Wireless Clinical Monitoring @ Scale

Chenyang Lu

Cyber-Physical Systems Laboratory
Department of Computer Science and Engineering
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.

- Goal: early warning of clinical deterioration → improved outcome

- Require real-time patient 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, medical informatics, clinical care
Two-Tier Clinical Warning

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

2. Detect events using real-time vital signs
   - Event detection algorithms [KDD 2012]
Two-Tier Clinical Warning

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

2. Detect events using real-time vital signs
   - Event detection algorithms [KDD 2012]
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
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
System Architecture

- Base station: laptop connected to Wi-Fi

- Relays: motes plugged into wall outlets
  - Redundant deployment → coverage, fault tolerance

- Patient node
  - Pulse oximeter + processor + radio
  - Battery operated
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 improve reliability only marginally.
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 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 sensors
  - Potential for detecting clinical deterioration

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
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?*
Relays Network Infrastructure
Network Reliability @ Scale

- On April 11: BS 50 and 52 and 11 relays were deployed.
- Bumped to 30 relays when the network did not perform.
- Too many relays disappeared.
- 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 and software for continuous operation
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 → higher reliability
- It is not just a wireless sensor network alone!
  - Consider IT procedures in the hospital
- Deal with human factors

---

Looking ahead

- Close the loop
  - End-to-end clinical warning
  - Clinical decision support and intervention

- Go beyond hospitals
  - Continuously health monitor in everyday life
  - Integration with mobile phones and Cloud
  - Scale to population across a city, a country, and the Globe
Readings

- **Wireless clinical monitoring**

- **Overview**

- **Clinical Trial**

- **Data Mining**

- **Wireless Clinical Warning Project:** [http://www.cse.wustl.edu/~lu/icts.html](http://www.cse.wustl.edu/~lu/icts.html)
- **Cyber-Physical Systems Laboratory:** [http://cps.cse.wustl.edu](http://cps.cse.wustl.edu)
- **Chenyang Lu:** [http://www.cse.wustl.edu/~lu/](http://www.cse.wustl.edu/~lu/)