Apple on Health

“I believe, if you zoom out into the future, and you look back, and you ask the question, 'What was Apple's greatest contribution to mankind?', it will be about health.”

--Tim Cook (Apple CEO)

“Every day I come into Apple, I love the impact we've had on people with our products. But when I got the first couple letters saying, ‘this saved my life’, it's just a whole different feeling. That's my octane for the day. If somebody had suggested five years ago that I would be able to work with a team of people and together we would be making contributions in the health space, I would have thought they were crazy. And it's such an exciting area, and it's so full of opportunities. Everyone says the biggest challenge in health is actually behaviour-change and awareness. They talk about the last mile and connecting with the patient. And when we've got hundreds of millions of phones in people's pockets and tens of millions of devices on people's wrists, plus trust from customers, well, this is an opportunity we can't squander.”

--Jeff Williams (Apple COO)

HOW THE HEART BECAME THE CENTRE OF THE APPLE WATCH, Independent
https://www.independent.co.uk/life-style/gadgets-and-tech/features/apple-watch-health-heart-world-day-jeff-williams-interview-features-a9124601.html
Google on Healthcare

“Health care is one of the most important fields that technology will help transform over the next decade, and it's a major area of investment for Google.”

-- Sundar Pichai (Google CEO)

Google Cloud will be at the cornerstone of Mayo Clinic’s digital transformation. We’ll enable Mayo Clinic to lay out a roadmap of cloud and AI-enabled solutions and will help Mayo Clinic develop a bold, new digital strategy to advance the diagnosis and treatment of disease.

In addition to building its data platform on Google Cloud, Mayo’s world-class physician leadership is partnering with Google to create machine-learning models for serious and complex diseases.

How Google and Mayo Clinic will transform the future of healthcare
https://cloud.google.com/blog/topics/customers/how-google-and-mayo-clinic-will-transform-the-future-of-healthcare
Wireless Clinical Monitoring @ Scale

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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.

- 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

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

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

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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**: 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 $\rightarrow$ 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 $\rightarrow$ ... $\rightarrow$ base station
   - Reuse well tested mesh routing protocol (CTP).
   - Isolated from patient mobility.
   - Wall-plugged $\Rightarrow$ no need to worry about energy.
Clinical Deployment

Ø Step-down cardiac care unit
  • 16 patient rooms, 1200 m²

Ø 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.

Ø 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?*
Relays Network Infrastructure

Legend:
- Patient
- Base station
- 802.15.4 network
- Message Queue
- Legacy

11-1 ward

11-2 ward

12-2 ward

14-4 ward

14-5 ward

EMR
On April 11: BS 50 and 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!
On April 11: BS 50 and 52 and 11 relays were deployed
Bumped to 30 relays when the network did not perform
Integrating multiple networks + 3D topology saved the day!

Base station 2 turned OFF

Integrating multiple networks + 3D topology saved the day!
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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

Integrating multiple networks + 3D topology saved the day!

Too many relays disappeared
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

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Looking ahead

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

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

- **Overview**

- **Wireless clinical monitoring**

- **Machine learning**

- **Clinical trial**

- **Monitoring outpatients with wearables**

**Internet of Medical Things (IoMT) project:** [http://www.cse.wustl.edu/~lu/iomt.html](http://www.cse.wustl.edu/~lu/iomt.html)