Smart Mobile Health Systems: Experience with Biological Rhythm Sensing and System Privacy

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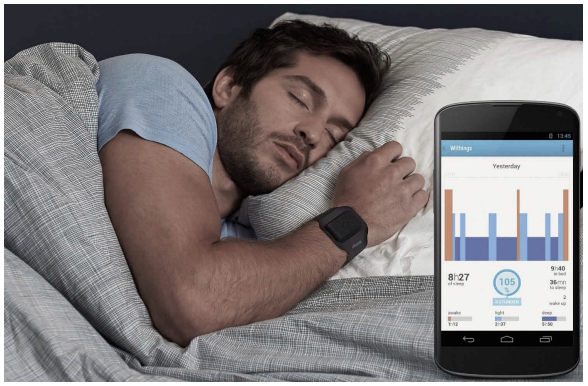
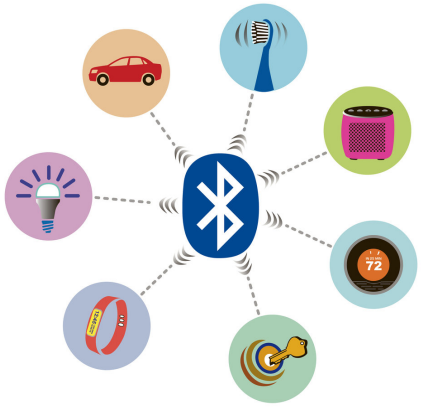
Outline

- Mobile health systems and privacy

Breath monitoring

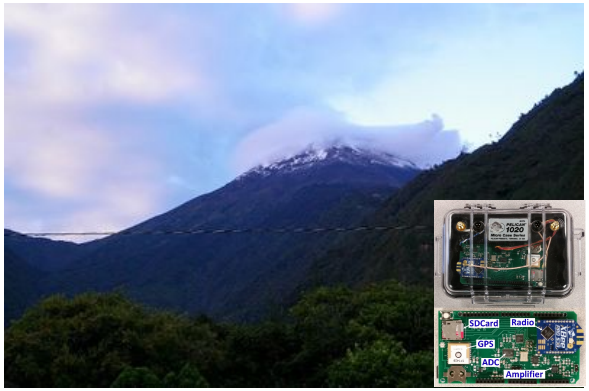


Sleep quality monitoring

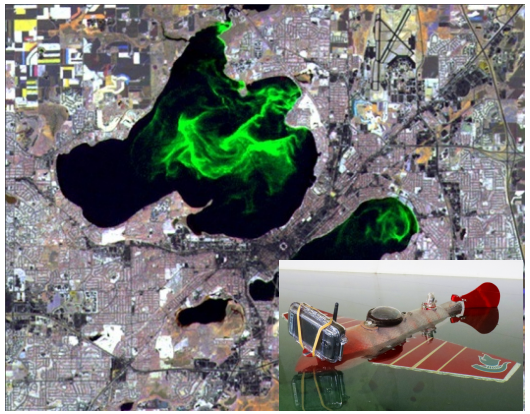


Privacy for smart devices

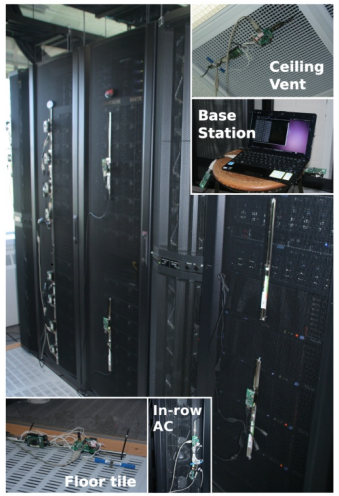
- Cyber Physical Systems



Real-time volcano tomography



Aquatic process profiling

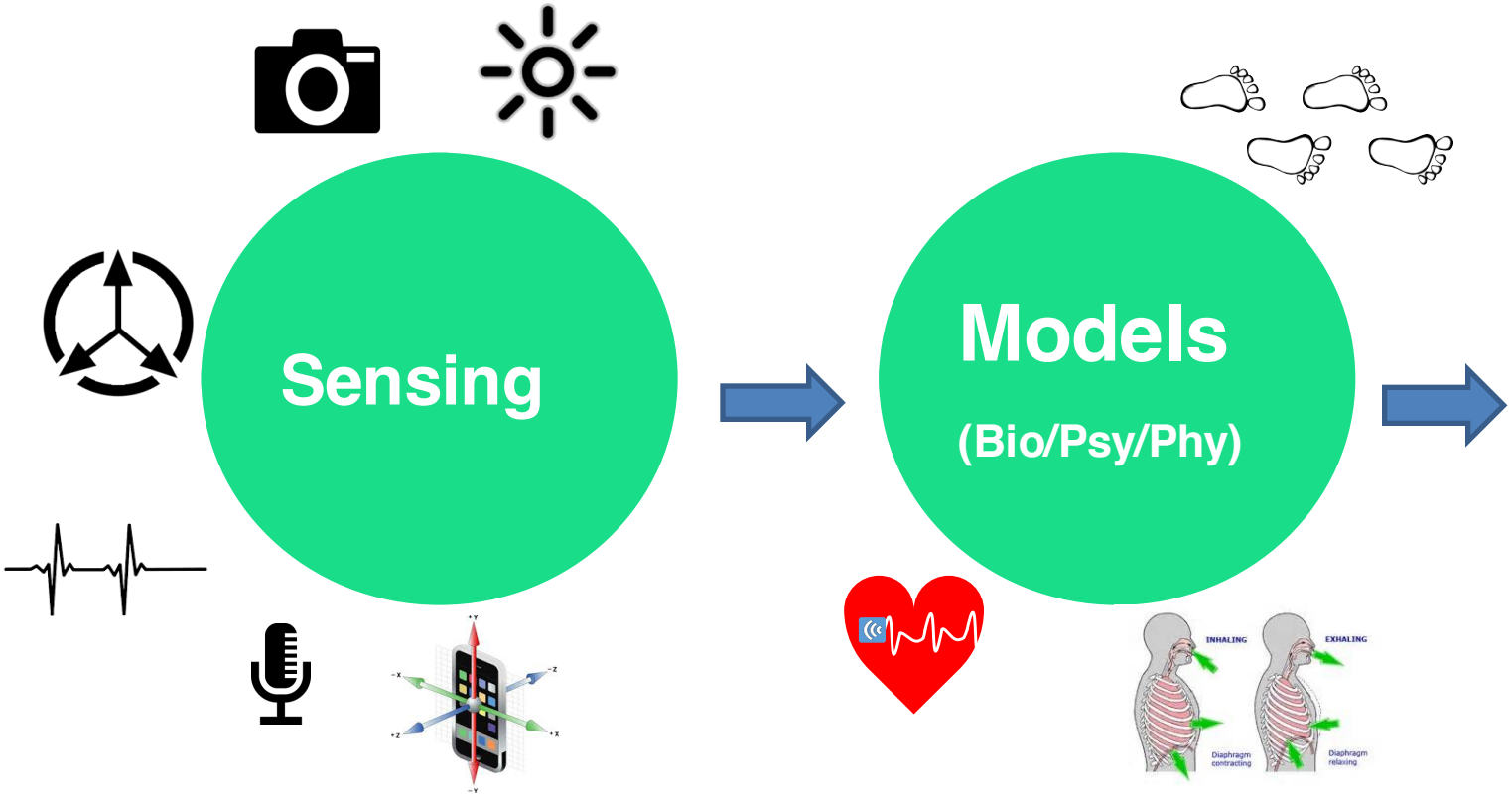


Data center thermal monitoring

Healthcare Crisis

- Total U.S. healthcare spending is 17.9% GDP
  - Avg. costs/stay $10,000, 47% up since 1997
  - 45K death annually due to lack of healthcare access
- World-wide aging problem
  - US: 3M/yr baby boomers retire for next 20 yrs
  - China: 1/10 population aged 65+, 18% in 20 yrs
  - HK: 1/8 population aged 65+, 1/4 in 20 yrs
- China's national strategy - Healthy China (健康中国) 2030

Mobile Health Approach

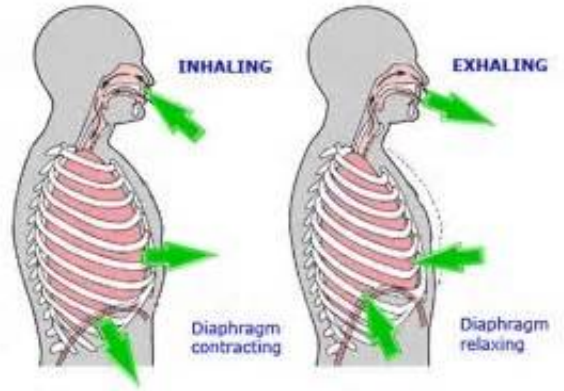


*"transformation of healthcare from **reactive** and **hospital-centered** to **preventive, proactive, ...person-centered** and focused on **well-being** rather than disease"*
-- National Science Foundation

Source: public pictures from the Internet

Biological Rhythms

- Cyclic changes of bodily chemical/function
  - Sleep/wakefulness cycle, body temperature, blood pressure, running/walking, feeding cycles, heartbeat and respiration…



Source: public pictures from the Internet

Significance

- Bio rhythms is essential for daily productivity and well-being

- Disruptions can affect vital body functions
  - Hormonal balance, metabolism, digestion, sleep
  - Diseases such as diabetes, obesity, and depression

Challenges

- Long-term monitoring proves critical for detecting early signs of many diseases
  - Have been largely limited to clinical settings
- Examples: sleep quality, breath pattern

Cardiopulmonary exercise testing (CPET)
http://www.mettest.net/cardiopulmonary_exercise_test.html

Running Rhythm Monitoring

https://www.youtube.com/watch?v=hZMZqt4Pae4

image source: http://vikyweb.co.in/

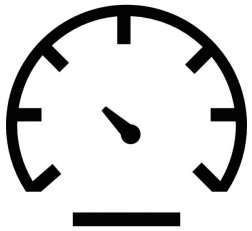
Running is a Popular Exercise

65.5 million (~20.6%)
jog/run in the U.S., 2014

~7% annual increase
since 2008

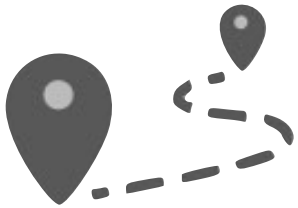
ource: Nielsen Scarborough 2014)

Image Credit: kris krüg @Flickr



SPEED

STEPS



DISTANCE

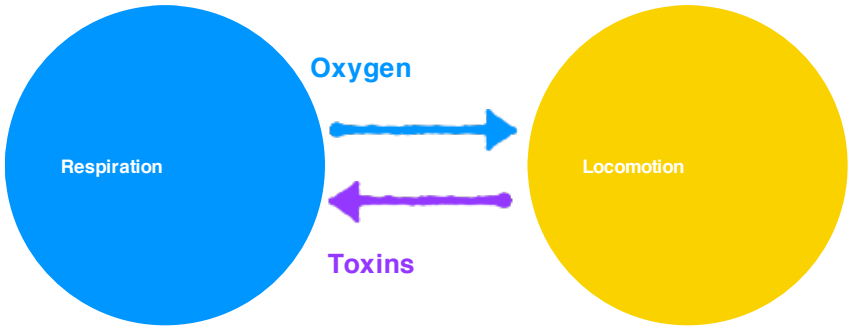
image source:

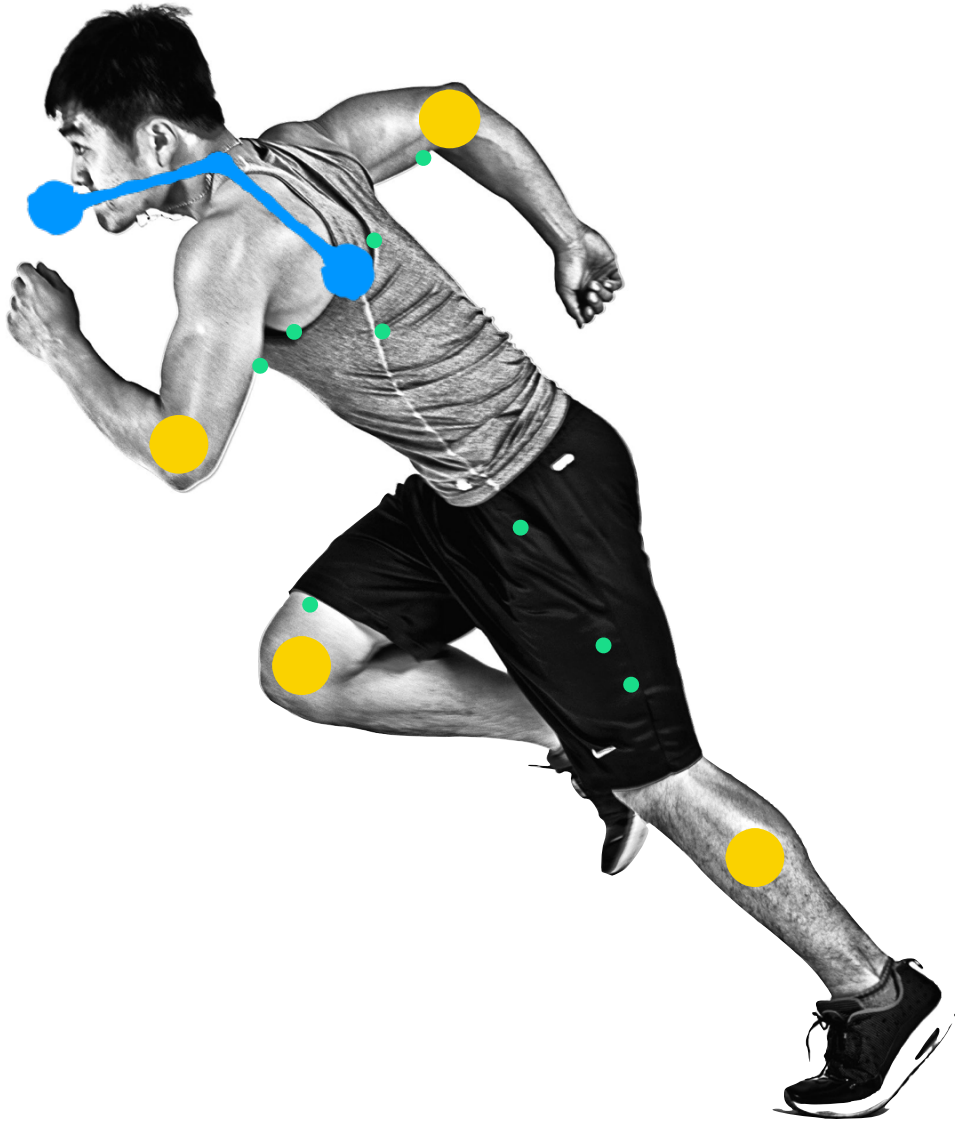
More than Just Footwork

Running Rhythm

the **Coordination** b/w

Breathing and **Strides**





More than Just Footwork

Running Rhythm

the **Coordination** b/w

Breathing and **Strides**

New Runner

Gasping for air

Regular Runner

Breathing with little effort

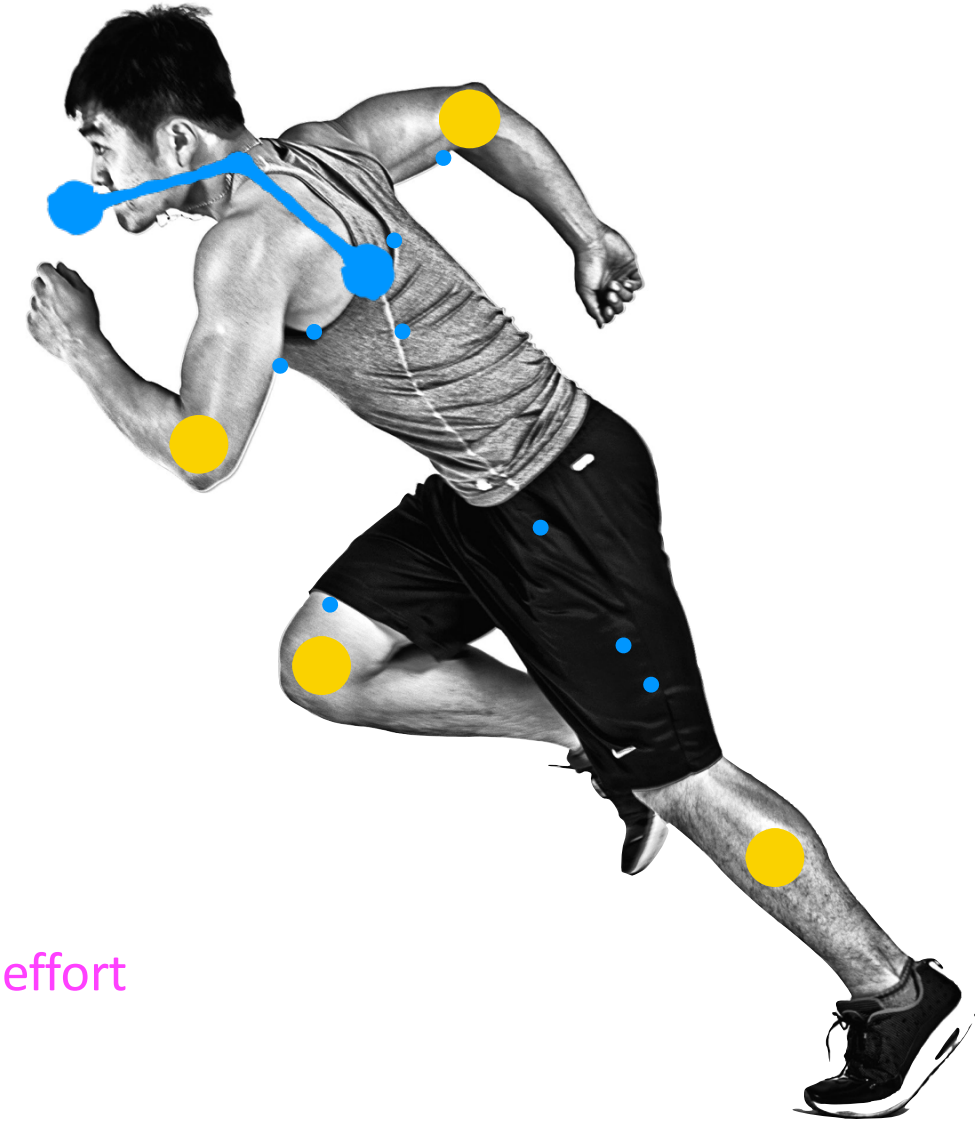
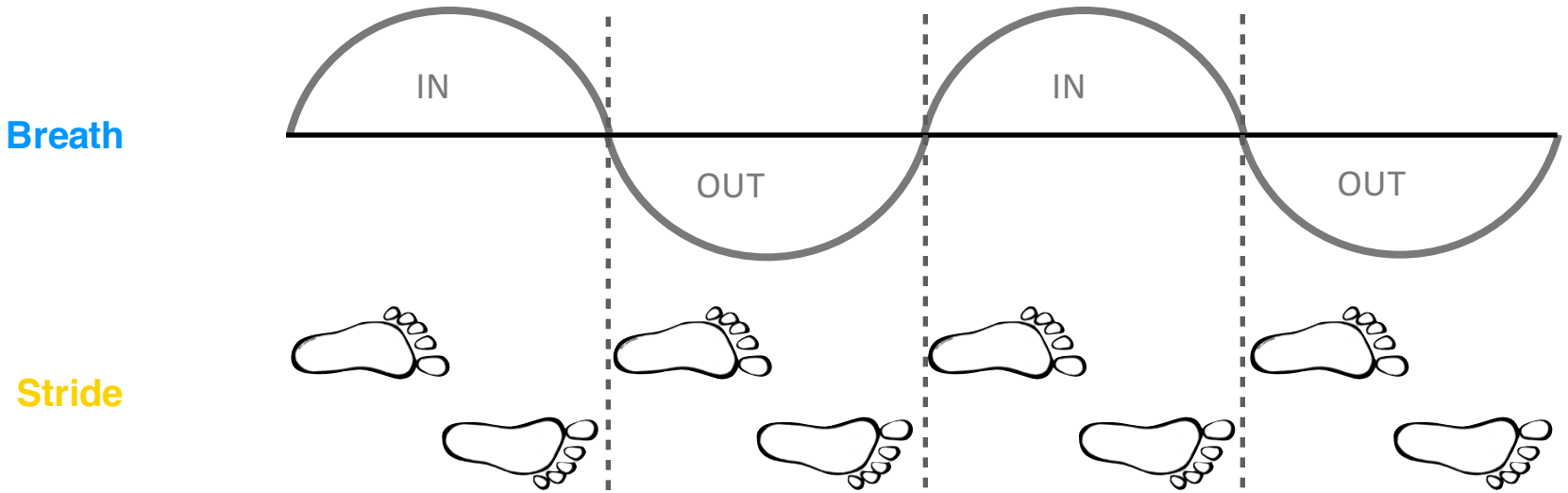


