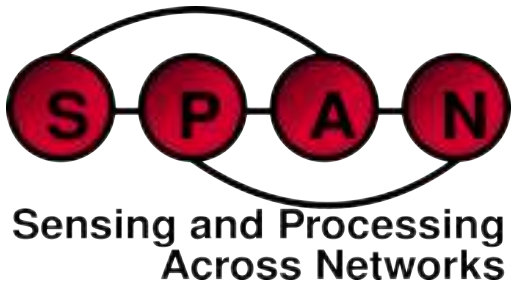
Tracking without Tags

Environmental Awareness using RF Tomography

Neal Patwari



IEEE RFID 2014

Outline

Outline

RFID / RTLS Goals

Image credit: `http://info.zentech.com/`

- Track everything
- Don’t pay much per thing
- RF is advantageous
- This talk: same goals

Tracking People

Image: http://www.rfidjournal.com/articles/view?11615

- People are often *the* application
- Not all people will wear tags
- Safety: Evacuations, aging-in-place
- Security: Monitoring, surveillance

Tracking Things

Image credit: Disney Pixar

Most things don't move themselves.

Device Localization (RTLS)

- RFID identifies, locates people's radio tags
- Passive tags must be close to a reader
- Ranging challenges in (indoor) multipath environments

Device-free Localization

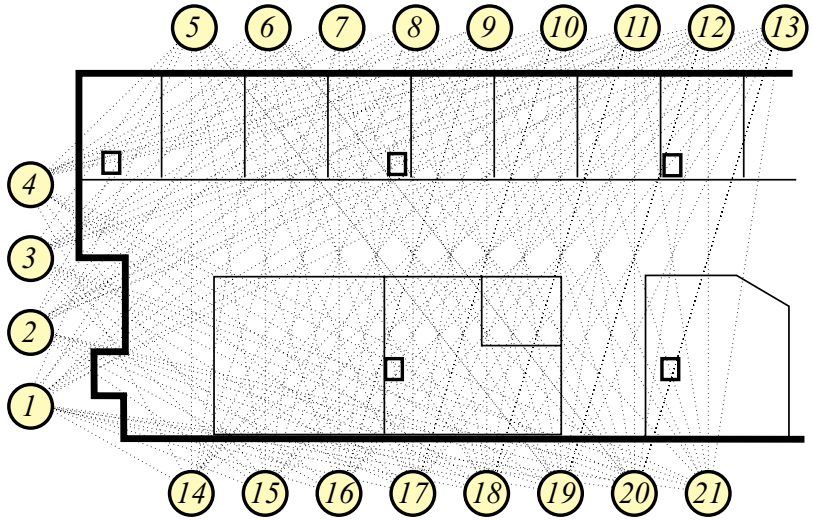
- Video cameras. Don't work in dark, through smoke or walls. Privacy concerns.
- Thermal imagers. Limited by walls. High cost.
- Motion detectors. Also limited by walls. High false alarms.
- Radar: High cost, bandwidth

RF Environmental Sensing

- Assume static L links
- Measure received signal strength (RSS)
- Standard (low cost) COTS radios
- RSS: Environment $\rightarrow \mathbb{Z}^L$
- RSS has spatial memory [1]

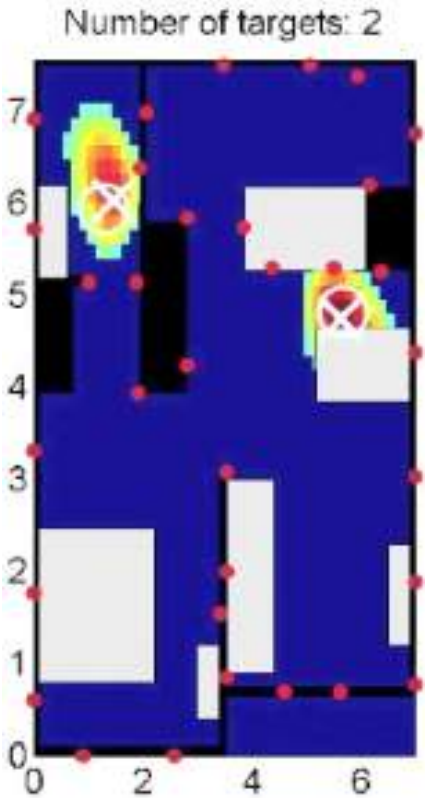
[1] K. Woyach et. al., "Sensorless sensing in wireless networks: implementation and measurements", *WiNMee 2006*.

RSS-DFL: Measure many spatially distinct links



- Link RSS changes 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

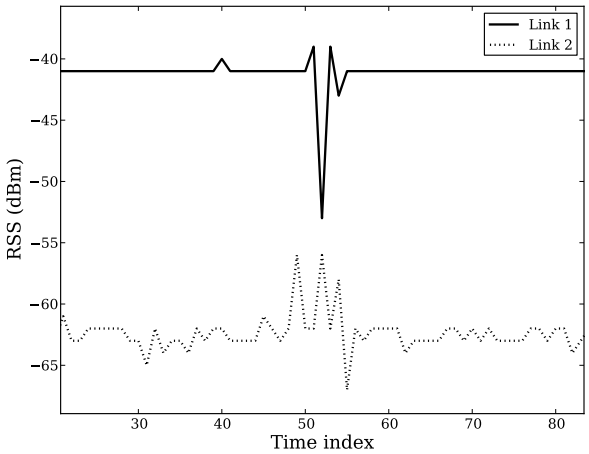
RSS-DFL: Current capabilities



Many experimental tests report 10 cm - 1 m avg. error using 10-35 nodes in 15-150 m^2, and can track 1-4 people.

