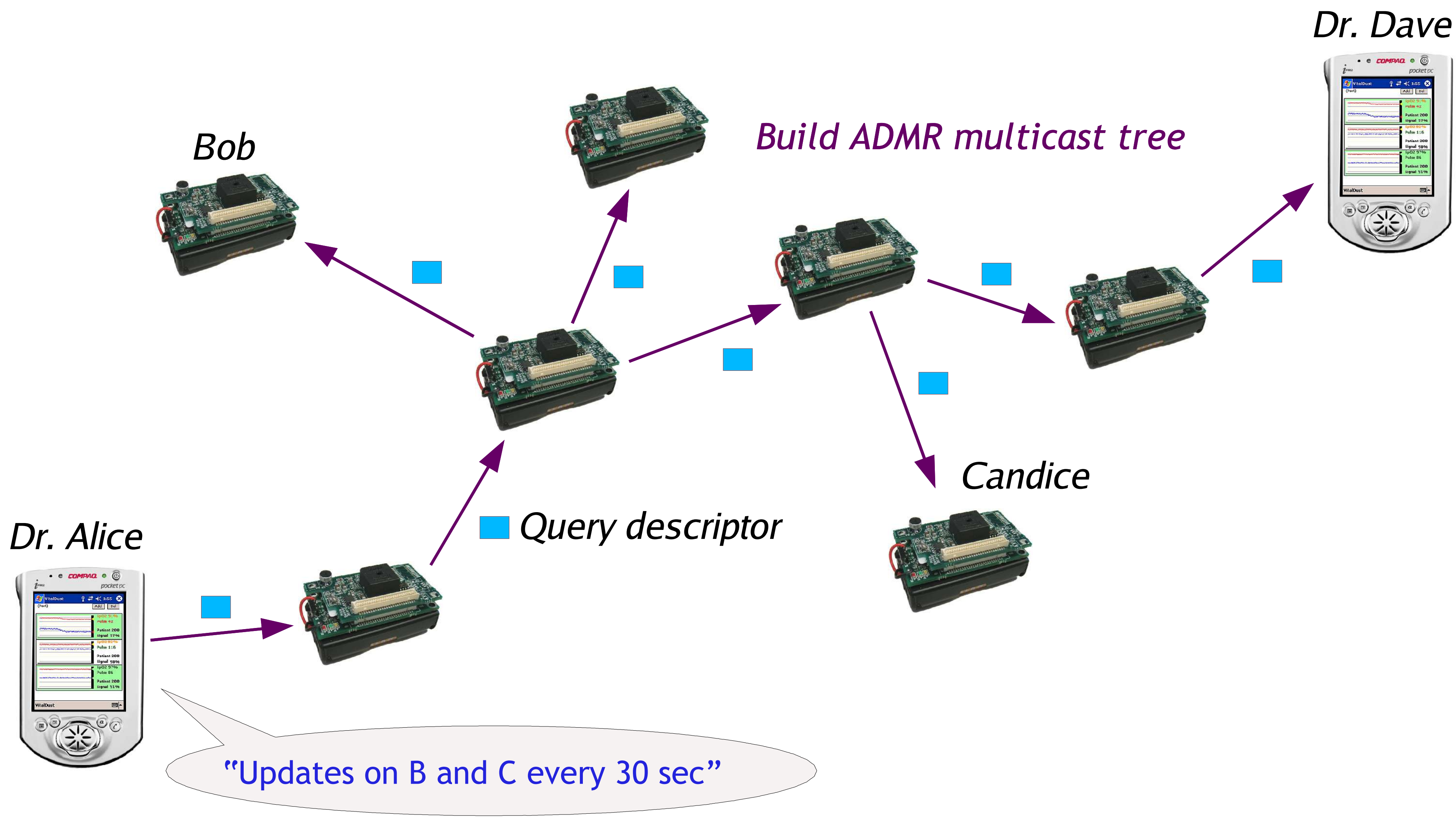
Reliable delivery of critical data

- Content-based prioritization
  - *e.g., Patient stops breathing or loss of network connectivity*
- Scale transmit power to limit interference or issue “SOS” messages

