SafeT-Net: Situational Awareness For Emergencies Through Network-Enabled Technologies

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Acronym Glossary

- BLE = Bluetooth Low Energy
- BT = Bluetooth
- CDMA = Code Division Multiple Access
- CSI = Channel State Information
- CP = Cyclic Prefix
- CPU = Central Processing Unit
- CV = Computer Vision
- DCT = Discreet Cosine Transform
- DFT = Discrete Fourier Transform
- ECD = End-User Communication Device
- eNodeB = E-Ultran Node B
- FDTD = Finite-Difference Time Domain
- FFT = Fast Fourier Transform
- FMCW = Frequency Modulated Continuous Wave
- GGA = Generalized Gradient Approximation
- GPS = Global Positioning System
- GSV = GPS Satellites in View
- HDOP = Horizontal Dilution of Precision
- IDCT = Inverse Discreet Cosine Transform
- IDFT = Inverse Discrete Fourier Transform
- IFFT = Inverse Fast Fourier Transform
- IMU = Inertial Measurement Unit
- IoT = Internet of Things
- IWT = Inverse Wavelet Transform
- LBS = Location-Based Services
- LOS = Line-of-Sight
- LTE = Long Term Evolution
- NCO = Numerically Controlled Oscillator
- NLOS = Non-Line-of-Sight
- OFDM = Orthogonal Frequency-Division Multiplexing
- PDFs = Probability Distribution Functions
- PSS = Primary Synchronization Signals
- RF = Radio Frequency
- RMC = Recommended Minimum Sentence C
- RSSI = Received Signal Strength Indicator
- RX = Receive/ Receiver
- SCBA = Self Contained Breathing Apparatus
- SDS-TWR = Symmetric Double Sided – Two-Way Ranging
- SLAM = Simultaneous Localization and Mapping
- SNR = Signal-to-Noise Ration
- SSS = Secondary Synchronization Signals
- ToF = Time of Flight
- TX = Transmit/ Transmitter
- UWB = Ultra Wide Band
- WT = Wavelet Transform
- ZUPT = Zero Velocity Update

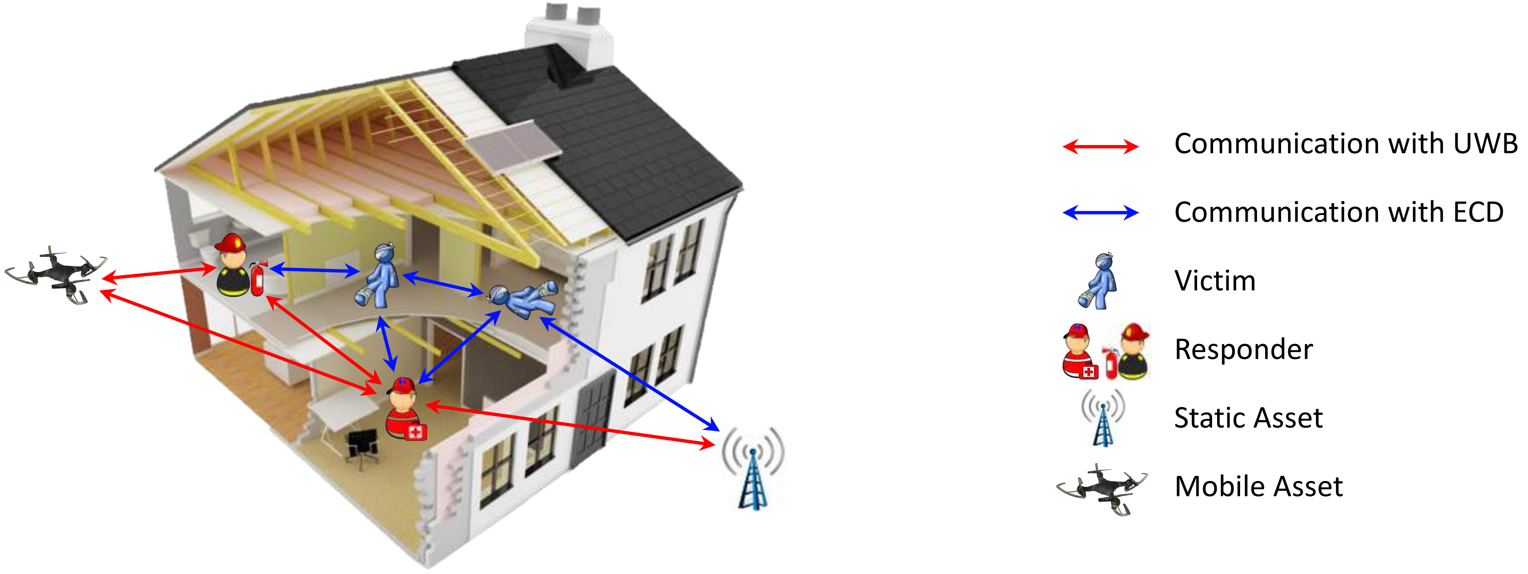
PSCR

Project Overview

- Project objective: raise situational awareness in first responder operations and public safety applications
- Challenges:
  - infeasibility of optical localization techniques
  - absence of line-of-sight conditions in indoor environments
  - unavailability of environment knowledge
  - inaccessibility of certain regions for assets deployment in public safety applications
- Project tasks:
  - robust localization and navigation: establish algorithms to localize responders, their assets, and victims accurately and timely
  - resource management and asset deployment: design context-aware optimization and control strategies for efficient use of resources and assets

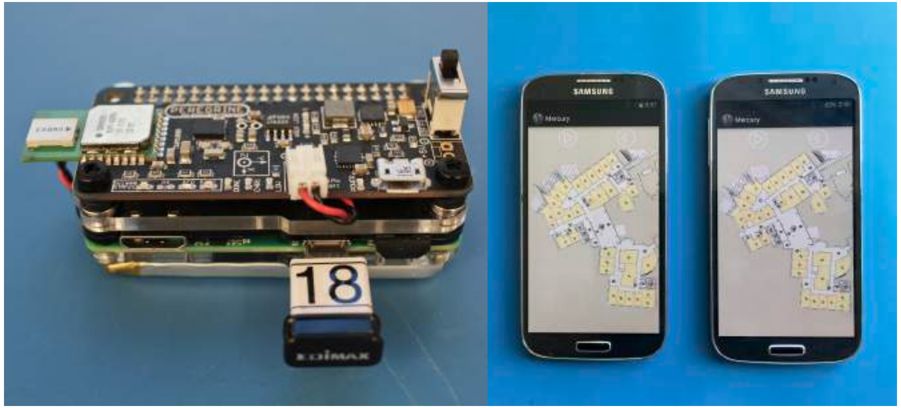
Network-Enabled Technologies

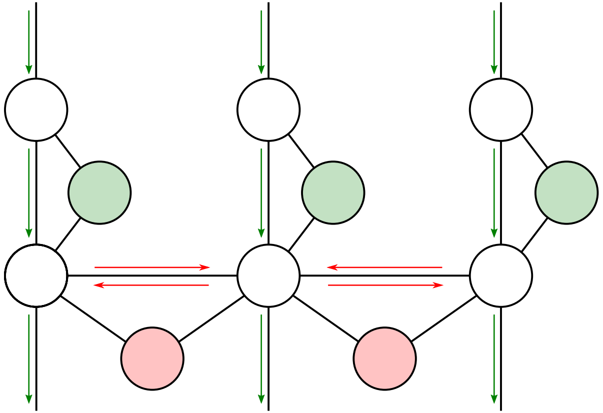
- Utilize different radio technologies, including ultra-wideband (UWB) and end-user communication devices (ECDs)
- Exploit cooperation among nodes to improve accuracy and robustness
- Perform efficient resource management and asset deployment



