Reliable Clinical Monitoring using Wireless Sensor Networks
Experiences from a Step-down Hospital Unit

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Motivation

- Clinical deterioration in hospitalized patients
  - 4-17% suffer from adverse events such as cardiac or respiratory arrest
  - Up to 70% of such events could have been prevented
- Early detection of clinical deterioration based on vital signs
  - Clinical deterioration is often preceded by changes in vitals
- Wireless patient monitoring is needed in general hospital units
  - Wired patient monitoring equipment in Intensive Care Units
  - Most general hospital units collect vitals manually
  - Wireless telemetry systems too expensive for wide adoption

Goal: **reliable wireless clinical monitoring for general hospital units**
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
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

- Pulse and oxygenation are collected every 30s/60s

- 46 patients enrolled
  - >41 days of monitoring
  - 2-68 hours per patient
Simple Design → High Network Reliability

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

- Dynamic Relay Association Protocol (DRAP): Patient -> 1st relay
  - Dynamically associate the patient node with a relay
  - The single-hop protocol handles patient mobility
  - Simplify power management in patient nodes (send only)

- Stationary relay network: 1st relay -> … -> base station
  - Build on the community’s effort on CTP
  - Isolated from patient mobility
  - Wall-plugged => no need to worry about energy
Sensing is the Reliability Bottleneck

- Network reliability >95% for all patients.
- Median sensing reliability > 80%.
- But 29% of patients with sensing reliability < 50%
Impacts

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

- **Challenges**: Sensing reliability of wearable sensors
  - Sensing is the problem, not the network

- **Promises**: Reliable wireless communication
  - Triumph of the sensor networking community
Scale Up Wireless Clinical Monitoring

- **Scale**: Integrate, don’t partition, your networks
- **Integrate**: Work with IT policies and infrastructure
- **Sustain**: Deal with human factors

- Deployed in 7 hospital wards spanning 4 floors
- Integrated with EHR and hospital IT
- Enrolled 97 patients over 14 months

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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

- **Imputation for short missing segments**
  - Heart rate Data
  - Step Data
  - Sleep stages

- **Daily feature extraction**
  - Imputed values
  - N: # of days
  - D: # of daily features

- **High-level feature extraction**
  - Clinical features
  - Imputed values
  - Inputs to predictive model

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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]
  - 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**