image source: pixabay

An Example of Running Rhythm

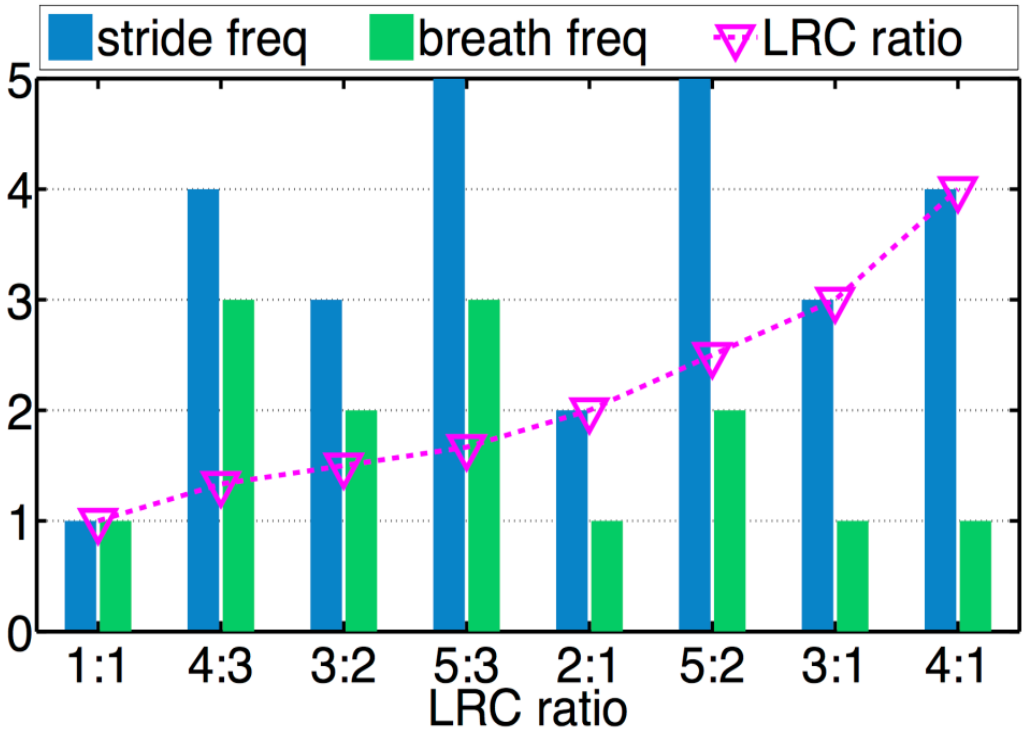


Breathe **IN** <—> 2 Steps

Breathe **OUT** <—> 2 Steps

Locomotor Respiratory Coupling (LRC)

Rhythmic exercises (e.g., running, cycling)



a small number of integer ratios
in humans during running

Tracking Progress

- Another aspect of the run
- Ability of maintaining stable LRC is a good indicator of **fitness level**

"Helps push that extra little bit"

— Avid Runner, RunBuddy Experiment Participant

Real-time Feedback

- Show promises to enhance running experience by **music suggestion**
- Play music with proper tempo to **guide new runners** to run in a comfortable rhythm
- Proper rhythm helps postpone fatigue and increase endurance

CPET: Cardiopulmonary Exercise Testing

Clinical or Professional Use

Intrusive and Expensive

Source: public pictures from the Internet

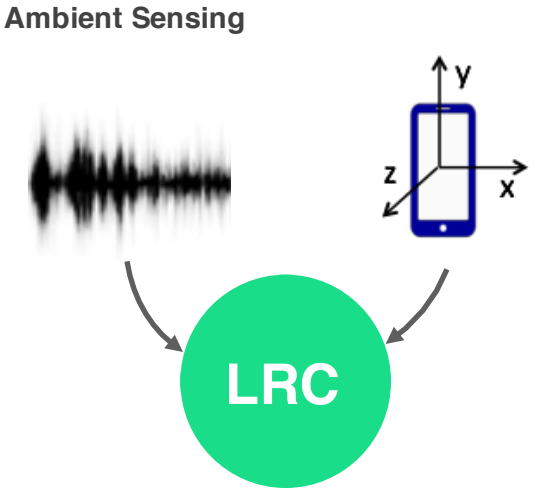
iBreath

- **Continuous running rhythm (LRC) monitoring**
- Convenient and unobtrusive
- Anytime, Everyone, Anywhere

Challenges

- **Low intensity** of breathing sound
- **Interferences** from noises

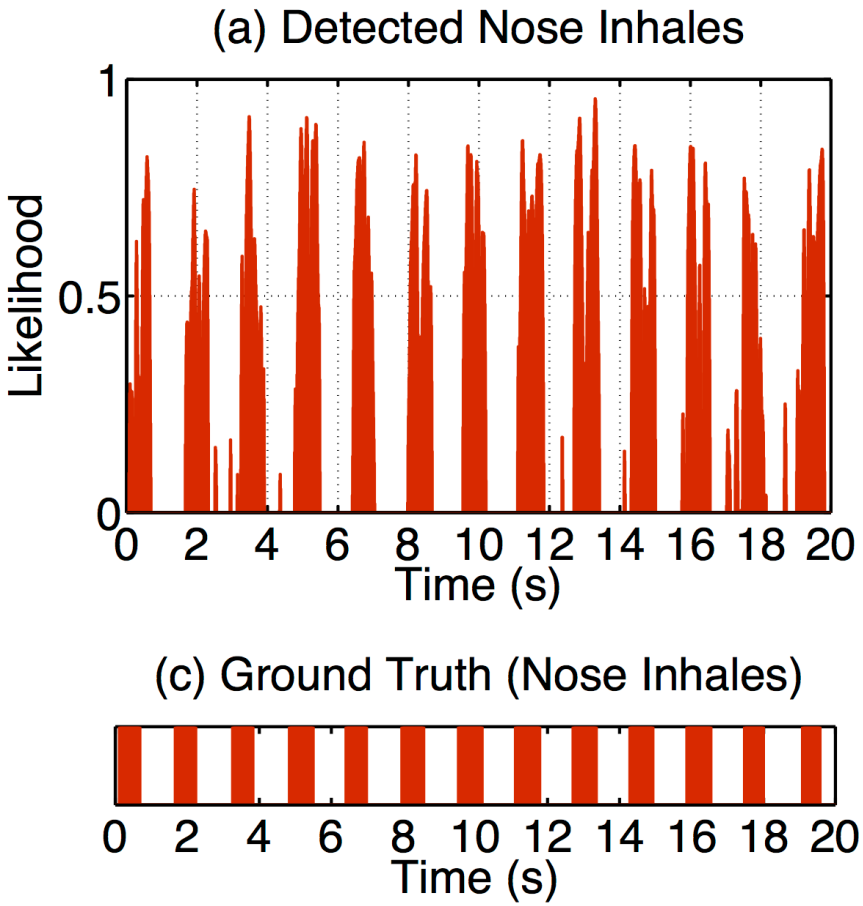
wind traffic music



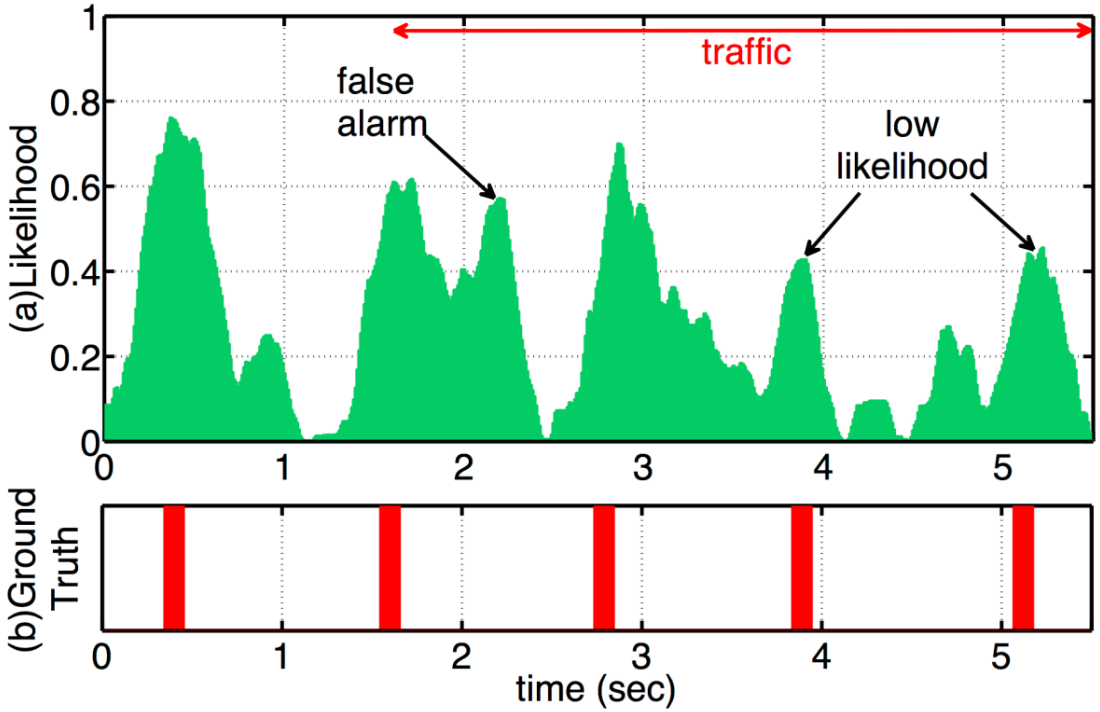
- **Privacy** requires real-time processing