Robust Localization

- Research objective: establish algorithms to localize responders, their assets, and victims accurately and timely in a robust manner
- Methodologies
  - exploit measurements obtained from devices with different hardware capabilities
  - develop Bayesian inference algorithms based on belief propagation (BP)
  - establish simultaneous localization and mapping (SLAM) algorithms for map information

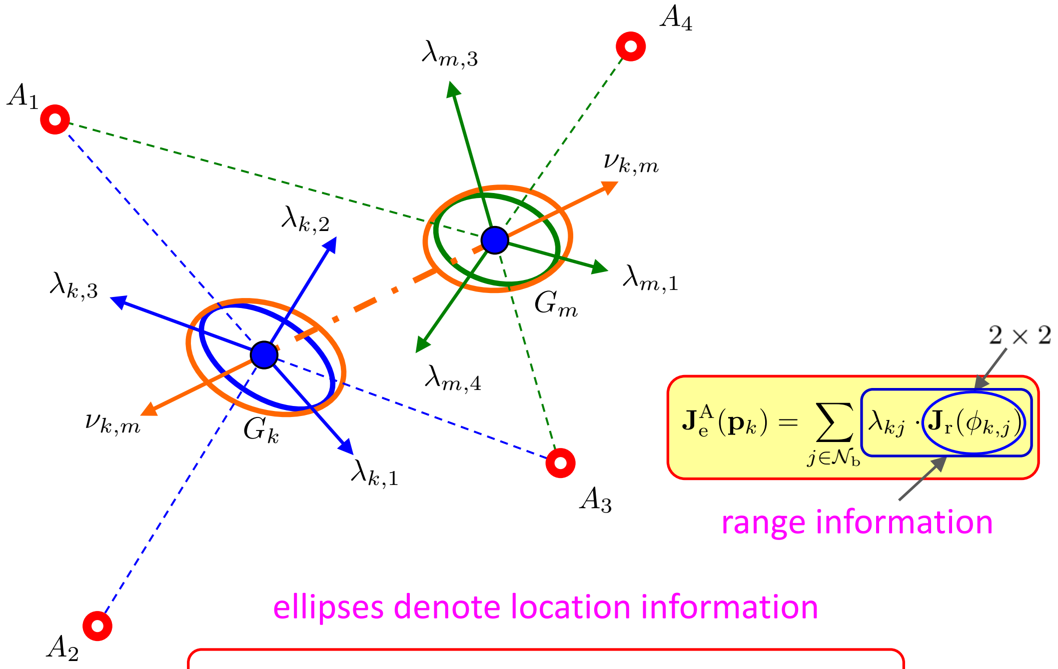




Asset Management and Deployment

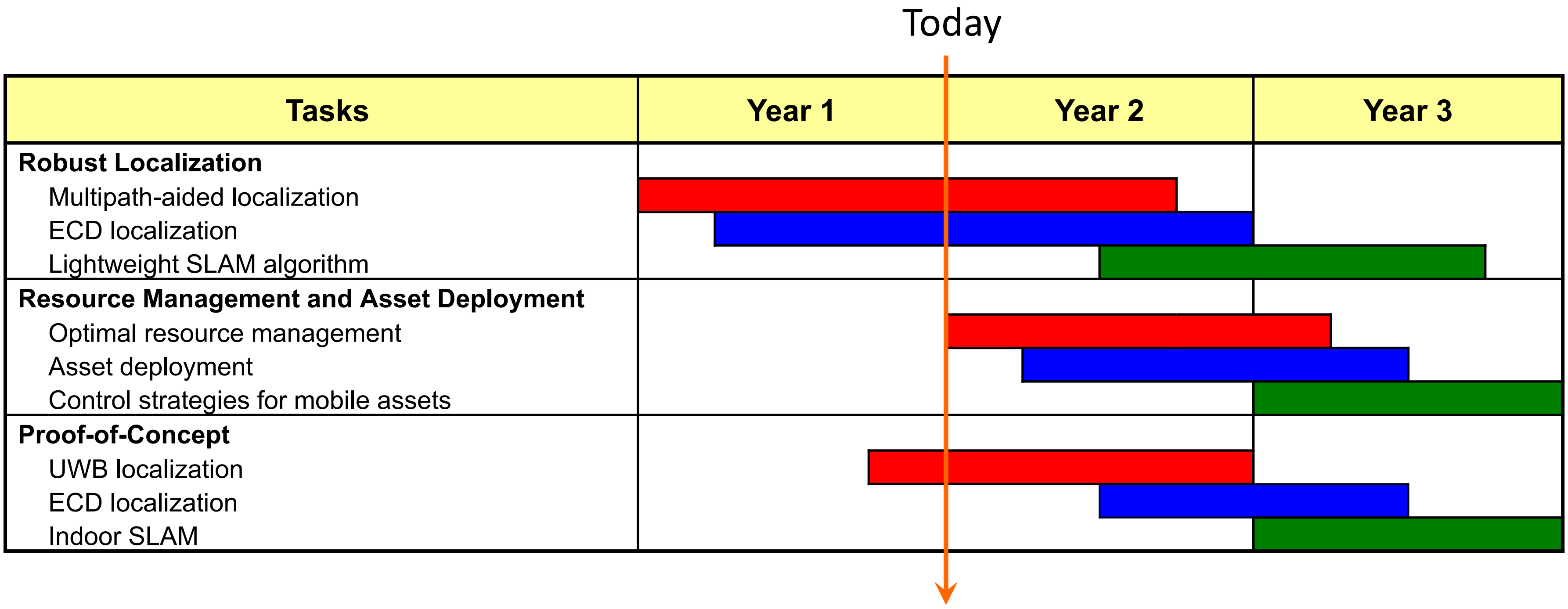
- Research objective: design context-aware optimization and control strategies for efficient use of localization assets

- Methodologies
  - adopt equivalent Fisher information matrix (EFIM) framework for algorithm design
  - develop holistic control strategies for efficient resource utilization and deployment of mobile assets



Overall $2N_{\mathrm{a}} \times 2N_{\mathrm{a}}$ EFIM $\mathbf{J}_{\mathrm{e}}(\mathbf{P}) = \mathbf{J}_{\mathrm{e}}^{\mathrm{A}} + \mathbf{J}_{\mathrm{e}}^{\mathrm{C}}$