Outline

RSS Demo

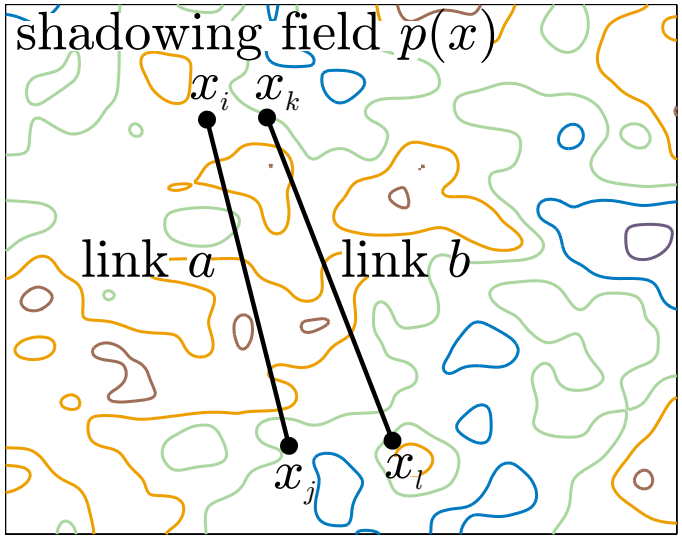


- CC2531 “TI dongle node”
- 2.4 GHz, IEEE 802.15.4
- 15 channels (11-25)
- RSS measured for each packet
- TDMA protocol

Radio Tomographic Imaging (RTI)

1. Quantify “presence” on link
2. Presume it is linear combination of presence in pixels
3. Pick regularization method
4. Solve inverse problem

History: Shadowing as Linear Spatial Filter



- Two nearby links' shadowing is correlated
- Model: shadowing is a line integral of a spatially correlated shadowing field[2]

[2] N. Patwari and P. Agrawal, "Effects of correlated shadowing: connectivity, localization, and RF tomography," *IPSN 2008*.

Discrete-space Model

- Consider simultaneously all M pair-wise links:

$$\mathbf{y} = W\mathbf{x} + \mathbf{n}$$

- $\mathbf{y} = [y_1, \ldots y_M]^T$ = measured "change" in RSS
- $\mathbf{x} = [x_1, \ldots x_N]^T$ = discretized presence field (e.g., dB/voxel)
- $W = [[w_{i,j}]]_{i,j}$ = weights; $\mathbf{n}$ = noise

Shadowing Field Estimation Problems

- Measure **y**, change in RSS from empty period
- Assume known W. Estimate **x**.
- Ill-posed! Pixels $\gg$ links, other issues
- Linear model isn't true physics; W is unknown.

Real-time Approaches to Image Estimation

- Real-time requirement: linear estimator

$$\hat{\mathbf{x}} = \Pi \mathbf{y}$$

- Projection Π needs only be calculated once
- Complexity: Order of # Links $\times$ # pixels
- Regularization: *e.g.*, Tikanov, Least-squares

Regularized Image Estimation Algorithms

1. Regularized inverse: minimize penalized squared error[3]

$$f(\mathbf{p}) = \|W\mathbf{p} - \mathbf{x}\|^2 + \alpha\|Q\mathbf{p}\|^2$$

when Q is the derivative:

$$\Pi_{Tik} = \left[W^T W + \alpha(D_X^T D_X + D_Y^T D_Y)\right]^{-1} W^T$$

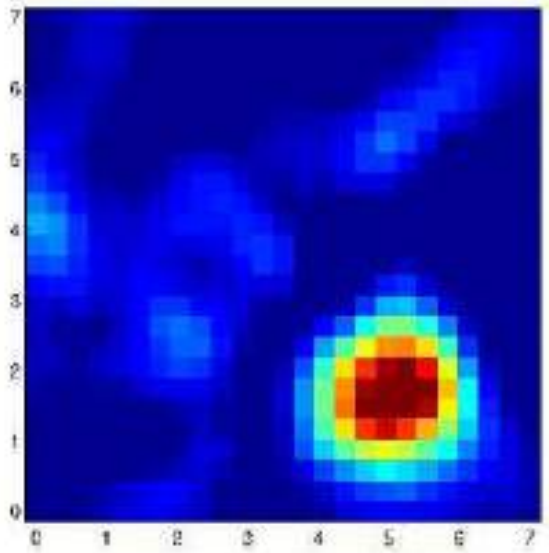
2. Assume correlated $\mathbf{p}$ and use regularized least squares.

$$\Pi_{RLS} = \left(W^T W + \alpha C_{\mathbf{p}}^{-1}\right)^{-1} W^T$$

[3] J. Wilson and N. Patwari, "Radio tomographic imaging with wireless networks", *IEEE TMC*, 2010.