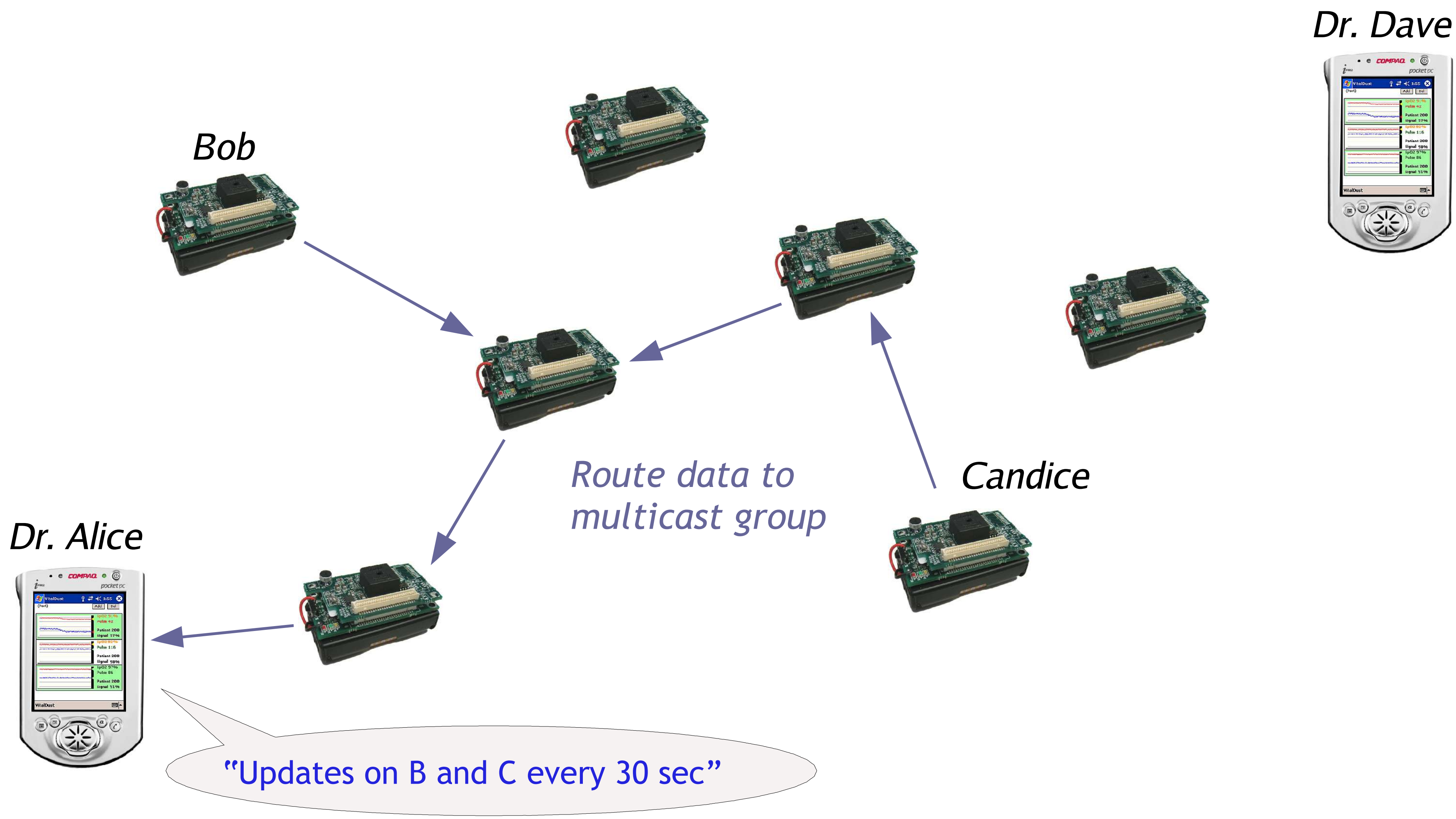
Decentralized authentication and security

- Handoff of credentials across rescue personnel
- Seamless access control across patient transfers

