After Motes and Multihop: Mobile Phones and the Global Mobile Sensor Network

Andrew T. Campbell, Dartmouth College

Wireless sensor networks have driven many great innovations over the last decade - represents a very active area of on-going research.

The mote have been a superb platform for research

But, challenges remain
- Not ubiquitous
- Energy problem
- Scaling (cost and performance) problem
- Event unpredictability
- Don’t have economy of scale

Importantly, sensor networks don’t impact our everyday lives. Why?

People are out of the loop

That’s all just changed because of this …

Embedded sensors:
- 3-axis accelerometer
- Proximity sensor
- Microphone
- Camera
- GPS
- Bluetooth

Solves many outstanding problems:
- Ubiquitous, energy problem
- Has economy of scale, scales, etc.

… or this

Nokia 6210 Navigator

Embedded sensors:
- 3-axis accelerometer
- Digital compass
- Microphone
- Camera
- GPS
- Bluetooth

Or, in the future …
The cool green “emotional” phone

Embedded sensors:
- 3-axis accelerometer
- Proximity sensor
- Digital compass
- Pollution/air quality sensor
- GSR “emotion sensor”
- RFID/NFC
- Microphone
- Camera
- GPS
- Bluetooth

You’ll be able to answer lots of questions and build new cool applications with these phones.

What is my personal air quality like today? Or, the air quality of my neighborhood, school, town, or city?

How stressed is the city this morning?

How do social “conversation” networks evolve?

Where are my friends and what are they doing right now?

Work on audio networks by Tanzeem Choudhury (Dartmouth)
I know what you are thinking

Sounds like an Orwellian nightmare!

Big challenges: trust, privacy, security are critical issues (David Kotz, Dartmouth)

Now imagine 1 billion “sensor enabled mobile phones” scattered across the planet

people are in the loop

This will lead to …

Societal scale sensing

The global mobile sensor network

You can’t cover a volcano with mobile phones!
On second thoughts, phones are getting cheaper and we have a ready supply of adventurous grad students ;-) 

My position for this talk

The mobile phone (and not the mote) will serve as the main platform for sensing innovation over the next 5 years.

Your mobile phone will sense your surroundings, learn your behavior (what you do, where you go and how you interact with people and your environment), and help you navigate your day.

Collectively, mobile phones will form societal scale sensor networks in support of community, urban, and global sensing applications and problem solving.

You don’t have to believe me, just wait for it to evolve

The new “mote” (minus the multihop problems)
We started in 2005 to study people-centric sensing.

Characteristics of existing mote networks:
- Small-scale, short-lived, mostly-static
- Application-specific
- Multi-hop wireless
- Very energy-constrained
- Mobility not an issue or driving factor
- People out of the loop

Characteristics of People-Centric Sensing:
- Large-scale, long-lived, mostly-mobile
- Application-specific
- Multi-hop wireless
- Very energy-constrained
- Mobility not an issue or driving factor
- People out of the loop

Characteristics of People-Centric Sensing:
- Large-scale, long-lived, mostly-mobile
- Application-agnostic
- Multi-hop wireless
- Very energy-constrained
- Mobility not an issue or driving factor
- People out of the loop

Characteristics of People-Centric Sensing:
- Large-scale, long-lived, mostly-mobile
- Application-agnostic
- No multi-hop wireless
- Very energy-constrained
- Mobility not an issue or driving factor
- People out of the loop
Characteristics of People-Centric Sensing

- Large-scale, long-lived, mostly-mobile
- Application-agnostic
- No multi-hop wireless
- Periodic recharging
- Mobility not an issue or driving factor
- People out of the loop

Characteristics of People-Centric Sensing

- Large-scale, long-lived, mostly-mobile
- Application-agnostic
- No multi-hop wireless
- Periodic recharging
- Mobility is a driving factor
- People in the loop

People-centric sensing application domains


I know what you are thinking
Static sensor networks don't scale to large areas, sensing coverage is costly, performance doesn't scale either, and events are unpredictable in time and space.

Public sensing gains scalability and sensing coverage by using people opportunistically as mobile sensors.

Public sensing gains scalability and sensing coverage by using people opportunistically as mobile sensors.

The beauty is that the infrastructure already exists (i.e., people and the global cellular network).

People-centric sensing is based on an "opportunistic sensing paradigm" and an "interaction model" that captures interaction between people, and, between people and their surroundings.

Emerging sensing paradigms

Next frontier in sensing is "people-centric" urban sensing.

Ron Fricke, timescape is a day in the life of a city (edited version)
Remainder of my talk

- Three people-centric sensing applications we developed
  - BikeNet (personal/public sensing)
  - CenceMe (social sensing app)
  - SoundSense (personal sensing app)
- Need for open sensing/comms software for mobile phones
- Wrap up

The BikeNet system – sensor bikes

Shane Eisenman, et al, “The BikeNet mobile sensing system for cyclist experience mapping”, ACM SenSys ’07

We can answer many questions from sensor data

- How fit are you?
- Many cars along the route?
- What was the air quality and noise like?
  - Lots of trivia: slopes, coasting, braking, working hard
- Overall health and performance along the route
- How did you compare to your buddies, community?

CO2 Map of Hanover

http://bikenet.cs.dartmouth.edu

Lots of cars on that route?
I know what you are thinking

How do you do ground truth?

