Intelligent Systems with Wireless Network

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November 2019

Outline

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5G Applications at GE

- GE Aviation
  - Sensor data collection from aircraft engines
  - Wireless communication for different ranges
- GE Healthcare
  - Patient monitoring
  - Medical image data collection (CT/MR images)
- GE Power and Renewable
  - Wireless sensors (remove cables to reduce cost)
  - Real-time control (reduce latency)

GE Applications and DoD 5G Initiative

- Time-sensitive network for industrial asset real-time control
- Reduce latency for wireless sensor data collection
- Remove cables to reduce cost
- GE Research in DoD 5G initiative

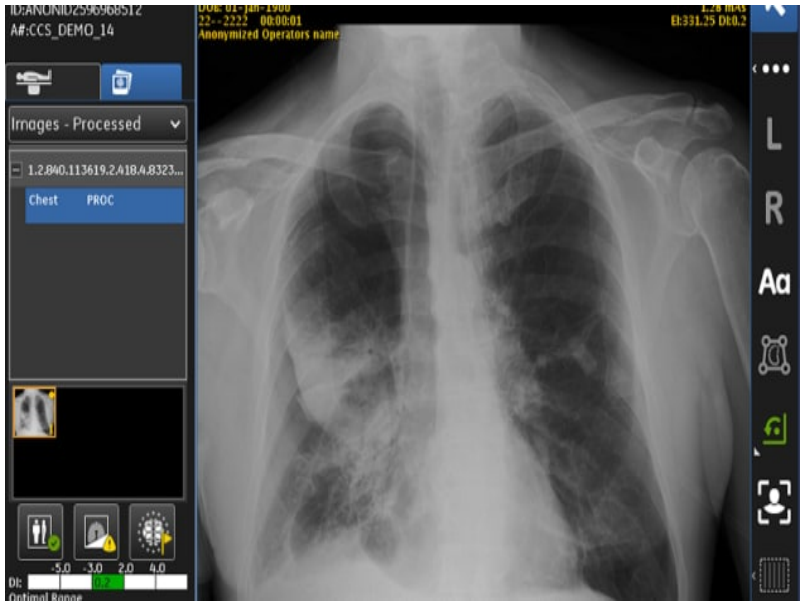
Aerial Inspection for Oil and Gas

- Autonomous Asset Inspection with Drones
- Project leads to a new business of GE Ventures [1]

[1] https://www.reuters.com/article/us-ge-drones/exclusive-ge-begins-testing-drones-to-inspect-refineries-factories-executive-idUSKBN1940I3

Medical Imaging: X-ray and Ultrasound

- Mobile X Ray System [2]
- Ultrasound Probe Tracking



[2] https://www.cnbc.com/2019/09/12/ges-health-unit-wins-first-fda-clearance-for-ai-powered-x-ray-system.html

Outline

Radio Tomographic Imaging (RTI): Model-based DFL

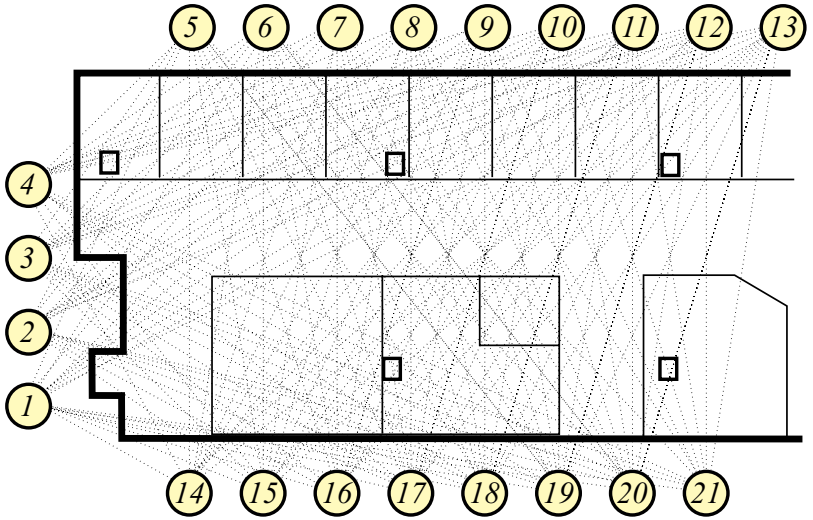
- RFID technique, locates people's tags
- How about people, objects not tagged?
- Applications: emergency response, smart homes, context-aware computing, etc.

Why Use RF Sensor Network for DFL?

- Video cameras: Don't work in dark, through smoke or walls. Privacy concerns.
- IR Motion detectors: Limited by walls. High false alarms.
- Military radars: High cost.
- Received signal strength (RSS) from RF sensor network: Noisy but low cost, not limited to line-of-sight scenario

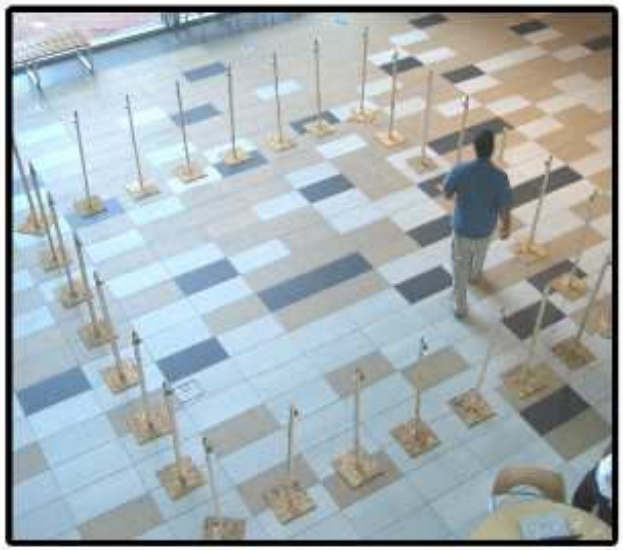
RSS-DFL: Measure Spatially Distinct Links