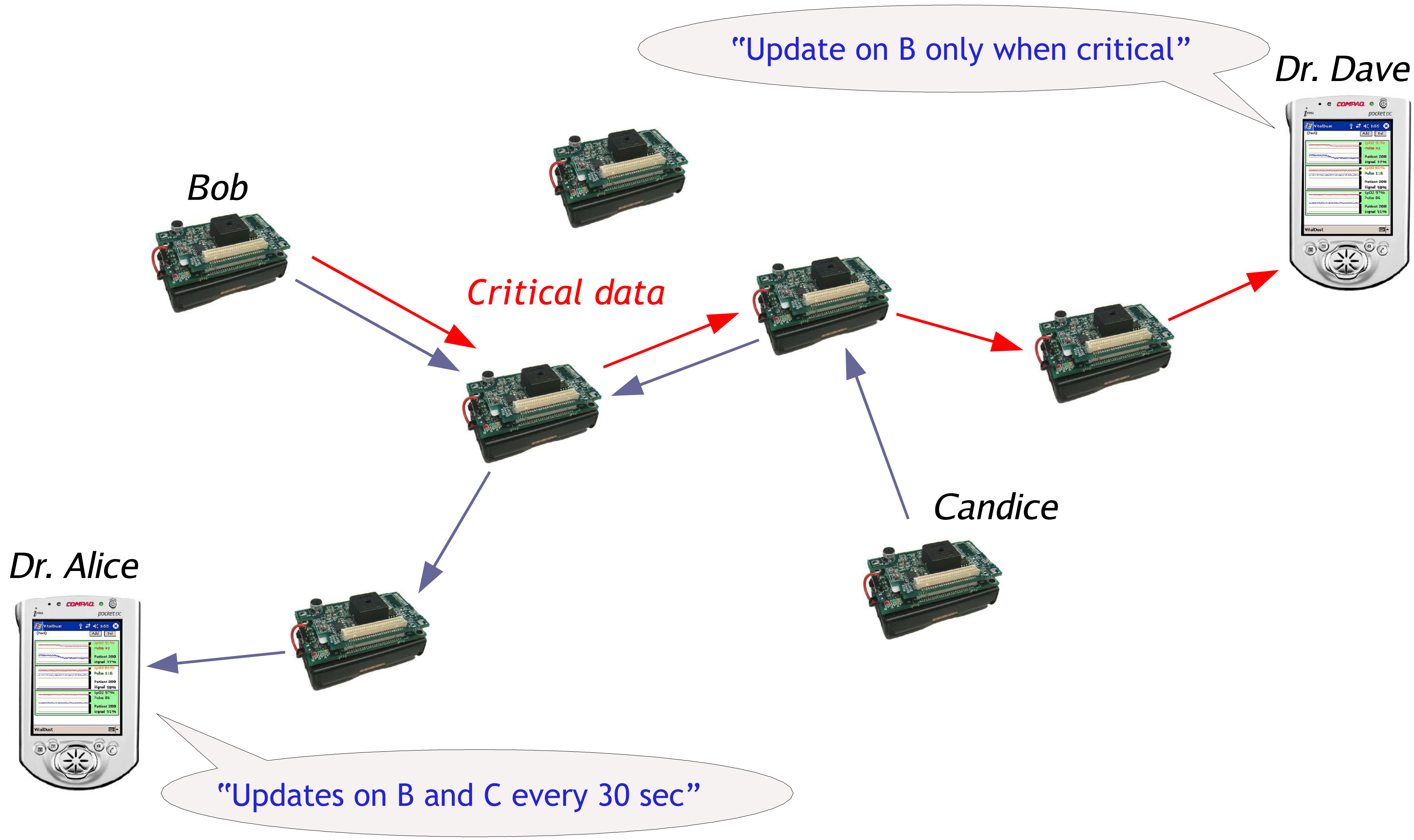
Query and Routing Model



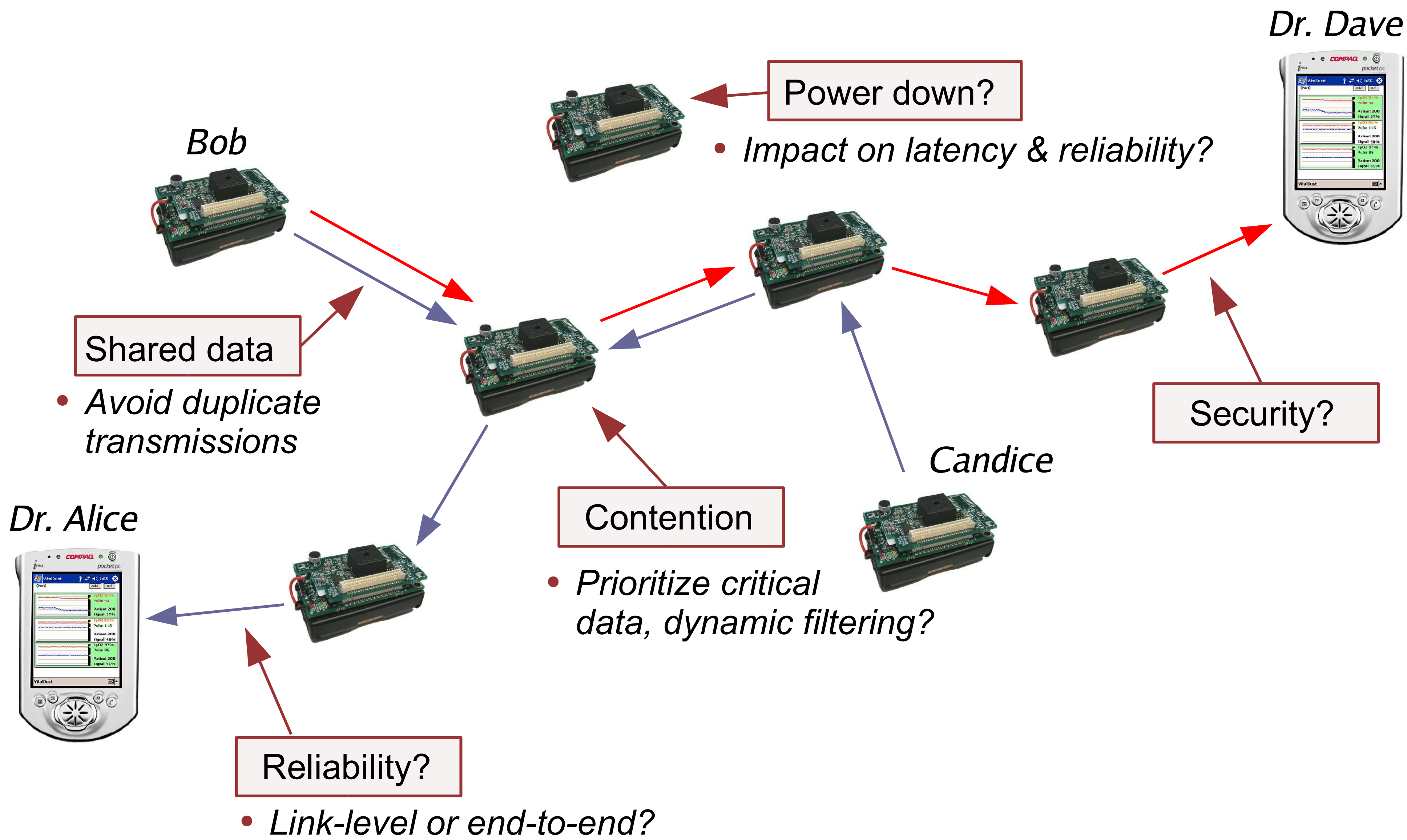
Query and Routing Model



Query and Routing Model



Challenges and Issues



Routing Protocol Design

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

TinyADMR

Adaptive Demand-driven Multicast Routing (ADMR)

