RF Sensing: Improved Context Sensing for Future Cyber-Physical Systems

Neal Patwari

SPAN
Sensing and Processing
Across Networks

Outline

Outline

Neal Patwari

- BS and MS in EE from Virginia Tech
- Research Engineer at Motorola Labs, FL
- PhD in EE:Systems from U. Michigan - Ann Arbor
- Background in radio propagation & statistical signal processing
- At the University of Utah since 2006

SPAN Lab

SPAN

Sensing and Processing Across Networks

We investigate novel ways in which wireless networks and humans are sensors and actuators

Our research is funded by the NSF (CPS, NeTS, SCH), NIH (NIDA, NIBIB), and ARO

SPAN Lab People


Alemayehu Solomon Abrar


Prof. Sneha K. Kasera


Dr. Kyeong T. Min


Charissa Che


Pranav S. Kulkarni

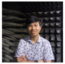

Goverdhan Pandla


Lucas M. Cowe


Phil Lundrigan


Snehapiriya


Dr. Ossi Kaltiokallio


Dr. Anh Luong


Gregory Spencer

Collaborators: Colleges of Medicine, Nursing, Science, Business, and Engineering (ChE, ME, CS, ECE)

Outline

Sensor Network Re-imagined

The radio itself, provided that it can measure the strength of the incoming signal, is the only sensor we use; with this sensorless sensing *approach, any wireless network becomes a sensor network.*

— From Kristen Woyach, Daniele Puccinelli, Martin Haenggi, "Sensorless sensing in wireless networks: implementation and measurements", IEEE WiOpt 2006

Re-purpose Radio Channel Measurements

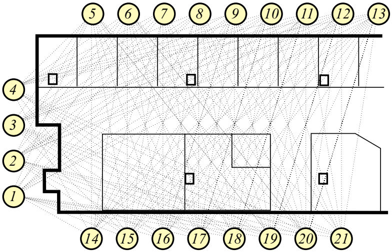
Large scale (low cost) wireless comms devices *must* est. the channel, but most don't allow access. We re-purpose:

1. Received signal strength (RSS)
2. Phase measurement unit (PMU)
3. MIMO channel state information (CSI)
4. Ultra-wideband channel impulse response (CIR)

Human Context: Device and Device-free

- **Device**: Locating transceivers in frequency, time, space. Applications in: *spectrum monitoring*, *ad hoc navigation*
- **Device-free**: tracking positions and vital signs of people who carry no device. Applications in: smart buildings, safety, *security*, *health*

Device-free Localization: Problem Statement



- Radio channel measurements change most due to people in environment near link
- One person / object affects multiple links
- Mesh network of N nodes $\rightarrow \mathcal{O}\left(N^2\right)$ RSS measurements
- Find: Count, locations of people

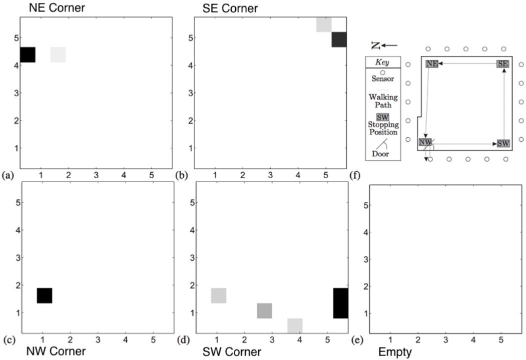
Radio Tomographic Imaging

We first explored radio tomographic imaging (RTI) for DFL:

1. Measure attenuation y_l on radio link l (or other channel measure)
2. Presume it is linear combination of presence x_p in pixels p close to link line
$$\mathbf{y} = W\mathbf{x} + \mathbf{n}$$
3. $W = [[w_{l,p}]]_{l,p} =$ weight of pixel p in link l
4. Pick regularization method
5. Solve inverse problem

Pros: Fast, real-time algorithm; scales with # people

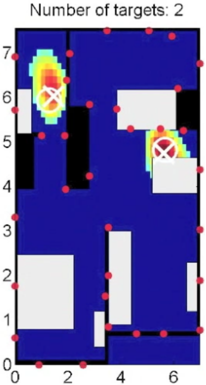
RTI: First Results



A person walks to four positions in an empty room. 20 sensors measure change in RSS at 915 MHz, calculated image ests. shown[1]

[1] N. Patwari and P. Agrawal, "Effects of Correlated Shadowing: Connectivity, Localization, and RF Tomography", *ACM/IEEE Information Processing in Sensor Networks (IPSN)*, 2008, St. Louis.