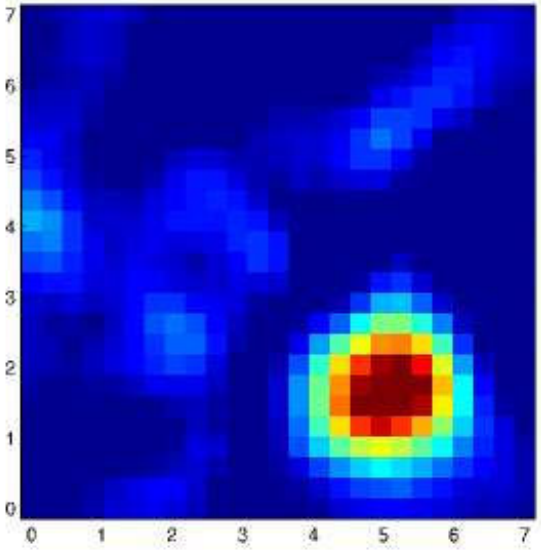
- Mesh network of N transceivers $\rightarrow \mathcal{O}\left(N^2\right)$ RSS measurements
- Link RSS changes due to people in environment near link



Radio Tomographic Imaging (RTI)

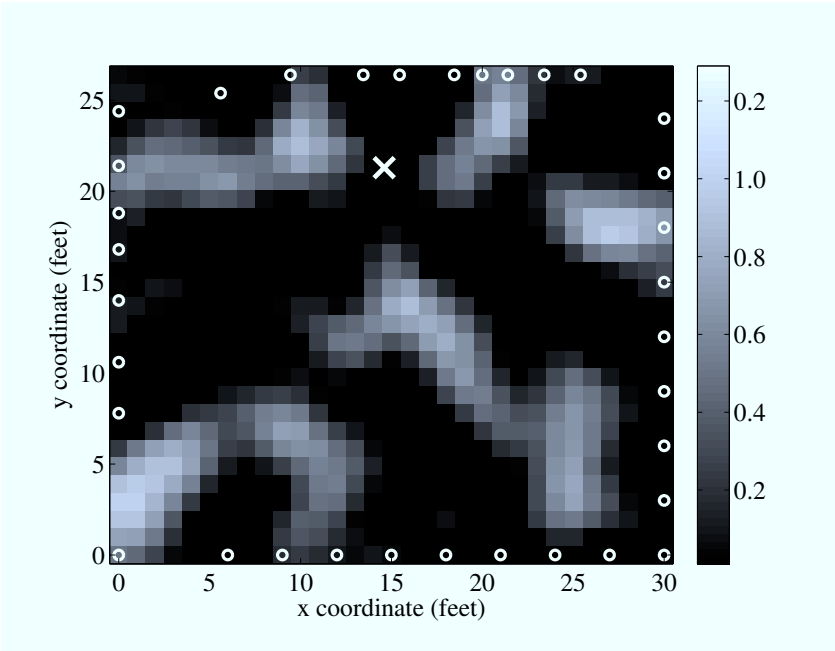
- Model-based, no training needed
- Submeter accuracy, real-time implementation



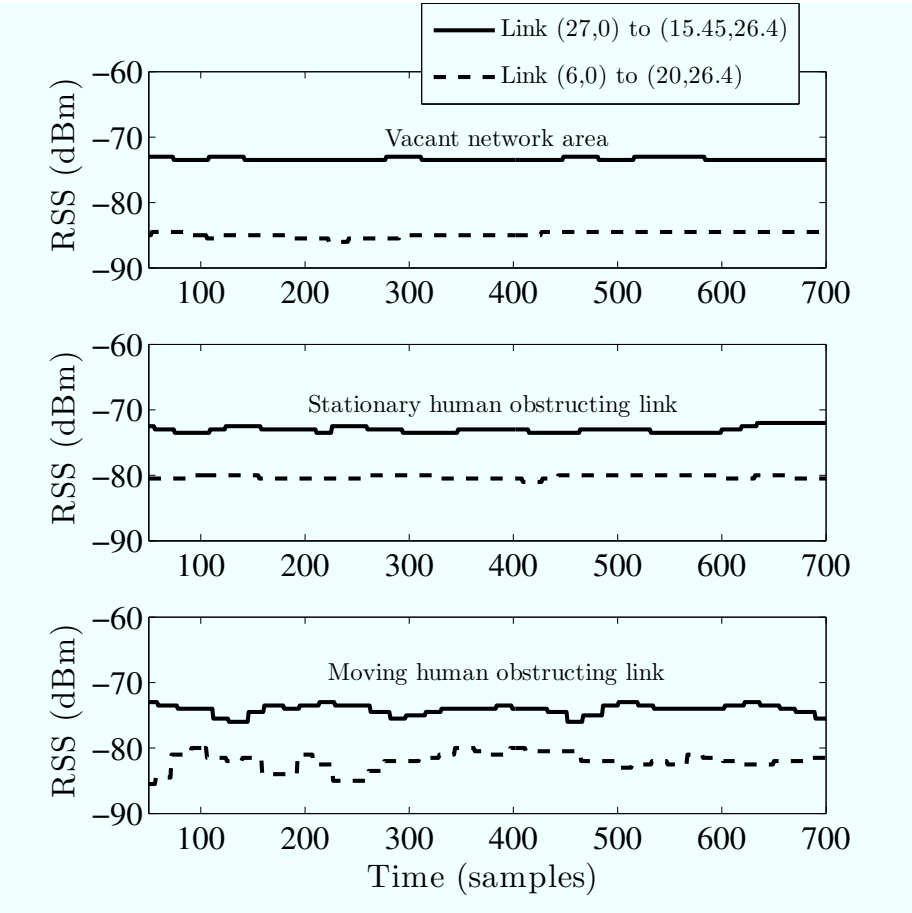


Problem of Through-wall Test

- Tested system with 34 nodes, outside of external walls of area of house
- Shadowing-based RTI does not indicate actual human location (X)



What Happened?



