CPSL
Cyber-Physical Systems Laboratory

Wireless Clinical Monitoring

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Motivation

- Clinical deterioration in hospitalized patients
  - 4-17% suffer adverse events (e.g., cardiac or respiratory arrest).
  - Up to 70% of such events could have been prevented.
  - Clinical deterioration is often preceded by changes in vitals.
- Early warning of clinical deterioration → improved outcome
- Require real-time monitoring in general hospital wards
  - Current practice: collect vital signs manually
  - Approach: wireless monitoring system collects data in real-time
- Large-scale, interdisciplinary research
  - Wireless sensor networks, data mining, informatics, clinical care

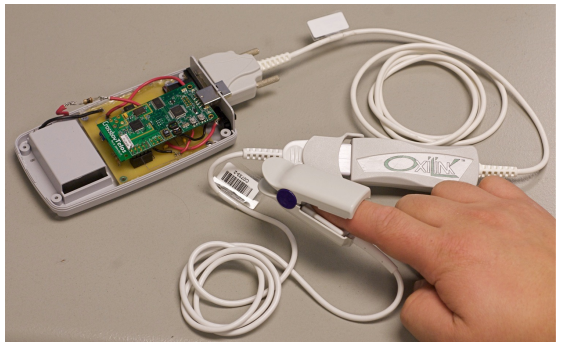
Two-Tier Clinical Warning

- Predict high-risk patients based on electronic medical records
  - Clinical data mining [J. Hospital Medicine 2013]



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- Detect events using real-time vital signs
  - Wireless monitoring [SenSys'10, Wireless Health'12]
  - Event detection algorithms [KDD'12]



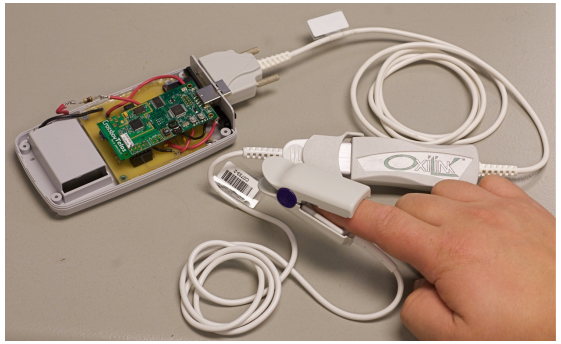
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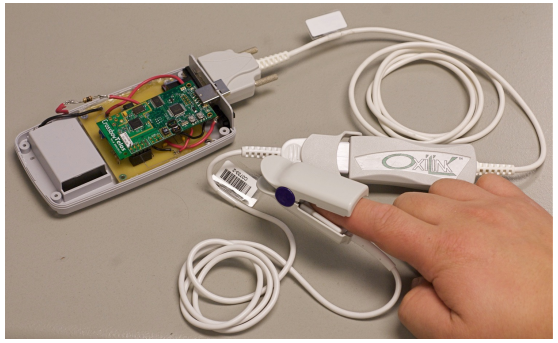


Wireless Sensor Networks vs. Wi-Fi

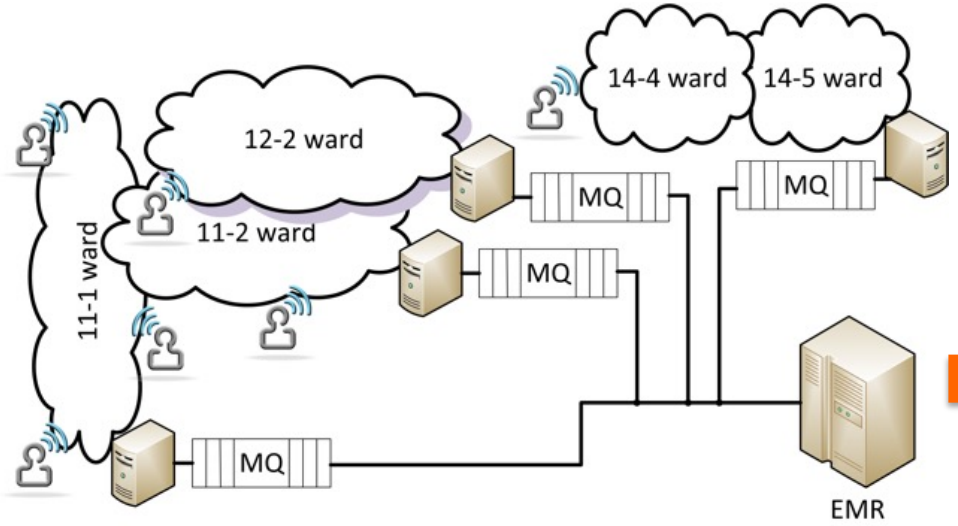
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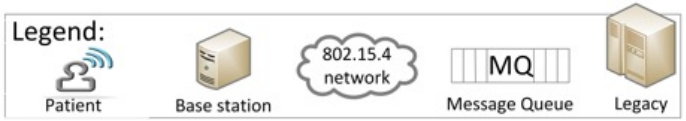
- More energy efficient than Wi-Fi at low data rate
  - Common vital signs have low data rate.
  - Nurses are too busy to change batteries!
- Low deployment cost
  - Mesh networks without wired infrastructure.
  - Ease adoption.
  - Even major hospitals may not guarantee full Wi-Fi coverage.
- Sufficient reliability
  - >99% median network reliability in our clinical trial
  - Even a wired network can only improve reliability marginally.

Wireless Clinical Monitoring









Rapid Response

R. Dor, G. Hackmann, Z. Yang, C. Lu, Y. Chen, M. Kollef and T.C. Bailey, Experiences with an End-To-End Wireless Clinical Monitoring System, Conference on Wireless Health (WH'12), October 2012.

