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 $\rightarrow$ 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]

- Detect events using real-time vital signs
  - Wireless monitoring [SenSys’10, Wireless Health’12]
  - Event detection algorithms [KDD’12]
Two-Tier Clinical Warning

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  - Wireless monitoring [SenSys’10, Wireless Health’12]
  - Event detection algorithms [KDD’12]
Wireless Sensor Networks vs. Wi-Fi

- 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

Wireless Clinical Monitoring

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
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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 → 1\textsuperscript{st} 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: 1\textsuperscript{st} 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 m²

- **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 1

- 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

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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
On April 11: BS 50, 52, and 11 relays were deployed
Bumped to 30 relays 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

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
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
Readings

- **Overview**

- **Wireless clinical monitoring**

- **Machine learning**

- **Clinical trial**
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

- Heart rate Data
- Step Data
- Sleep stages

Imputation for short missing segments

Daily feature extraction

High-level feature extraction

D: # of daily features
N: # of days

Clinical features

Inputs to predictive model

Internet of Medical Things → Healthcare

- 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]
  - Mental disorders [IoTDI’23]
  - 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](https://www.cse.wustl.edu/~lu/iomt.html)