- SNR is too low due to multipath effect
- Blocking person increases RSS (- - - -)
- But, moving person increases RSS variance (both links)

Idea: Use Variance to Image Motion

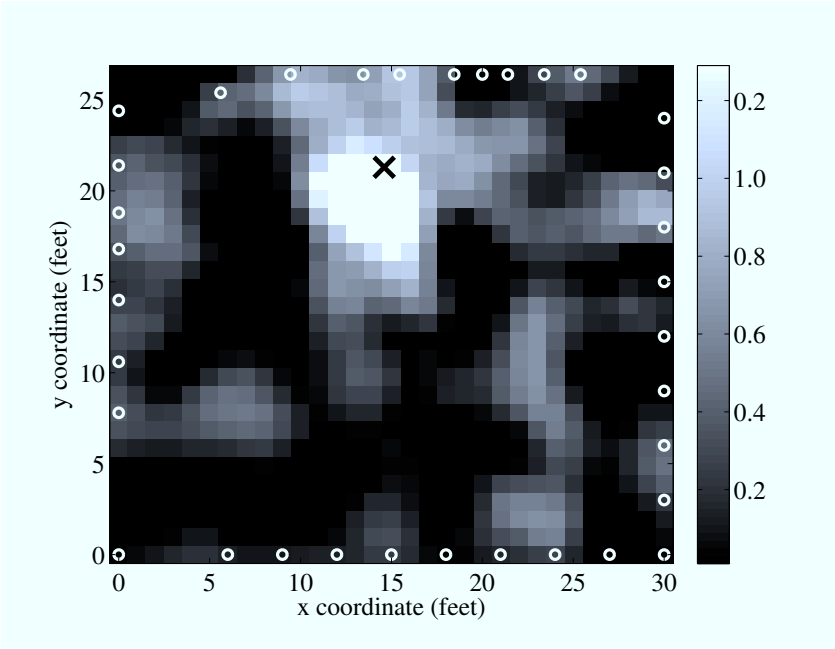
- Model: Assume variance is linear combination of motion occurring in each pixel:

$$\mathbf{s} = W\mathbf{m} + \mathbf{n}$$

- $\mathbf{s} = [s_1, \ldots s_M]^T$ = windowed sample variance
- $\mathbf{m} = [m_1, \ldots m_N]^T$ = motion $\in [0, 1]$
- $W = [[w_{i,j}]]_{i,j}$ = variance added to link i caused by motion in pixel j

Variance-based Radio Tomographic Imaging

- Ill-posed: apply regularized inversion to estimate **m**.
- VRTI image indicates actual human location (X)



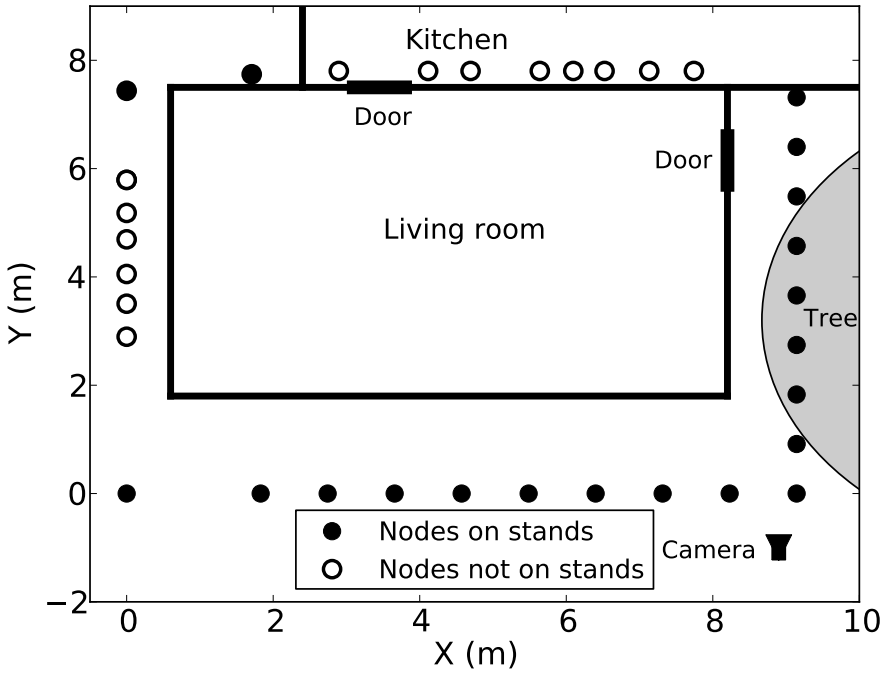
VRTI Video

- http://span.ece.utah.edu/radio-tomographic-imaging (avg. error = 0.63 m)

Start From Two Experiments

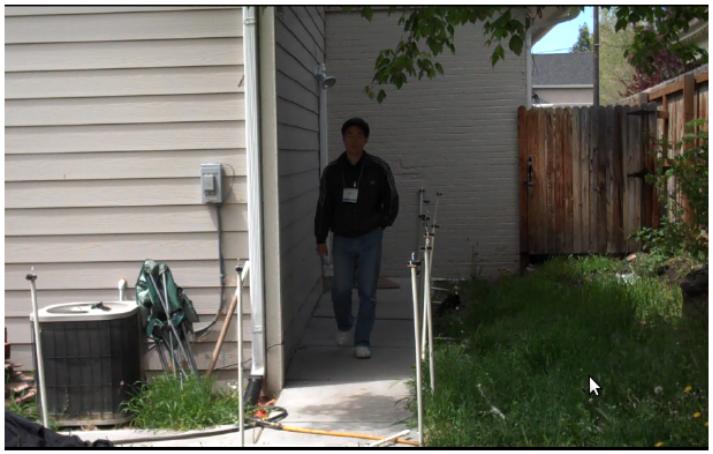
Experiments 1 and 2 are performed

- in the same residential house
- using 34 TelosB nodes, and TinyOS Spin program
- following the same procedure: calibration and real-time measurements.