Wireless Clinical Monitoring

CPSL Cyber-Physical Systems Laboratory

1. Build a clinical monitoring system with sensor networks.

2. Clinical trial 1: **feasibility**
   - Deployed in a general hospital ward for 7 months
   - Enrolled 46 patients.

3. Clinical trial 2: **scaling up**
   - Deployed in 7 general hospital wards for 14 months
   - Enrolled 97 patients
   - Large wireless sensor networks spanning 4 floors
   - Integrated with electronic medical records and hospital IT

Wireless Clinical Monitoring

CPSL Cyber-Physical Systems Laboratory

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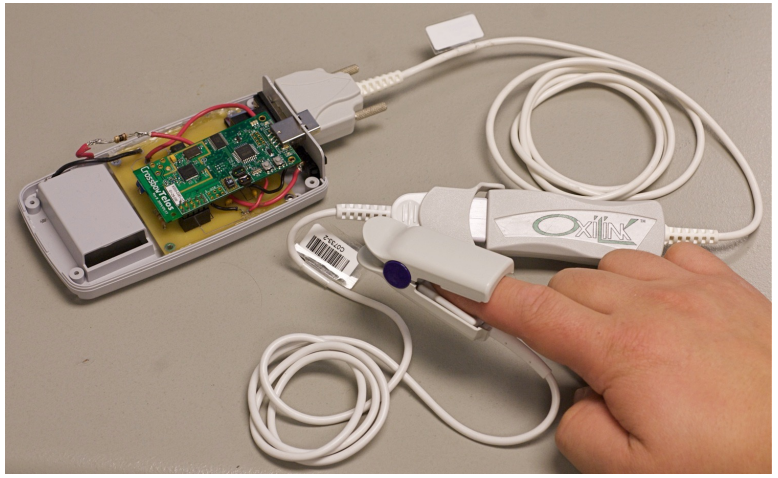
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System Architecture

- Base station
  - laptop connected to Wi-Fi
- Relays
  - plugged into wall outlets
  - redundant deployment
    - coverage
    - fault tolerance
- Portable pulse oximeter
  - pulse oximeter + microcontroller + radio
  - battery operated





Reliable Network Architecture

- Problem: Patients in general hospital units are ambulatory.
- Approach: Two-tier architecture for end-to-end data delivery.

1 Dynamic Relay Association Protocol (DRAP): Patient → 1st relay
  - Patient node dynamically discovers and associates with a relay.
  - Single-hop protocol handles patient mobility.
  - Simplifies power management in patient nodes (send only).

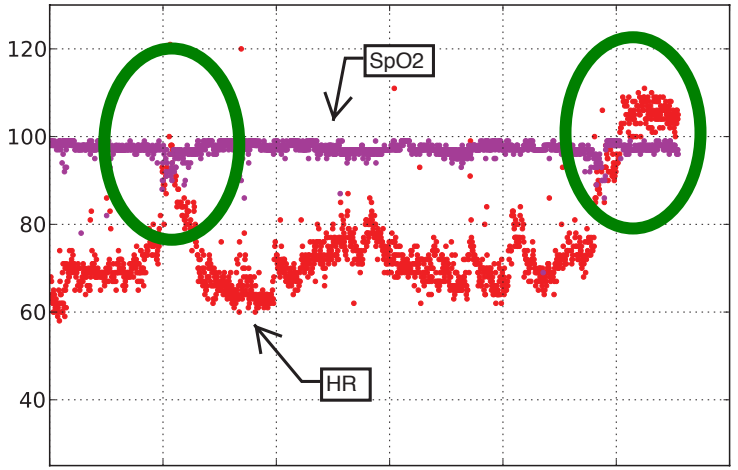
2 Stationary relay network: 1st relay → … → base station
  - Reuse well tested mesh routing protocol (CTP).
  - Isolated from patient mobility.
  - Wall-plugged => no need to worry about energy.

Clinical Deployment

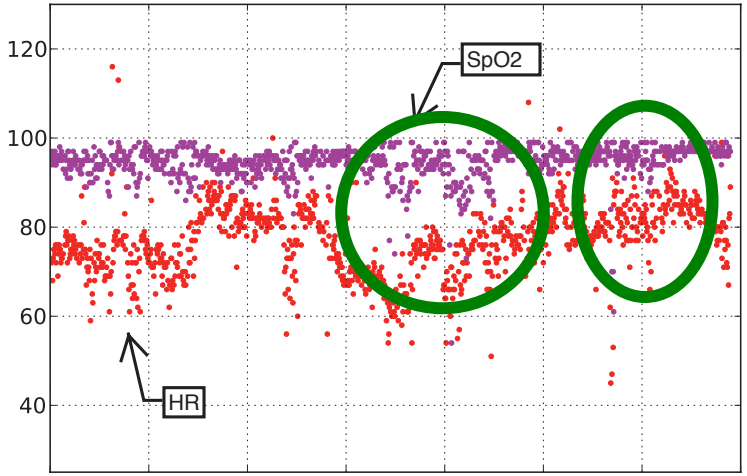
- Step-down cardiac care unit
  - 16 patient rooms, 1200 m^2
- Network
  - 18 relays: redundant network
  - Longest path: 3-4 hops
  - Channel 26 of IEEE 802.15.4
  - 1-2 pulse and oxygenation values per minute.
- 46 patients enrolled
  - >41 days of monitoring
  - 2-68 hours per patient
  - Up to 3 patients at a time
  - 5 patients excluded from analysis