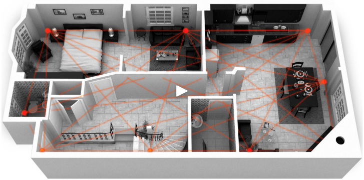
RSS-DFL: Survey of Current Capabilities

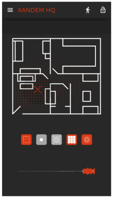


- Error: 7cm - 2m (5-35 nodes in 15-150 m^2)
- Multiple people, building structure, motion vs. change, 2D & 3D, in & outdoors
- Algs: RTI, ML, statistical inversion
- Challenge: true spatial model $w_{l,p}$ in multipath
- Our focus: Spatio-temporal statistical models, algorithms, estimation bounds

[1] N. Patwari, “One decade of sensorless sensing: Wireless networks as human context sensors”, IEEE Signal Processing and Wireless Communications (SPAWC) 2015, Plenary Talk Slides

Commercialization





- RSS-based security system / home automation sensor
- Indiegogo crowdfund: raised US $160k in 2016
- Next gen: embedded in switches, outlets
- Also: Aura (CSC), Origin Wireless

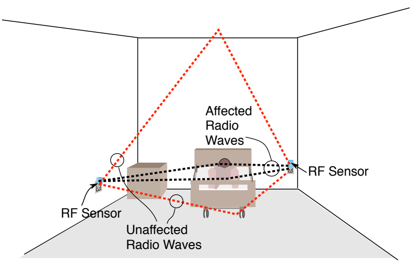
Our Current DFL Research

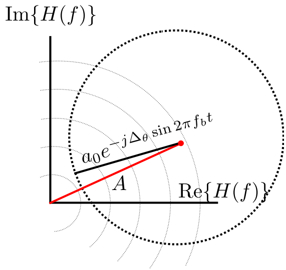
1. Extended Kalman Filter (EKF): Approaches bound (CRLB) but diverges
2. RTI: Robust to unknown link params but higher variance
3. RTI & EKF Fusion: Robust & low variance[2](10 cm RMSE)[3]
4. Current: Est. link params using unlabelled RSS data

[3] O. Kaltiokallio, R. Hostettler, N. Patwari, "A Novel Bayesian Filter for RSS-based Device-free Localization and Tracking", (in preparation).

Outline

RF-based Breathing Rate Estimation

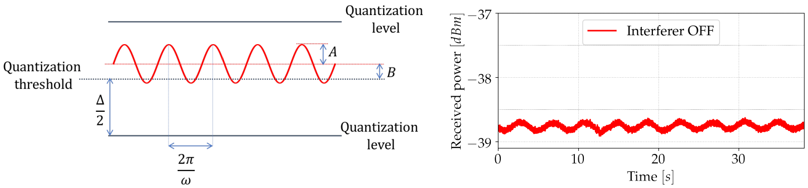




RX sees a phasor sum of affected (black) and not affected (red) paths. A phase change to affected paths changes the RSS (squared magnitude of the sum).

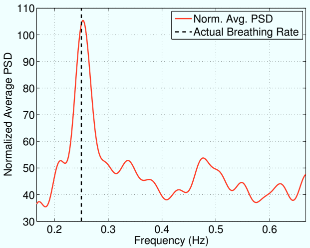
- Related: radar reflectometry for vitals monitoring
- Observation: Breathing *also* changes RSS on some links

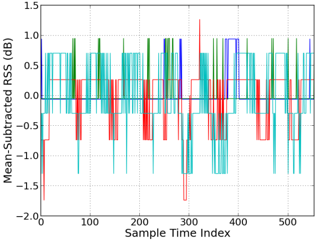
RF-based Breathing Monitoring: Problem



- Typical RSS peak-to-peak change of 0.1-0.2 dB
- Quantization step size: 1 dB
- Many links will not observe breathing-induced changes