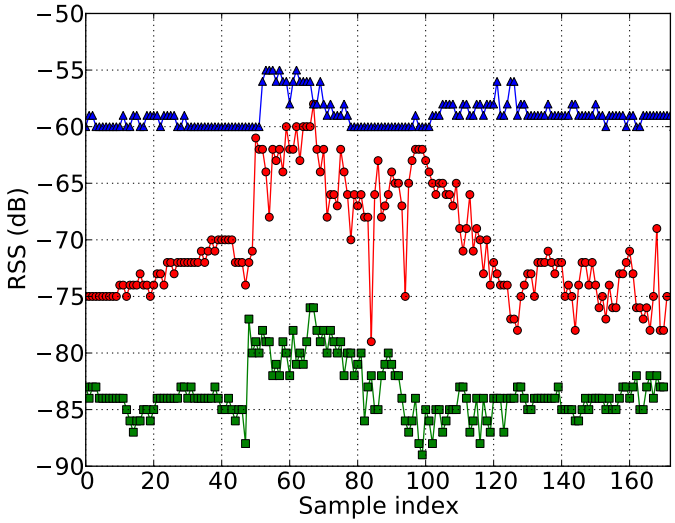
Problem of VRTI: Noise from Intrinsic Motion

- Identical experiments show very different VRTI performance on a still (Left) vs. windy day (Right)



RSS Variations Due to Intrinsic Motion

- Intrinsic motion: motion of objects that are intrinsic parts of an environment, *e.g.*, trees, fans, moving machines.



- Extrinsic motion: motion of people and other objects that enter and leave an environment

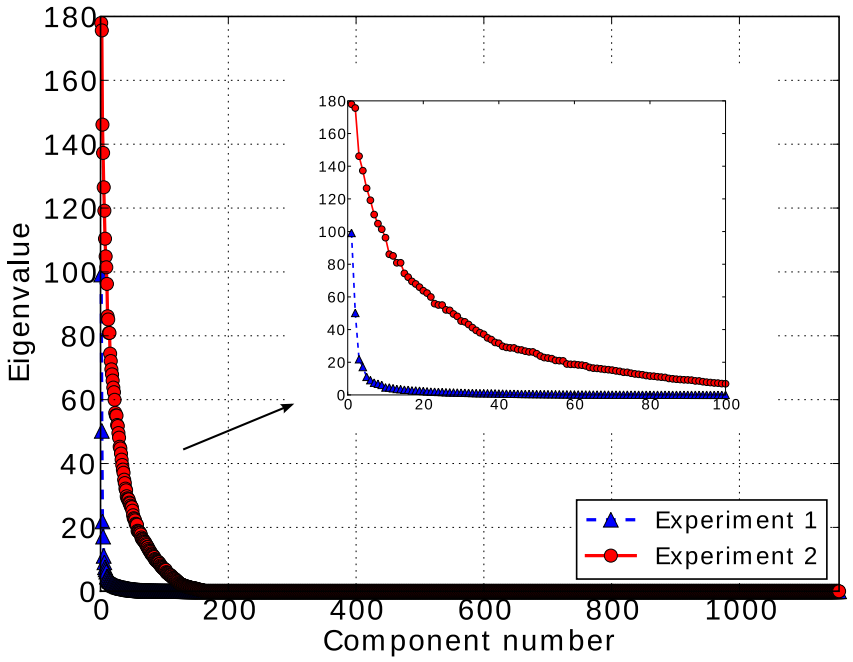
Subspace Variance-based Radio Tomography (SubVRT)

- Principal component analysis (PCA): capture the major feature of intrinsic motion
- Subspace decomposition: remove/reduce the effect of intrinsic motion [3]

[3] Y. Zhao and N. Patwari, "Noise reduction for variance-based device-free localization and tracking", *IEEE SECON 2011*.

PCA on Calibration Measurements

- Calibration measurements $\mathbf{s}_c$ only contain the effect from intrinsic motion
- Estimate the covariance matrix $C_{\mathbf{s}_c}$ of $\mathbf{s}_c$
- Perform SVD on $C_{\mathbf{s}_c}$: $C_{\mathbf{s}_c} = U \Lambda U^T$
- Capture intrinsic motion by the first k eigenvectors



Subspace Decomposition

- Divide all eigenvectors into two sets: $\hat{U} = [\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_k]$ and $\tilde{U} = [\mathbf{u}_{k+1}, \mathbf{u}_{k+2}, \cdots, \mathbf{u}_L]$.
- One subspace is spanned by $\hat{U}$ – the intrinsic subspace, the other is spanned by $\tilde{U}$ – the extrinsic subspace
- Project $\mathbf{s}$ on intrinsic and extrinsic subspaces to obtain intrinsic signal component $\hat{\mathbf{s}}$ and extrinsic signal component $\tilde{\mathbf{s}}$:

$$\hat{\mathbf{s}} = \Pi_I \mathbf{s} = \hat{U}\hat{U}^T \mathbf{s}$$

$$\tilde{\mathbf{s}} = \Pi_E \mathbf{s} = (I - \hat{U}\hat{U}^T)\mathbf{s}$$

SubVRT Formulation

VRTI

Using real-time measurement vector $\mathbf{s}_r$, the Tikhonov regularized solution is:

$$\hat{\mathbf{m}} = \Pi_1 \mathbf{s}_r \quad \text{where } \Pi_1 = (W^T W + \alpha Q^T Q)^{-1} W^T$$

SubVRT

Using decomposed extrinsic signal component $\tilde{\mathbf{s}}_r = \Pi_E \mathbf{s}_r$:

$$\hat{\mathbf{m}} = \Pi_2 \mathbf{s}_r \quad \text{where } \Pi_2 = (W^T W + \alpha Q^T Q)^{-1} W^T \Pi_E$$