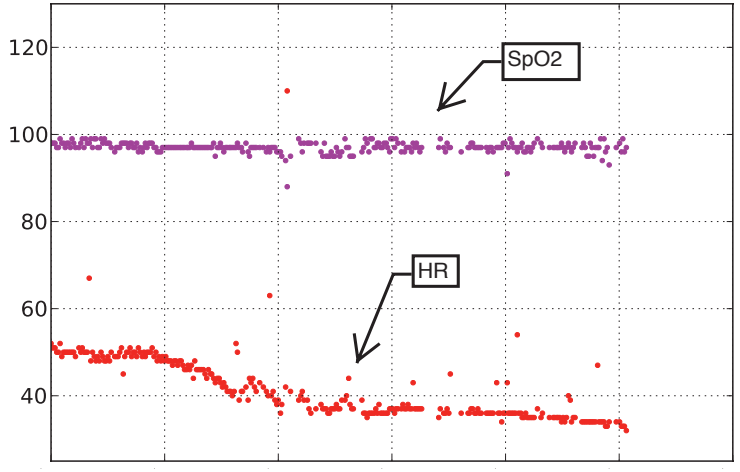
Potential for Detecting Clinical Events



Pulmonary edema



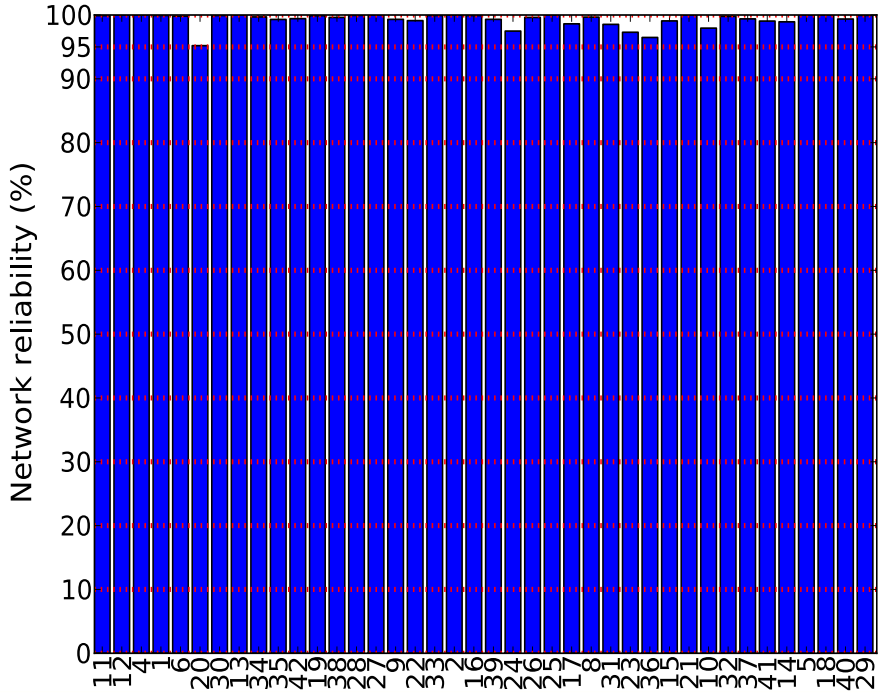
Sleep apnea

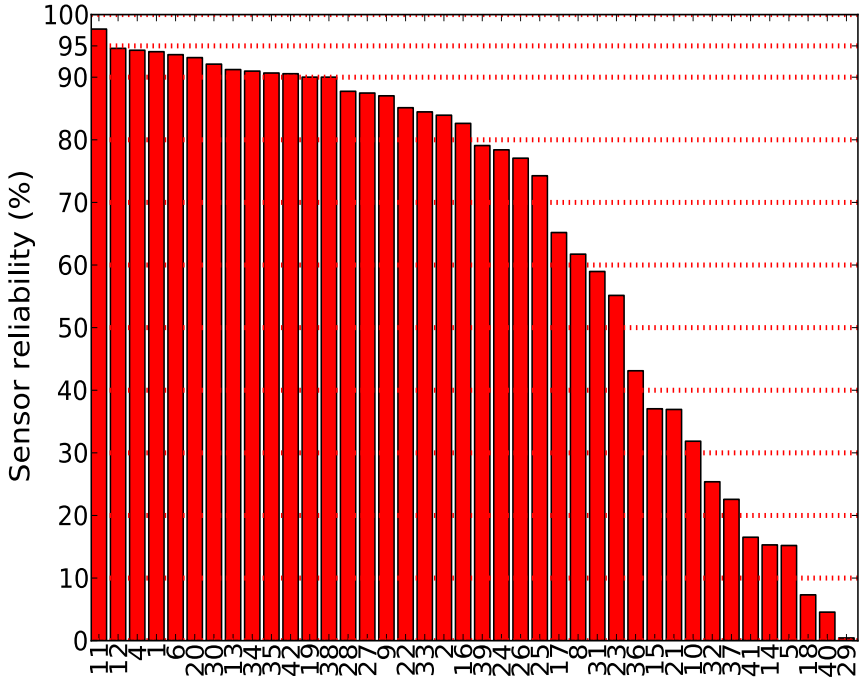


Bradycardia

System Reliability

- Network reliability >95% for all patients.
  - DRAP+CTP is effective!
- Median sensing reliability > 80%.
  - But 29% of patients had sensing reliability < 50%.
- System reliability dominated by sensing reliability!





"Surprises"

- Sensing is the problem, not the network!
  - System failures are dominated by the sensors.
- Must minimize manual intervention - nurses are busy!
  - Change batteries
  - Sensor disconnection alarms
  - False alarms in event detection
- Wi-Fi is not dependable in hospitals!
  - Value-added service with no guarantee of coverage or reliability
  - Wi-Fi was the weakest link in our deployment!

Summary: Trial I

- Wireless clinical monitoring system for hospitalized patients.
- First deployment of wireless sensor networks in a hospital ward.
- Clinical trial with patients in a hospital ward.
  - Highly reliable network
  - System reliability dominated by pulse oximeter
  - Potential for detecting clinical deterioration

O. Chipara, C. Lu, T.C. Bailey, and G.-C. Roman, Reliable Clinical Monitoring using Wireless Sensor Networks: Experience in a Step-down Hospital Unit, ACM Conference on Embedded Networked Sensor Systems (SenSys), November 2010.

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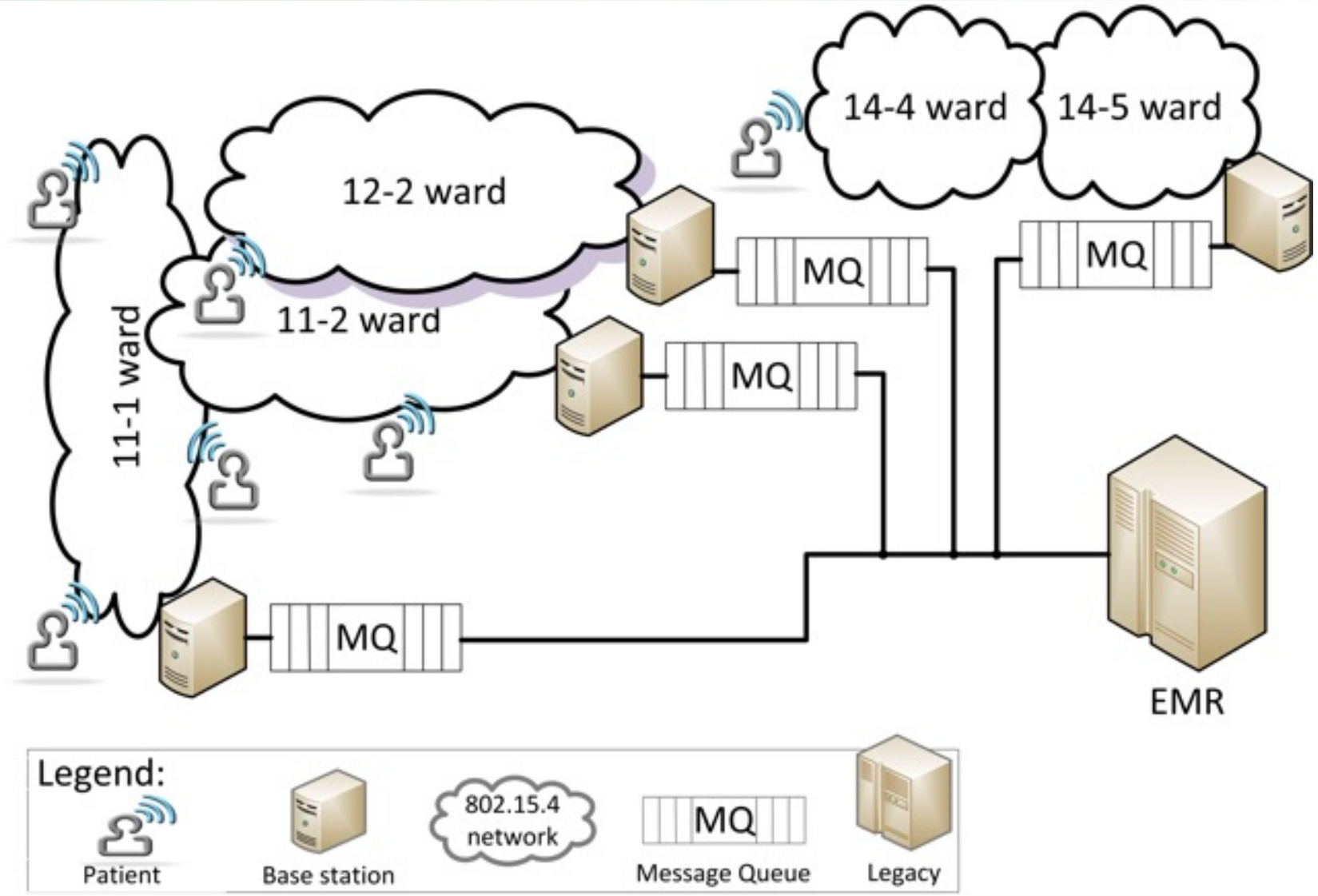
3. Clinical trial 2: scaling up
   - Deployed in 7 general hospital wards for 14 months
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   - Large wireless sensor networks spanning 4 floors
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Overview: Trial 2