Breathing Rate Estimation



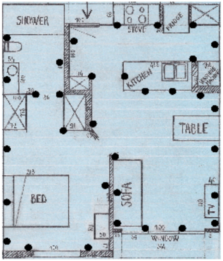


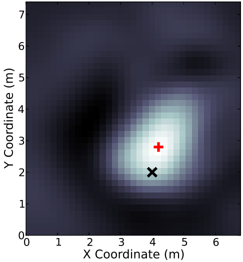
Patient breathing at 0.25 Hz: (Left) Avg. PSD over all links. (Right) RSS vs. time (30 sec duration) for five best links.

- One solution: Measure many links; RSS changes in some
- This setup: 20 sensors around patient bed [4]
- Estimator: Peak of avg. PSD (MLE) has 0.4 bpm error

[4] N. Patwari, et al. “Monitoring Breathing via Signal Strength in Wireless Networks”, *IEEE Trans. Mobile Computing*, 2014.

Breathing Localization

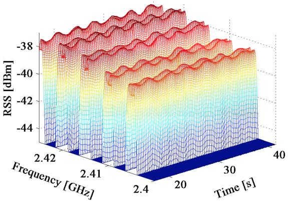




- Amplitude at breathing rate $\propto$ link - person proximity
- Breathing Tomography: Locate breathing w/ 2 m avg. error[5]

[5] N. Patwari, et al. “Breathfinding: A Wireless Network that Monitors and Locates Breathing in a Home”, *IEEE J. Sel. Topics in Signal Processing*, 2013.

Breathing Monitoring: Two Devices

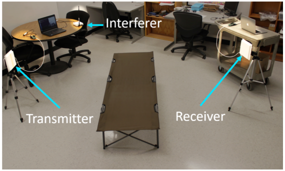


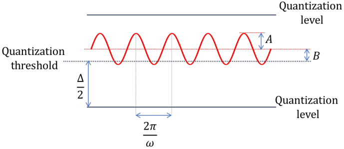
Filtered RSS in 2.4 GHz band, 30 sec

- Another solution: oversample 100X & measure many freq. channels[6]
- Due to noise, probability of each RSS value changes over time
- Error: about 0.4 breaths/min

[6] O. Kaltiokallio, H. Yiğitler, R. Jäntti, and N. Patwari,"Catch a breath: non-invasive respiration rate monitoring via wireless communication", IPSN 2014.

Breathing Monitoring: Add Noise

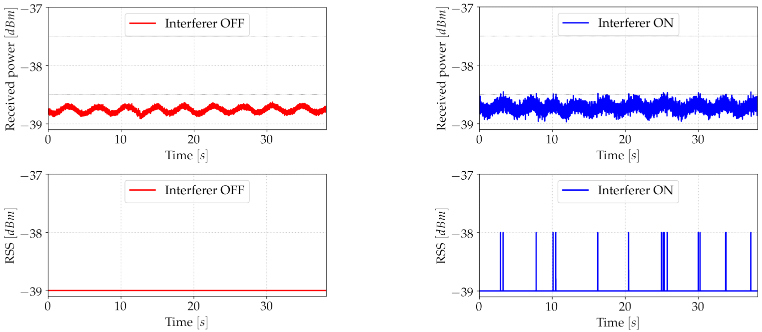




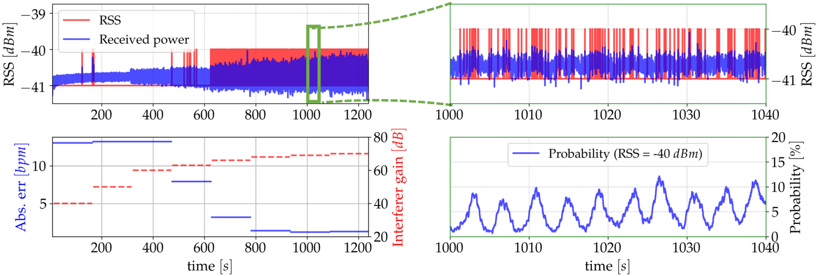
- Another solution: transmit interference from 3rd device[7]
- Setup: TX 64 square QAM signal, known power
- Increases probability RSS takes two quantized values

[7] A. S. Abrar, N. Patwari, A. Baset, S. K. Kasera, “Bounding the Ability to Monitor Breathing via Received Signal Strength”, ACM CCS 2018 (submitted).