→ **Lightweight & Efficient Signal Processing**

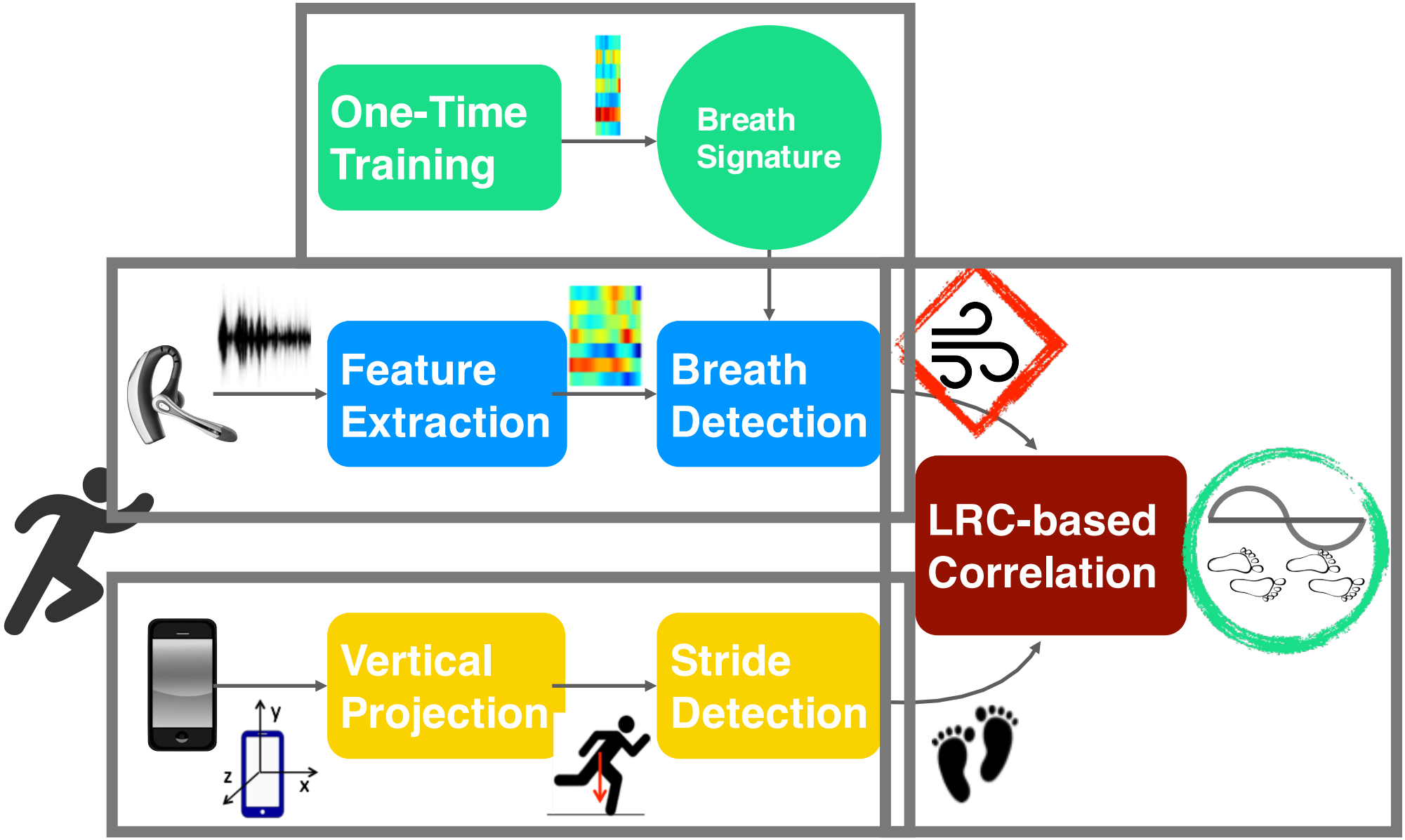
quiet environment



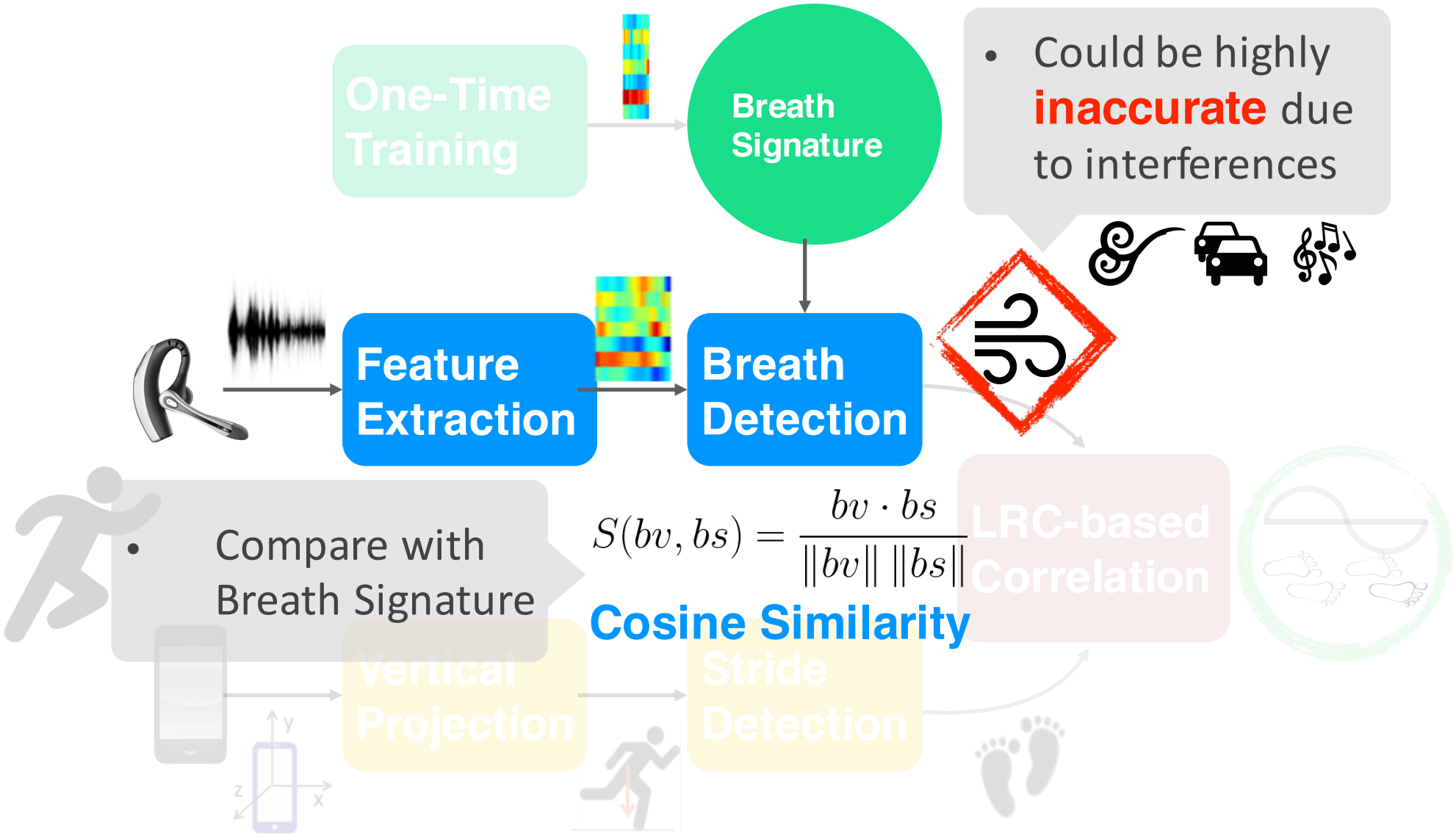
public road w/ traffic



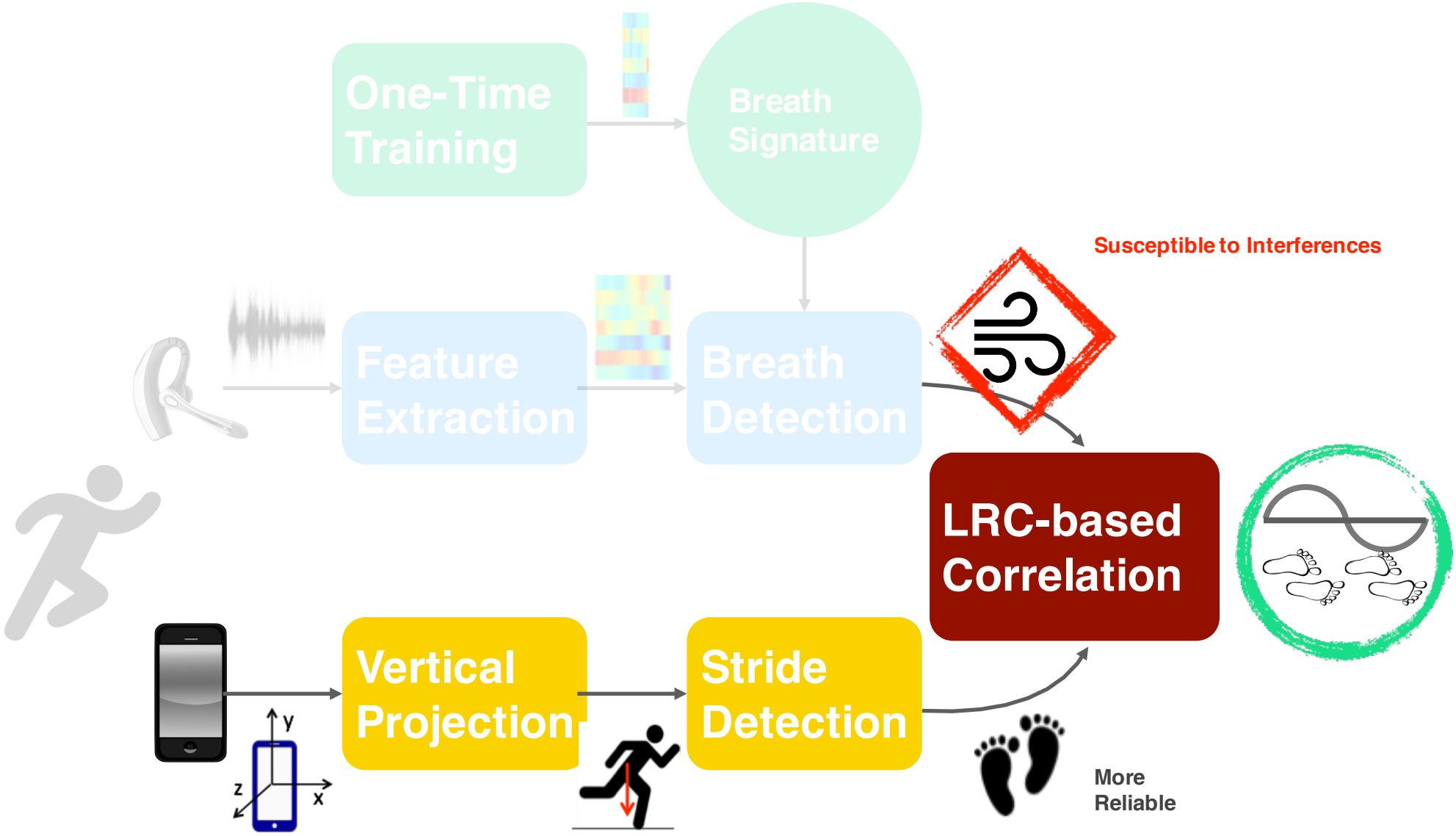
System Architecture



Preliminary Breath Detection

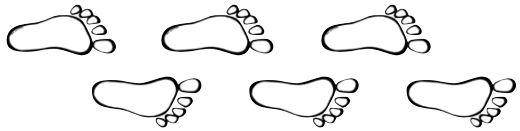


LRC-based Correlation

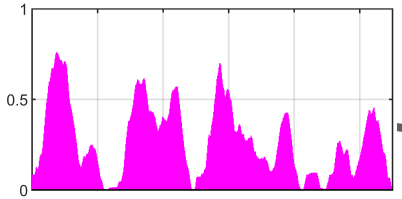


LRC-based Correlation

10-second moving window



Detected Strides



Detected Breaths

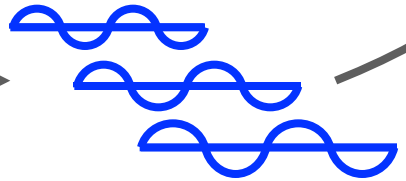
Cross Correlation

X:Y

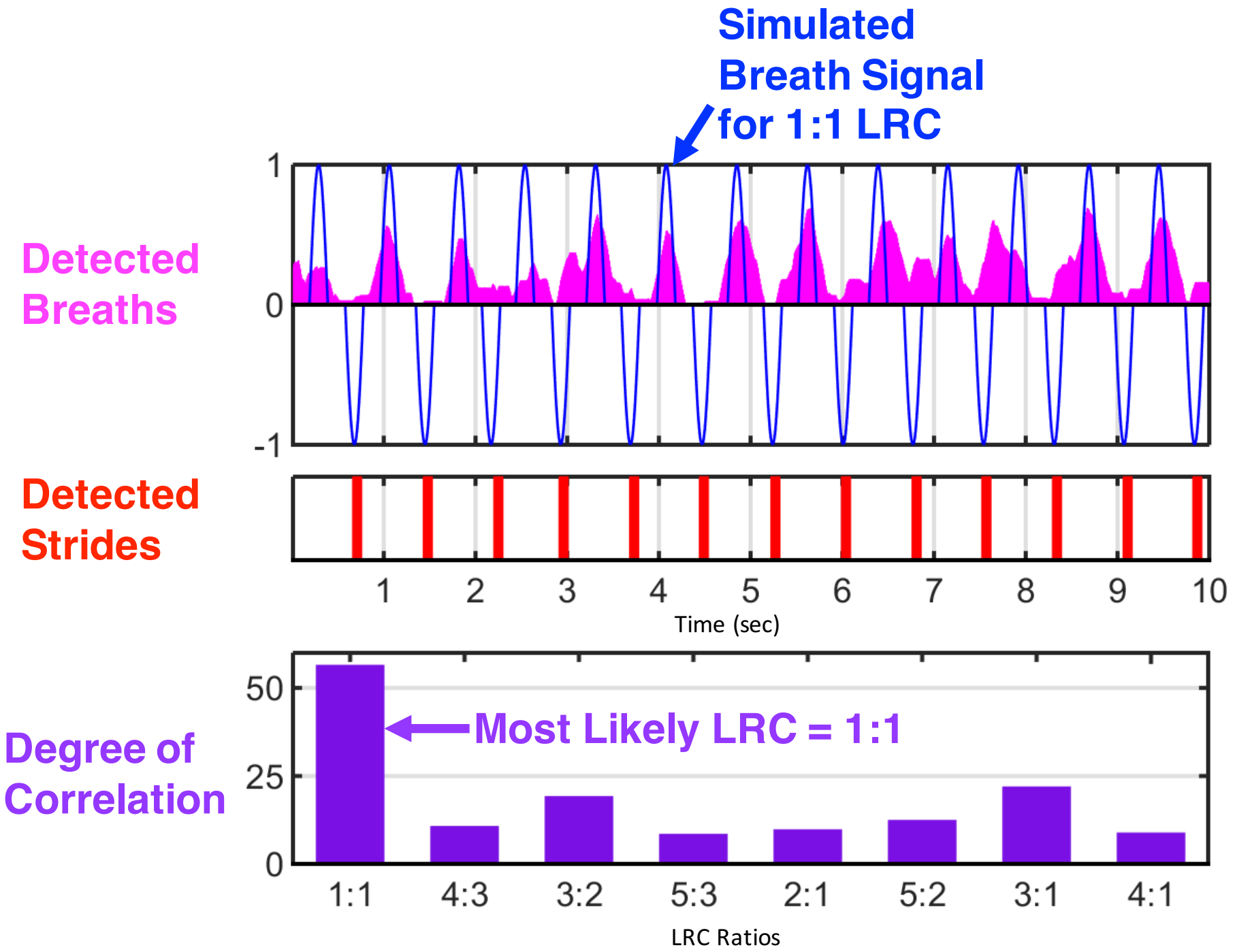
D • S(r)

Most Likely LRC ratio (Running Rhythm)

Running LRC in Humans

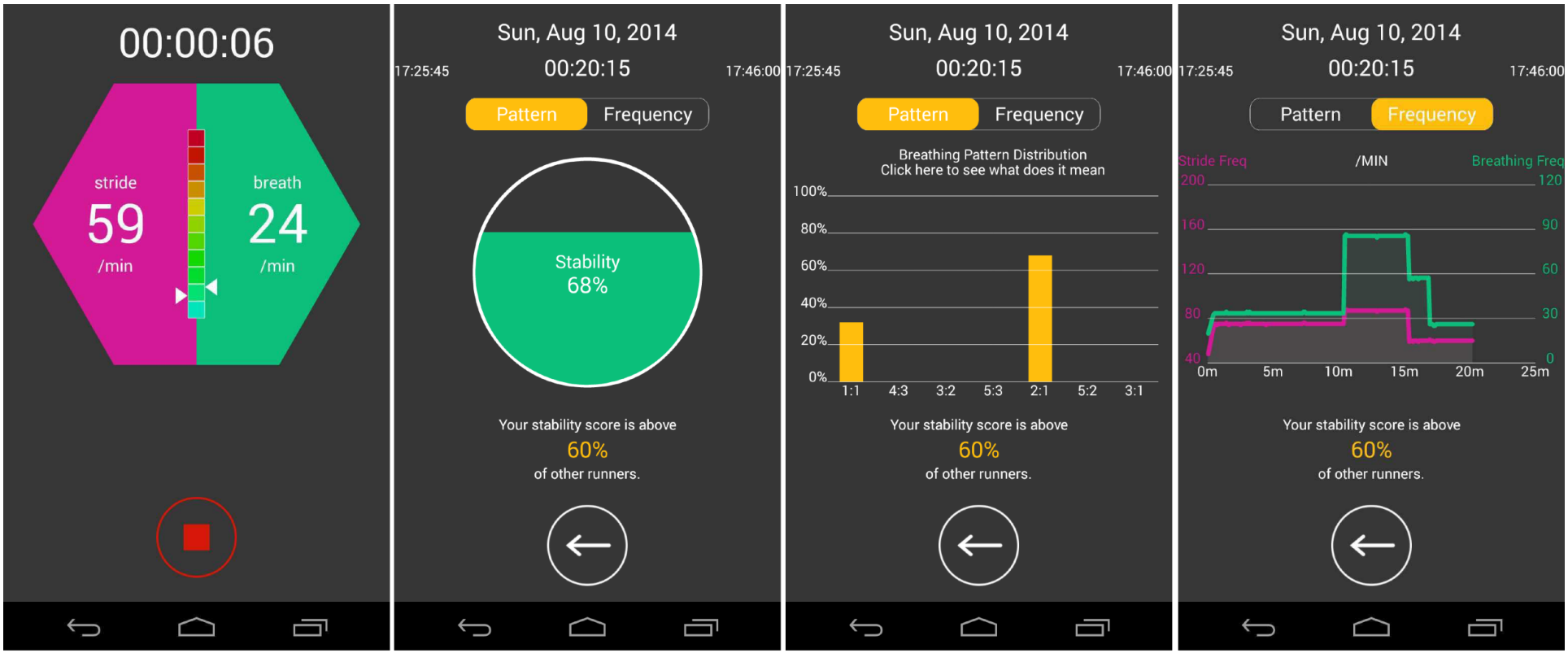


Simulated Breath Signals for each LRC ratio


Simulated
Breath Signal
for 1:1 LRC
Detected
Breaths
Detected
Strides
1
0
-1
1
2
3
4
5
6
7
8
9
10
Time (sec)
Degree of
Correlation
Most Likely LRC = 1:1
50
25
0
1:1
4:3
3:2
5:3
2:1
5:2
3:1
4:1
LRC Ratios

iBreath Mobile App

MobiCom 2014
Best Mobile App
Third Place



Real-time Monitoring

LRC Stability

LRC Distribution

Frequencies Overtime

Evaluation

Measurement

every 5 sec, with 10-sec window

Metric

% of Correct Measurement

Accurately measure LRC Ratio

92.7% of the time

IRB-Approved

by the Institutional Review Board at Michigan State University

Procedure

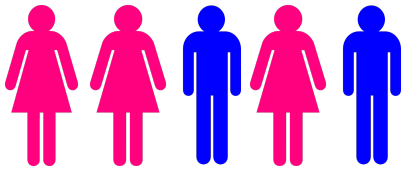
- Run as usual
- No limit on speed, distance and phone placement

Ground Truth

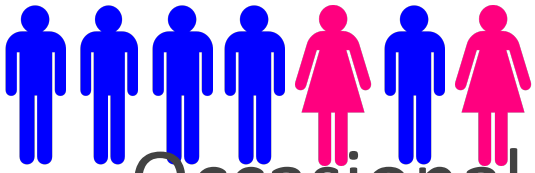
- Inline mic under nose (34/39)
- Manual counting (5/39)

13

Subjects



Non-runner



Occasional Runner

Regular Runner

39

Runs

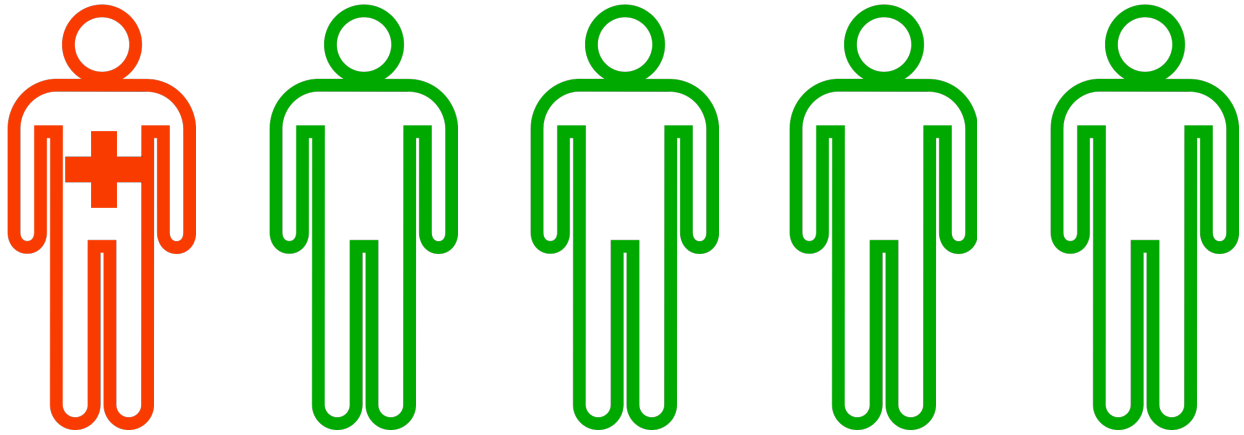
29 Indoor / 10 Outdoor


Freq (/min)
Ratio
Stride
Breath
LRC
Regular Runner
Non-runner
time (min)
breath freq
stride freq
breath freq (truth)
measured LRC
LRC (truth)

Unobtrusive Sleep Monitoring

image source: http://cdn.dailysundial.com

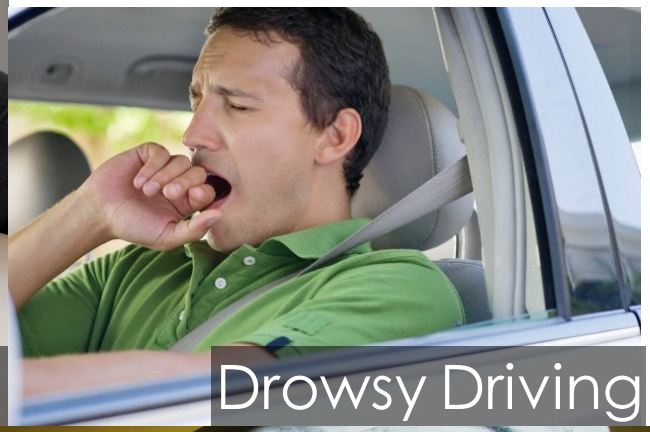
Poor Sleep is Common



1 out of 5 Americans are affected by various sleep disorders

[National Institutes of Health]

RLS	OSA	DSPD	RBD
Restless Legs Syndrome	Obstructive Sleep Apnea	Delayed Sleep Phase Disorder	Rapid Eye Movement Behavior Disorder