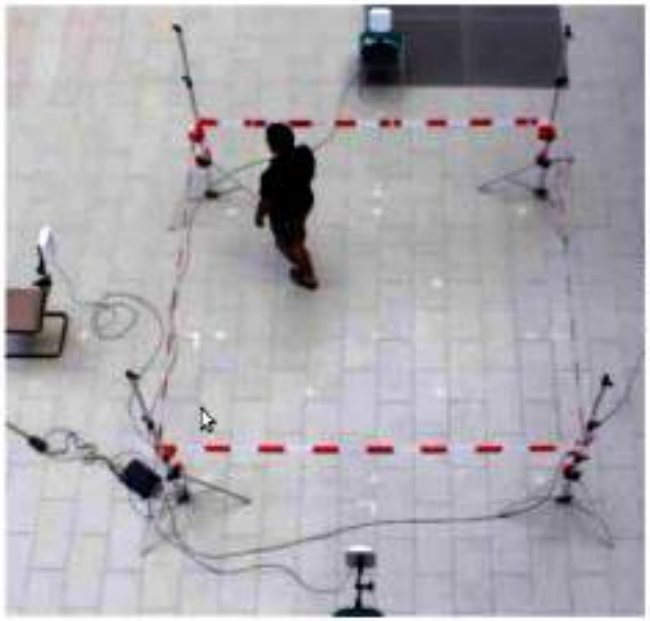
Shadowing RTI

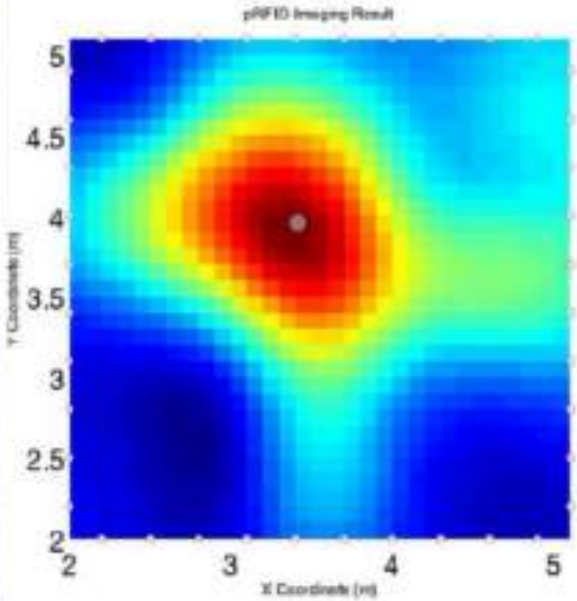
- Experiment: Open deployment in atrium



Shadowing RTI with Passive Tags

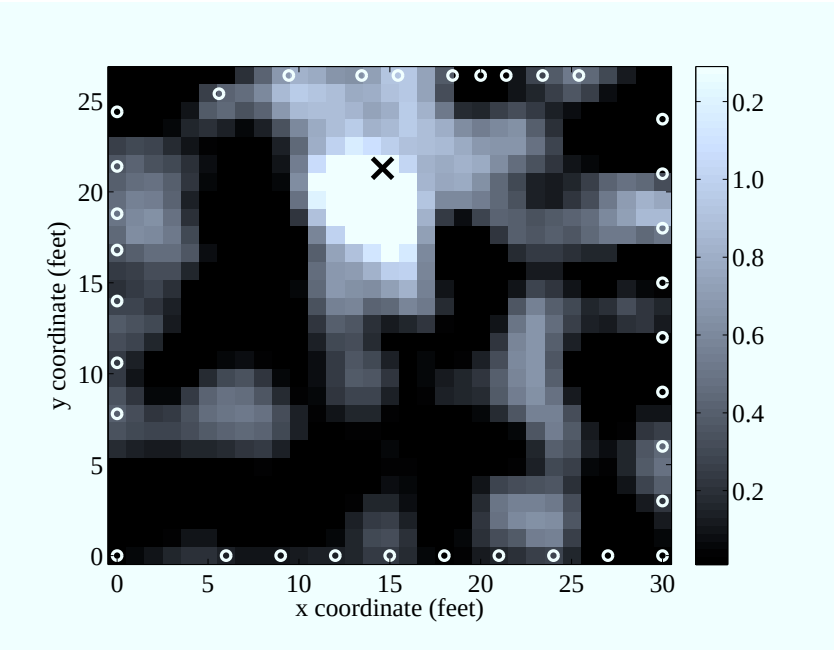
- Reader: 2 TX, 2 RX; 40 passive tags on floor of 16 m^2 area[4]
- 30 cm average error





[4] B. Wagner, B. Striebing, D. Timmermann, "A system for live localization in smart environments", *IEEE ICNSC*, 2013.

Variance-based RTI



- Use variance for $\mathbf{y}$, for through-building[5]
- Same regularized inversion approach

[5] J. Wilson and N. Patwari, " See through walls: motion tracking using variance-based radio tomography networks", *IEEE TMC*, 2011.

VRTI Through Building

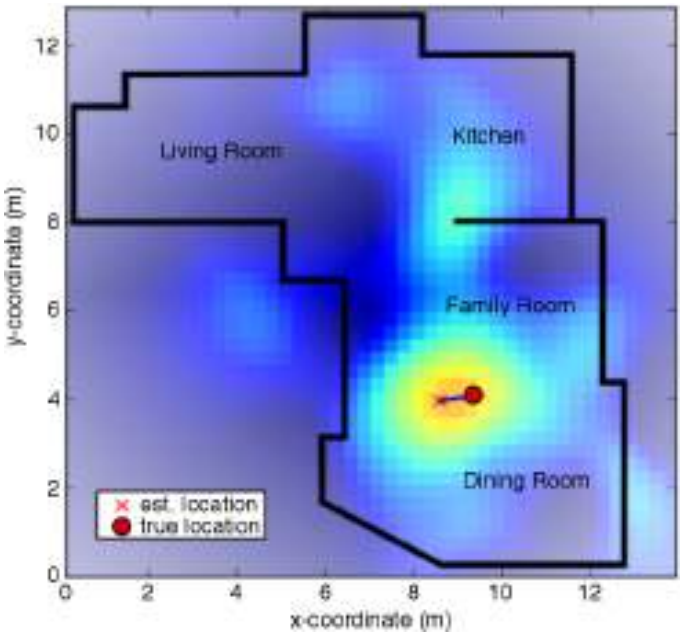
Average error: 45 - 63 cm, in 72 m^2 area

Noise Reduction for RTI

- Wind causes movement of branches, leaves
- Covariance of noise can be measured in “empty periods”
- Least-squares (LS) method can negate it[6]
- Avg. error during wind: VRTI 3.0 m; LS-VRT 50 cm

[6] Y. Zhao and N. Patwari, “Robust estimators for variance-based device-free localization and tracking", arXiv:1110.1569v1, 2011.