Add Noise = Add Robustness



Exp Results: Error vs. Interference Power



Interferer power is increased each 180 sec (- - - -). At high power, abs. err. is reduced, and has a minimum. (RIght)

Zoomed in quantized RSS (red) shows increased probability of being $= -40$ dBm once per period.

Breathing Monitoring: Privacy Issue

- Hesitation to place a video camera in private spaces
- People know what a hacker might access from video
- Most don't know a hacker could est. your vital signs & activity from any transceiver

[7] Image credit: "Amazon's Echo Spot is a sneaky way to get a camera into your bedroom", The Verge, 28 Sep 2017.

Attack on Breathing Privacy

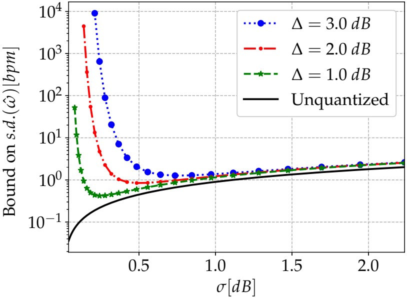
Assume a hacker can run s/w on transceivers in your home, and access RSS $y[k]$:

$$y[k] = Q\left\{A \cos(\omega k/f_s + \phi) + B + \nu[k]\right\},$$

quantization function $Q\{\}$, amplitude A, phase ϕ, time k, and offset B, in noise $\nu[k]$, at the highest sample rate f_s possible from the transceiver IC.

What is this attacker's ability to est. breathing rate?
How should transceiver RSS output be limited?

Attack on Breathing Privacy: Our Approach

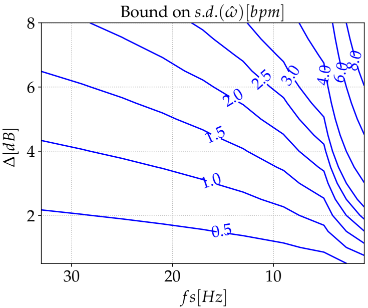


- Cramér-Rao lower bound (CRLB) on variance of unbiased est. of rate ω
- Assume noise is iid $\mathcal{N}(0, \sigma^2)$
- Offset from quantization threshold B is uniform

- Bound: fcn. of Δ (step size), f_s, σ[8]
- Assume best case for attacker: optimal interference power

[8] A. S. Abrar, N. Patwari, A. Baset, S. K. Kasera, “Bounding the Ability to Monitor Breathing via Received Signal Strength”, ACM CCS 2018 (submitted).

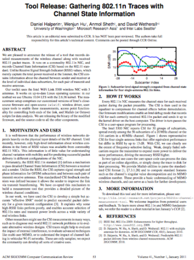
Implications of Our Approach



- CRLB: std. dev. ($\hat{\omega}$) only guaranteed high when RSS step size is high (6 dB) & RSS update frequency is low (2 Hz)
- Bad news for transceivers for mobile (fading) channels (e.g., power control)
- Future work: Adaptive RSS schemes in h/w that reduce rate, accuracy in static channels

Outline

WiFi CSI


Tool Release: Gathering 802.11n Traces with Channel State Information

Daniel Halperin, Wenjun Hu, Anmol Sheth, and David Wetherall
University of Washington, Microsoft Research Asia, and Intel Labs Seattle

ABSTRACT

1. MOTIVATION AND USES

2. HOW IT WORKS

3. MORE INFORMATION

4. REFERENCES

ACM SIGCOMM Computer Communication Review 53 Volume 41, Number 1, January 2011

- Release of Halperin CSI Tool → revolution in device-free *
- Hack of Intel WiFi 5300 driver: complex gain per subchannel, antenna pair
- Also: Atheros CSI Tool (Yaxiong Xie, NTU)
- E.g. apps: Gesture recognition, fall detection, identification, vitals monitoring, occupancy, smoking detection, secret key generation, object tracking