Estimates from VRTI and SubVRT

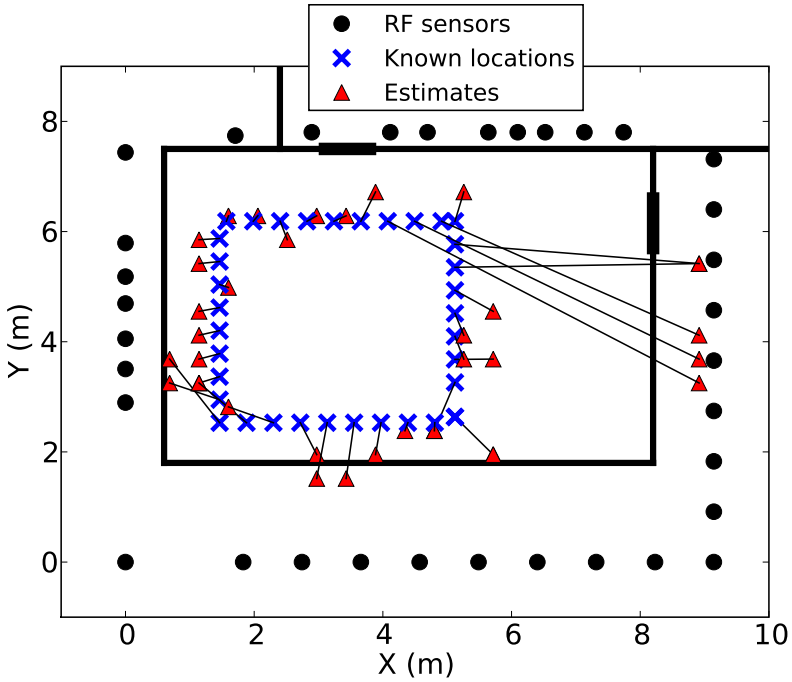


Figure: VRTI estimates.

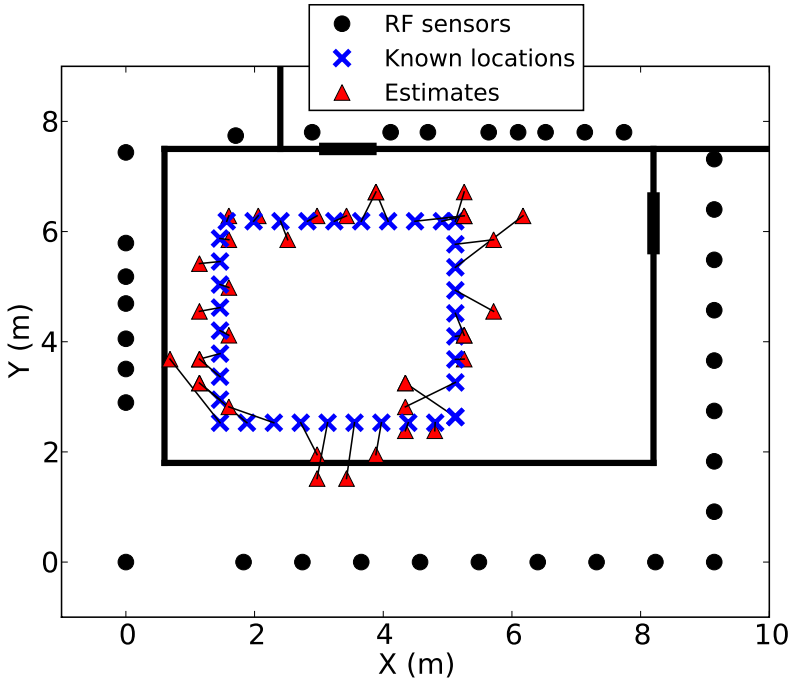
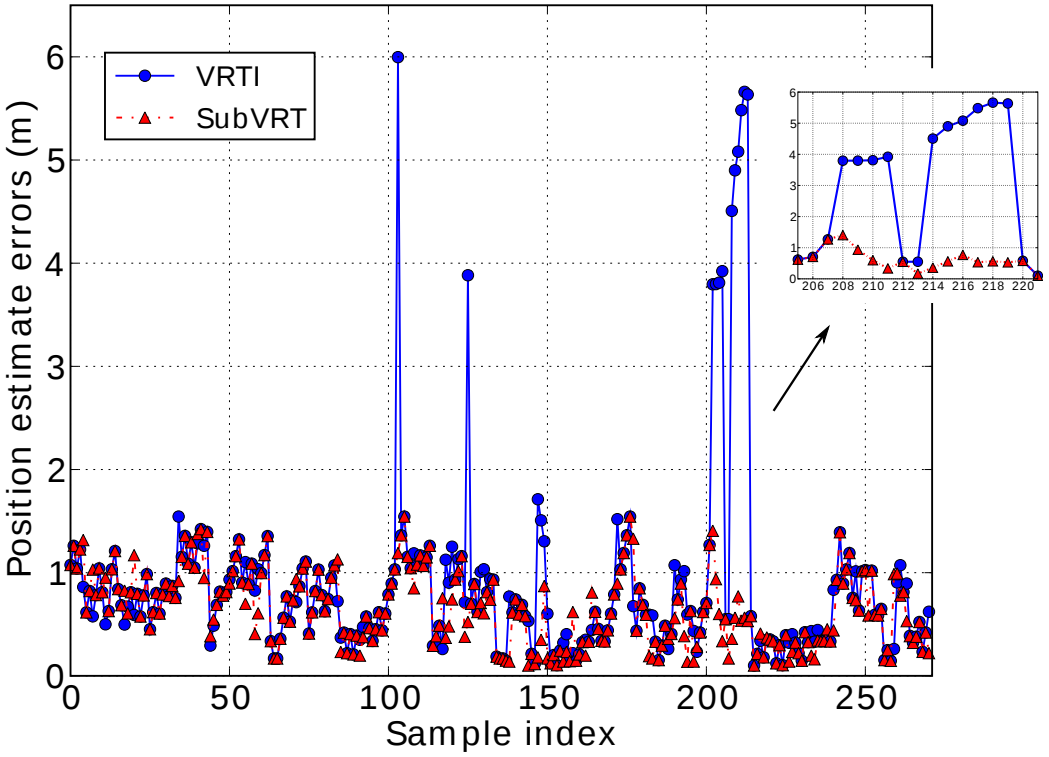


Figure: SubVRT estimates.