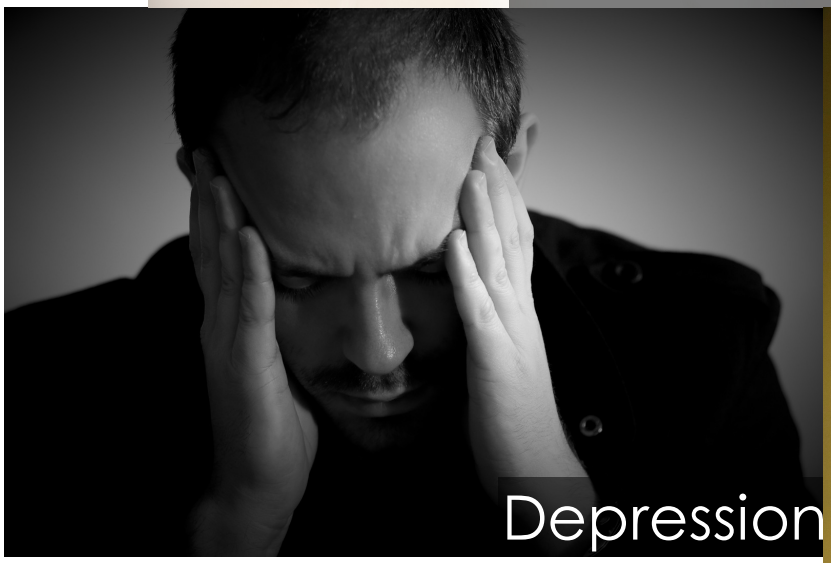
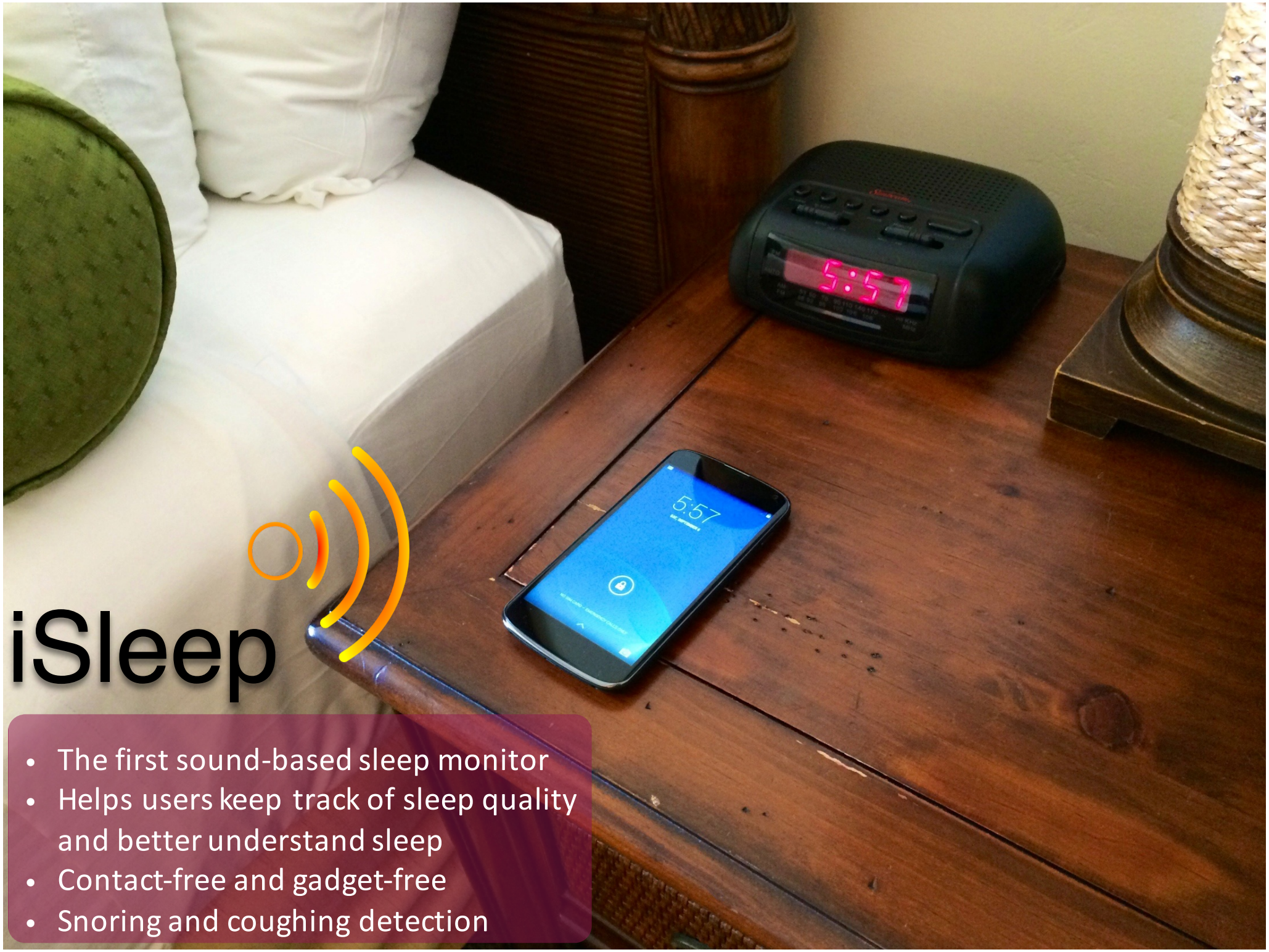


image (top left) source: http://www.venusbuzz.com/archives/28076/study-lack-of-sleep-slows-down-productivity/sleepy-at-work/
image (top right) source: http://www.dchtsdf.org/news_and_press/driver_fatigue_a_factor_in_20_percent_of_crashes.aspx
image (bottom left) source: http://micah.sparacio.org/05/16/2011/10-ways-to-fight-depression/
image (bottom right) source: http://thinkprogress.org/health/2012/06/18/501286/17-million-tons-overweight/

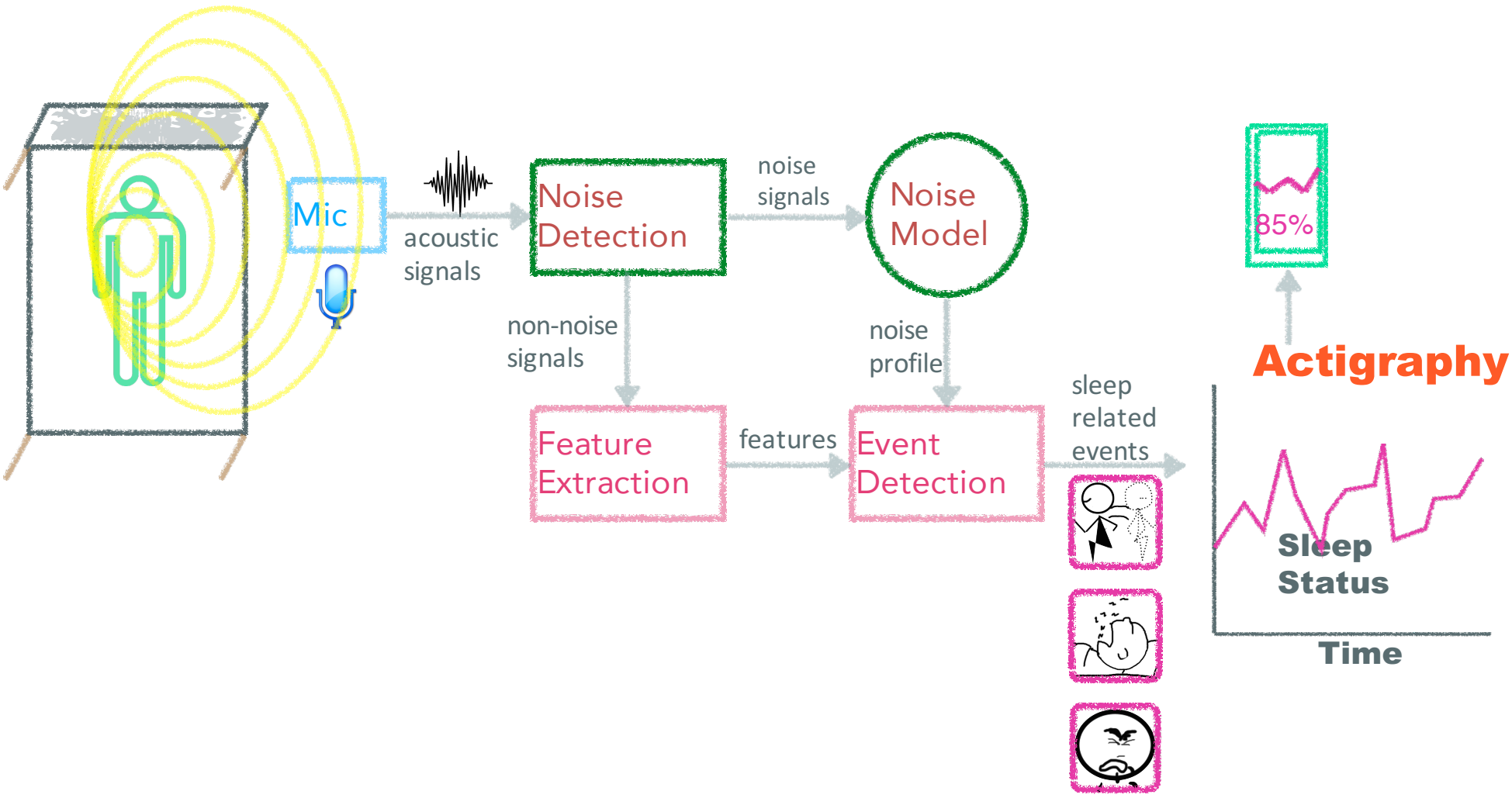

PSG-based Sleep Test
Invasive
2 Technicians
1 Hour
20+ Wires



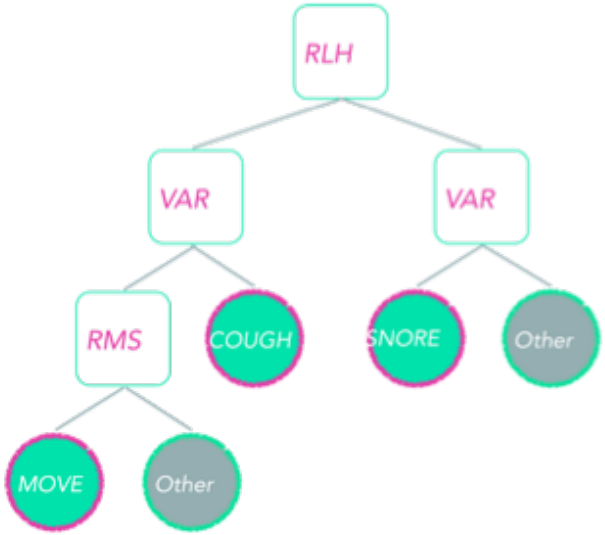
iSleep

- The first sound-based sleep monitor
- Helps users keep track of sleep quality and better understand sleep
- Contact-free and gadget-free
- Snoring and coughing detection

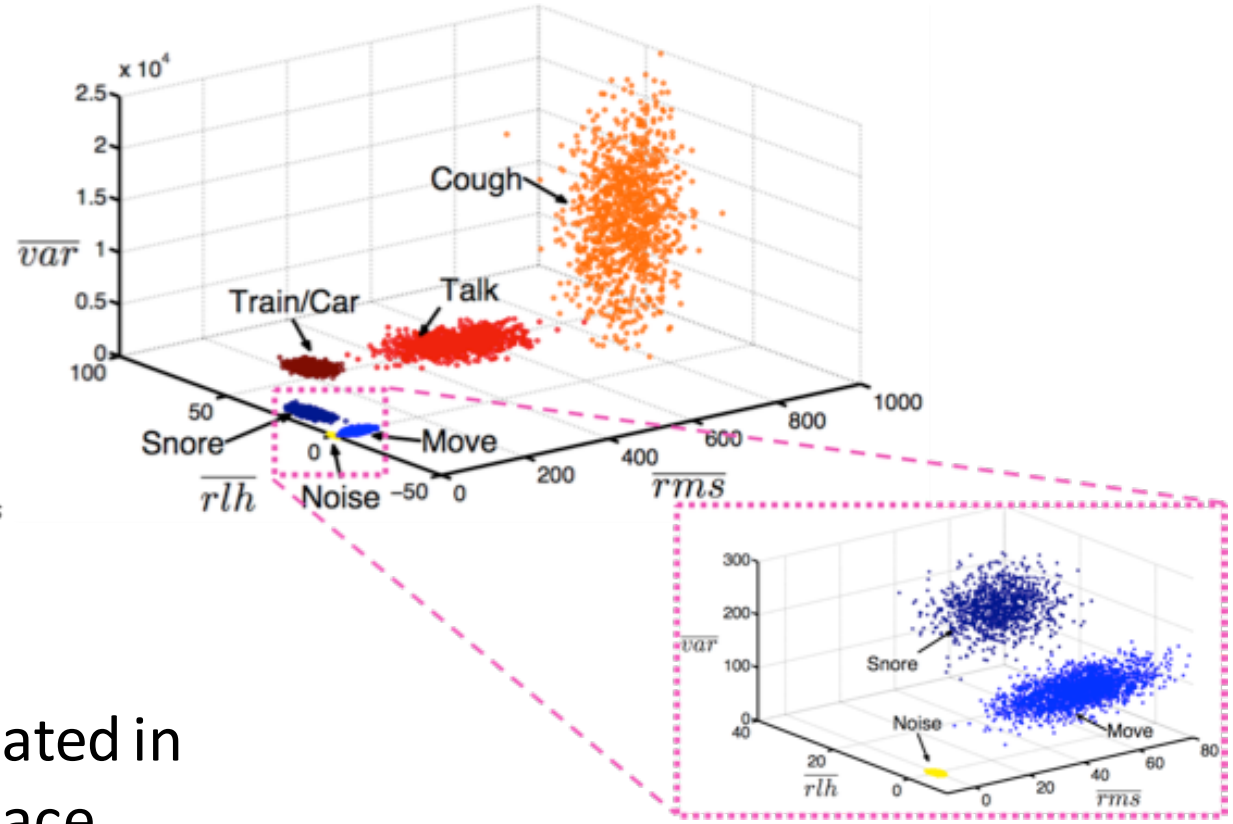
System Overview



Feature Space & Decision Tree



RLH: Ratio of Low-band and High-band Energies
VAR: Variance
RMS: Root Mean Square



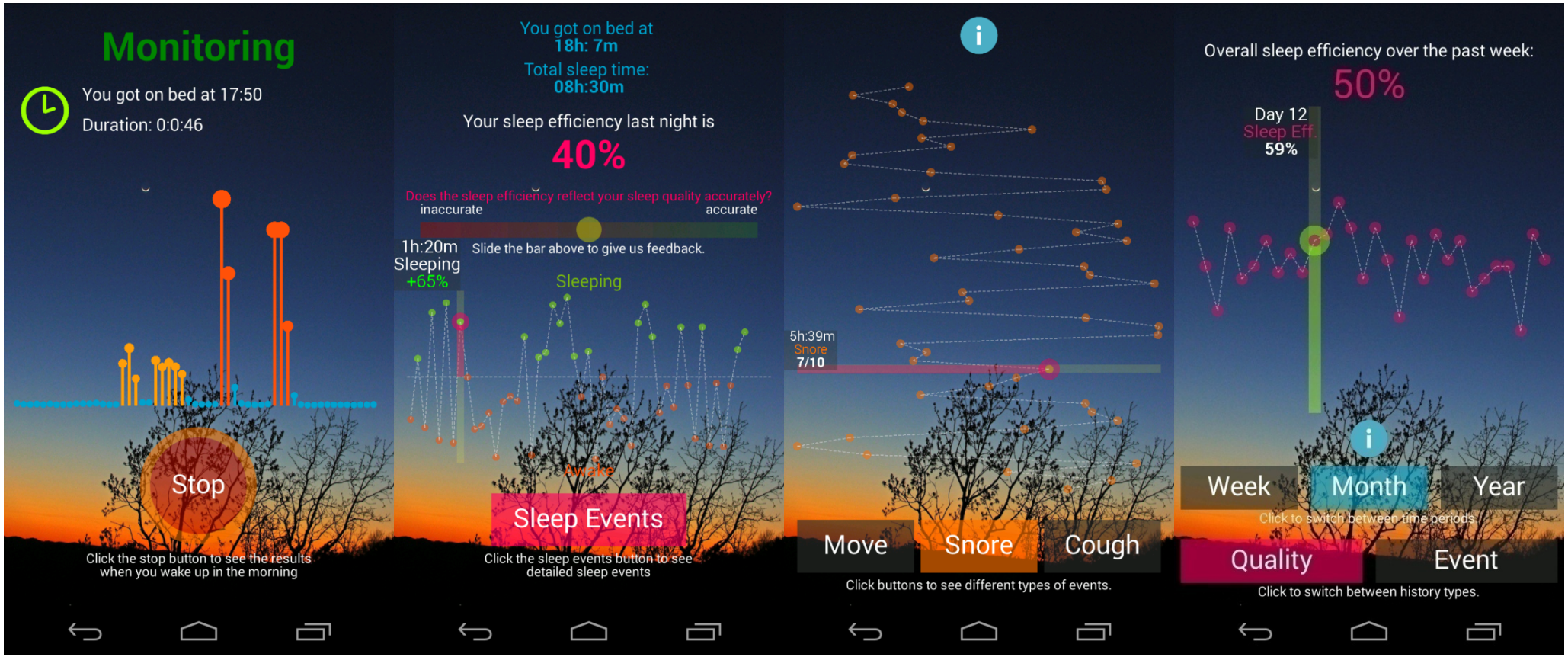
Diff. events are well separated in the normalized feature space

(plotted using data from 7 subjects)

iSleep Mobile App

5K Users/2 mo
without marketing

Best Mobile App
Third Place, MobiCom 2013



Monitoring | Sleep Quality | Sleep Events | History

Evaluation

MSU IRB#12-1178
Approved by the Institutional Review Board at Michigan State University