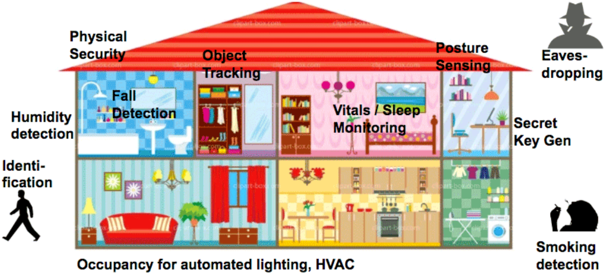
[8] D. Halperin, "Tool Release: Gathering 802.11n Traces with Channel State Information", ACM SIGCOMM CCR, 2011.

[8] Yaxiong Xie, Zhenjiang Li, and Mo Li. "Precise power delay profiling with commodity WiFi" in ACM MobiCom 2015.

Decawave UWB Impulse Response

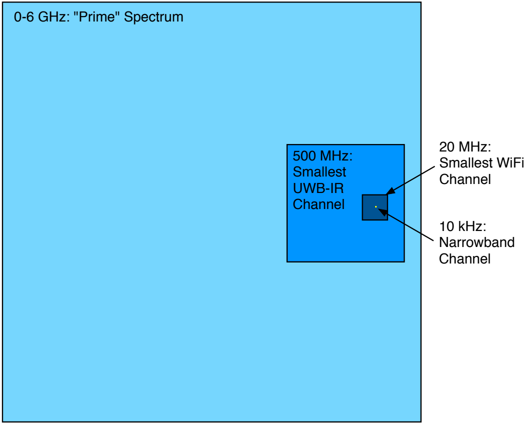
- Similar effect: Decawave DW1000 UWB-IR transceiver
- Module Cost: $20 vs. $1000
- *IPSN Localization Competition* winners

Proposed Applications



Each application occupies a single channel 50% to 100%

Problem: Where's the Bandwidth?



Wideband RF sensing will place significant strain on the spectrum

New Platform: Goals

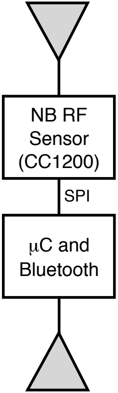
Implement the method in software, place examples of the software's use in the paper, make the software of broad functionality, and give the software away for free.

— From David Donoho, "How to be a widely cited author in the mathematical sciences", 2002.

Key: Enable NB RF sensing

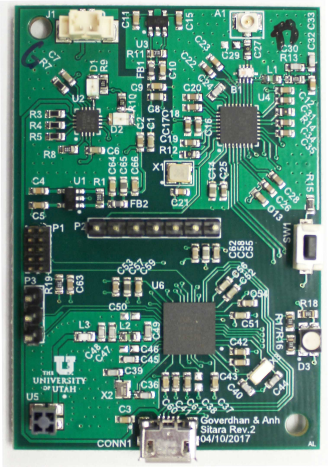
- Hypothesis: the major benefit is the *channel measurement resolution*.
- Current NB: RSS quantized to 1 dB. Goal: remove this limitation
- Enable: phase & frequency measurement, raw IQ samples, 2nd radio for data xfer
- Keep it low cost so that individuals, students have them for fun (be the Raspberry Pi of RF Sensing)

New Platform: Sitara



- RF Sensor: TI CC1200 $<$ 1 GHz radio
  - Provides complex baseband samples at 45 kHz
  - Transmit (limited modulations) and receive
- μController: Nordic nRF52
  - Good computation: ARM Cortex M4, floating pt.
  - Bluetooth 5 radio (1.5 Mbps data out)

New Platform: Sitara



- Total cost: $25 (ICs, antenna, battery, PCB, case)
- vs. RTL-SDR: +TX and BLE, but narrowband
- vs. WiFi-CSI: no need for uP

Outline

1. Capability of Sub-dB RSS

- Calculate RSS from $\sum_i |s_i|^2$
- Cable / Attenuator test shows 0.012 dB RMSE: "Sub-dB"
- Setup: Person breathing in bed at 0.25 Hz, CC1200 at 434 MHz. Breathing rate errors of 0.1 breath/min.