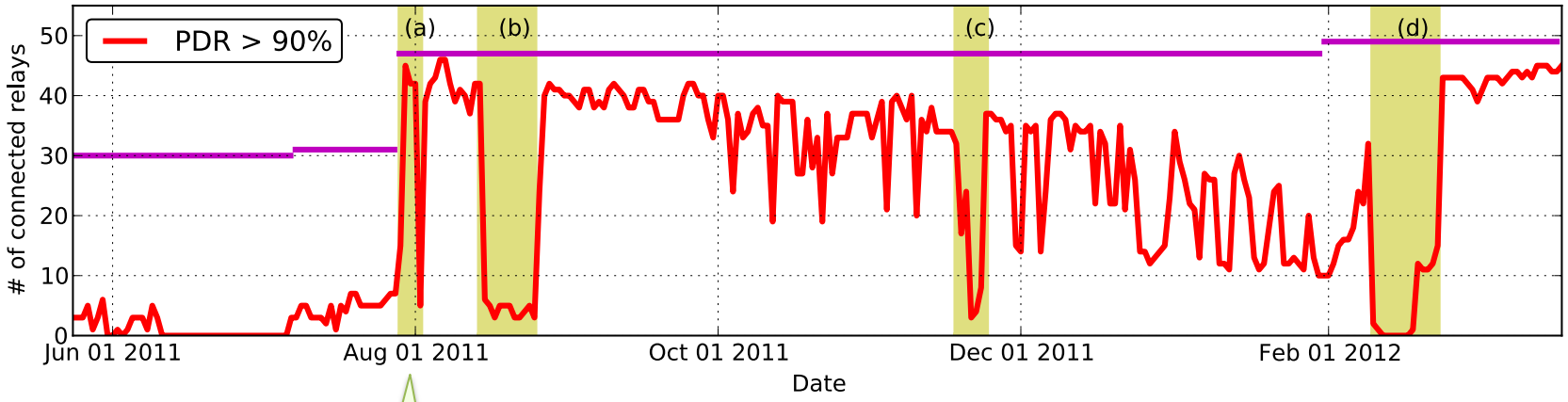
- Large scale: multiple wireless sensor networks.
  - Monitored patients in 4 hospital floors and 7 wards
  - *Can wireless clinical monitoring scale to a large hospital?*

- End-to-end: integrate with hospital IT infrastructure.
  - *Can wireless sensor networks work with enterprise IT infrastructure?*

Relay Network Infrastructure



Network Reliability @ Scale



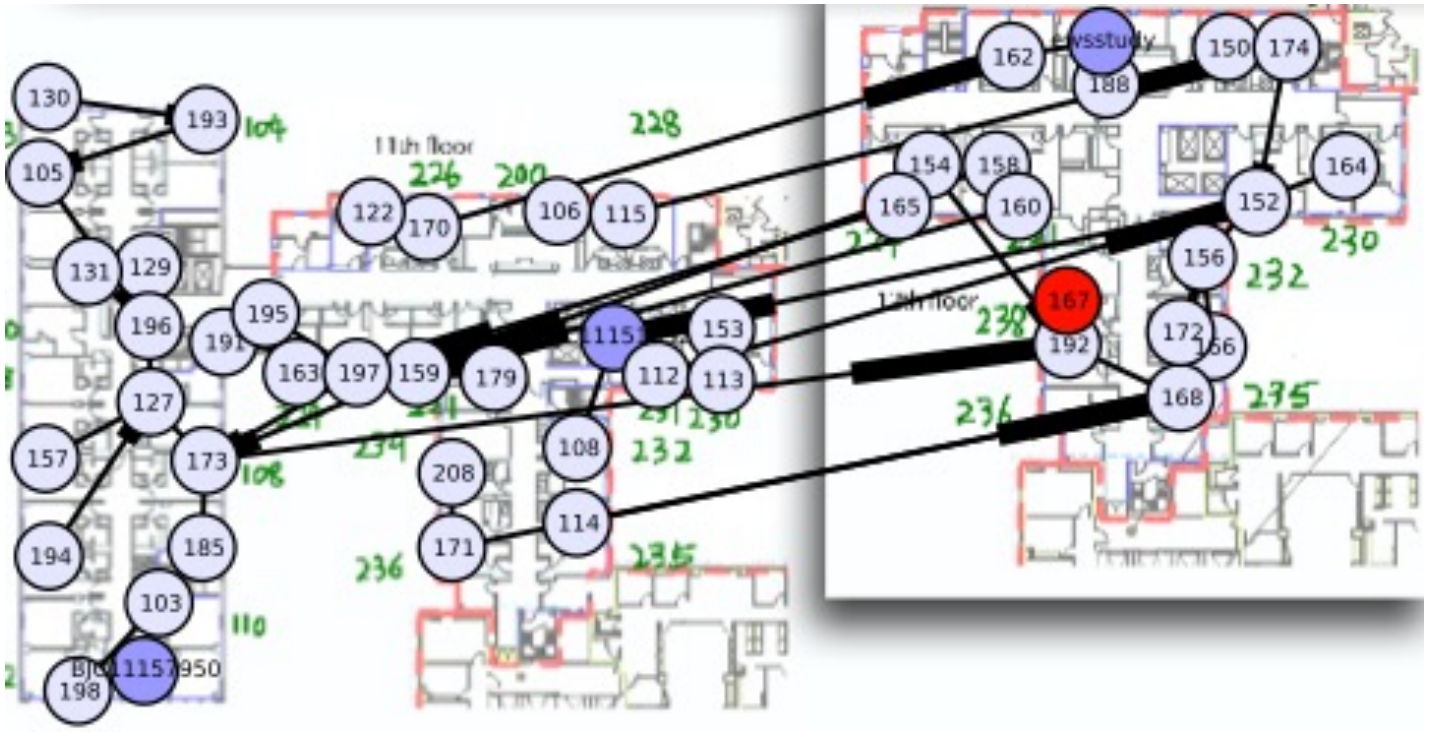
- On April 11: BS 5 and 52 and 11 relays were deployed
- Bumped to 30 r ys when the network did not perform