Kernel Distance RTI

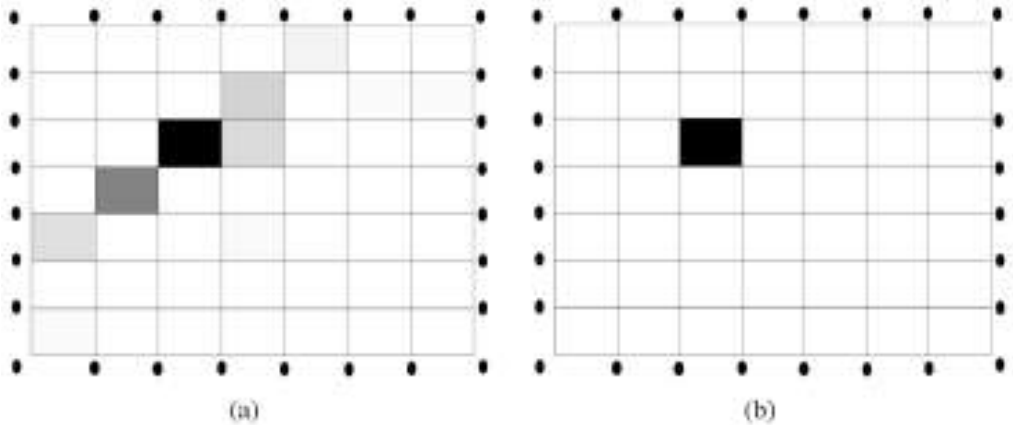


- Variance, mean: measures of distribution
- Alt: Kernel dist. btwn. long-, short-term histograms[7]
- Achieves 1.1 m error in through-wall system across 110 m^2 home[8]

[7] Y. Zhao et al., "Radio tomographic imaging and tracking of stationary and moving people via kernel distance", *IPSN 2013*.

[8] D. Maas, J. Wilson, N. Patwari, "Toward a rapidly deployable rti system for tactical operations," SenseApp 2013.

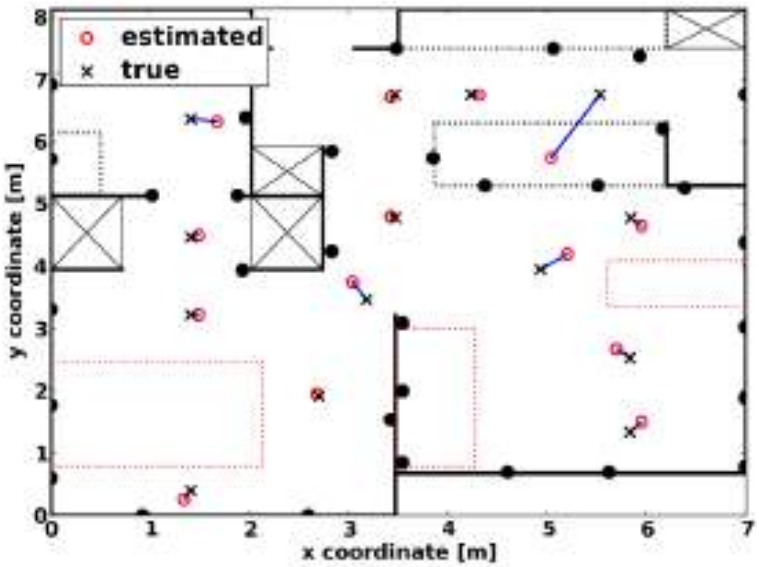
Exploit Sparsity



- Compressed sensing: send few meas'ts, recreate sparse image[9]
- Can be distributed

[9] M.A. Kanso and M.G. Rabbat, "Compressed RF tomography for wireless sensor networks: Centralized and decentralized approaches", DCOSS 2009.

Multiple Channel

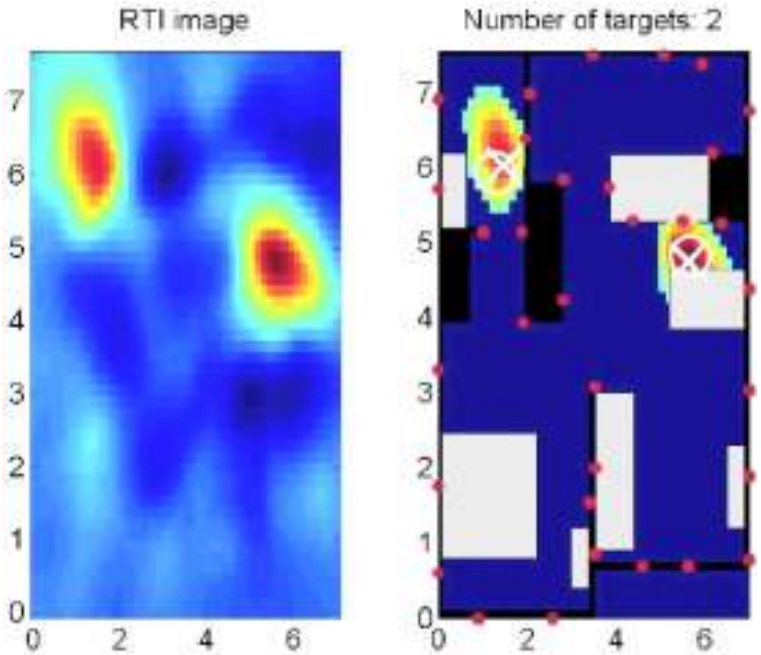


- Fading condition diversity. *Anti-fade* links are most informative
- Spatial model (ellipse width) should be a function of fade level and sign of RSS change[10]
- Auto-update calibration for long-term apartment (23 cm error)[11]

[10] O. Kaltiokallio, M. Bocca, N. Patwari, "A fade level-based spatial model for radio tomographic imaging," *IEEE TMC*, 2013.