Timeline and Milestones

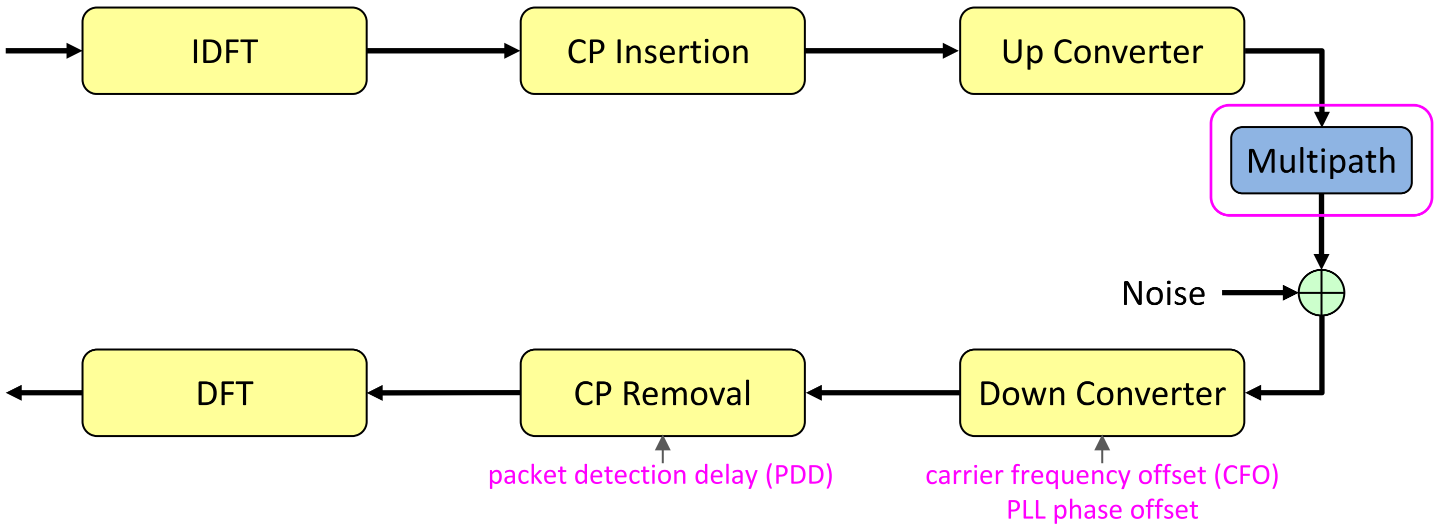


Localization with ECDs

- Goal: achieve accurate ranging and cooperative localization with ECDs (e.g., devices employing OFDM waveforms)
- Ranging with ECDs is challenging due to
  - processing impairments
  - insufficient bandwidth
  - inaccessibility of physical layer information
- Ranging with ECDs requires
  - theoretical foundation for OFDM ranging systems in the presence of multipath and processing impairments
  - band stitching methods to increase effective bandwidth for reliable and accurate ranging
  - ranging algorithms based on the channel state information (CSI) with processing impairment mitigation

Theoretical Foundation for OFDM Ranging

- Objective: determine the fundamental limit of the accuracy of OFDM ranging systems under processing impairment
- Two types of unknown parameters
  - channel parameters
  - processing parameters



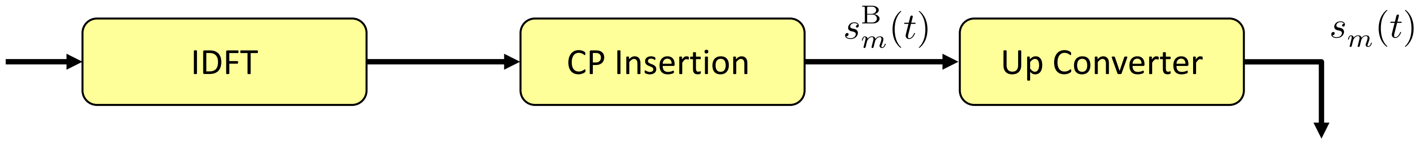
Theoretical Foundation for OFDM Ranging

- Consider the packet transmitted from node 1 to node 2 on channel j
- Real passband transmitted signal of packet m

$$s_m(t) = \Re\{s_m^{\mathrm{B}}(t) \cdot \exp\{+\mathrm{i}(2\pi \boxed{f_j^{\mathrm{C1}}} t + \boxed{\phi_j^1})\}\}$$

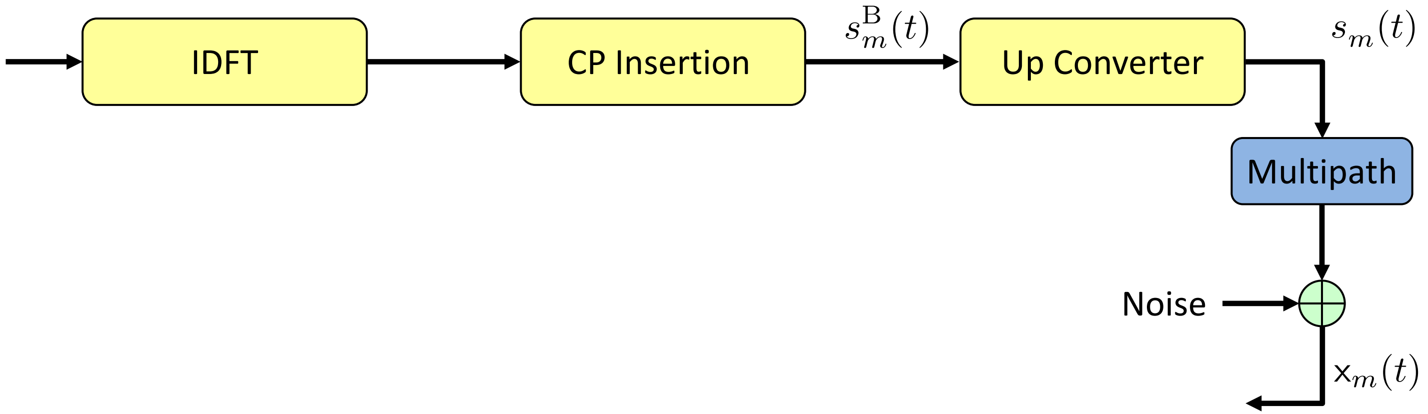
carrier frequency of node 1 at channel j

carrier phase of node 1 at channel j



Theoretical Foundation for OFDM Ranging

- Received signal $\mathrm{x}_m(t) = h(t) * s_m(t) + \boxed{\mathrm{n}(t)}$ white Gaussian noise
- channel impulse response
  - $h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l)$
  - α_l, τ_l : amplitude and delay of l th path

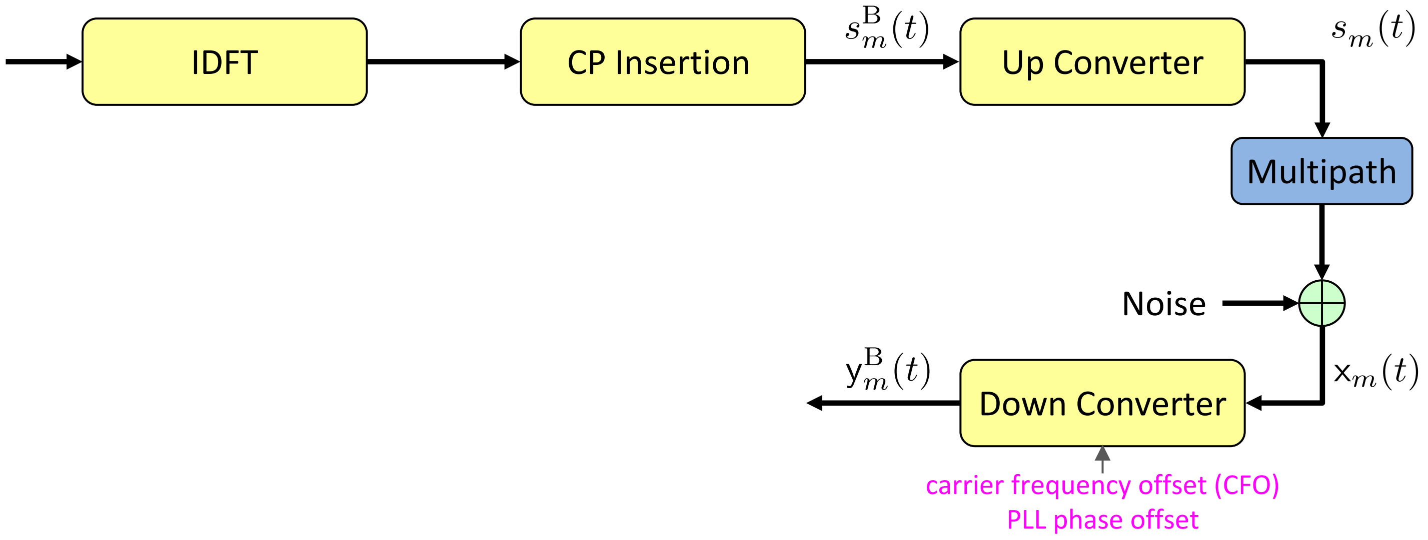


Theoretical Foundation for OFDM Ranging

- Received signal in baseband

$$\mathrm{y}_m^{\mathrm{B}}(t) = \mathrm{x}_m(t)\exp\{-\mathrm{i}(2\pi \boxed{f_j^{\mathrm{C2}}} t + \boxed{\phi_j^2})\}$$