Movement
91.9%

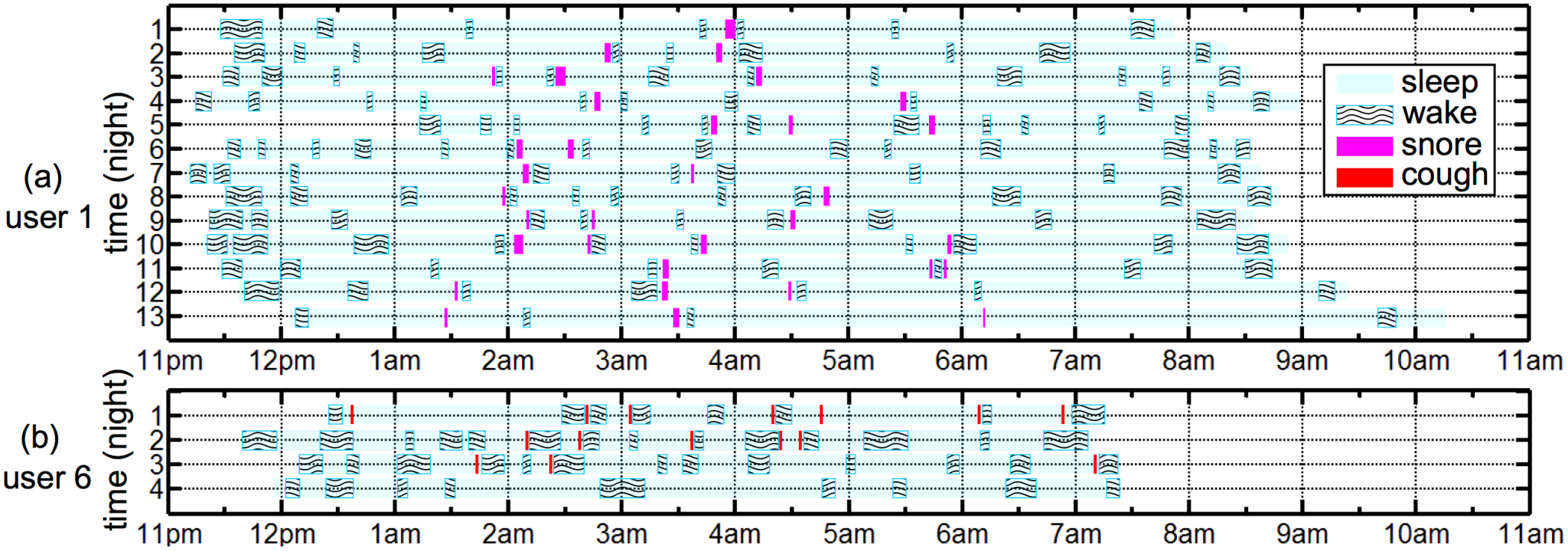
Snoring
96.7%

Coughing
100%

7
Subjects

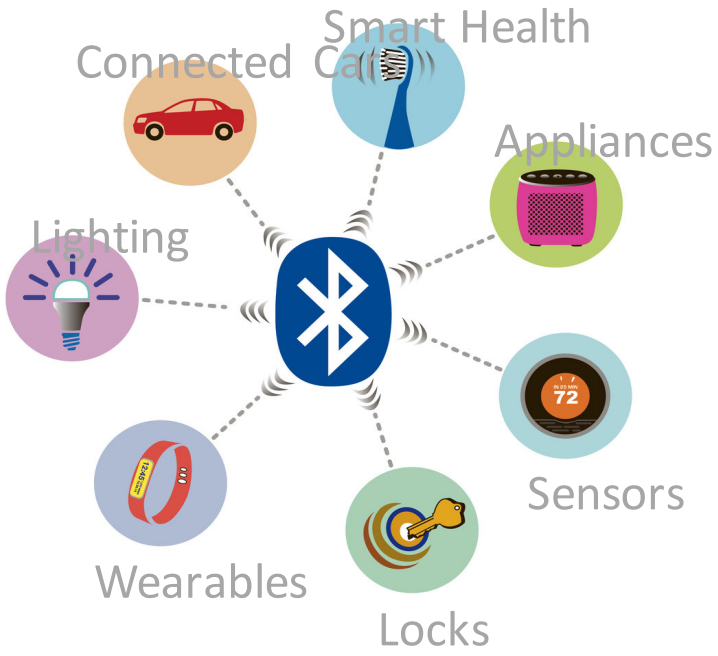
51
Sleeps

Long-term Result



Wireless Privacy for Smart Devices

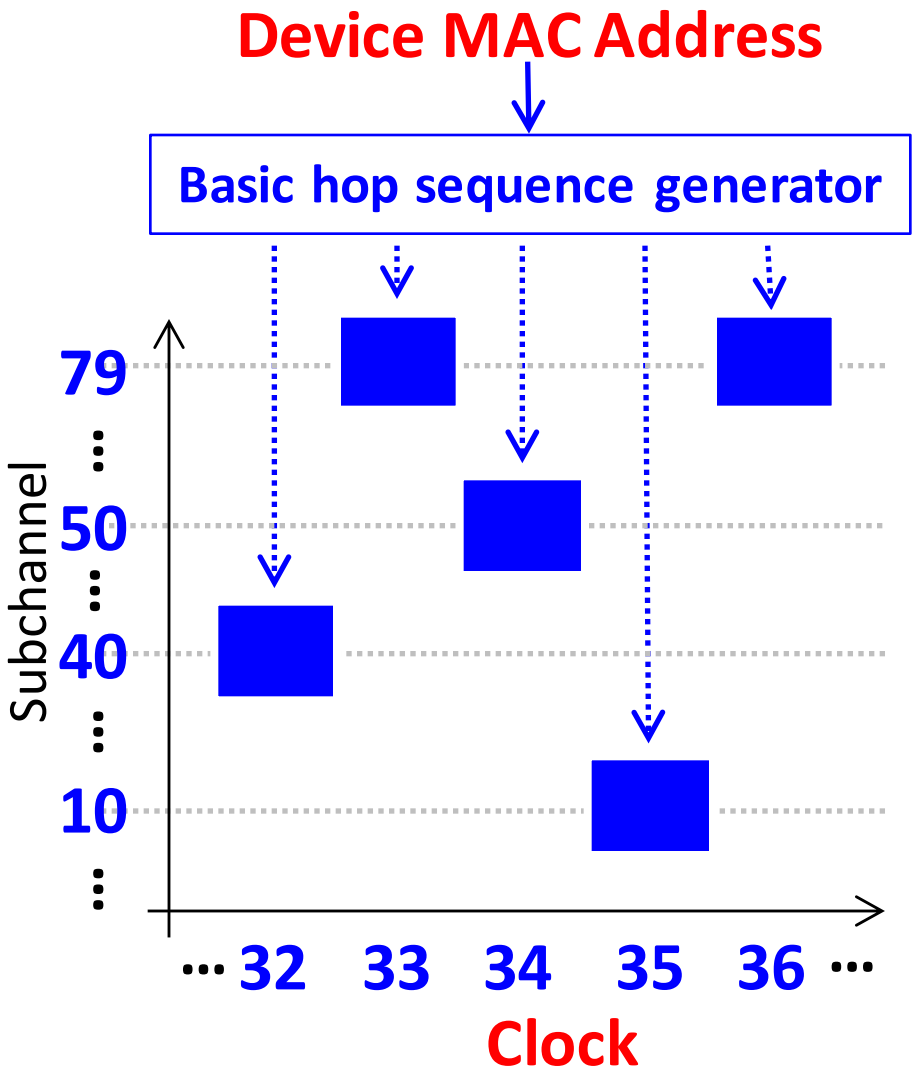
- Bluetooth
  - 3 billions Bluetooth devices were shipped in 2015
- Near-field communication (NFC)
  - 200 M NFC equipped smartphones shipped in 2013
  - 50% smartphones support NFC in 2015



Source: public pictures from the Internet

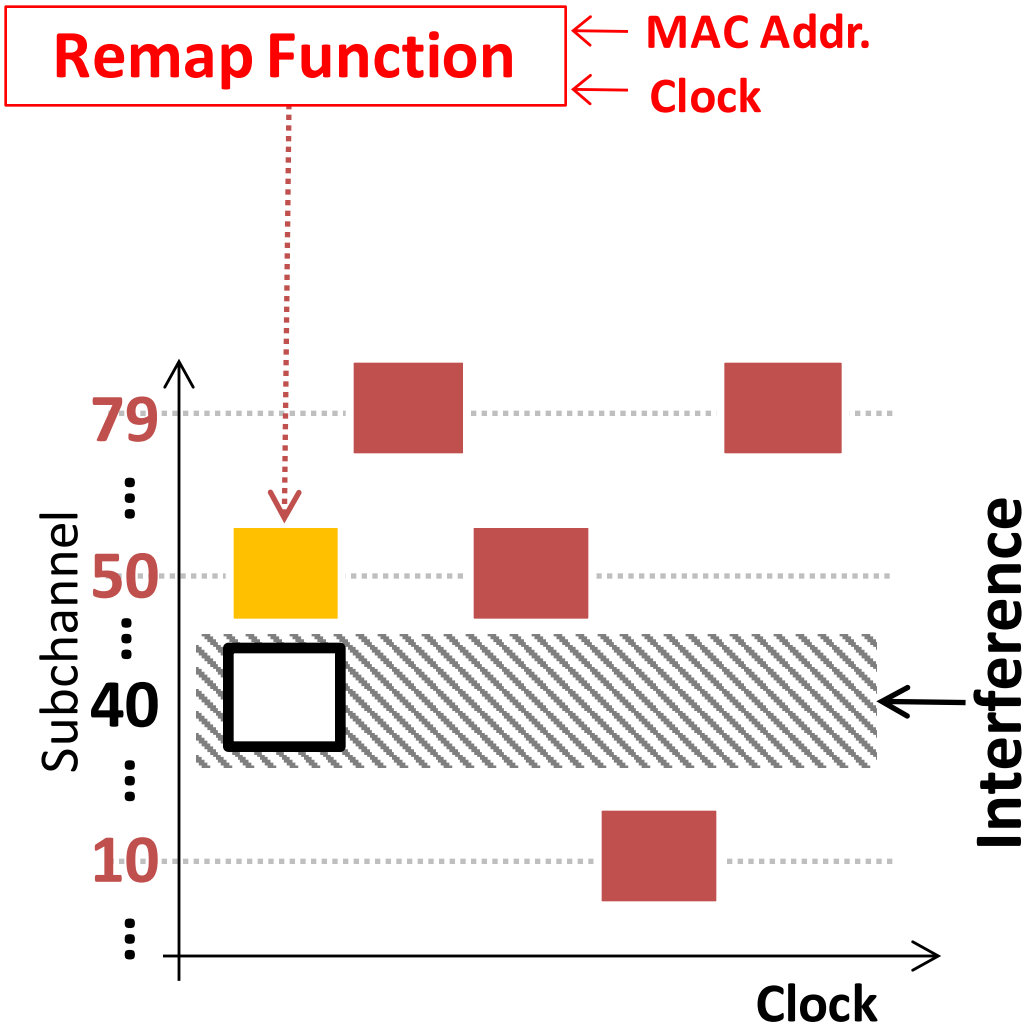
Basic Frequency Hopping

- **Switch b/w 79 subchannels randomly**
  - 1600 hops/s
- **Current hop is defined by**
  - Device MAC address (public)
  - A 27-bit logic clock (secret)
    - Index of current hop
    - A basic hop seq. of 227 long



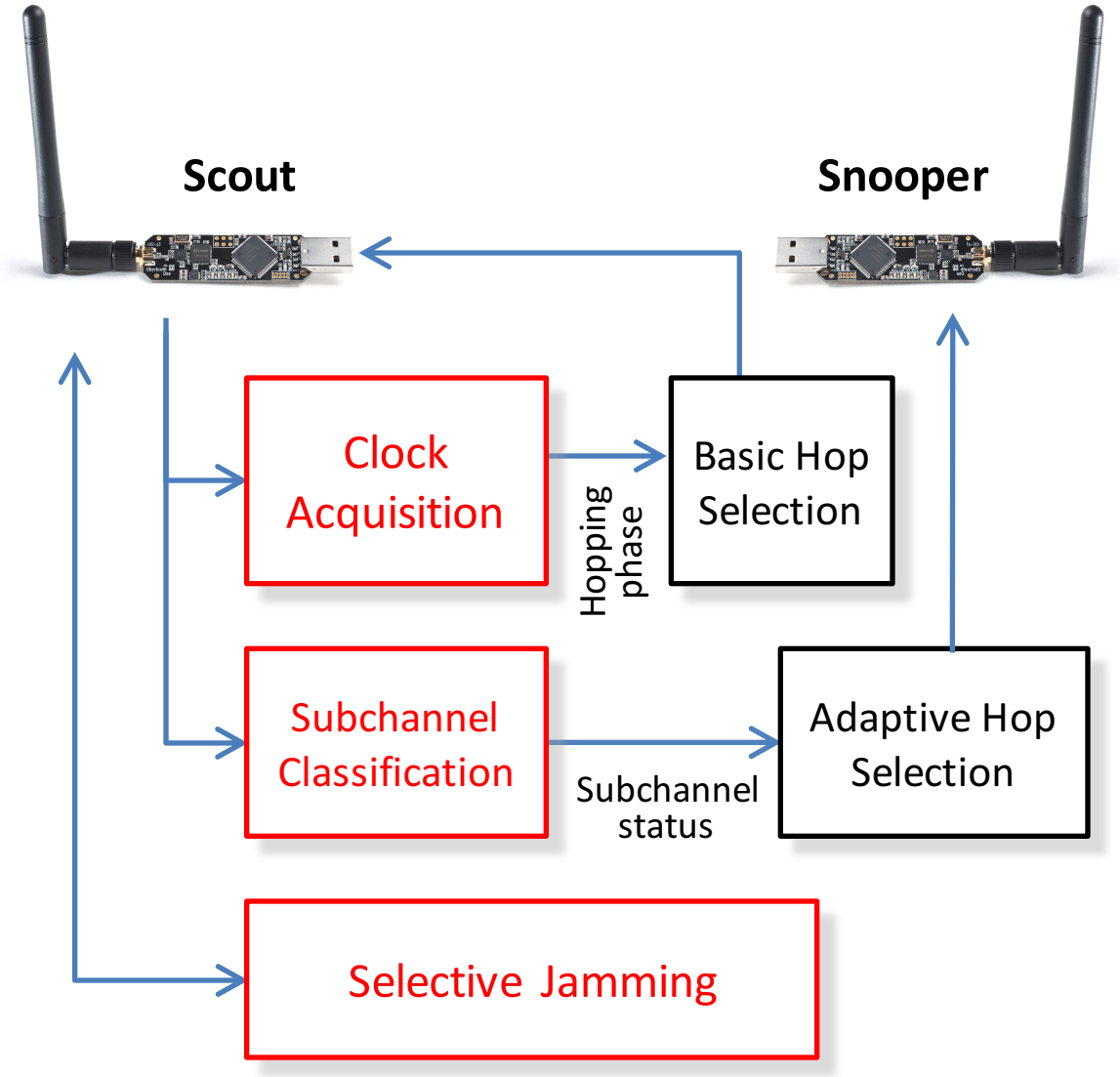
Adaptive Frequency Hopping

- **Remaps `bad' subchannels**
  - MAC address (public)
  - Clock (secret)
- **Vendor-dependent behavior**
  - No standard definition of 'good' and 'bad' sub-channel conditions



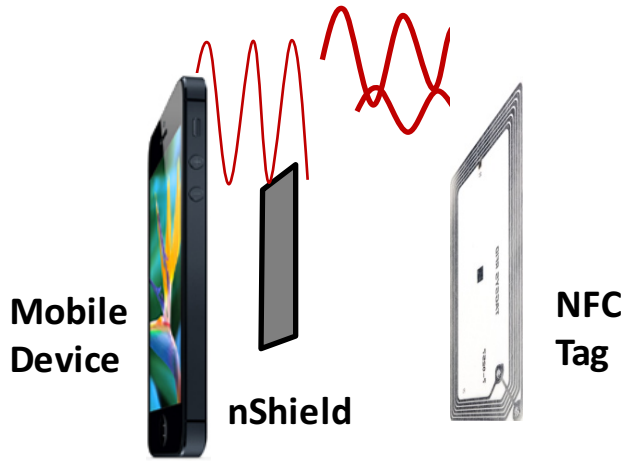
BlueEar: A Dual-Radio Sniffer

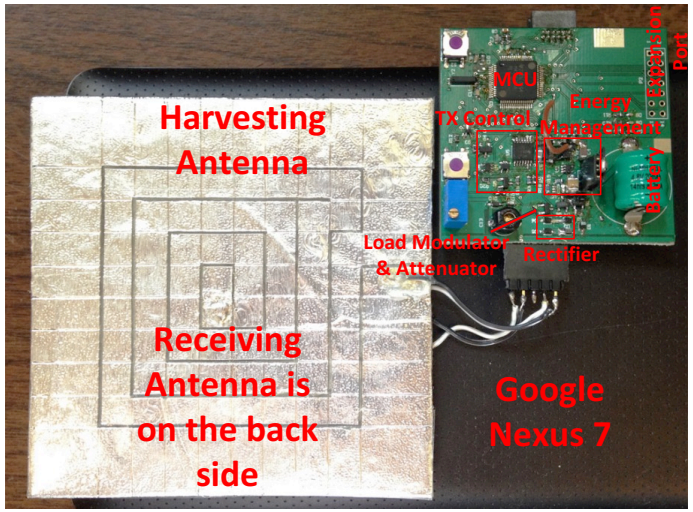
- **The *Scout* radio**
  - Sniffs a single subchannel to acquire clock value
  - Perform basic hoping to learn subchannel status
  - Selectively jam to avoid interference
- **The *Snooper* radio**
  - Follow adaptive hopping to capture packets



nShield: A Noninvasive Security Device

- Dynamic NFC signal strength attenuator
  - Absorbs excess NFC RF energy
  - Variable attenuation w/o sacrificing communication reliability
- Noninvasive
  - No modification, no physical connection to host
- Harvest and store absorbed RF energy
  - Enable perpetual operation





Cyber-Physical Systems

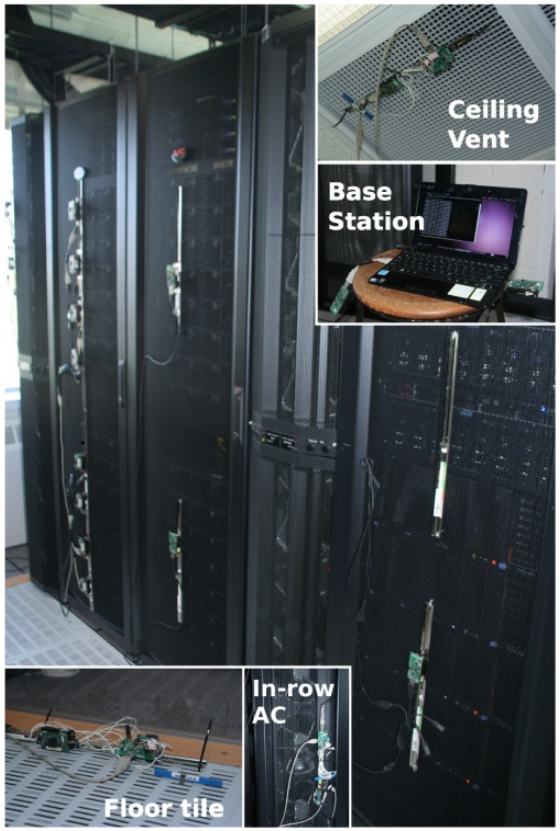
- "Cyber-physical systems are engineered systems that are built from and depend upon the **synergy** of **computational** and **physical** components"[1]

- Many critical sustainability application domains
  - Environment, smart grid, medical, auto, transportation…

- No. 1 national priority for Networking and IT Research and Development (NITRD)
  - NITRD Review report by President's Council of Advisors on Science and Technology (PCAST) titled "Leadership Under Challenge: Information Technology R&D in a Competitive World", 2007