Performance Improvement

- In windy experiment, location error reduced by $> 40\%$



Real-time SubVRT Demo in SECON

- Use an electronic fan to create intrinsic motion (noise)
- Robust localization performance

Least Squares Solution

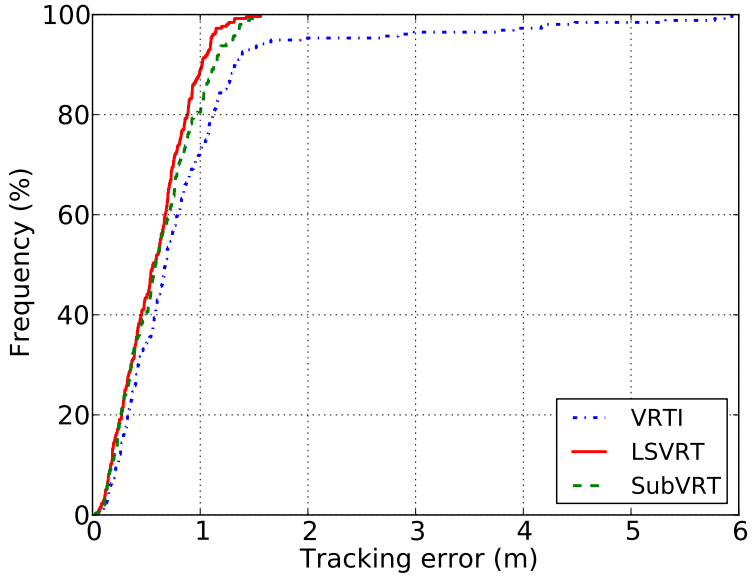
- Idea: Instead of performing PCA on the covariance matrix, use the covariance matrix directly
- Formulation: [4]

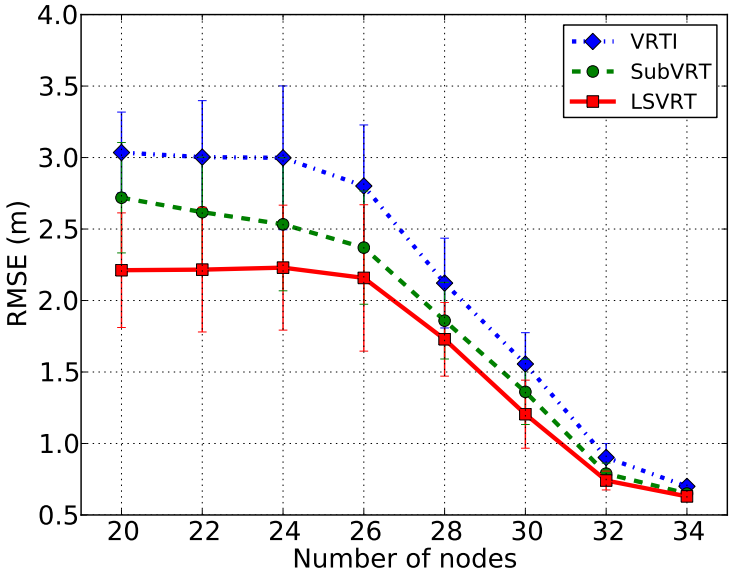
$$\hat{\mathbf{m}} = \Pi_3 \mathbf{s}_r$$
$$\Pi_3 = (W^T C_{\mathbf{n}}^{-1} W + C_{\mathbf{m}}^{-1})^{-1} W^T C_{\mathbf{n}}^{-1}.$$

[4] Y. Zhao and N. Patwari, "Robust Estimators for Variance-Based Device Free Localization and Tracking", IEEE Transactions on Mobile Computing, Oct. 2015.