carrier frequency of node 2 at channel j carrier phase of node 2 at channel j



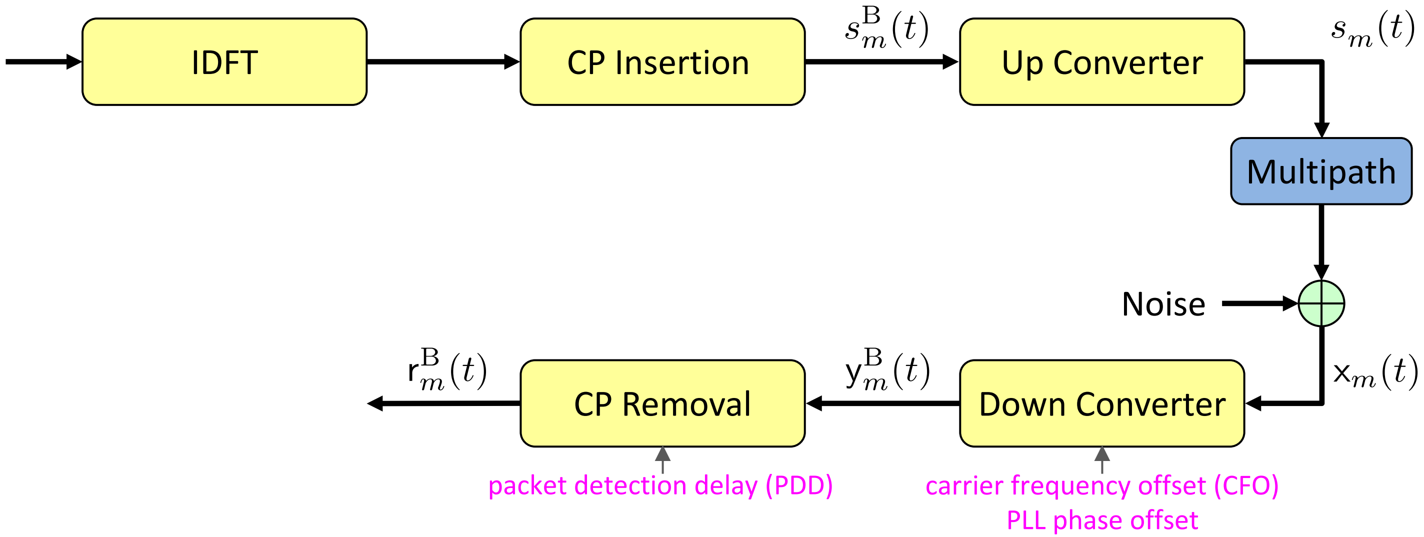
Theoretical Foundation for OFDM Ranging

- Received signal in baseband

$$\mathrm{y}_m^{\mathrm{B}}(t) = \mathrm{x}_m(t)\exp\{-\mathrm{i}(2\pi \boxed{f_j^{\mathrm{C2}}} t + \boxed{\phi_j^2})\}$$

carrier frequency of node 2 at channel j carrier phase of node 2 at channel j

- Received signal after CP removal $\mathrm{r}_m^{\mathrm{B}}(t) = \mathrm{y}_m^{\mathrm{B}}(t - \boxed{\tau_m^{\mathrm{D}}})$ detection delay of packet m

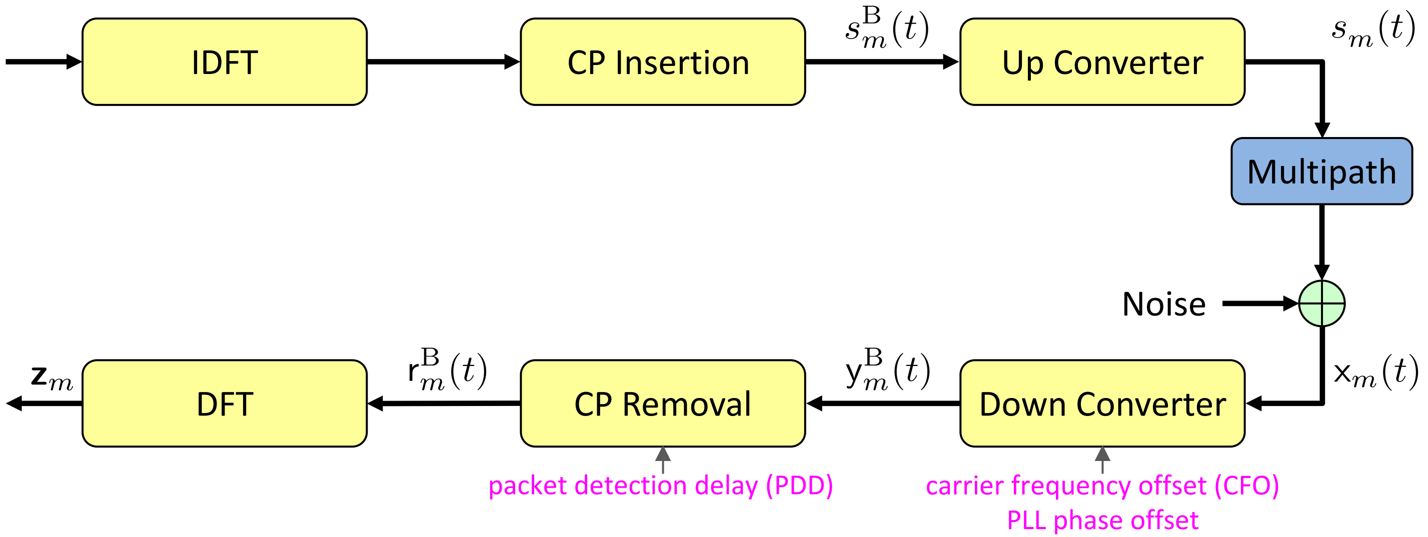


Theoretical Foundation for OFDM Ranging

- Received signal in frequency domain

$$\mathbf{z}_m = \begin{bmatrix} \mathrm{z}_{m0} & \mathrm{z}_{m1} & \ldots & \mathrm{z}_{m(K-1)} \end{bmatrix}^{\mathrm{T}}$$

number of subcarriers



Theoretical Foundation for OFDM Ranging

- Unknown parameters $\boldsymbol{\theta} = [\, \boldsymbol{\kappa}^{\mathrm{T}} \quad \boldsymbol{\eta}^{\mathrm{T}} \,]^{\mathrm{T}}$
  - $\boldsymbol{\kappa}$: channel parameters
  - $\boldsymbol{\eta}$: processing parameters
- Estimate $\boldsymbol{\theta}$ based on measurements $\mathbf{z} = \left[\mathbf{z}_1^{\mathrm{T}} \; \mathbf{z}_2^{\mathrm{T}} \; \cdots \; \mathbf{z}_M^{\mathrm{T}}\right]^{\mathrm{T}}$
- Fisher information matrix (FIM)

$$\boldsymbol{J}(\boldsymbol{\theta}) = \mathbb{E}\left\{ -\frac{\partial^2 \ln f_{\mathbf{z}}(\mathbf{z};\boldsymbol{\theta})}{\partial\boldsymbol{\theta}\partial\boldsymbol{\theta}^{\mathrm{T}}} \right\}$$