Unit added on the floor above

- Integrating multiple networks + 3D topology saved the day!

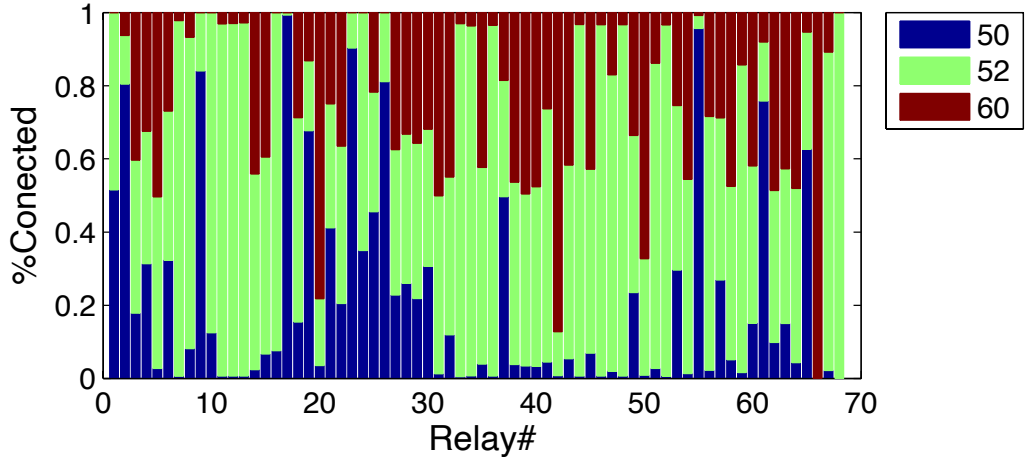
Wireless in a Hospital

- Wireless in large and busy buildings is complex and unpredictable.
  - Base station in a same ward was hard to reach.
  - Vertical links were highly effective and instrumental for reliability.
- Hence, we need as much route diversity as possible!



Integrate or Isolate Networks?

- Integrating multiple wireless sensor networks saved the trial!
  - Relay networks used an *anycast* protocol (CTP).
  - Sensor data may be routed to *any* existing base station.
  - Integration of multiple networks greatly improved route diversity.



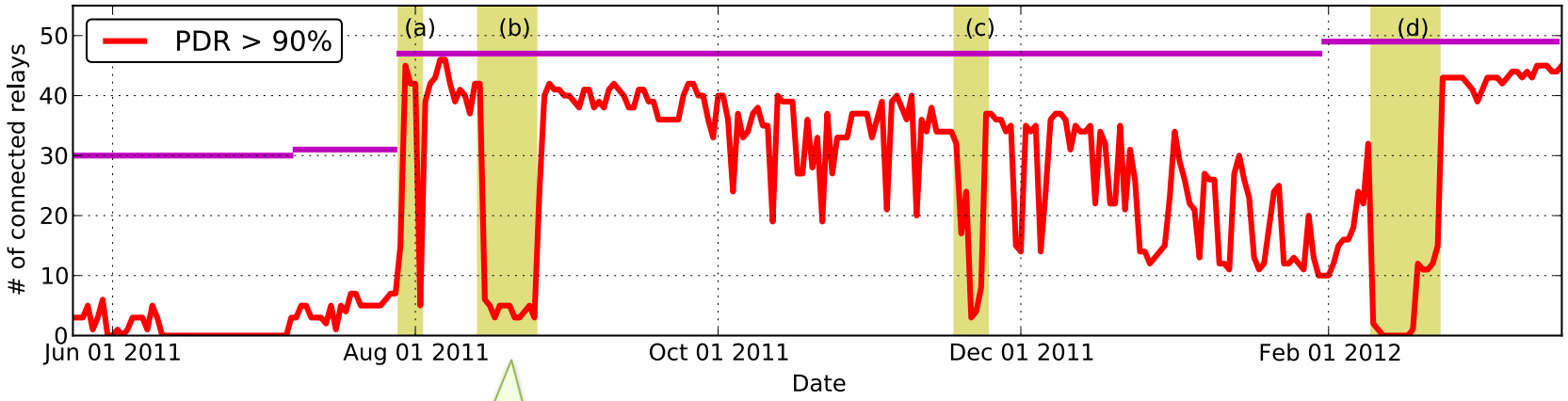
- This would not have happened if we had
  - isolated the networks in different wards (on different channels) or
  - used a unicast routing protocol.