1 NSF Cyber-physical systems solicitation13502

Our CPS Projects

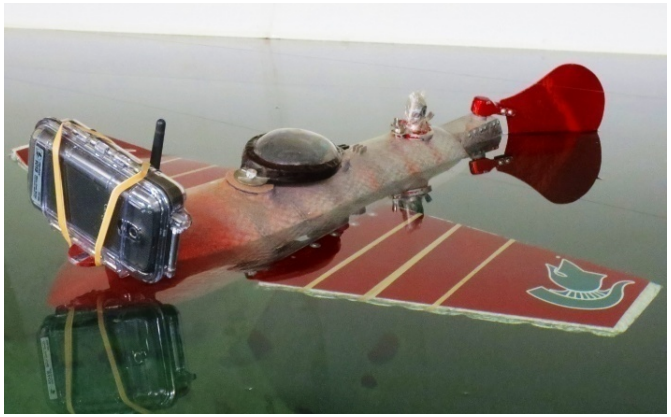


Data Center Monitoring, HPCC, MSU

Tungurahua Volcano, Ecuador

Volcano Monitoring Sensors

Harmful Algae Bloom in Lake Mendota in Wisconsin, 1999

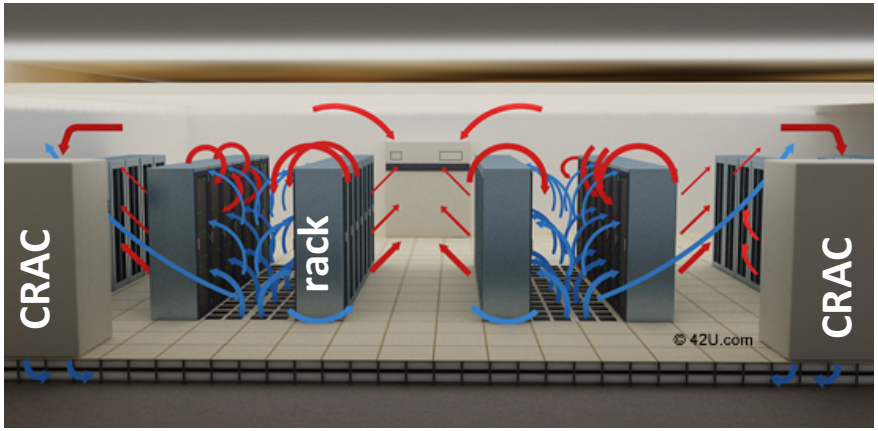


Robotic fish, Smart Microsystems Lab, MSU

- Data center thermal monitoring
- Real-time volcano monitoring
- Aquatic process profiling

Motivation

EMC's new data center in Durham, NC

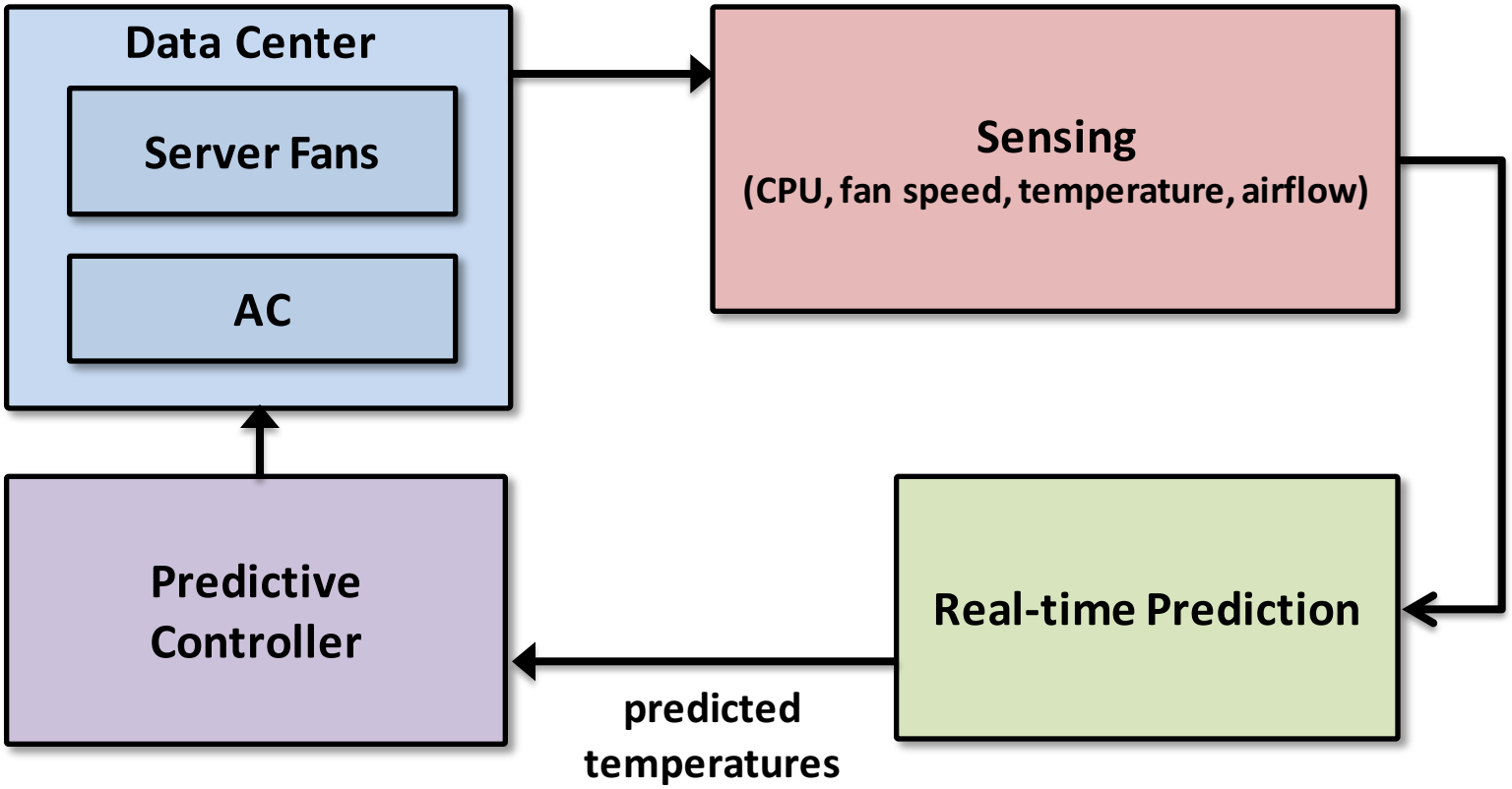


Raised-floor cooling [www.42u.com]

- **Data centers eat massive energy**
  - An industry data center = a mid-size town
- **60% non-computing energy ratio** [Uptime 2012]
  - **50% for cooling**
    24°C** in 90% data centers vs. recommended **27°C
  - **10% for circulation**
    High fan speeds and simple control

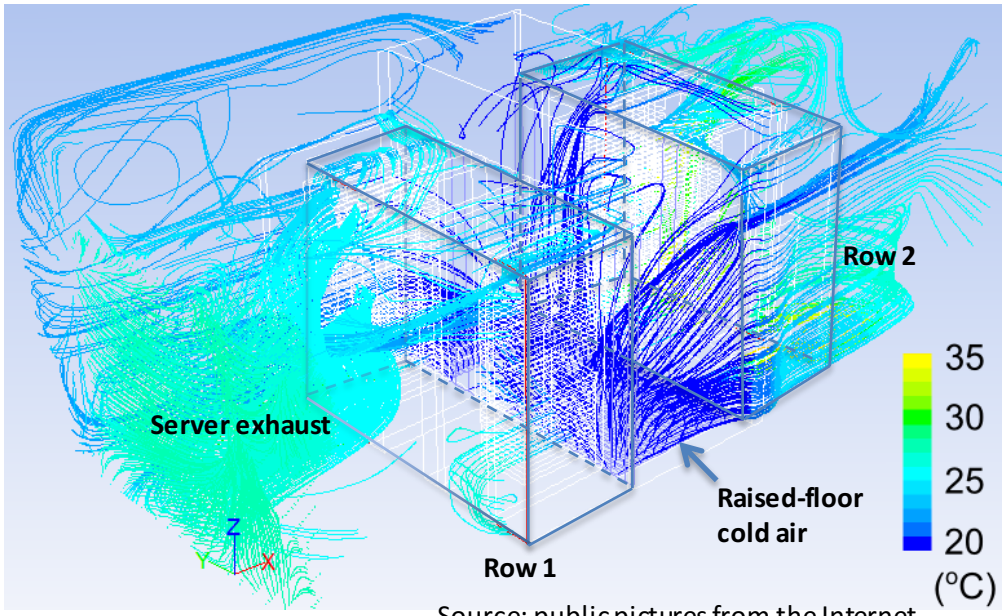
Our Solutions

- **Data center sensor system**
  - Built-in sensors, external sensor network
- **Temperature & energy prediction [RTSS'12, TOSN'15]**
  - Sensor data + energy models + candidate control action
- **Predictive control [RTSS'14]**
  - Constrained optimization



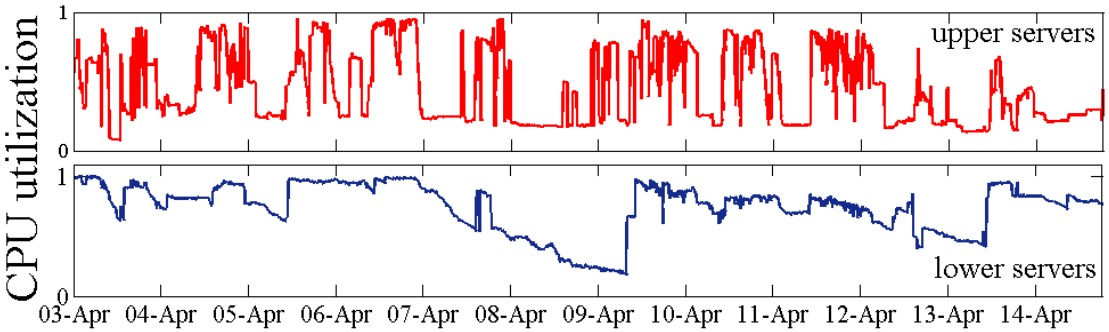
Challenges

- Complex air and thermal dynamics



Source: public pictures from the Internet

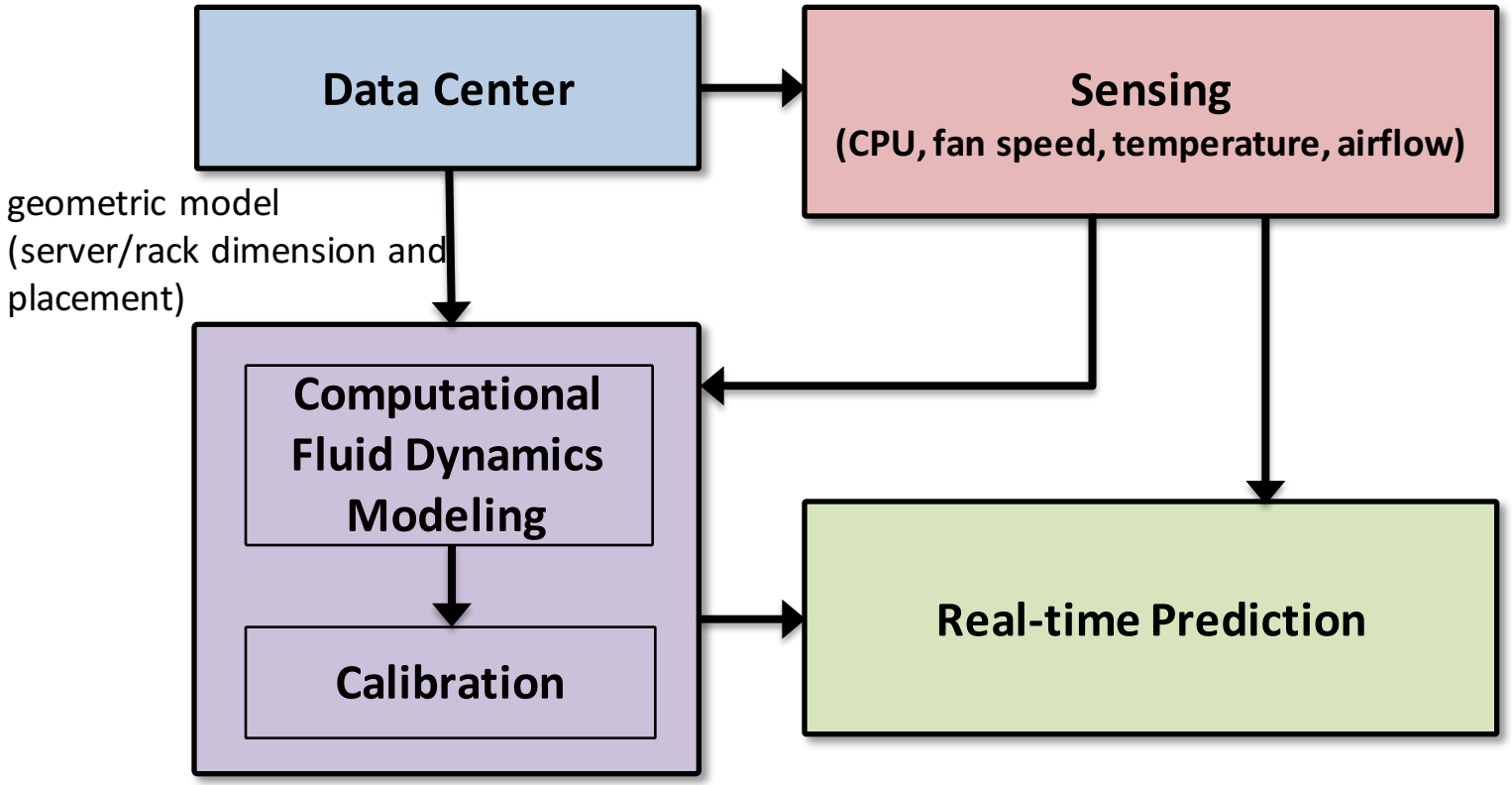
- Highly dynamic workloads



12-day CPU utilization data of one rack (64 servers with 512 CPU cores) in High Performance Computer Center at Michigan State University

System Architecture

- CFD Simulation + Wireless Sensing + Data-driven Prediction
  - Preserve realistic physical characteristics in training data
  - Capture dynamics by *in situ* sensing and real-time prediction



CFD Modeling & Calibration

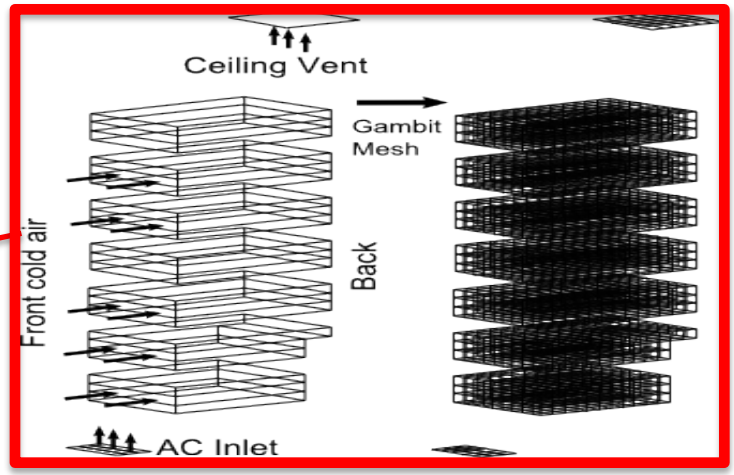
CFD Modeling

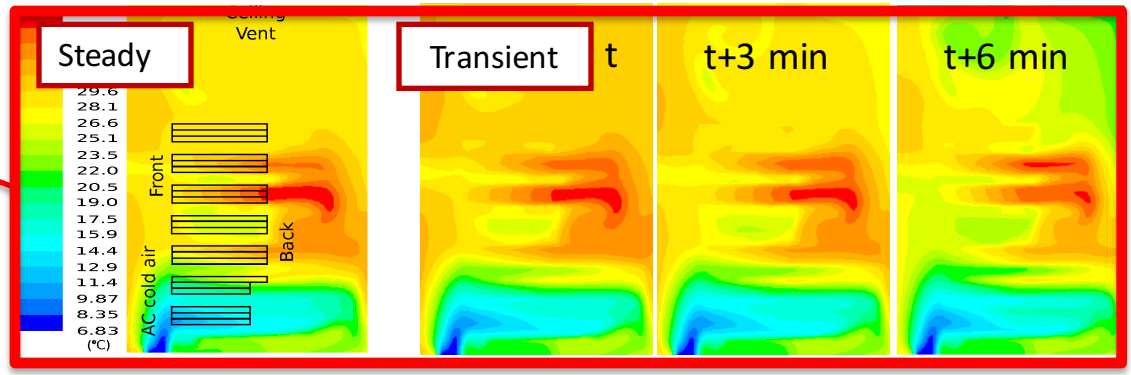
Physical Geometry Model

Steady/Transient CFD

Polynomial Calibration

Sensor Data





$$y_i = \sum_{k=1}^{K} a_{i,k} \cdot x_i^k$$

Calibration order

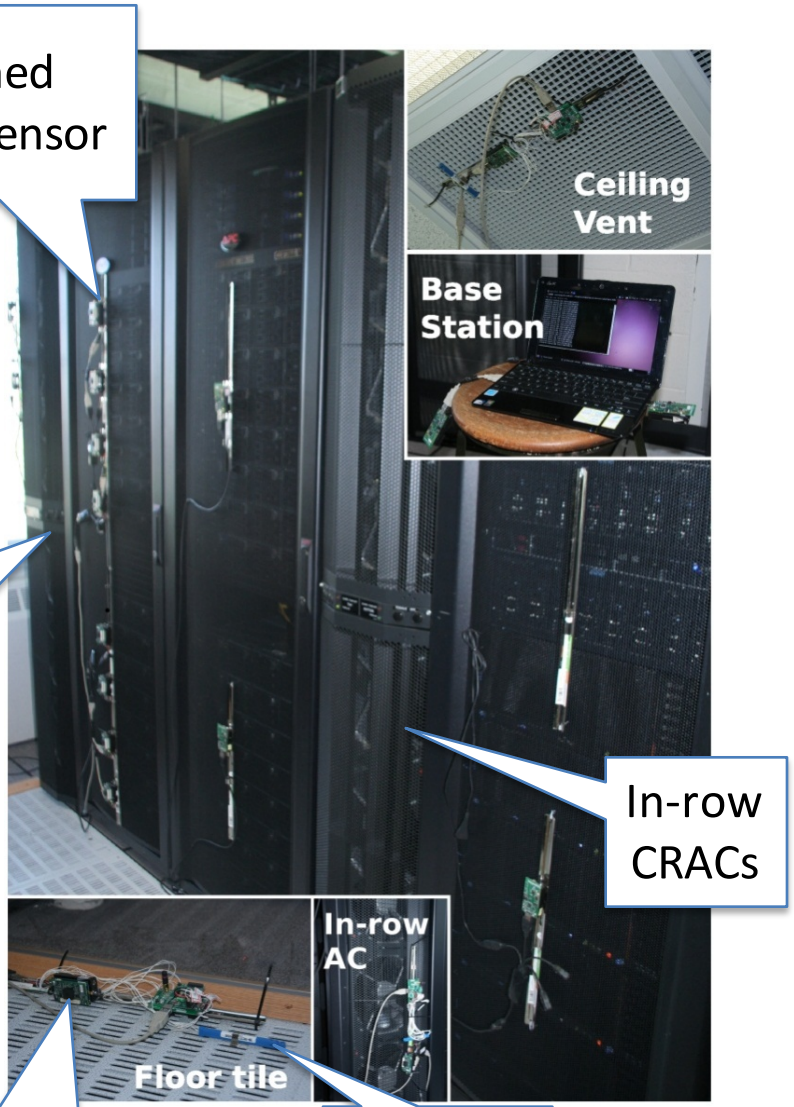
Training: sensor reading
Runtime: calibrated temperature