- Information inequality: for any estimator $\hat{\boldsymbol{\theta}}(\mathbf{z})$ of $\boldsymbol{\theta}$

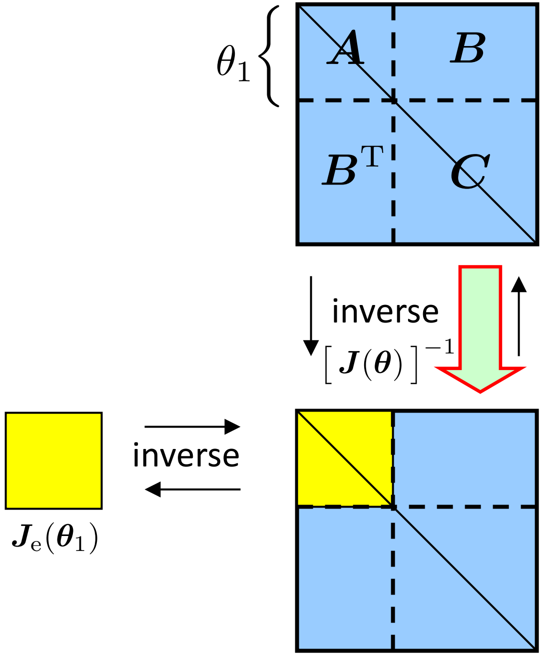
$$\mathbb{E}\left\{(\hat{\boldsymbol{\theta}}(\mathbf{z}) - \boldsymbol{\theta})(\hat{\boldsymbol{\theta}}(\mathbf{z}) - \boldsymbol{\theta})^{\mathrm{T}}\right\} \succeq \boldsymbol{J}^{-1}(\boldsymbol{\theta})$$

Theoretical Foundation for OFDM Ranging

- FIM is a matrix of high dimensions; however, only the part for τ_1 is of interest
- Use Schur's complement to reduce the dimension of the FIM
- Equivalent Fisher information matrix (EFIM)
  - original FIM for $\boldsymbol{\theta} = [\boldsymbol{\theta}_1^{\mathrm{T}} \ \boldsymbol{\theta}_2^{\mathrm{T}}]^{\mathrm{T}}$

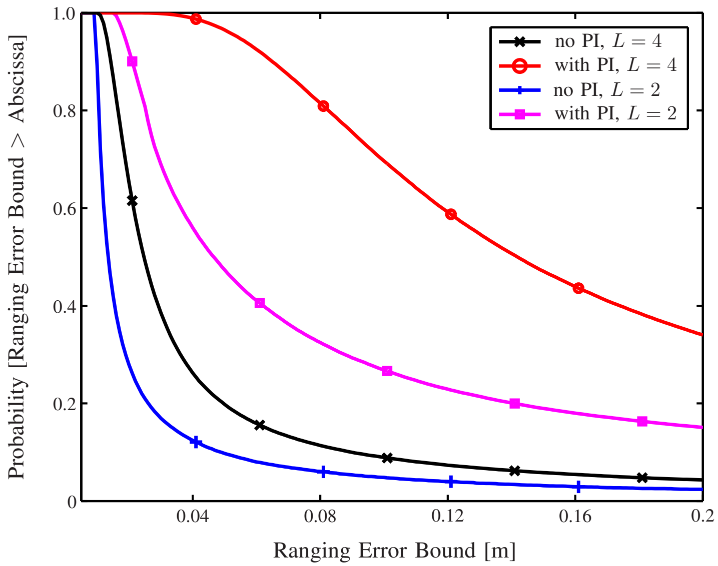
$$\boldsymbol{J}(\boldsymbol{\theta}) = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{B}^{\mathrm{T}} & \boldsymbol{C} \end{bmatrix}$$

  - EFIM $\boldsymbol{J}_{\mathrm{e}}(\boldsymbol{\theta}_1) := \boldsymbol{A} - \boldsymbol{B}\boldsymbol{C}^{-1}\boldsymbol{B}^{\mathrm{T}}$
  - retains all necessary information to derive the information inequality for $\boldsymbol{\theta}_1$



Theoretical Foundation for OFDM Ranging

- Numerical results
  - single wireless channel at 2.4 GHz is used
  - SNR for the first path is 0 dB
  - number of multipath components $L \in \{2, 4\}$



- Conclusions
  - ranging accuracy increases with bandwidth
  - processing impairment needs to be taken into account

Ranging with OFDM Devices

- Objective: obtain range measurements using commodity WiFi cards

- Approaches
  - extract CSI of multiple WiFi channels within coherence time
  - mitigate processing impairments via signal processing techniques

- Challenges
  - CSI is only measured intermittently by WiFi cards
  - several WiFi channels are not accessible directly
  - channel switching is not rapid enough in nominal operations

- SafeT-Net controls the WiFi driver to overcome these challenges!

WiFi Driver Control

- Extract CSI for all packets intended for ranging
- Unlock all the available channels in both 2.4 and 5 GHz
- Implement rapid channel switching using monitor mode

CSI Extraction

- WiFi cards measure CSI only for packets that satisfy the following two conditions
  - packet is transmitted using 802.11n High Throughput rate
  - the ‘Sounding Bit’ of the transmitted packet is set to ‘1’

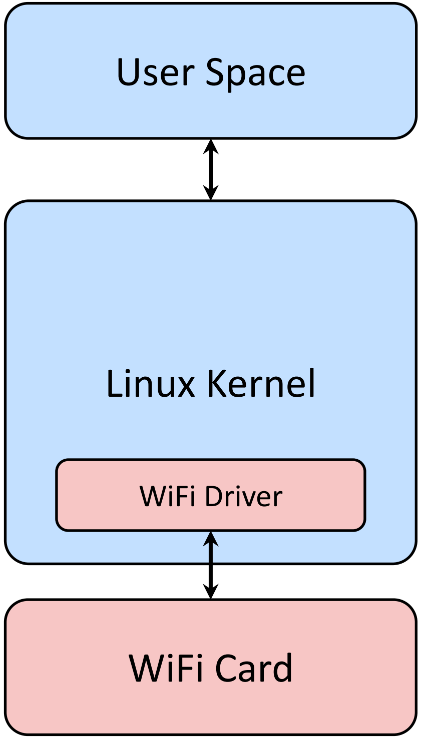
- SafeT-Net measures CSI for all packets during ranging process
  - transmit all packets using High Throughput rate
  - activate ‘Sounding Bit’ for every outgoing packet intended for ranging

CSI Extraction

- WiFi card reports CSI to WiFi driver running in Linux kernel space

- Layers of Linux system
  - user space: the space in which user processes run
  - Linux kernel: the space where the core of operating system executes and provides its services
  - WiFi driver: interface between kernel and card
  - WiFi card: the hardware which processes signals in order to transmit and receive packets

- SafeT-Net extracts CSI from WiFi driver and processes the CSI measurements in the user space