Impact of IT procedures

- It is not just a standalone sensor network!
  - Data security and privacy is a chief concern
  - User-grade equipment → almost daily OS and security patches
  - Laptops → full disk encryption

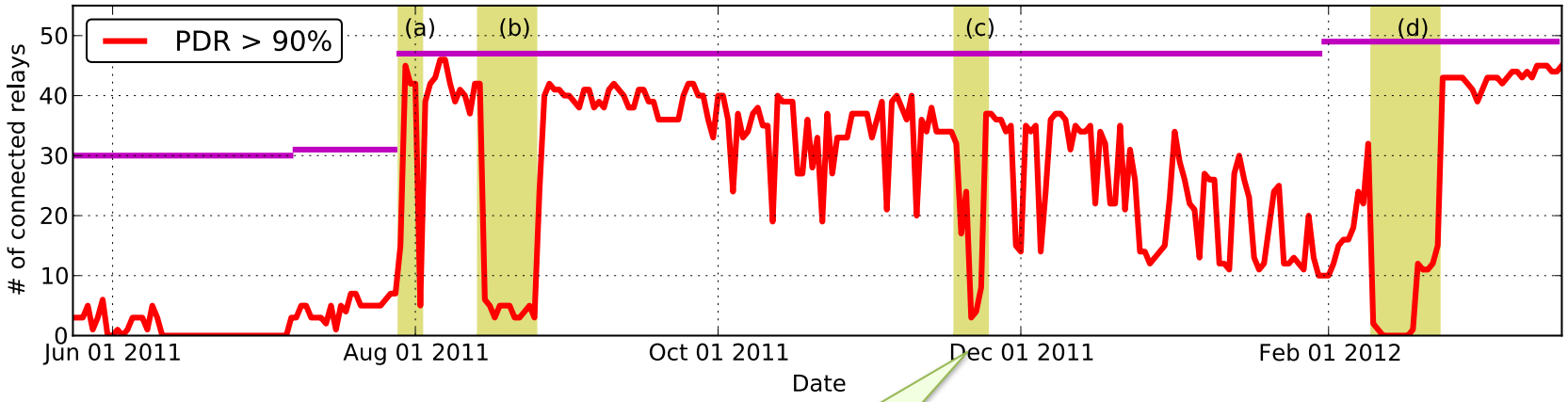
- Recommendations
  - Do not transport identifying information
  - Use server-class hardware/software for continuous operation

Impact of Human Behavior



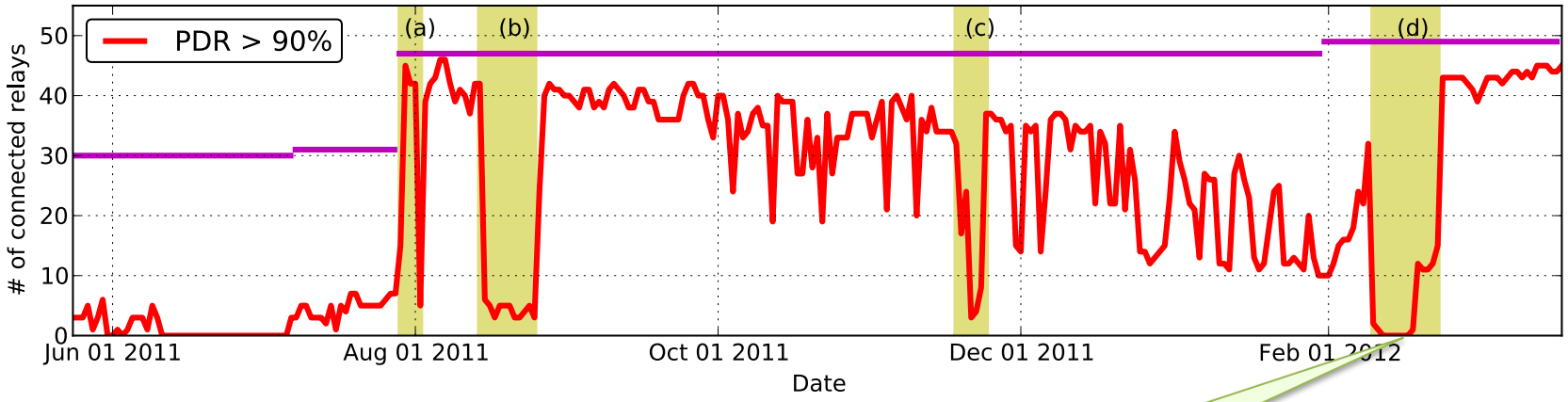
Base station 2 turned OFF

Impact of Human Behavior



Base station 2
relay disconnected

Impact of Human Behavior



Too many relays disappeared

Human Factors

- Can sensor networks survive in a hospital?
  - Mote disappearing
  - Base stations disconnections
  - Web surfing
- Recommendations
  - Equipment should look “medical grade”
  - Installed in appropriate places
  - Label everything
  - Disconnection alarm



Summary: Trial 2

- Wireless clinical monitoring can scale up and work with hospital IT infrastructure.

- Lessons learned
  - Integrate, don't partition, your subnetworks
    - Use multiple base stations to enhance route diversity
    - Integrate networks across wards and floors
  - It is not just a wireless sensor network alone!
    - Consider IT procedures and policies in the hospital
  - Deal with human factors

R. Dor, G. Hackmann, Z. Yang, C. Lu, Y. Chen, M. Kollef and T.C. Bailey, Experiences with an End-To-End Wireless Clinical Monitoring System, Conference on Wireless Health (WH'12), 2012.

More

- Close the loop
  - Clinical decision support and intervention

- Go beyond hospitals
  - Continuous health monitoring in everyday life
  - Integration of wearables, smart phones, and cloud
  - Scalability for outpatient population

Impacts

SenSys Test of Time Award

for expanding sensing network systems into the medical setting and showing their challenges and promises in this domain