[11] M. Bocca, O. Kaltiokallio, and N. Patwari, "Radio tomographic imaging for ambient assisted living," *Evaluating AAL Systems Through Competitive Benchmarking*, 2013.

Multiple Person Tracking

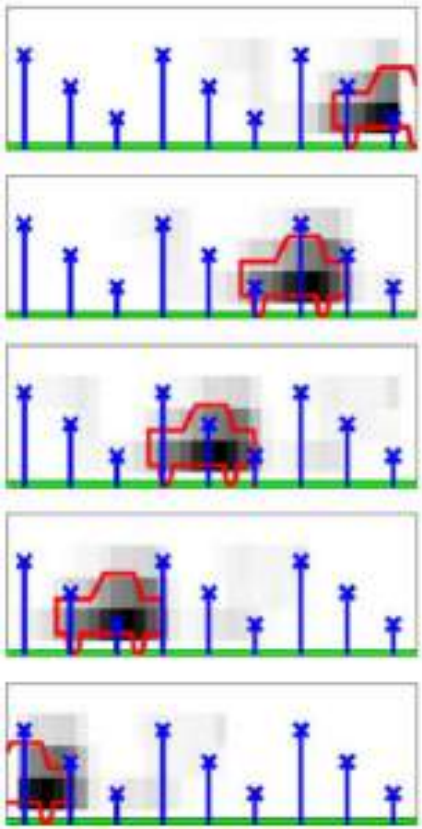


- Particle filtering, 0.7-1.0 m error [12]
- RTI-based, real-time, 1-4 people, < 55 cm error[13]

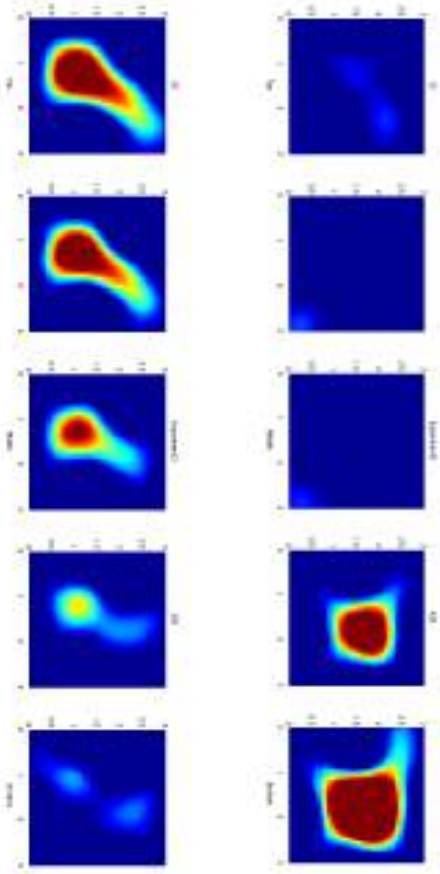
[12] F. Thouin, S. Nannuru and M. Coates, "Multi-target tracking for measurement models with additive contributions," ICIF 2011.

[13] M. Bocca et al., " Multiple target tracking with RF sensor networks," *IEEE TMC*, 2013.

RTI in 3-D



- Detect, classify vehicles on road [14]
- Classify person's pose [15]

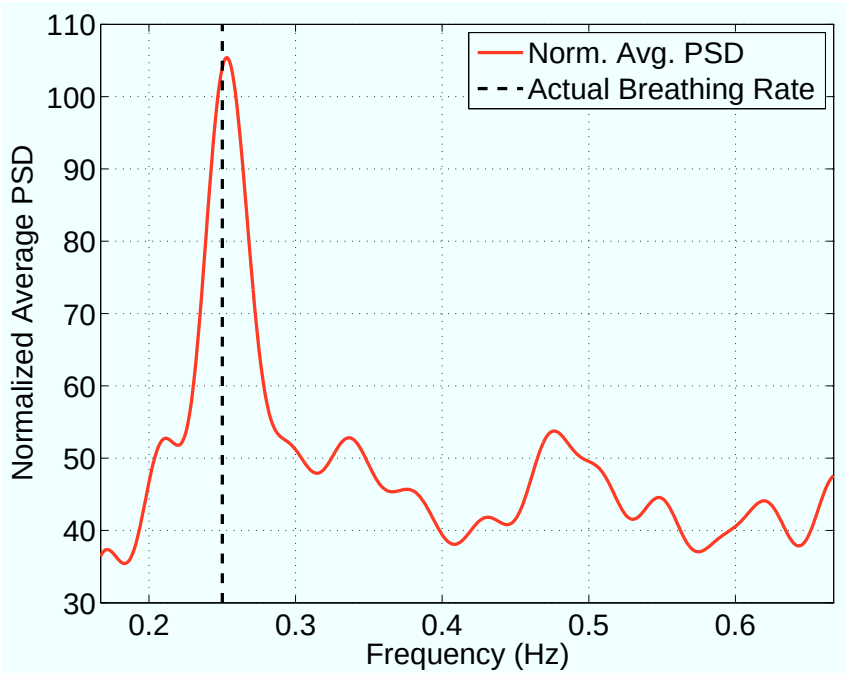


[14] C.R. Anderson, R.K. Martin, T.O. Walker, R.W. Thomas, "Radio tomography for roadside surveillance", *IEEE JSTSP*, 2014.