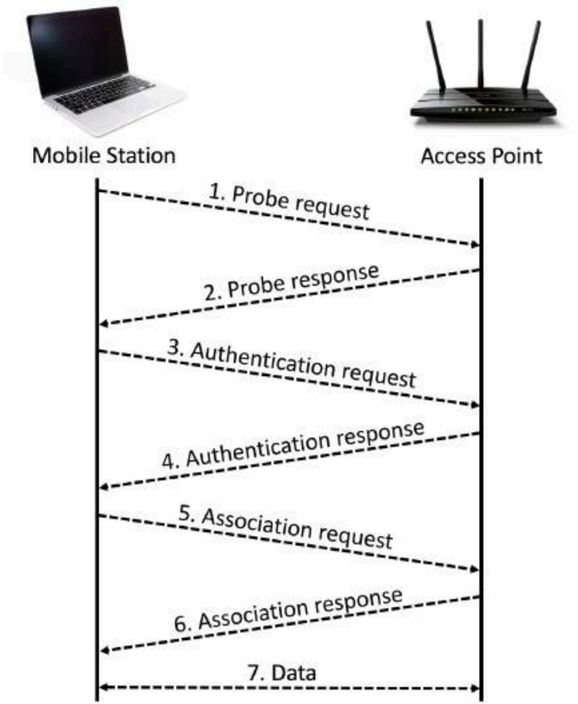
Unlocking WiFi Channels

- Several WiFi channels cannot be used directly
  - WiFi cards do not operate in 5 GHz band by default
  - the Federal Communications Commission (FCC) requires WiFi devices to employ Dynamic Frequency Selection (DFS)
- SafeT-Net controls the WiFi driver
  - 35 channels (550 MHz bandwidth in total) are accessible for ranging

Center frequency (MHz)	Bandwidth (MHz)	Before unlocking	After unlocking
2412	20	Yes	Yes
2417	20	Yes	Yes
2422	20	Yes	Yes
2427	20	Yes	Yes
2432	20	Yes	Yes
2437	20	Yes	Yes
2442	20	Yes	Yes
2447	20	Yes	Yes
2452	20	Yes	Yes
2457	20	Yes	Yes
2462	20	Yes	Yes
5180	20	No	Yes
5200	20	No	Yes
5220	20	No	Yes
5240	20	No	Yes
5260	20	DFS	Yes
5280	20	DFS	Yes
5300	20	DFS	Yes
5320	20	DFS	Yes
5500	20	DFS	Yes
5520	20	DFS	Yes
5540	20	DFS	Yes
5560	20	DFS	Yes
5580	20	DFS	Yes
5600	20	DFS	Yes
5620	20	DFS	Yes
5640	20	DFS	Yes
5660	20	DFS	Yes
5680	20	DFS	Yes
5700	20	DFS	Yes
5745	20	No	Yes
5765	20	No	Yes
5785	20	No	Yes
5805	20	No	Yes
5825	20	No	Yes

Operating in Monitor Mode

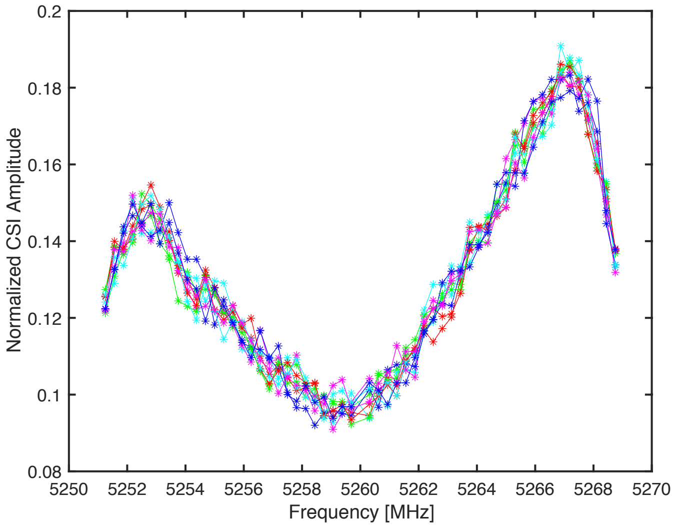
- A pair of WiFi cards can communicate in different modes
  - one in master mode, the other in managed mode
  - both in monitor mode
- Monitor mode enables rapid channel switching
  - procedures specified for master/managed mode can be avoided
  - 'beacons' used in master/managed mode to coordinate the data transmission and channel switching are not required
- SafeT-Net measures the CSI and switches channel every 5-6 ms!

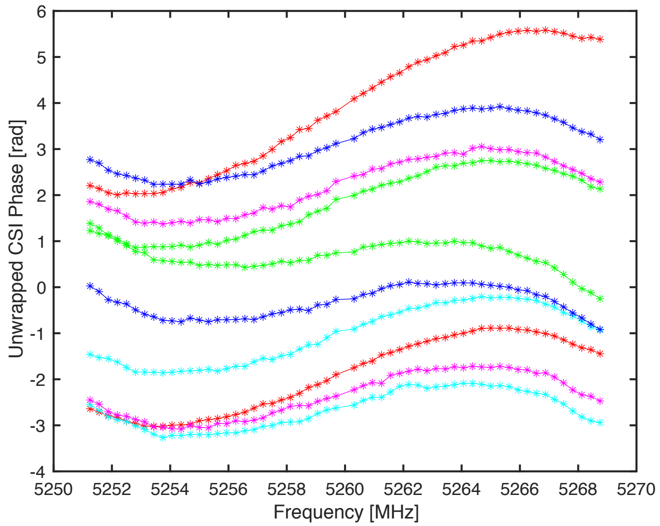


Procedure in master/managed mode

CSI Amplitude and Phase

- SafeT-Net obtains CSI from 2.4 GHz band (11 channels) and 5 GHz band (24 channels)
- 56 subcarriers in each channel (20 MHz/channel)
- CSI amplitude: affected by multipath
- CSI phase: affected by multipath, PDD, CFO, and PLL phase offsets





CSI Phase Error Mitigation

- Phase of the measured CSI is time-varying even when the channel is static due to processing impairments!

- Phase error is affine w.r.t. subcarrier frequency

$$\angle \mathbf{g}_m(f_k) = \boxed{\angle h(f_k)} - \boxed{2\pi f_k \tau_m^{\mathrm{D}}} + \boxed{2\pi \triangle f_j^{\mathrm{C1}} t_m} + \boxed{\triangle \phi_j^1}$$

true CSI phase

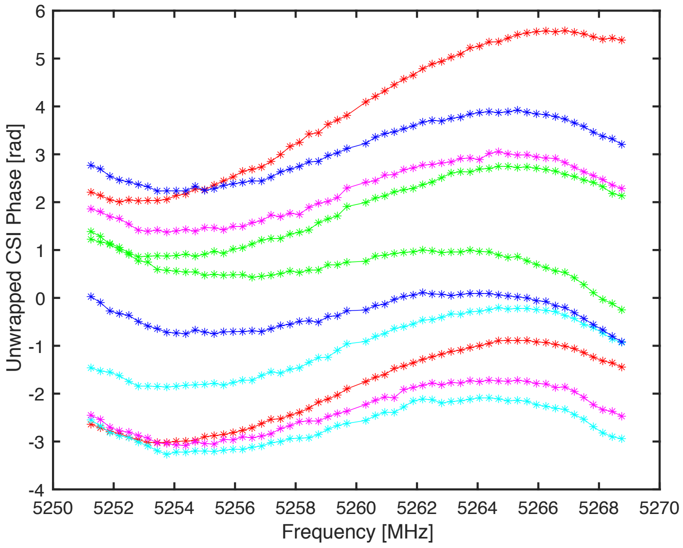
error due to PDD

error due to CFO

$$\triangle f_j^{\mathrm{C1}} = f_j^{\mathrm{C1}} - f_j^{\mathrm{C2}}$$

error due to PLL phase offset

$$\triangle \phi_j^1 = \phi_j^1 - \phi_j^2$$



CSI Phase Error Mitigation

- Elimination of PDD error: CSI at 'subcarrier 0' ($f_0 = 0$) is unaffected by PDD

$$\angle \mathrm{g}_m(f_0) = \angle h(f_0) + 2\pi \triangle f_j^{\mathrm{C1}} t_m + \triangle \phi_j^1$$