Further Improvement

- No need to choose the k parameter as in SubVRT





Tracking

- Apply Kalman filter to location estimates for tracking

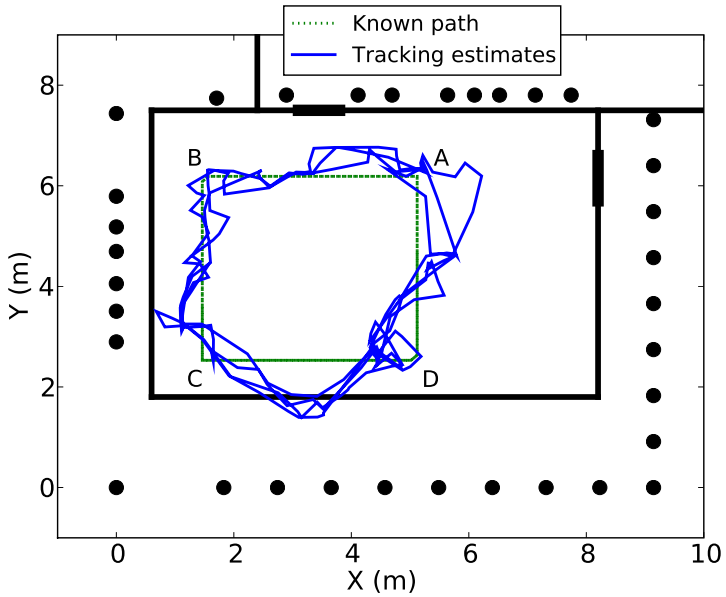


Figure: SubVRT estimate as input

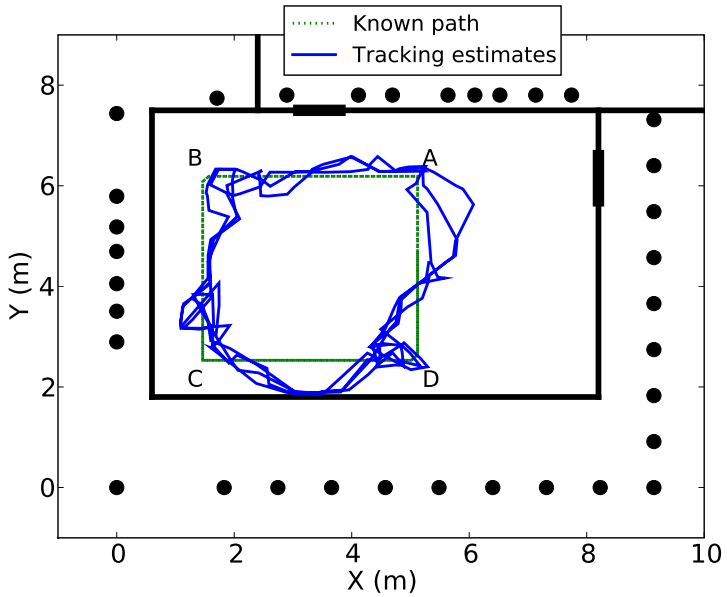


Figure: LSVRT estimate as input

RTI Localization Algorithms

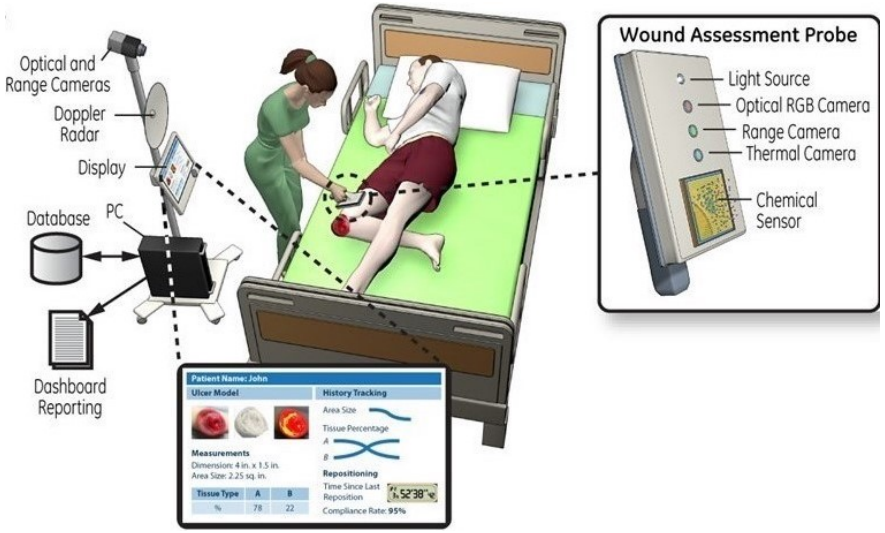
- VRTI can detect and locate people even through-walls, but it is sensitive to intrinsic motion
- SubVRT uses subspace decomposition method and is more robust with calibration measurements
- LSVRT uses covariance matrices of noise and prior to further improve the robustness of VRTI
- Kernel distance-based RTI (KRTI) is further developed to locate stationary and moving people through walls [5]

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

Outline

Pressure Ulcer Prevention and Care

Mobile system for patient motion sensing [6]

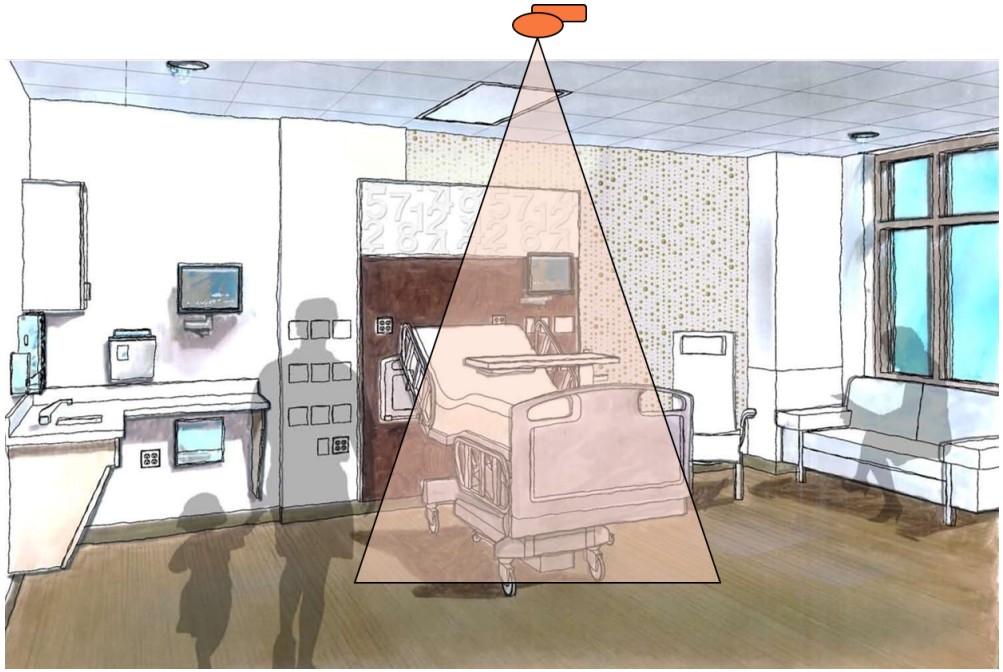


[6] M. Chang et al., “Multimodal Sensor System for Pressure Ulcer Wound Assessment and Care," in IEEE Transactions on Industrial Informatics, vol. 14, no. 3, pp. 1186-1196, March 2018.