[15] B. Mager, N. Patwari, M. Bocca, "Fall detection using RF sensor networks", PIMRC 2013.

Breathing Rate Estimation

- Breathing causes periodic change in RSS (if o.w. stationary)
- Measure many links' RSS over time (30 s)[16]
- Or one link RSS over many channels[17]
- Average spectrum plot
- Within 0.2-0.4 bpm of actual

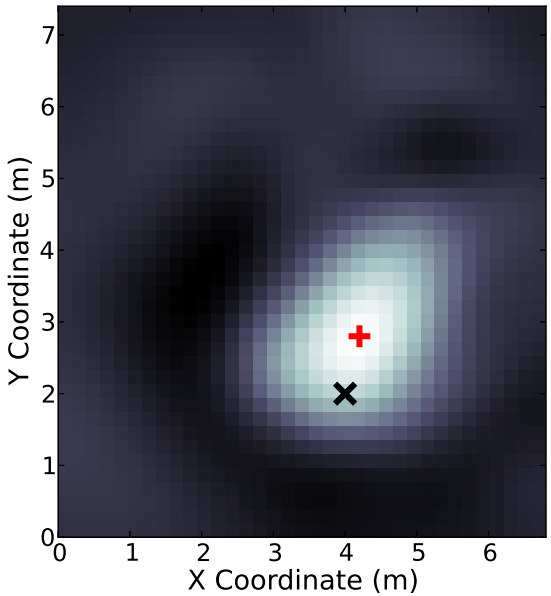


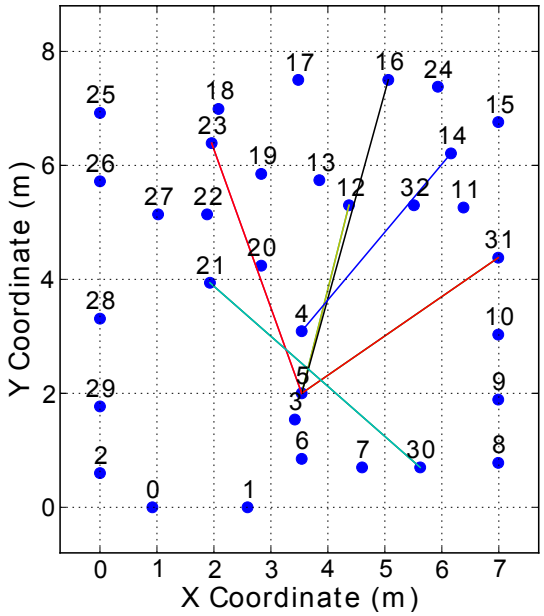
[16] N. Patwari et al., "Monitoring breathing via signal strength in wireless networks", *IEEE TMC*, 2014.

[17] O. Kaltiokallio et al., "Catch a breath: non-invasive respiration rate monitoring via wireless communication", IPSN 2014.

Breathing Localization

When a person is perfectly still in home they can still be located by breathing alone w/ 2m error[18]





[18] N. Patwari et al., " Breathfinding: a wireless network that monitors and locates breathing in a home", *IEEE JSTSP*, 2013.

RSS Fingerprint

- Attenuation/variance/histogram on each link forms high dimensional vector
- Train w/ person at each grid location
- Learn map from RSS vector to coordinate
- 2 m median error in hallways of 1500 m^2 area[19]
- 1.7 m avg. error in 150 m^2 area, tracking four people[20]

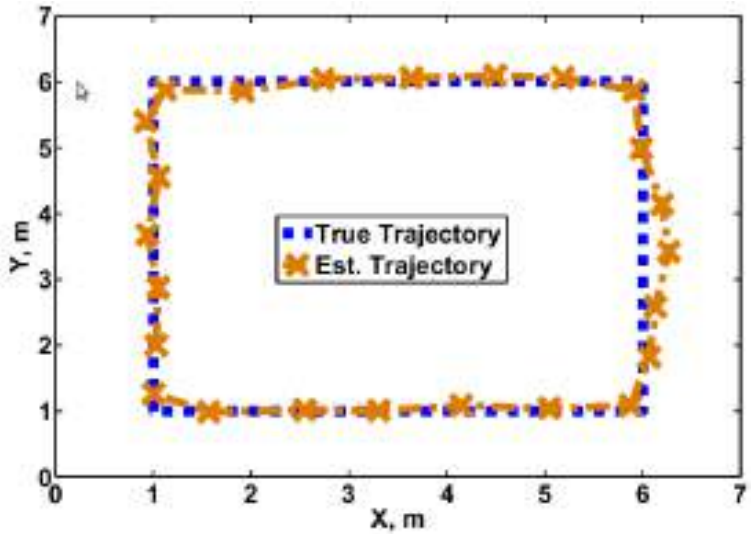
[19] M. Seifeldin et al., "Nuzzer: a large-scale device-free passive localization system for wireless environments", IEEE TMC 2013.

[20] C. Xu et al., "SCPL: indoor device-free multi-subject counting and localization using RSS", IPSN 2013.