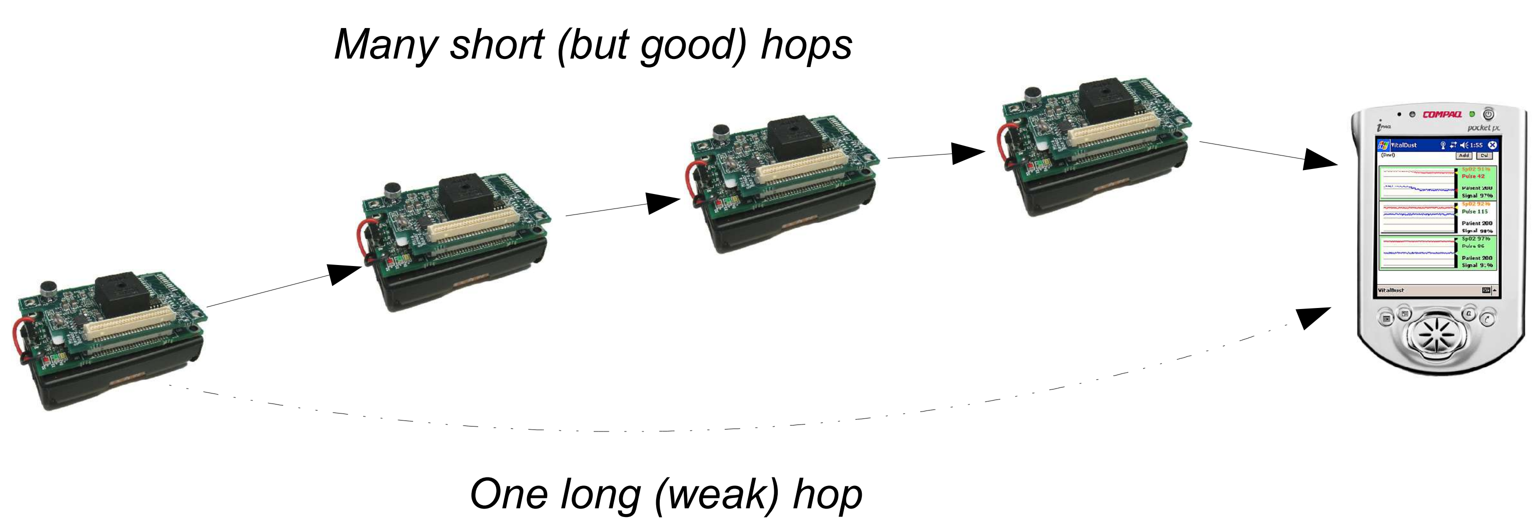
- [Jetcheva and Johnson, Proc. MobiHoc 2001]
- Mature, well-designed multicast protocol for wireless networks

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)



TinyADMR

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)

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

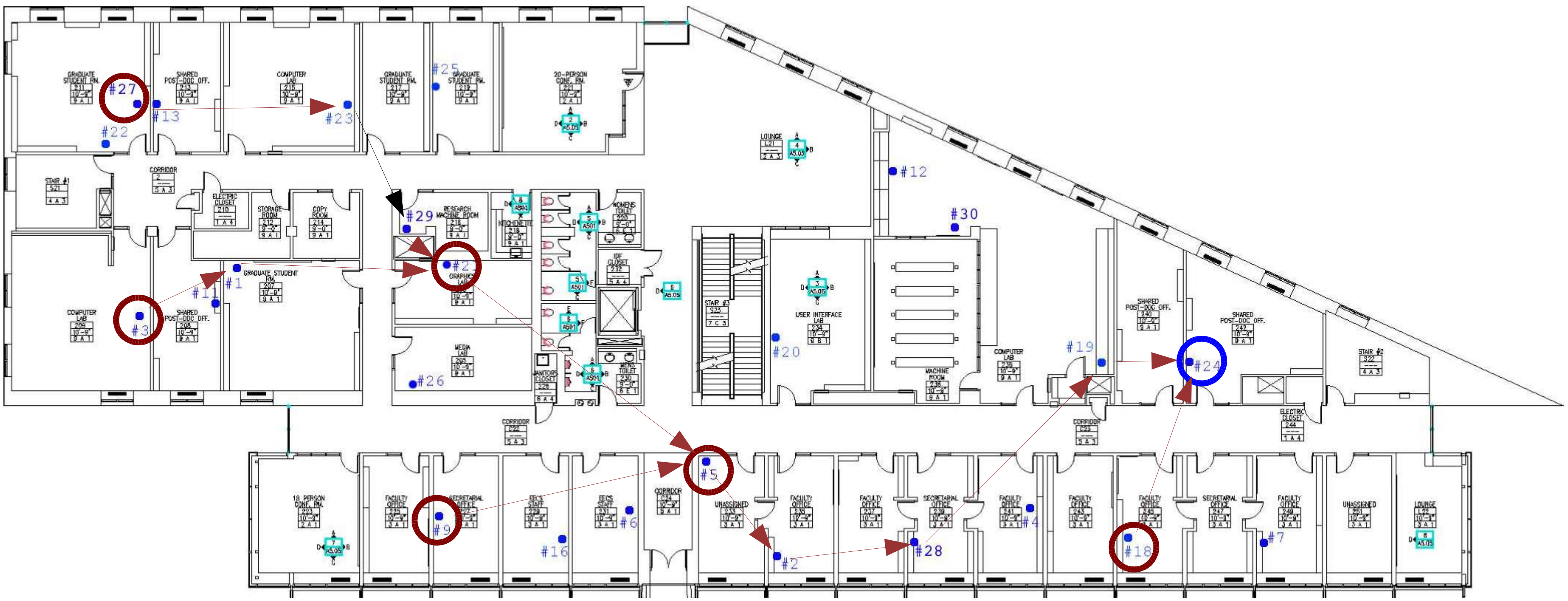
Evaluation Methodology

Testbed of 30 MicaZ nodes distributed throughout our building

- Reprogram and debug via web interface at motelab.eecs.harvard.edu

Set up certain nodes as "virtual patients" and others as "virtual doctors"