- Elimination of CFO error
  - CFO can be estimated using difference of CSI phases

$$\angle \mathrm{g}_m(f_0) - \angle \mathrm{g}_n(f_0) = 2\pi \triangle f_j^{\mathrm{C1}} (t_m - t_n)$$

  - impact of CFO can then be compensated using its estimated value

- Elimination of PLL error
  - PLL error in node 1 and 2 are opposite

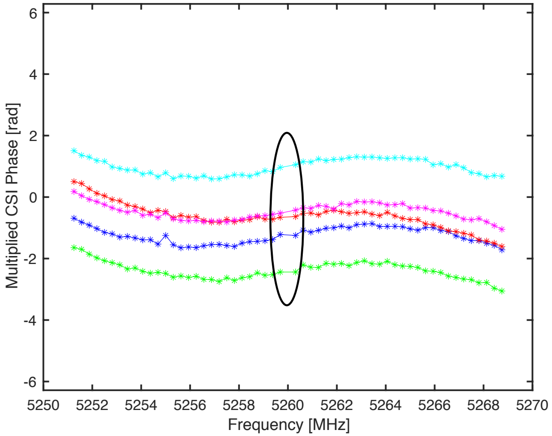
$$\triangle \phi_j^1 = \phi_j^1 - \phi_j^2 = -\triangle \phi_j^2$$

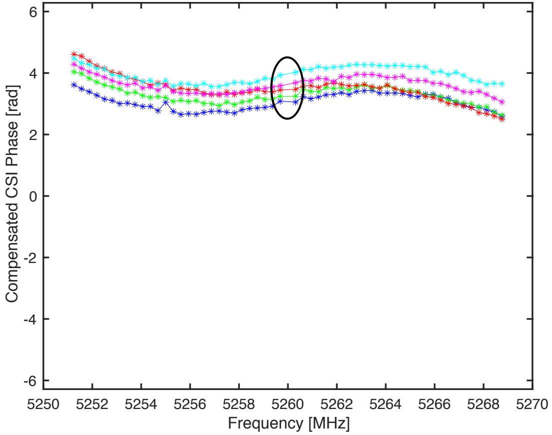
  - PLL error can be cancelled by multiplying CSI of node 1 and 2

CSI Phase Error Mitigation

- CSI phase error mitigation steps
  - measure the CSI and receiving time of each packet
  - estimate the CFO
  - multiply CSI of node 1 and 2 to eliminate PLL error
  - compensate CFO error using the estimated CFO
  - extract the result at ‘subcarrier 0’

- CSI phase mitigation results
  - phase variation decreased from 3.5 rad to 0.9 rad
  - residual variation is due to inaccurate CFO estimation, inaccurate time measurement, and noise



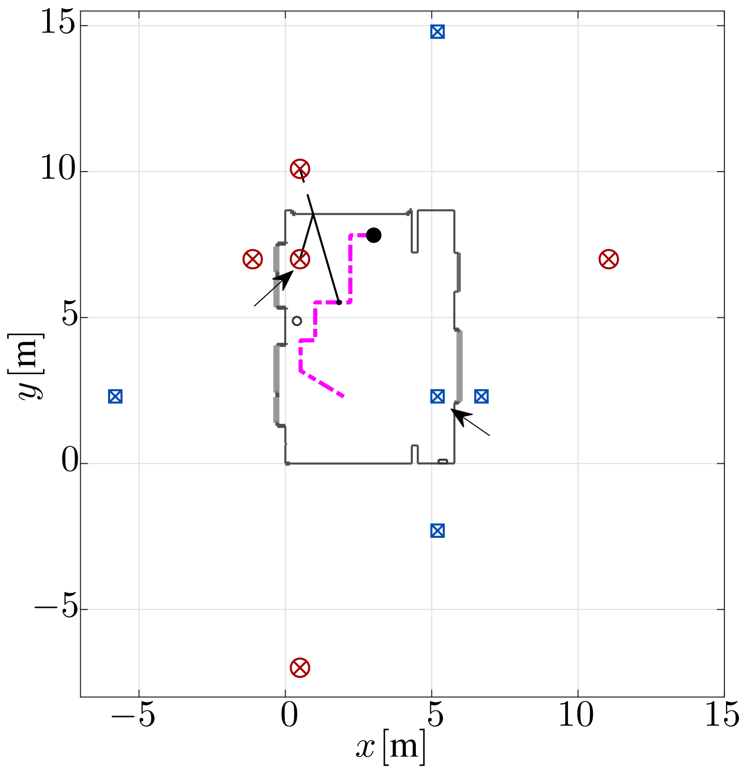


Multipath-aided Localization

- Goal: exploit position-related information in the multipath components of the received UWB signals to increase localization robustness and reduce the amount of required infrastructure
- Specular reflections of UWB radio signals at flat surfaces are modeld by virtual point sources
- Multipath-aided localization is accomplished using a new messaging algorithm
  - perform localization of virtual sources either by
    - using floor plan information, or
    - performing real-time SLAM
  - associate distance measurements (related to multipath delays) with the virtual point sources

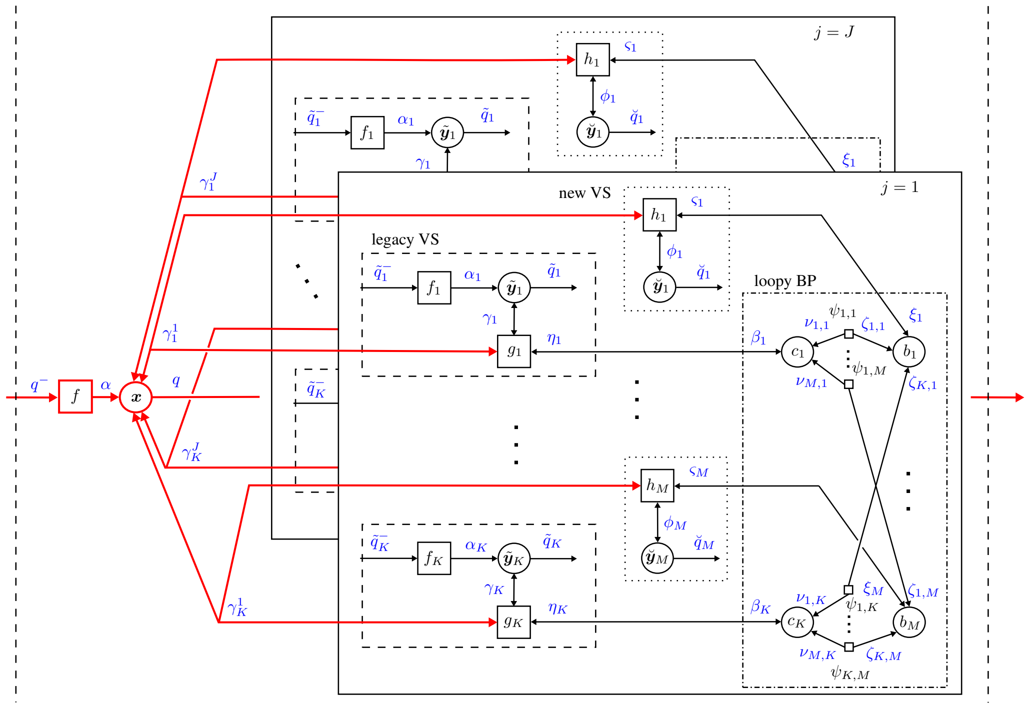
Floor Plan with Virtual Sources

- Example of an environment map (floor plan)
  - two static assets are indicated by a red circle-cross and a blue square-cross within the floor plan
  - the magenta dashed-dotted line represents the trajectory of a responder
  - the starting position of the mobile agent is indicated by a **black** circle
  - the red circle-crosses and blue square-crosses outside the floor plan indicate expected virtual source positions



