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

- Real-time patient monitoring is required
  - 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**
Our Approach

1. Build a clinical monitoring system using sensor networks.
2. Deploy it in a general hospital unit over 7 months.
3. Clinical trial with 46 hospitalized patients.
4. Holistic system reliability study: network and sensor.
5. Demonstrate potential for clinical event detection.
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.
Solution: Two-tier architecture for end-to-end data delivery.

1. **Dynamic Relay Association Protocol (DRAP):** Patient -> 1st relay
   - Dynamically associate the patient node with a relay
   - Single-hop protocol handles patient mobility
   - Simplify 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 m²

- Network
  - 18 relays: redundant network
  - Longest path: 3-4 hops
  - Channel 26 of IEEE 802.15.4

- Pulse and oxygenation collected every 30 or 60 seconds

- 46 patients enrolled
  - >41 days of monitoring
  - 2-68 hours per patient
  - 5 patients excluded from analysis
  - Up to 3 patients at a time
Potential for Detecting Clinical Deterioration

- Pulmonary edema
- Sleep apnea
- Bradycardia
System Reliability

- Network reliability >95% for all patients.
  - Effectiveness of DRAP+CTP
- Median sensing reliability > 80%.
  - But 29% of patients with sensing reliability < 50%
- System reliability dominated by sensing reliability.
Network Reliability

- **Time-to-failure**
  - Time interval during which a system continuously operate till a failure occurs.

- **Time-to-recovery**
  - Time interval from the occurrence of a failure till when the system recovers.

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**CDF of time-to-failure**

- Median time to failure = 19 min

**CDF of time-to-recovery**

- Recover from 90% of failures within 2 min => Quick recovery from failure
Sensing Reliability

- Failures are common: median time-to-failure < 2 min
- Recover from 90% of sensing failures within 4 min
  - Transient failures caused by human movement
- Long-tailed distribution for time-to-recovery
  - Sensor disconnection

*CDF of time-to-failure*

*CDF of time-to-recovery*
Relax Sampling Rates

- Increase required sampling period to 5, 10, 15 min
  - Oversample at 1-2 reading/min
  - Considered a success if one valid measurement per required sampling period
  - Still orders of magnitude higher rate than manual measurement

- Higher reliability at a sampling period of 5 min
  - Diminishing return at longer sampling periods

![Graph showing sensing reliability at different sampling rates](graph.png)
Sensor Disconnection Alarms

- Automatically notify nurse after receiving no data for a timeout threshold
- 15 min timeout balances #alarms vs. reliability gain
  - Infrequent alarms: 1.55 interventions per patient, per day
  - Similar reliability to 5 and 10 min timeouts

Sensing reliability with different timeouts

![Graph showing sensing reliability with different timeouts.](image)

#alarms per day

![Graph showing #alarms per day vs. sensor disconnection threshold.](image)
Putting them together

- Disconnection alarms and oversampling are complementary.
  - Disconnection alarms => handles sensor disconnection
  - Oversampling => handles intermittent failures caused by movement

- 88% of patients with >70% sensing reliability with 5 min sampling period and 15 min timeout
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 (e.g., field hospitals, rural areas).
  - Even major hospitals may not guarantee full Wi-Fi coverage.

- Sufficient reliability
  - Median network reliability > 99% in our clinical trial.
  - Even a wired network would improve reliability only marginally.
Related projects

- Assisted living: ALARM-NET
- Disaster recovery: AID-N, CodeBlue, WIISARD
- Emergency room: MEDISN, SMART
- Motion analysis: Mercury
- Commercial wireless telemetry (Phillips, Cisco, GE)
  - WiFi => single-hop wireless, wired backbone
  - adoption limited to specialized hospital units
Conclusion

- Wireless clinical monitoring for general hospital units.
- Clinical trial in a step-down hospital unit
  - Highly reliable network
  - System reliability dominated by pulse oximeter sensors
    - Oversampling
    - Disconnection alarms
  - Potential for detecting clinical deterioration

- On-going: real-time clinical event detection
  - Integration with electronic medical records
  - Event detection based on machine learning
  - Automatic alarms for early intervention
  - Larger clinical trial of event detection system
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