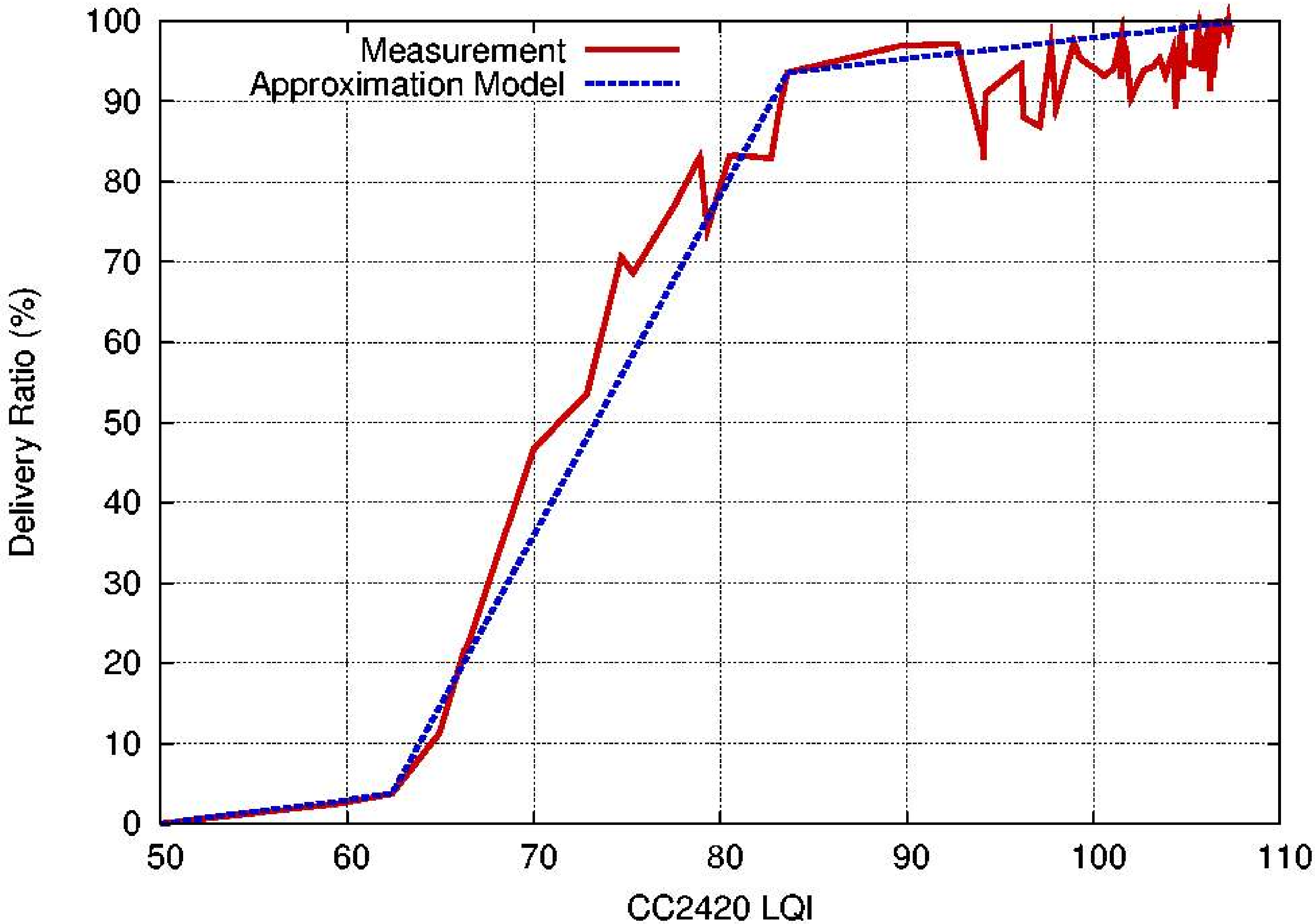
- Vary parameters such as generated data rate, number of senders and receivers



TinyADMR Route Selection

We make use of CC2420 Link Quality Indicator (LQI) metric:

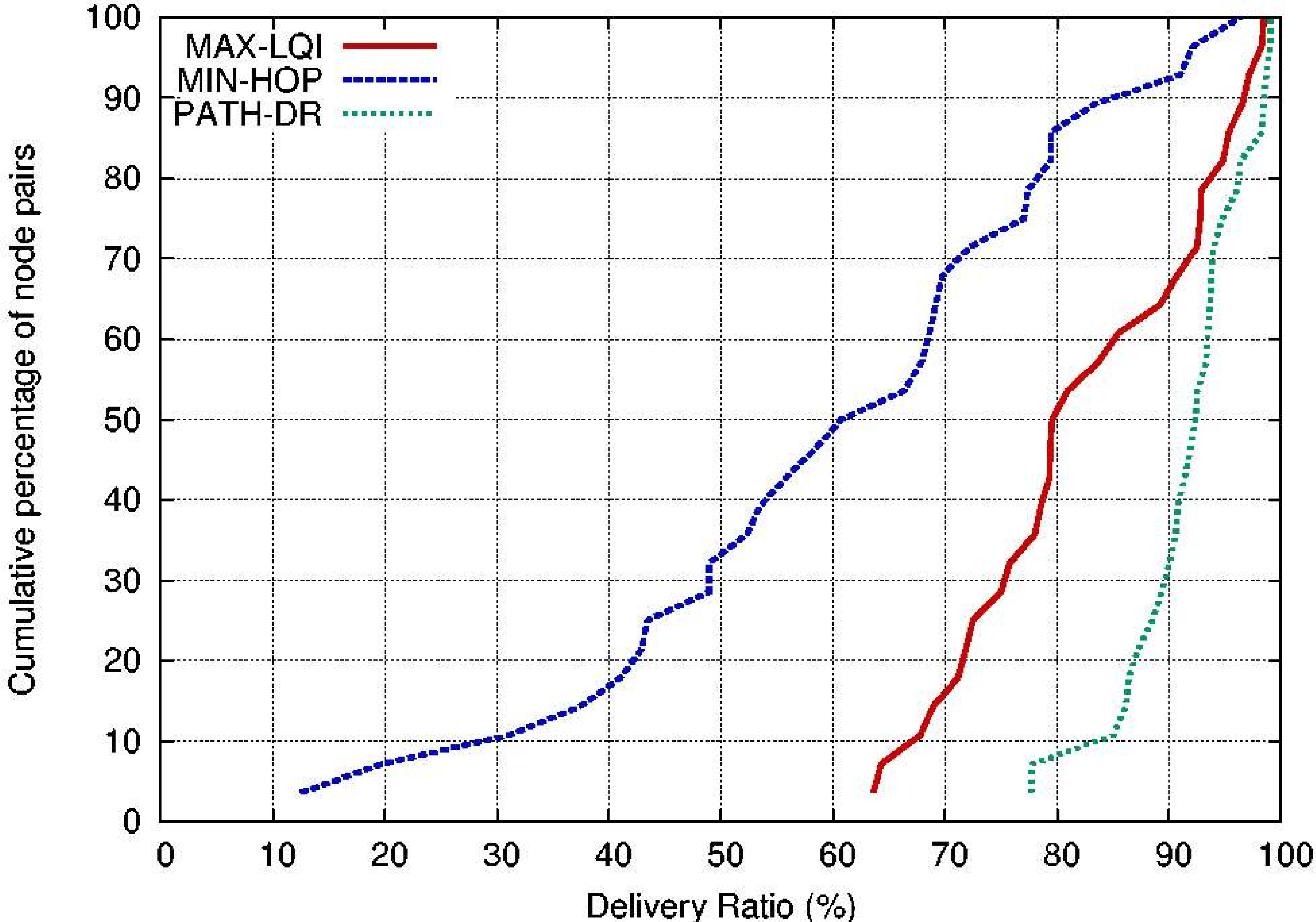
- *Indicates ability of radio to decode start symbol of packet*
- LQI is highly correlated with packet delivery ratio
- Can be measured with a single packet reception (no probing traffic required)