RSS Fingerprint: Pros and Cons

- Need training w/ person on each grid point
- No need for sensor coords
- Exponential training complexity in # people
- Database degrades as other things move

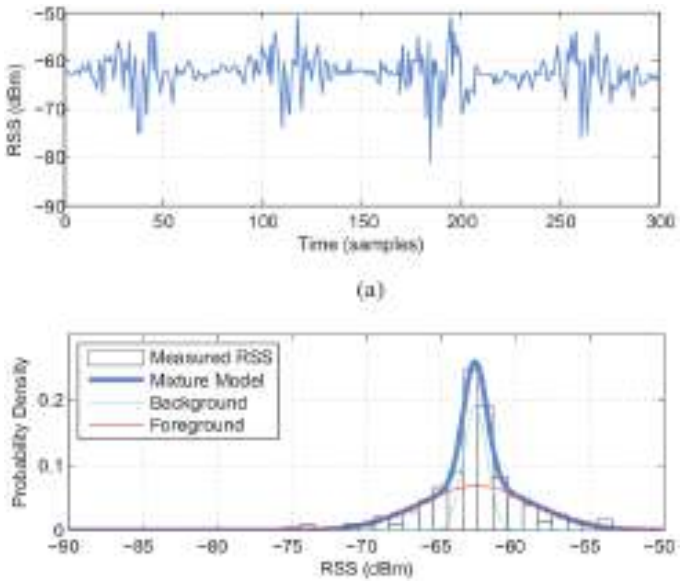
Statistical Inversion Method I



- Joint person tracking and sensor location[21]
- Expectation Maximization (EM)-based algorithm
- 30 cm error (open field, 49 m^2)

[21] Xi Chen et al., "Sequential Monte Carlo for simultaneous passive device-free tracking and sensor localization using received signal strength measurements", IPSN 2011.

Statistical Inversion Method II



- Learning of distribution of each link[22]
- Gaussian mixture model[23]
- 13 cm error (open field)

[22] A. Edelstein, M. Rabbat, "Background subtraction for online calibration of baseline RSS in RF sensing networks", IEEE TMC 2013.

[23] Yi Zheng and Aidong Men, "Through-wall tracking with radio tomography networks using foreground detection", WCNC 2012.

Outline

Model Intro

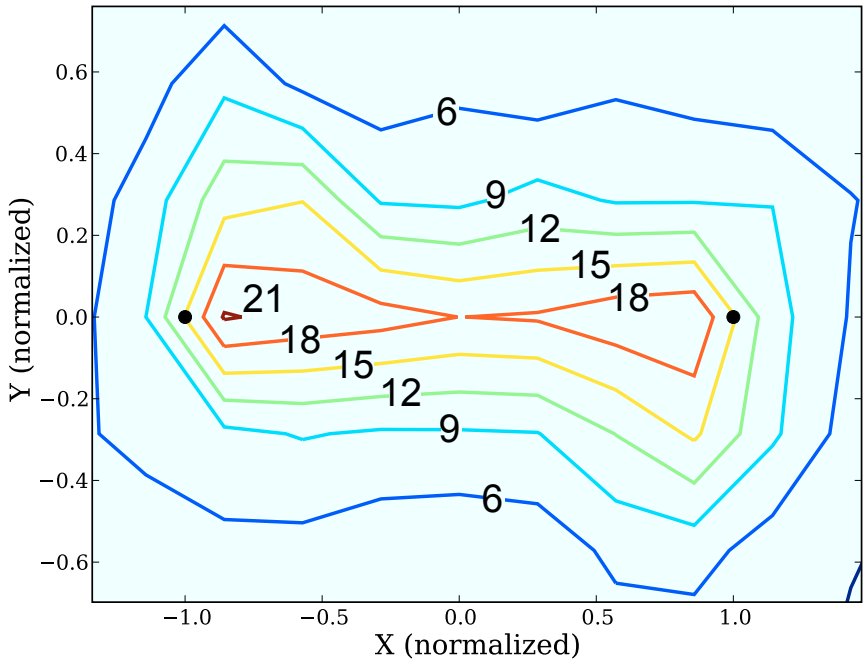
- *Spatial Models*: Where does a person's presence change RSS?
- *Temporal Models*: How does the change occur as a function of time?
- *Physical EM models*: What EM phenomena are most important? How can we predict effects for untested objects?
- *Statistical Models*: What distribution will be measured?
- *Multi-target models*: What are the effects of multiple people compared to one?

Spatial Model: Experimental

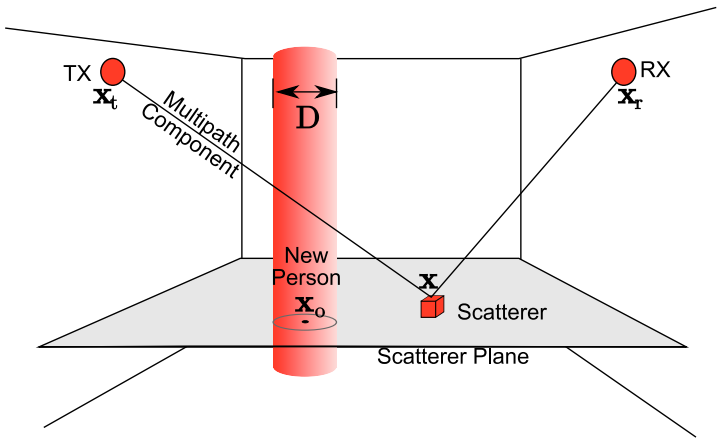
- Where does motion have highest impact on RSS variance?
  1. Near TX, RX [Yao et al. 2008]
  2. At midpoint between TX, RX [Zhang et al. 2007]
  3. Our work: In (narrow) ellipse w/ TX & RX as foci
  4. Pixels which intersect link line [Kanso and Rabbat 2009]
- Need for measurements, analytical models