Calibration coefficients

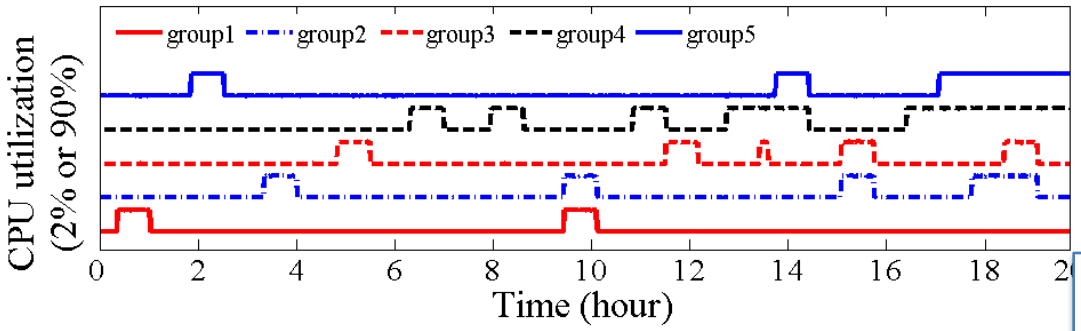
Temperature from CFD

Data Center Experiment

- Testbed configuration
  - 5 racks, 229 servers, 2016 cores
  - 4 in-row CRAC units
  - 35 temperature sensors
  - 4 airflow sensors

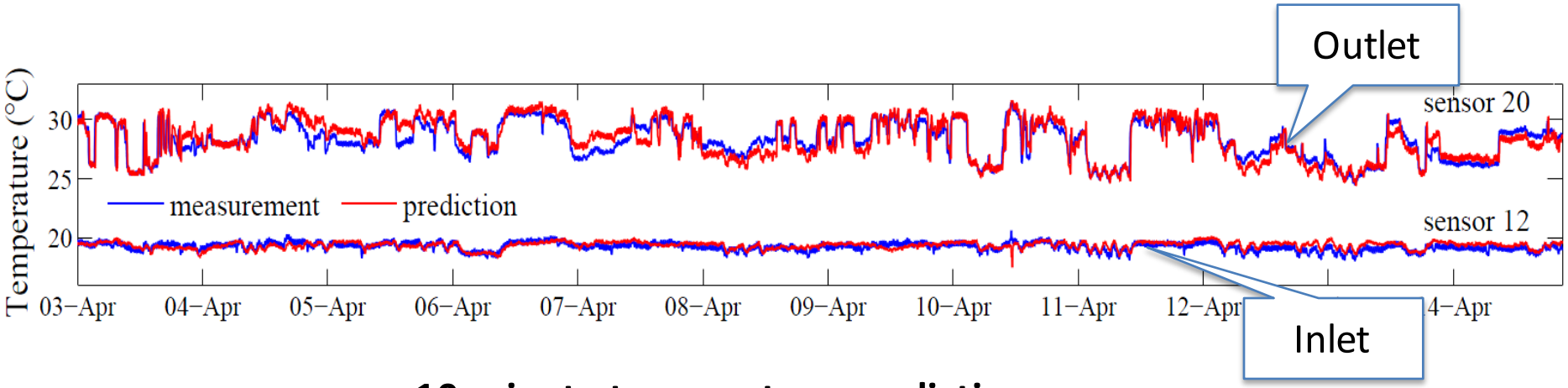


- Dynamic CPU utilization



Experiment Results

- 12-day experiment



10-minute temperature prediction

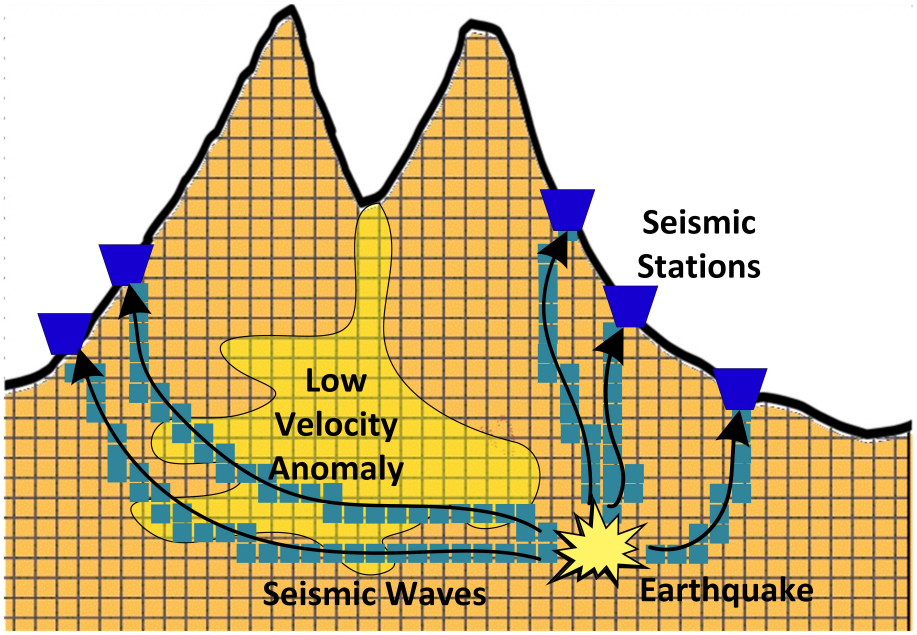
Volcano Hazards

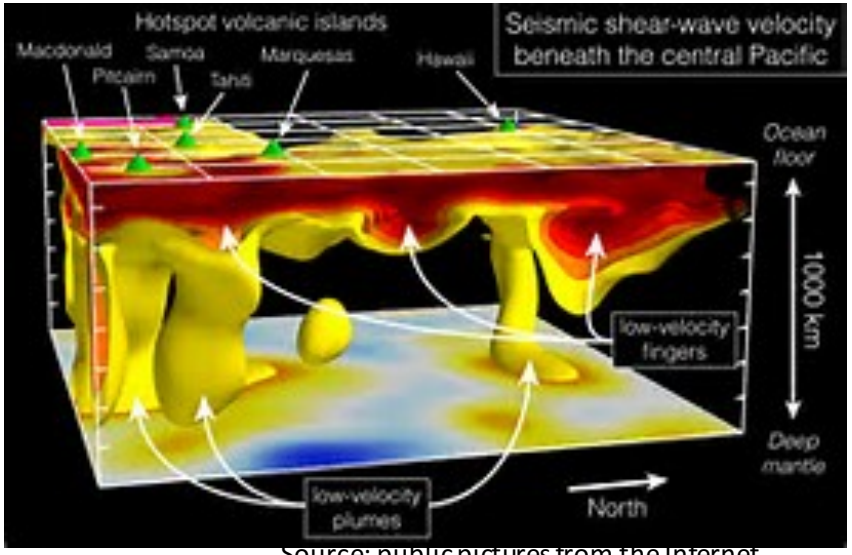
Eruption in Chile, 6/4, 2011
$68 M instant damage, $2.4 B future relief.
www.boston.com/bigpicture/2011/06/volcano_erupts_in_chile.html

Eruptions in Iceland 2010
A week-long airspace closure
[Wikipedia]

- 7% world population live near active volcanoes
- 20 - 30 explosive eruptions/year

Volcano Tomography





Source: public pictures from the Internet

Sensor Sampling and Timing → Event Detection → Event Hypocenter Determination → Compute Velocity Model (Tomography) → Visualization

State of the Art

- Seismic activity monitoring
  - Earthquake localization, tomography, early warning etc.
- Traditional seismometer
  - Expensive (~$10K/unit), difficult to install & retrieve
  - Only ~10 nodes installed for most threatening volcanoes!

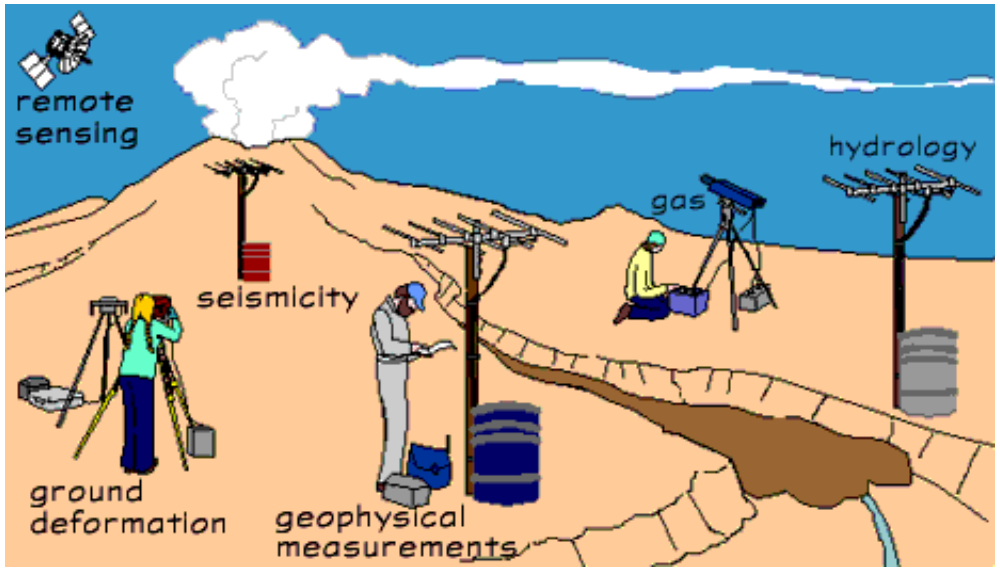
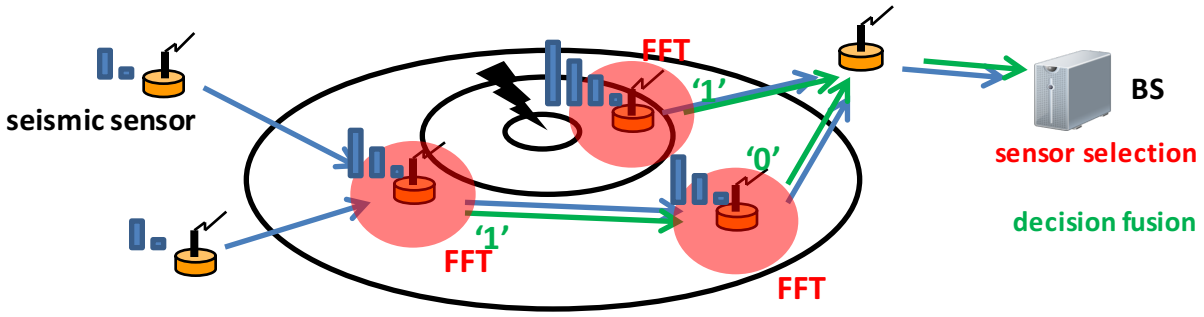


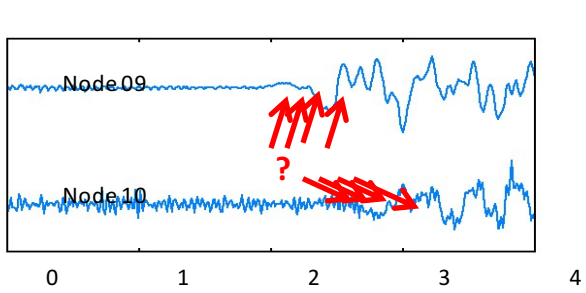
Photo credit: USGS, http://volcanoes.usgs.gov/activity/methods/

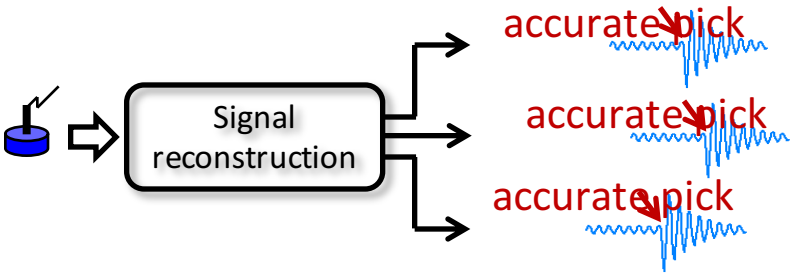
Our Solutions

- In-network sensor selection & fusion [RTSS'10, TOSN'13]



- Seismic event timing [IPSN'13]



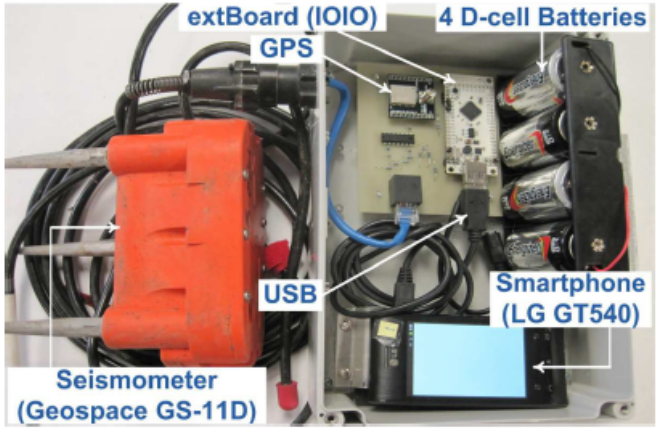


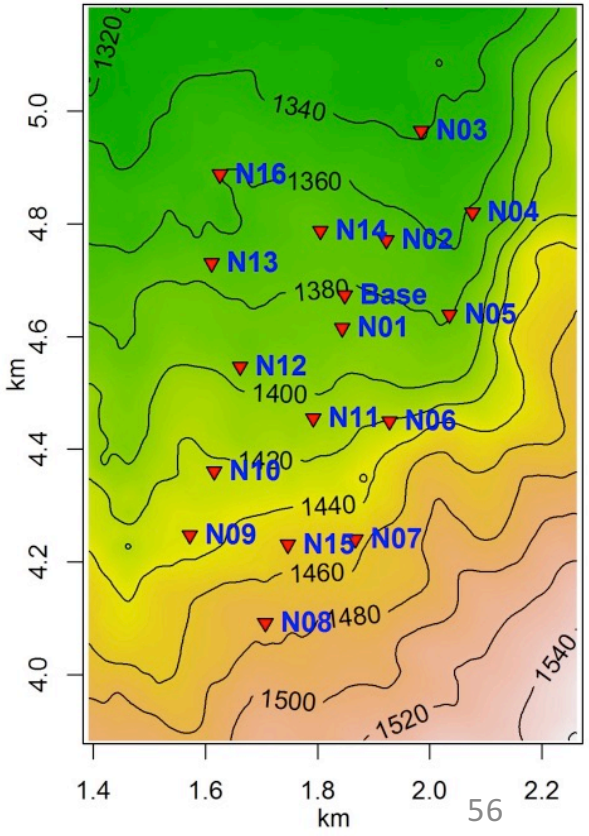
Source localization
Seismic tomography
…

- In-network tomography [SECON'13]

Systems and Deployments

- Ecuador - June 2013
  - Detected event 20Km from Tungurahua Volcano
- Chile – January-March 2015
  - 16 nodes plus base station





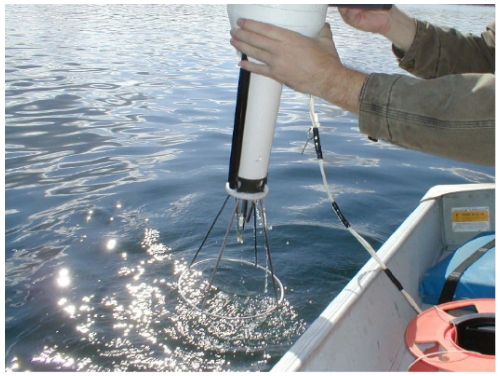
Aquatic Environment Monitoring

- Monitoring aquatic ecosystems is critical for urban planning, public safety etc.
  - HABs, oil spills, invasive species…

harmful algal blooms (HABs)

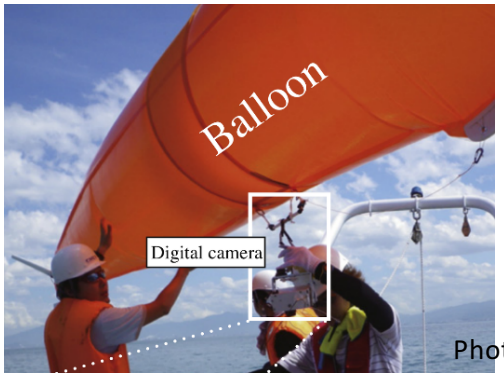
oil spill

Existing Approaches

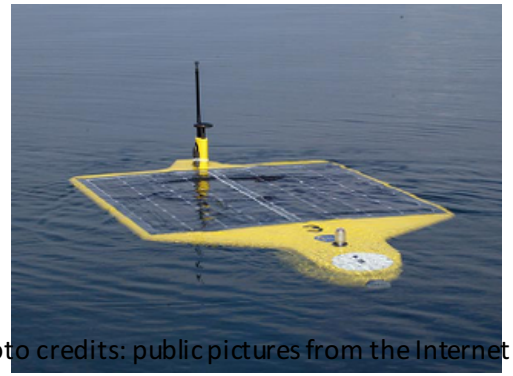


manual sampling

patrol boat/ship



remote sensing



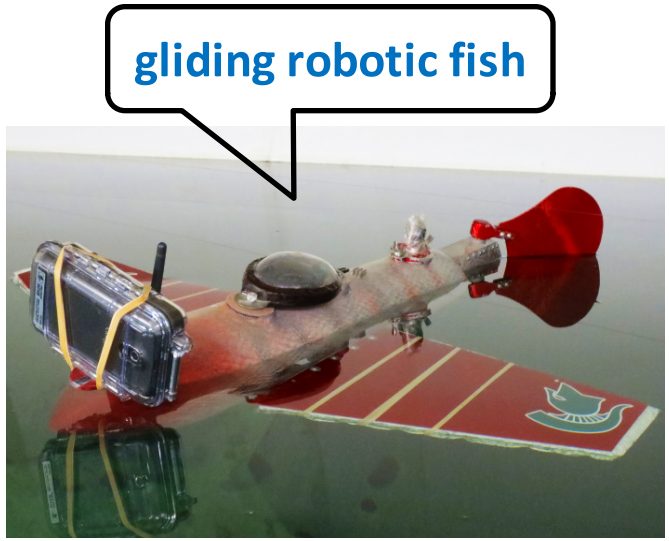
AUV/sea-glider

Photo credits: public pictures from the Internet

- **Manual sampling**
  - Small-scale, labor-intensive
- **Patrol boat/ship**
  - Costly, short-term
- **Remote sensing** (e.g., balloon, satellite)
  - Highly costly, low-resolution
- **AUV/sea-glider**
  - Costly (~$50k), bulky, heavy