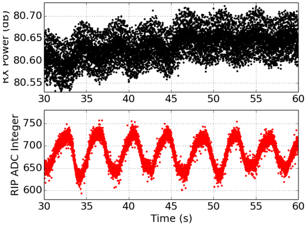


Figure: (top) Sub-dB RSS while person is breathing, (bottom) ground truth via resp. impedance plethysmography (RIP)

1. Implications of Sub-dB RSS

- Good performance with $\geq$ 12 bits ($\leq \frac{1}{16}$ dB step size) RSS
- Need about 30 Hz sample rate

[8] Anh Luong, Alemayehu S. Abrar, T. Schmid, N. Patwari, “RSS Step Size: 1 dB is not Enough!”, ACM HotWireless 2016.

1. How Does Sub-dB RSS Compare?

Conducted human subjects study at U. Sleep-Wake Center[9]:

- 20 participants, each >8 hours of data (public data set, 90 GB)
- Four technologies side-by-side
- Results: 1) WiFi CSI, 2) UWB-IR, 3) Sub-dB RSS, 4) Zigbee RSS
- Lesson: Sub-dB accurate when “on”, more chs. to be robust

9 P. Hillyard et al., “Comparing Respiratory Monitoring Performance Using Commercial Wireless Devices,” conditionally accepted for *ACM Mobicom 2018*.

1. Applications of Sub-dB RSS

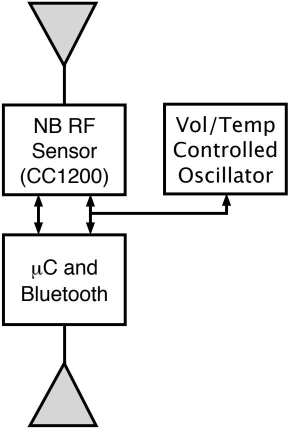
Sub-dB has low noise and a high sampling rate → surprising applications:

- Gesture recognition [Luong 2016]
- Pulse rate estimation
- Remote structural monitoring via vibrations
- Audio eavesdropping
- Detection of drones
- Walking speed estimation[10]

Current and future work: outdoor applications of Sub-dB

[10] A. S. Abrar, A. Luong, P. Hillyard, N. Patwari, “Poster Abstract: Link Line Crossing Speed Estimation with Narrowband Signal Strength”, ACM MobiCom 2017.

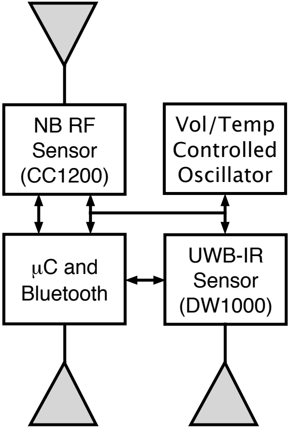
2. Sitara in Frequency Synchronization



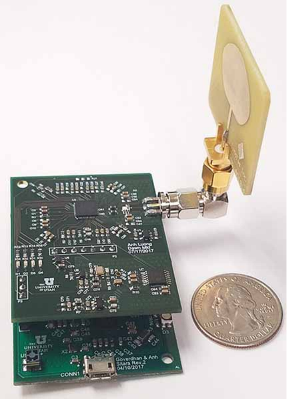
- Phase is sent to μC
- Frequency Est: Unwrap & linear regression
- Move VCTCXO, which moves RF
- Repeat.
- We synch devices' osc. to within 3 ppb[11]

[11] Anh Luong et al., "A stitch in time and frequency synchronization saves bandwidth" *ACM/IEEE IPSN 2018*.

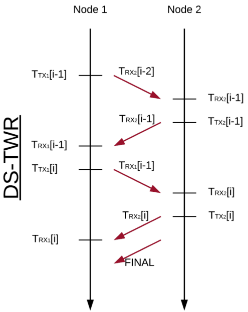
2. Sitara in Time Synchronization



NSF Project: Locate football players at high rate for collision detection (& actuation). We connect a UWB-IR radio to Sitara for high-resolution ranging.