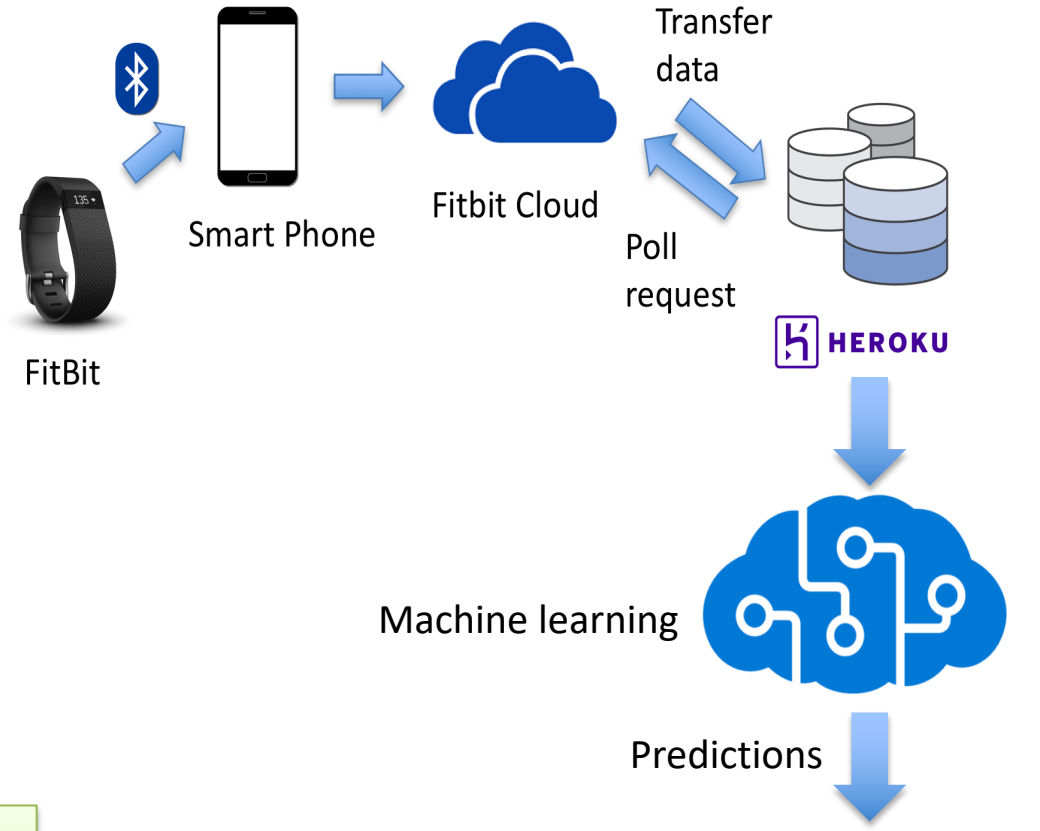
- **Medicine**: Open the door to clinical applications
  - Impact healthcare with IoT
- **Challenge**: Sensing reliability of wearable sensors
  - Sensing is the problem, not the network
- **Promise**: Reliable wireless communication
  - Triumph of the sensor networking community

Readings

- Overview
  - G. Hackmann, M. Chen, O. Chipara, C. Lu, Y. Chen, M. Kollef, T.C. Bailey, Toward a Two-Tier Clinical Warning System for Hospitalized Patients, American Medical Informatics Association Annual Symposium (AMIA'11), October 2011.
- Wireless clinical monitoring
  - O. Chipara, C. Lu, T.C. Bailey, G.-C. Roman, Reliable Clinical Monitoring using Wireless Sensor Networks: Experience in a Step-down Hospital Unit, ACM Conference on Embedded Networked Sensor Systems (SenSys'10), November 2010.
  - R. Dor, G. Hackmann, Z. Yang, C. Lu, Y. Chen, M. Kollef and T.C. Bailey, Experiences with an End-To-End Wireless Clinical Monitoring System, Conference on Wireless Health (WH'12), October 2012.
- Machine learning
  - D. Li, P. Lyons, J. Klaus, B. Gage, M. Kollef, C. Lu, Integrating Static and Time-Series Data in Deep Recurrent Models for Oncology Early Warning Systems, ACM International Conference on Information and Knowledge Management (CIKM'21), November 2021.
  - D. Li, P. Lyons, C. Lu, M. Kollef, DeepAlerts: Deep Learning Based Multi-horizon Alerts for Clinical Deterioration on Oncology Hospital Wards, AAAI Conference on Artificial Intelligence (AAAI-20), February 2020.
  - Y. Mao, Y. Chen, G. Hackmann, M. Chen, C. Lu, M. Kollef, T.C. Bailey, Early Deterioration Warning for Hospitalized Patients by Mining Clinical Data, International Journal of Knowledge Discovery in Bioinformatics, 2(3):1-20, 2012.
- Clinical trial
  - T. Bailey, Y. Chen, Y. Mao, C. Lu, G. Hackmann, S.T. Micek, K. Heard, K. Faulkner, M. Kollef, A Trial of a Real-Time Alert for Clinical Deterioration in Patients Hospitalized on General Medical Wards, Journal of Hospital Medicine, 8(5): 236-242, 2013.
  - M. Kollef, Y. Chen, K. Heard, G.N. LaRossa, C. Lu, N.R. Martin, N. Martin, S.T. Micek, T. Bailey, A Randomized Trial of Real-Time Automated Clinical Deterioration Alerts Sent to a Rapid Response Team, Journal of Hospital Medicine, 9(7):424-429, 2014.

Internet of Medical Things

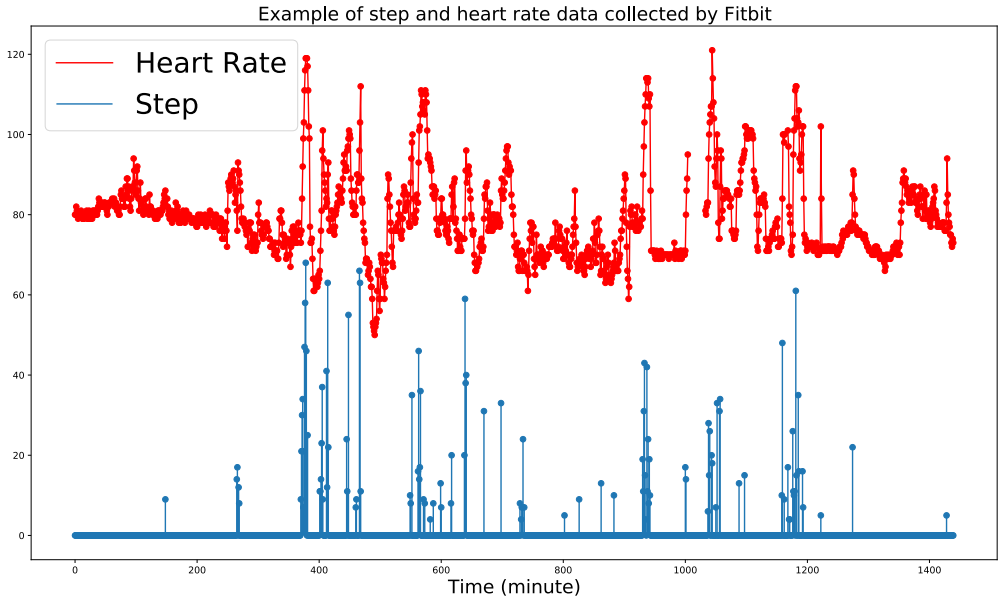
- **Wearables**: wristband, smartwatch, ring…
  - Long-term, non-obtrusive monitoring
- **Connectivity**: Bluetooth, WiFi, cellular
  - Real-time monitoring and intervention
- **Cloud**: computing and storage
  - Scalable to large population
- **Analytics**: machine learning
  - Predict outcomes and support intervention