Performance index

Health index

Many lessons learnt
Debugging on the go is hard

cencing with cenceme

supported inferences: sensing presence
activity
social context
significant places
behaviour
green, healthy, party, internal,               healthy

CenceMe demo
Sensor presence is published on Facebook

Activity classifier confusion matrix

<table>
<thead>
<tr>
<th></th>
<th>Sitting</th>
<th>Standing</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting</td>
<td>0.6818</td>
<td>0.0644</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Standing</td>
<td>0.2096</td>
<td>0.7844</td>
<td>0.0060</td>
<td>0.0000</td>
</tr>
<tr>
<td>Walking</td>
<td>0.0025</td>
<td>0.0455</td>
<td>0.9444</td>
<td>0.0076</td>
</tr>
<tr>
<td>Running</td>
<td>0.0084</td>
<td>0.0700</td>
<td>0.1765</td>
<td>0.7451</td>
</tr>
</tbody>
</table>

Supervised learning approach
Differentiated between sitting and standing is hard
Custom sensing hardware (e.g., Intel’s MSP) can do better but these results are from the Nokia N95
Conservation classifier confusion matrix

<table>
<thead>
<tr>
<th></th>
<th>Conversation</th>
<th>Non-Conversation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversation</td>
<td>0.8382</td>
<td>0.1618</td>
</tr>
<tr>
<td>Non-Conversation</td>
<td>0.3678</td>
<td>0.6322</td>
</tr>
</tbody>
</table>

Design decision of 2/5 talk primitives to get into conversation and 4/5 to get out – more conservative

Poor performance for non conservation results because people aren’t talking but others nearby are.

Deployment, user study – 22 people over three weeks lets look at the portal

Results: Location and activity
Results: Location and activity

Observations from the 22 user study

Willingness to share sensitive presence information with friends when 'sensor off' button is clearly available

Valued access to presence information from the phone

Enjoyed comparing themselves with friends and the population

“CenceMe made me realize I'm lazier than I thought and encouraged me to exercise a bit more”

Injecting sensor presence into second life

SoundSense – listen to the “significant sound events” in your life

Hong Lu, Tanzeem Choudury, et al., “Scalable Sound Sensing for People-Centric Sensing using Mobile Phones”, ACM MobiSys 2009 (provisionally accepted)
System design for phone

Real-time sound sensing system with privacy
• No backend server
• No raw audio stored on phone only features, models

Computationally efficient feature extraction and classification
• Features provide good discrimination but remain low cost
• Features must be robust to noise and energy variance
• Multi-stage classification structures

Combination of supervised learning and semi-supervised learning technique

SoundSense system

Classification confusion matrix

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<th>Music</th>
<th>Speech</th>
</tr>
</thead>
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<tr>
<td>Ambient Noise</td>
<td>0.9159</td>
<td>0.0634</td>
<td>0.0207</td>
</tr>
<tr>
<td>Music</td>
<td>0.1359</td>
<td>0.8116</td>
<td>0.0525</td>
</tr>
<tr>
<td>Speech</td>
<td>0.0671</td>
<td>0.1444</td>
<td>0.7885</td>
</tr>
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Accuracy of the decision tree classifier

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<tbody>
<tr>
<td>Ambient noise</td>
<td>0.9494</td>
<td>0.0402</td>
<td>0.0104</td>
</tr>
<tr>
<td>Music</td>
<td>0.0379</td>
<td>0.9178</td>
<td>0.0444</td>
</tr>
<tr>
<td>Speech</td>
<td>0.0310</td>
<td>0.0657</td>
<td>0.9033</td>
</tr>
</tbody>
</table>

Accuracy of the markov model recognizer output

Daily diary app

Music tagger app
If the phone is the new mote – then, do we need a new TinyOS?

Yes – not an OS, but some libraries or dare I say, sensor phone middleware.

Toward Sensor PhoneWare
Supporting continuous sensing significant challenge
Many open challenges

Growing interest in sensing on mobile phones

Applications
- WatchMe, iCAM, PEIR, Nericell
- Sensing with mobile phones
- UCLA, UIUC, Intel, Nokia, Microsoft, Motorola,
- UW, Duke, start ups: e.g., Sense Networks
- Human activity inferencing
- MIT, Intel, UW

Workshops
- UrbanSense 08, MODUS 08

Finally, ……

My title is a little loaded, isn’t it?
The title implies that the phone is the “new mote”, multihop is dead, and that the sensor network community should now direct its intellectual energy toward programming phones not motes.

Why do this?

Today you can ship your cool new sensor app to thousands, perhaps millions of phones.

Today you can build a global “sensor network” of thousands, perhaps millions of “nodes” if you have a really good idea.

Interesting problems will emerge. Your ideas can have significant impact.

Tomorrow? You’ll be able to reach billions of phones instantly forming societal scale sensor networks.
PS You don’t need any infrastructure to do this! 😊

What’s MetroSense?

It’s about a societal scale sensor network built on everyday mobile phones

http://metrosense.cs.dartmouth.edu/

Thanks for listening!

- Project page, papers, etc:
  http://metrosense.cs.dartmouth.edu
- Thanks to many people’s contributions
  http://metrosense.cs.dartmouth.edu/metro-people.html
- Sponsors