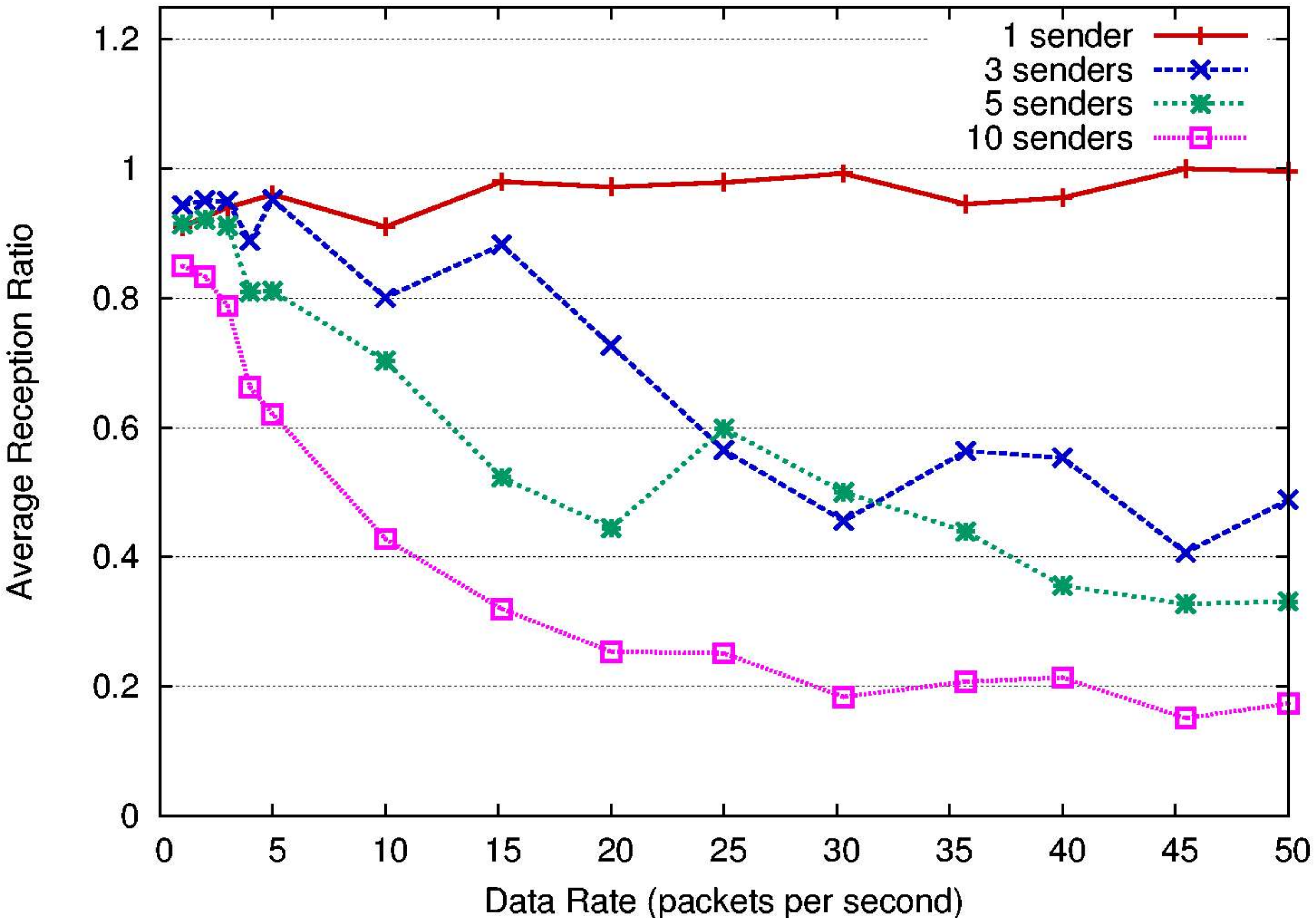
TinyADMR Route Selection

Comparison to other route selection metrics

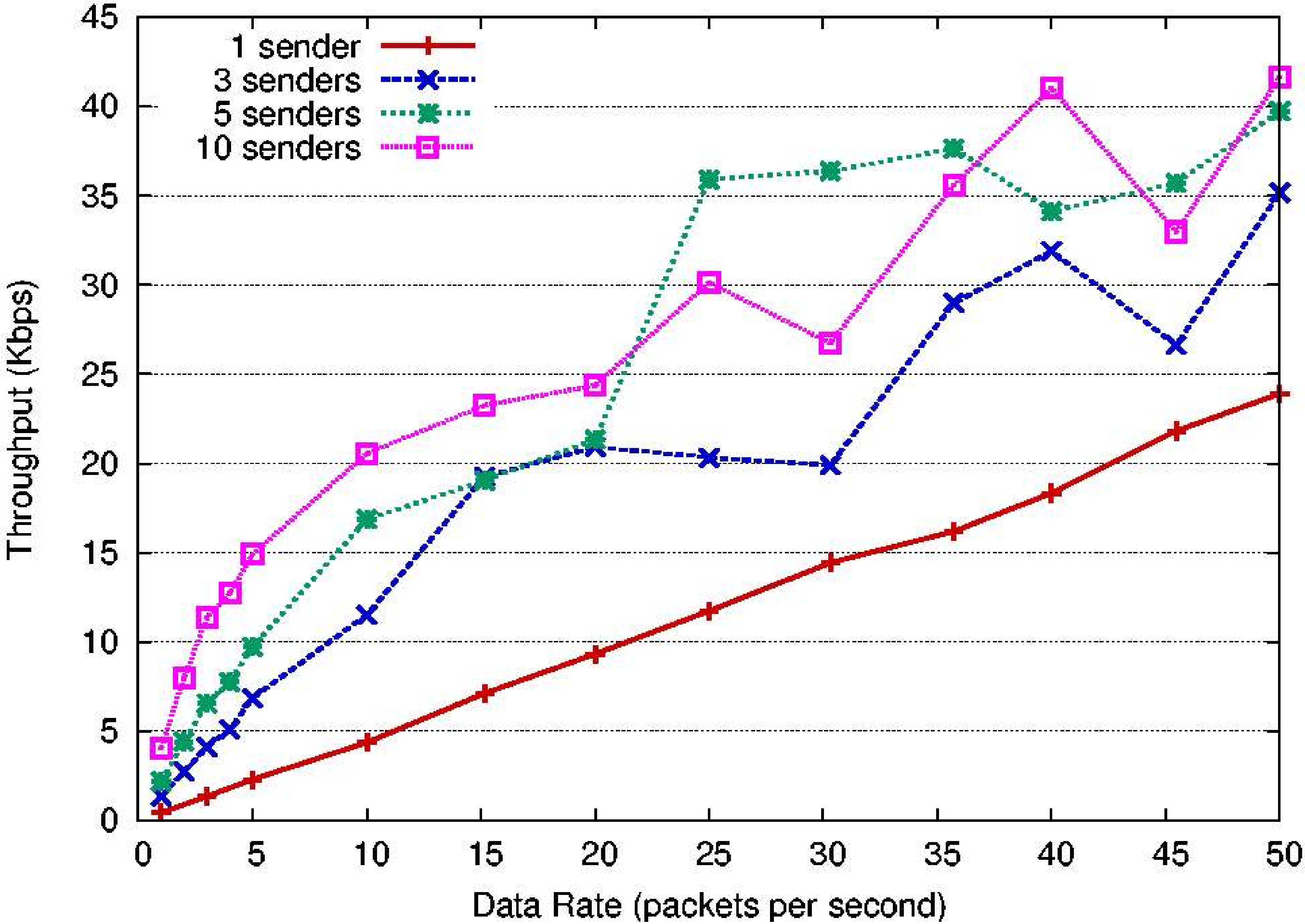
- MIN-HOP: Lowest hopcount path
- MAX-LQI: Path with worst LQI rating per link
- PATH-DR: Estimated path delivery ratio from LQI model