Spatial Model: Experimental

- Measurement at THE UNIVERSITY OF UTAH Bookstore, nodes on shelves
- Normalize link, person position s.t. $\mathbf{x}_r = (-1, 0)$, $\mathbf{x}_t = (1,0)$
- Find average variance by human position w.r.t. RX, TX



Spatial Model: Setup



- Human = tall cylinder diameter D [Ghaddar et al. 2004, Huang et al. 2006]
- Scatterers/Reflectors in a plane. TX, RX, in plane Δz above[24]
- Propagation via single bounce

[24] N. Patwari and J. Wilson, "Spatial models for human motion-induced signal strength variance on static links", IEEE Trans. Info. Forensics & Security, 2011.

Spatial Model: Details

- Locations: TX $\mathbf{x}_t$, RX $\mathbf{x}_r$, bounce at $\mathbf{x}$
- Propagation mechanism (a) scattering or (b) reflection

$$\text{(a):} \qquad P_s(\mathbf{x}) = \frac{c_s}{\|\mathbf{x}_t - \mathbf{x}\|^2 \|\mathbf{x}_r - \mathbf{x}\|^2}$$

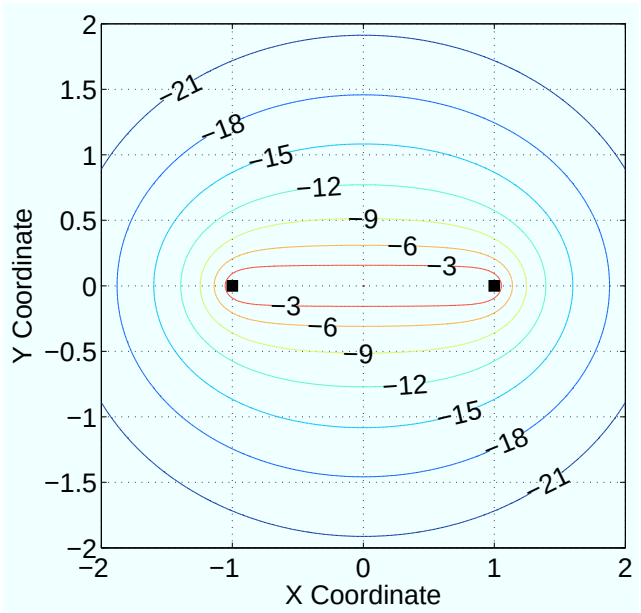
$$\text{(b):} \qquad P_r(\mathbf{x}) = \frac{c_r}{(\|\mathbf{x}_t - \mathbf{x}\| + \|\mathbf{x}_r - \mathbf{x}\|)^{n_p}}$$

- $c_r, c_s, n_p \in \mathbb{R}^+$ are propagation parameters [Nørklit & Andersen 1998, Liberti and Rappaport 1996]
- Variance prop. to expected total affected power (ETAP)

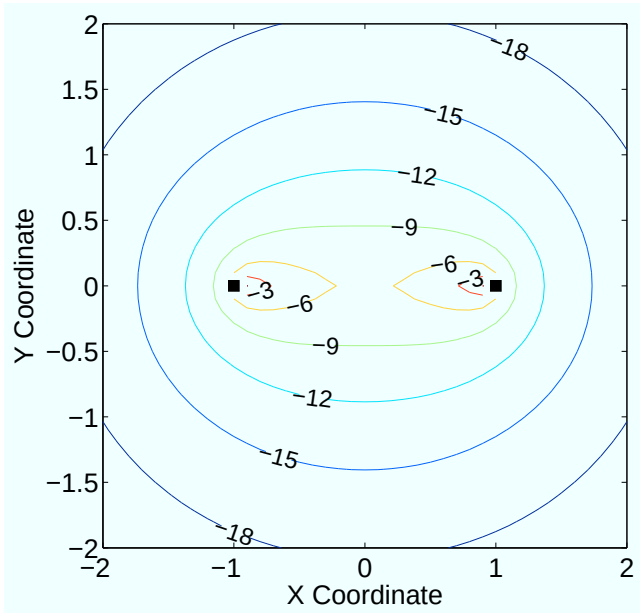
Spatial Model: Results

- Variance $\propto$ spatial functions:

(a)



(b)



- Ours & [Yao 2008]: similar to reflection ETAP, low Δz
- Those of [Zhang 2007]: high Δz, either modality

Statistical Model Challenge

Distribution of link RSS random process:

1. Function of person/people locations
2. Function of link length
3. Function of multipath fading characteristics

Enable estimation bounds, better algorithms

Outline

Open Research Areas

- Fundamental models
- Estimation bounds
- Tracking algorithms
- Other (wideband) channel information
- Other physical layers
- Merging tag and tag-free (+other modes?)

Commercialization

- `http://www.xandem.com`
- RSS-based motion detection system, *Xandem TMD*

Xandem TMD

MIAMI - Police in Miami say thieves broke through a wall in a neighboring store to steal the safe and surveillance equipment from the Caribe Restaurant overnight.

According to investigators, the burglary happened between midnight and 4 a.m. and the alarm did

Conclusion

- Person crossing causes informative changes in RSS on static link
- System of many links can be used in tracking
- Surprisingly accurate
- Look ma, no tags!

Questions and Comments

More info on `http://span.ece.utah.edu/`