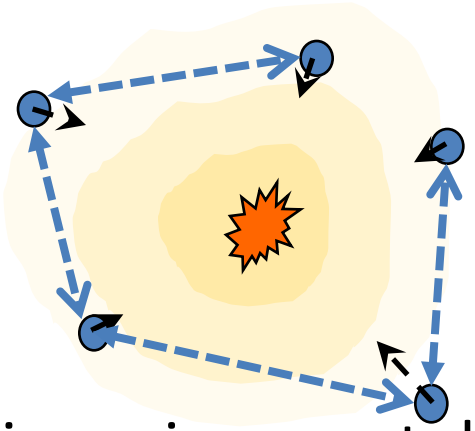
Our Prototypes

- **Multi-modality sensing**
  - Camera(s)
  - Inertial sensors
- **Rich storage & computation power**
  - Online learning algorithms
  - Computer vision algorithms
- **Controlled mobility**
  - Adaptation to environment dynamics
- **Low-cost** (~$3k)



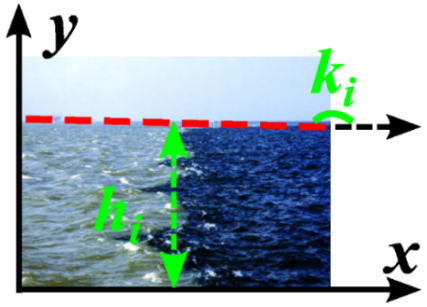
Overview of Our Work

- Diffusion process profiling & reconstruction [IPSN'12, RTSS'12]

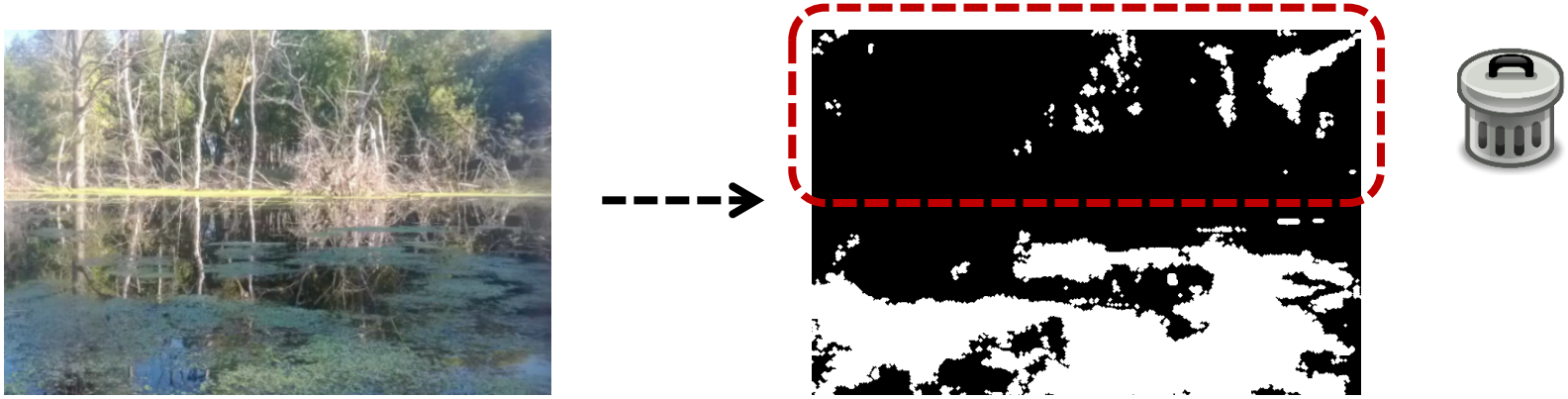


$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} - u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y}$$

- Debris detection using smartphone-based robotic fish [IPSN'14, IPSN'15]



Detection in Complex Environment



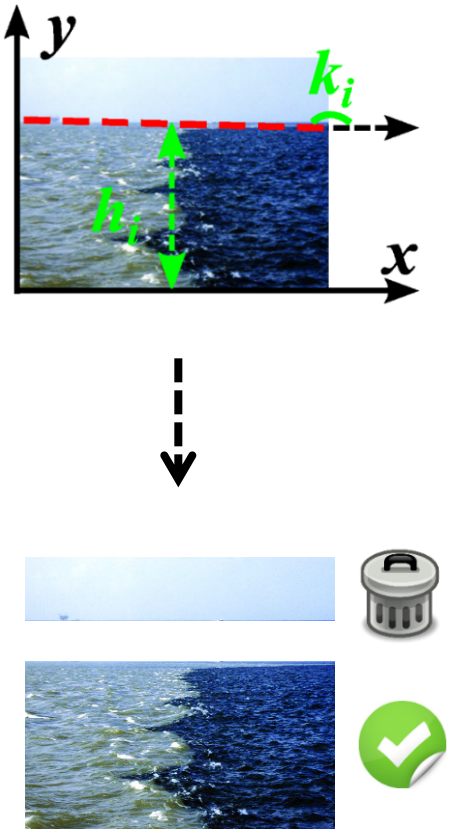
captured image

detection result

- **Excessive false alarms**
  - Water area: target algal patches in green
  - Non-water area: trees in similar color
- **Partition water and non-water areas**
  - Focus on the water area only

Vision-based Segmentation

- **Segmentation reference**: shoreline
- **Hough transform**
  - Line extraction
  - Visual features: h_i and k_i
- **Drawbacks**
  - Compute-intensive (> 2 seconds/frame)
  - Low image quality
  - Blocked line-of-sight



Inertia-assisted Segmentation

- **Motivation**
  - Camera orientation characterizes projection
  - Various on-board inertial sensors
- **Mapping models**
  - Relate inertial with visual sensing

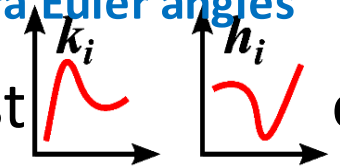
$$k_i = \omega_1 \times \frac{f_1 - \omega_2 \times f_2}{f_3 - \omega_2 \times f_4}$$

Euler angles (yaw, pitch, roll)

f_1, f_2, f_3, f_4: composed by trigonometric functions of camera Euler angles

ω_1 and ω_2 are unknown but constants

Visual features k_i, h_i

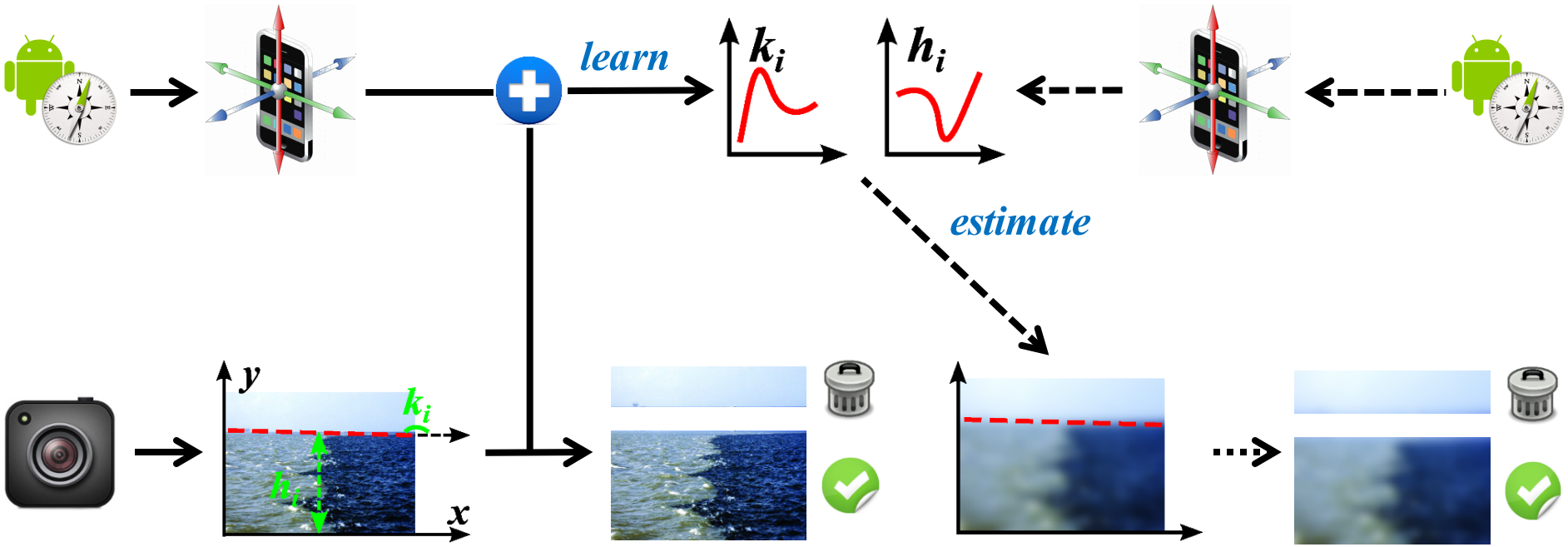


  - Model learning (e.g., regression)

Observation: $k_i \leftarrow$ camera

Variables: $f_1, f_2, f_3, f_4 \leftarrow$ inertial sensors

Energy-efficient Image Segmentation



Learning Phase →

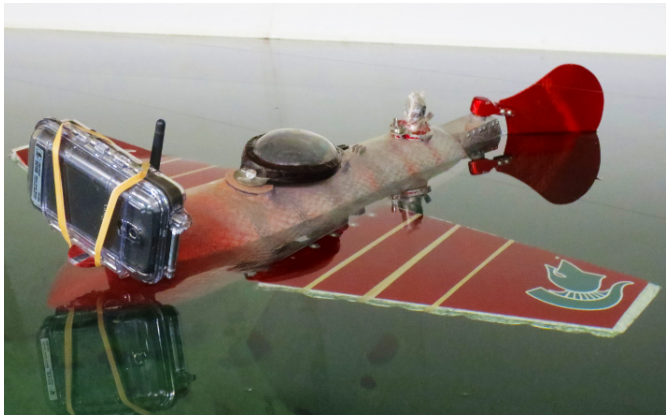
- **Use detected visual features**
- **Learn mapping models**

Estimation Phase -->

- **Use estimated visual features**

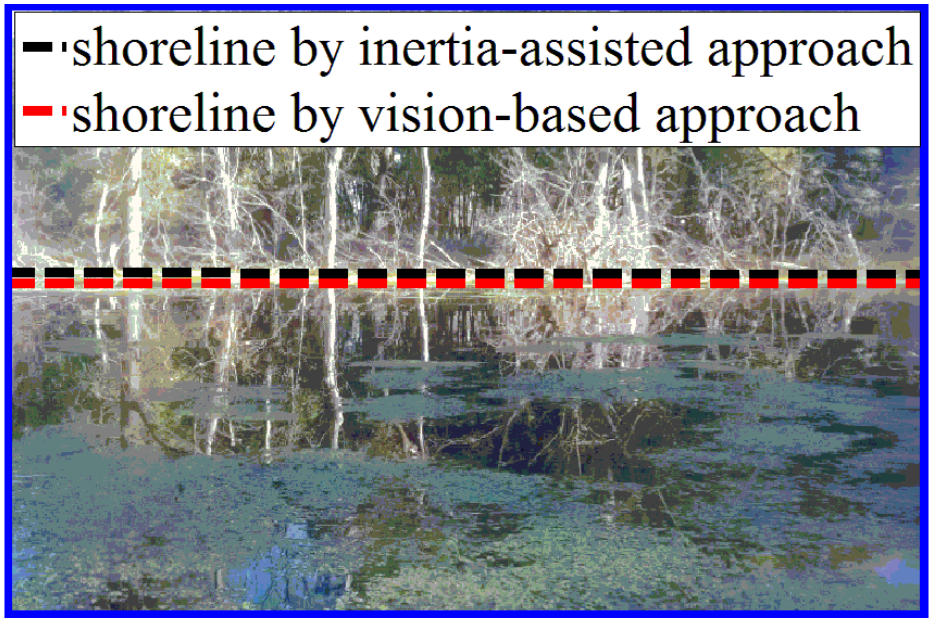
Experiment Settings

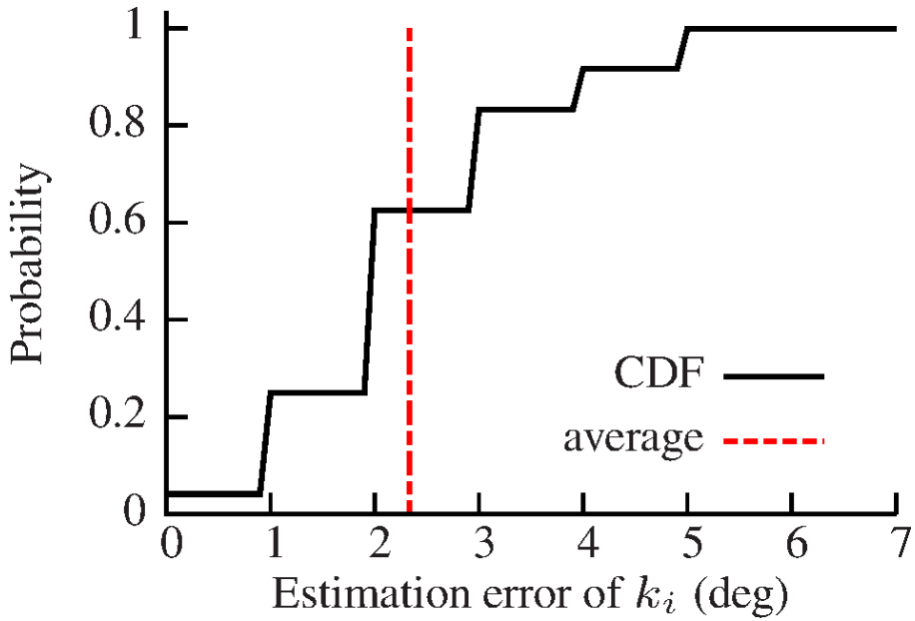
- **Samba prototype**
  - Samsung Galaxy Nexus
  - Gliding robotic fish
  - 6.24 MB storage, 10.8 MB RAM
  - Frame: 720 × 480 @ 0.5 fps



- **Experiment environments**
  - Field experiments in an inland lake: ~ 200,000 square feet
    Captured and processed 5,211 frames
  - Lab experiments in a water tank: 15 feet × 10 feet
    Evaluated under more dynamic environment

Image Segmentation Performance





Inertia-assisted approach accurately estimates the shoreline

Acknowledgement

- Current & past group members
  - 15 Ph.D students, 4 postdocs
- Collaborators
  - 20+ top experts in algorithms, signal processing, robotics, image processing, mechanical engineering, volcanology, communications, nursing
- National Science Foundation
  - Total 10 grants (8 as PI, 2 as Co-PI), over 8M USD since 2009

Representative Publications

- Practical Bluetooth Traffic Sniffing: Systems and Privacy Implications, The 14th International Conference on Mobile Systems, Applications, and Services (**MobiSys**), 2016, acceptance ratio: 31/197 = 15.7%.
- RunBuddy: A Smartphone System for Running Rhythm Monitoring, The ACM International Joint Conference on Pervasive and Ubiquitous Computing (**UbiComp**) 2015, acceptance ratio: 93/394 = 23.6%.
- Unobtrusive Sleep Quality Monitoring using Smartphones, The 11th ACM Conference on Embedded Networked Sensor Systems (**SenSys**), 2013, acceptance ratio: 21/123 = 17%.
- Nemo: A High-fidelity Noninvasive Power Meter System for Wireless Sensor Networks, ACM/IEEE Conference on Information Processing in Sensor Networks (**IPSN**), acceptance ratio: 24/115=21%, **SPOTS Best Paper Award**.
- Beyond Co-existence: Exploiting WiFi White Space for ZigBee Performance Assurance, The 18th IEEE International Conference on Network Protocols (**ICNP**), 2010, acceptance ratio: 31/170 = 18.2%, **Best Paper Award.**
- Supero: A Sensor System for Unsupervised Residential Power Usage Monitoring, 11th IEEE International Conference on Pervasive Computing and Communications (**PerCom**), 2013, acceptance ratio: 18/170 = 10.6%, **Best Paper Award Runner-up**.
- Passive Interference Measurement in Wireless Sensor Networks, The 18th IEEE International Conference on Network Protocols (**ICNP**), 2010, acceptance ratio: 31/170 = 18.2%, **Best Paper Candidate (6 out of 170 submissions).**
- Negotiate Power and Performance in the Reality of RFID Systems, The 8th Annual IEEE International Conference on Pervasive Computing and Communications (**PerCom**), 2010, acceptance ratio: 27/227=12%, **Best Paper Candidate (3 out of 227 submissions)** .
- ZiFi: Wireless LAN Discovery via ZigBee Interference Signatures, The 16th Annual International Conference on Mobile Computing and Networking (**MobiCom**), Chicago, USA, September 2010, acceptance ratio: 33/233=14.2%.
- LEAD: Leveraging Protocol Signatures for Improving Wireless Link Performance, The 10th International Conference on Mobile Systems, Applications, and Services (**MobiSys**), acceptance ratio: 33/210 = 15.7%
- COBRA: Color Barcode Streaming for Smartphone Systems, The 10th International Conference on Mobile Systems, Applications, and Services (**MobiSys**), acceptance ratio: 32 / 182 = 17.5%.
- PBN: Towards Practical Acitvity Recognition Using Smartphone-Based Body Sensor Networks, **SenSys**, 2011, acceptance ratio: 24/123=19.5.


THANKS
Image Credit: Giuseppe Milo @Flickr