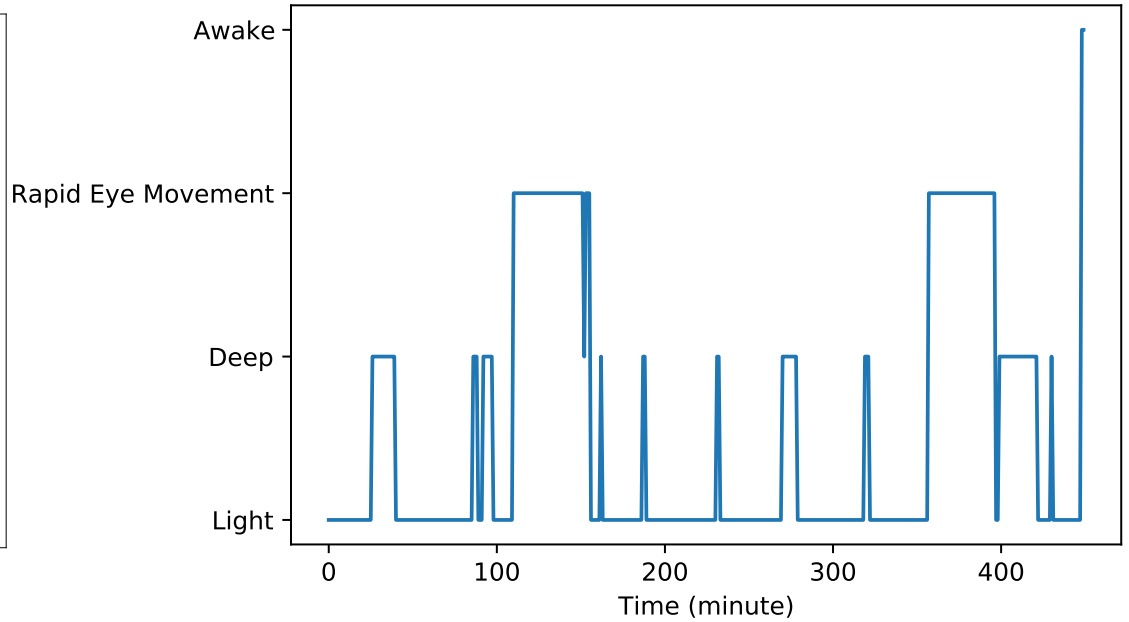


- ***500+ million wearables sold in 2021***
- ***Unprecedented monitoring capability!***

Data from a Fitbit Wristband

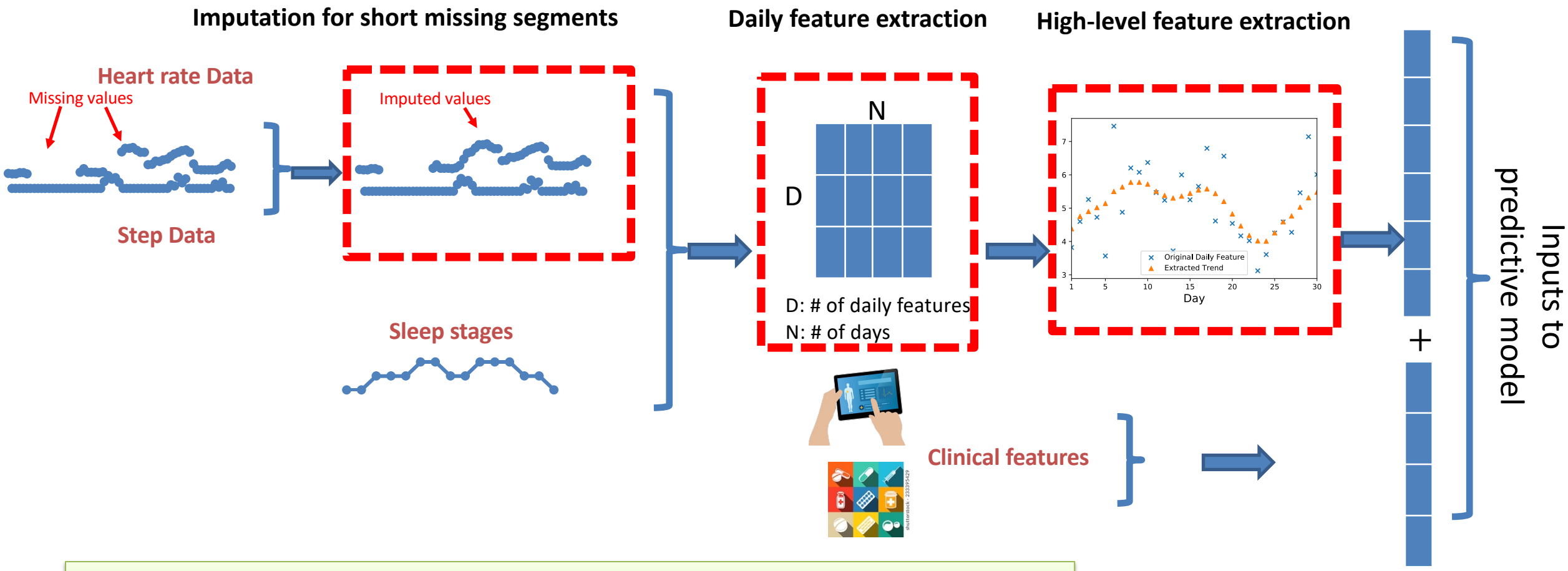
- Time series: step count, heart rate, and sleep stage
- The same reliability challenges we faced in the SenSys'10 paper!





***Fine-grained, lossy, noisy* time-series**

Features Extraction from Unreliable Data



J. Zhang, D. Li, R. Dai, H. Cos, G.A. Williams, L. Raper, C.W. Hammill, and C. Lu, Predicting Post-Operative Complications with Wearables: A Case Study with Patients Undergoing Pancreatic Surgery, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (UbiComp'22), 6(2), Article 87, July 2022.

Internet of Medical Things → Healthcare

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- Significant **clinical information** can be learned from wearables.
  - **Hospital readmission** of congestive heart failure patients [HEALTH'21]
  - **Surgical complications** of patients undergoing pancreas surgery [UbiComp'22]
  - **Treatment response** to depression therapy [UbiComp'22]

- **AI** is key to extract clinical information from noisy and lossy wearable data.

- Rigorous **clinical studies** are needed to validate IoMT models.

- IoMT + informatics + clinicians → **healthcare delivery**

https://www.cse.wustl.edu/~lu/iomt.html