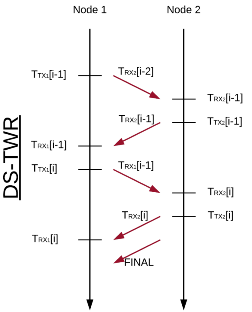
2. Time Synchronization Motivation



All messages are sent via UWB

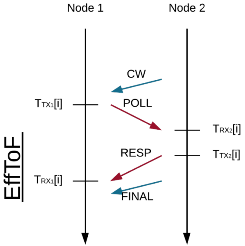
- Standard protocol: 1/2 of messages for freq. synch
- Limited by UWB-IR channel – 8 nodes can be located at 3.5 Hz

2. Time Synchronization Results



All messages are sent via UWB

- EffToF: Use NB radio for freq. synch, time stamp comms
- Results: Same accuracy, 60% less UWB channel than SOTA



(red) messages are sent via UWB, (blue) via NB radio

2. Future Work

Detection of impending collision (< 200 ms) using UWB range meast's

- Simplest alg: measure range, alarm when predicted to be low
- CRLB: it may help to *also* measure with neighbors
- Need: new algorithms

3. Sitara as a Pocket SDR

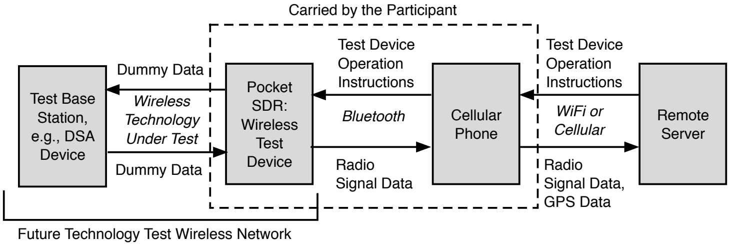
- Future: Our devices are DSA / cognitive
- How well will they work? Depends on our mobilities
- Simulation is limited by mobility, channel models
- We propose giving 100s of “Pocket SDRs” to people to carry as they do their phones
- Researchers can remotely run SDR experiments

3. Sitara as a Pocket SDR

- Application: Crowd-sourced localization of spectrum offenders
- E.g.: jamming worm serially infects phones
- How to find simultaneous transmitters?
- Must preserve privacy: Locate and count TXes via power measts
- Initial work: 1 m avg. err. on Orbit testbed (400 m^2)[12]

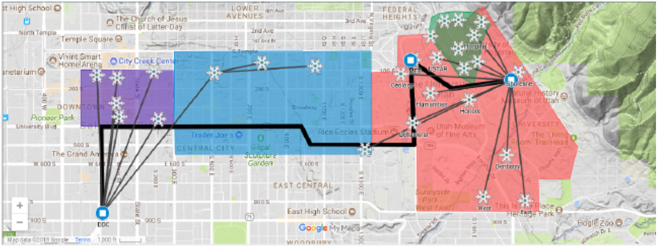
[12] M. Khaledi et al., “Simultaneous power-based localization of transmitters for crowdsourced spectrum monitoring”, ACM MobiCom 2017.

3. Sitara as a Pocket SDR



A user's cell phone is the control channel / data backhaul for the Pocket SDR, which interacts with other Pocket SDRs and deployed devices.

3. Powder: Platform For Advanced Wireless Research



- Largest SDR testbed: 18 BS deployed over 10 km^2
- Mobility: buses, city vehicles, volunteers
- Remote access to “bare metal” of each device
- `https://powderwireless.net/`

3. Pocket SDR: Future Work

- Build flexibility, reprogramability into Sitara for Pocket SDR applications
- Run real world experiments with 100s of participants

Outline

Conclusion

- Wireless interface is a sensor for use in device-free and device localization, breathing monitoring, synchronization
- Flexible easy-to-use platforms can influence research directions
- Sitara provides narrowband RF sensing platform
- Many estimation, detection, classification problems yet to be solved