Effect of increasing data rate and number of senders



Effect of increasing data rate and number of senders



MoteTrack: RF-Based Localization

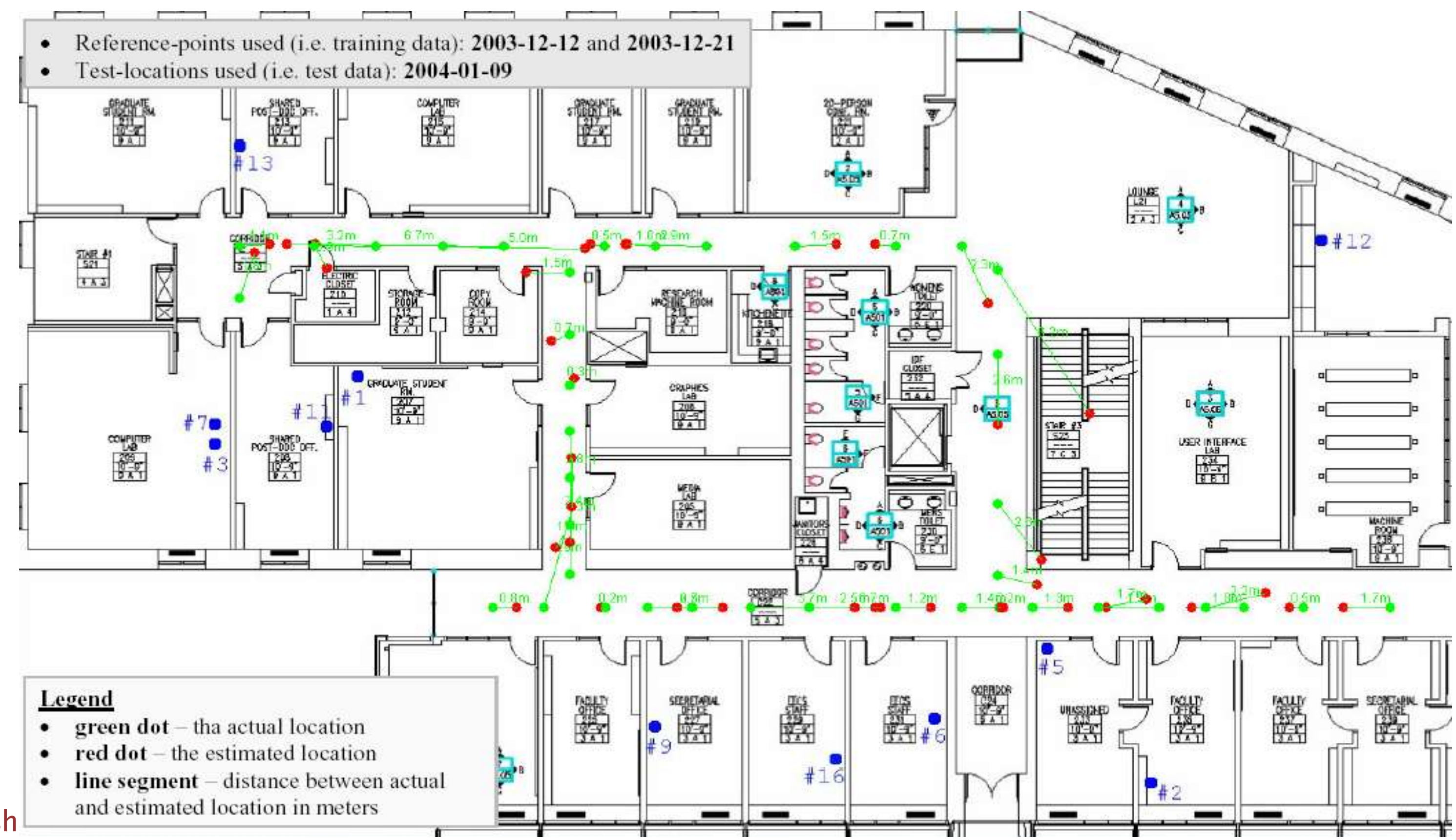
Collect RF signal “signatures” from various points in building

- 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*



Current Status

First prototype of CodeBlue protocol framework is complete

- TinyADMR for multicast routing
- MoteTrack for indoor localization
- Simple query interface for vital sign data
- Java-based GUI for real-time visualization

Range of medical sensors based on motes

- Pulse oximeter, EKG, accelerometer/gyro/EMG board
- Pluto custom mote for wearable applications

Customizing the system for multi-sensor motion analysis

- Collaboration with Spaulding Rehabilitation Hospital
- Study of motion disorders in post-stroke and Parkinson's Disease patients

All hardware and software is publically available at:

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

Integrating wireless sensors with the Internet