Hospital Operation Management

Dual Doppler occupancy sensor [7]

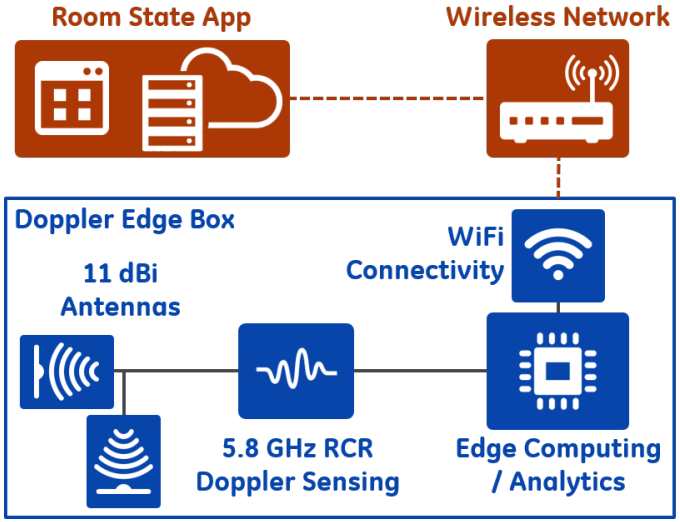
- Detection of sleeping patients
- Room-level coverage
- No privacy concern
- Low-cost

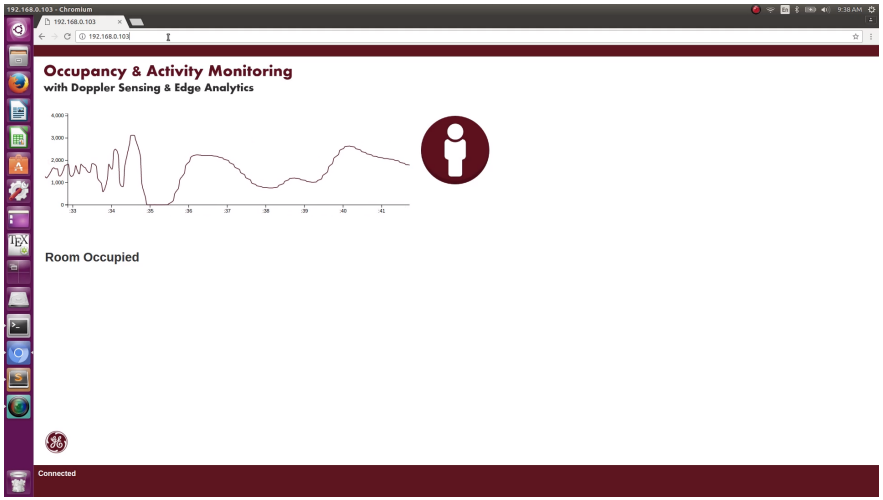


[7] Y. Zhao, et al., "Occupancy and Activity Monitoring with Doppler Sensing and Edge Analytics", ACM SenSys, Nov. 2016.

SenSys Demo

Real-time demo to monitor respiration of multiple people [8]



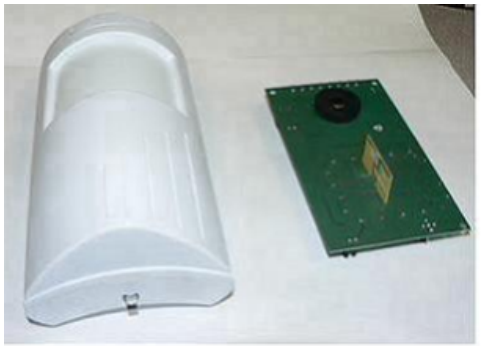


[8] Y. Zhao, et al., "Occupancy and Activity Monitoring with Doppler Sensing and Edge Analytics", ACM SenSys, Nov. 2016.

Multi-modality Sensing System

Four types of data: RGB image, Depth image, Doppler and RSS from three devices [9]

(a) Kinect RGB-D camera



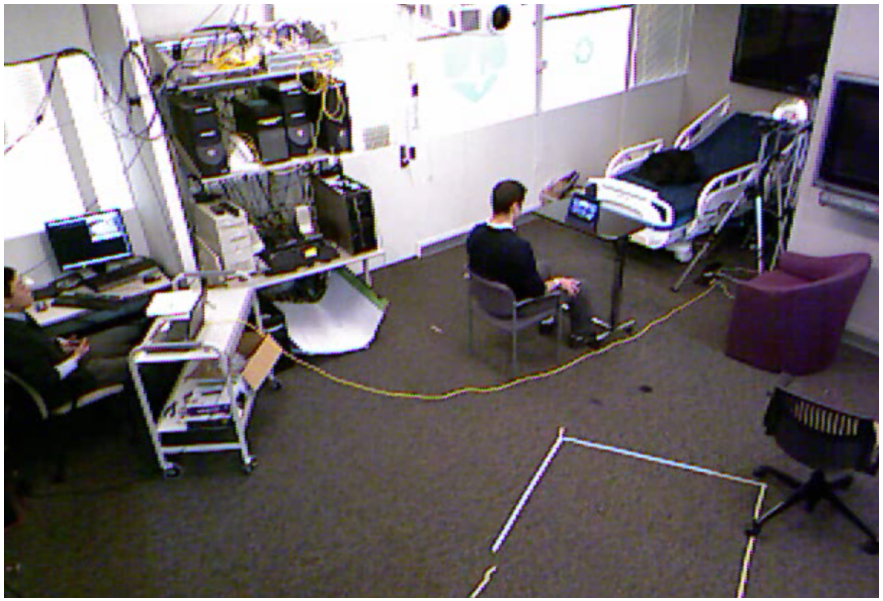
(b) Doppler sensor

(c) CC2531 wireless node

[9] Y. Zhao, et al., “Occupancy Sensing and Activity Recognition with Cameras and Wireless Sensors", ACM SenSys DATA workshop, 2019

Human Subject Study and Dataset

- Human subject study with over a dozen participants (Vital signs monitoring)
- Dataset (wireless sensors) published for human activity recognition `https://doi.org/10.5281/zenodo.3454785`



Thank you!

Acknowledgment

- Dr. Ting Yu at Google Cloud AI
- Dr. SM Hasan, Dr. David Toledano at GE Research
- Dr. Neal Patwari at Washington University in St. Louis
- Support and grants from GE Healthcare and Department of Veterans Affairs (VA118-13-C-0049)

Questions?