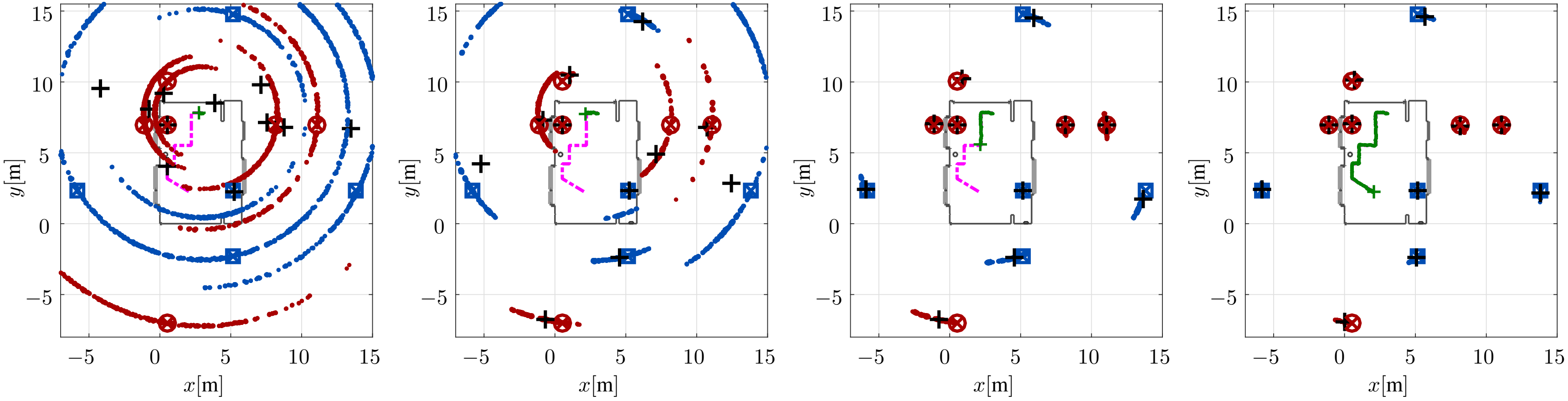
Factor Graph for Multipath-aided SLAM

- Develop a statistical model for multipath-assisted SLAM
- Develop a messaging algorithm based on factor graph
- Messages are passed along the edges of the graph to infer the states of interest



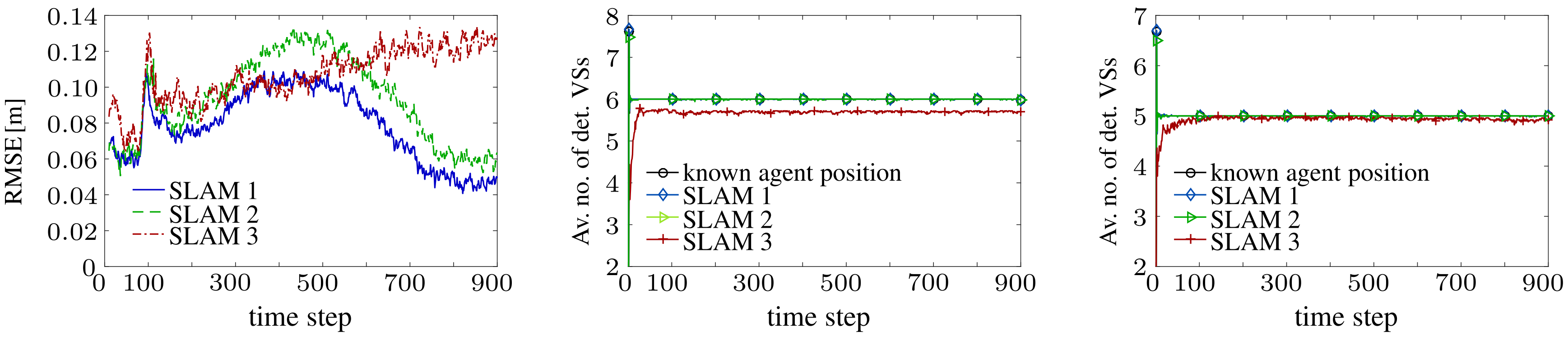
Multipath-aided Localization

- Convergence analysis of multistatic SLAM messaging algorithm using simulated measurement
  - four different time steps are shown
  - particles represent the posterior pdfs of the mobile agent state and the virtual source states related to asset 1 and asset 2
  - **black** crosses represent the estimated positions of the detected virtual sources



Simulation Results

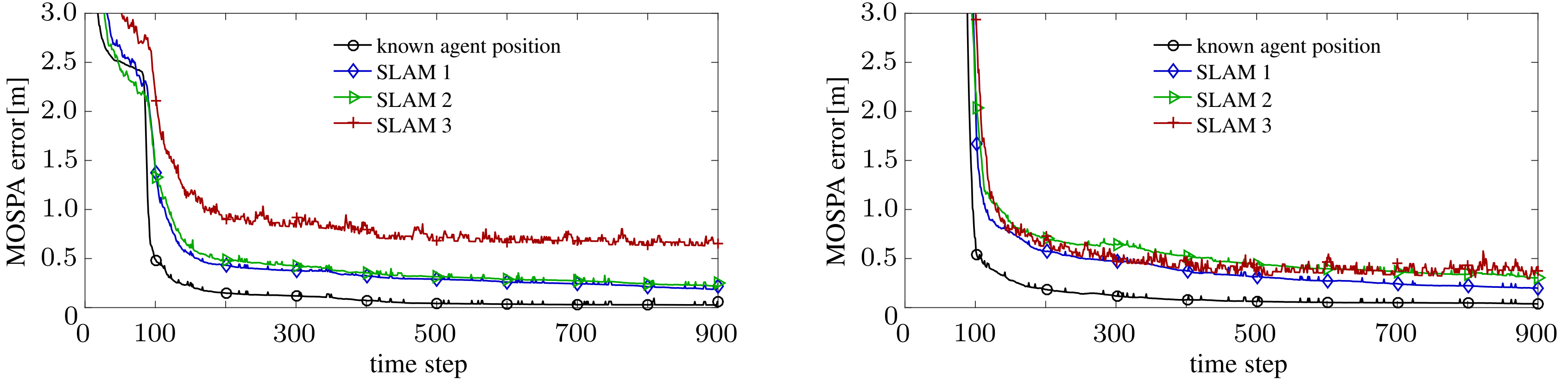
- The measurement noise standard deviation was set to 0.1m
- In SLAM 1 and SLAM 2, we used detection probability 0.95 and mean number of false alarms of 1; 100K and 30K particles are used for SLAM 1 and SLAM 2, respectively
- In SLAM 3, we used detection probability 0.5 and mean number of false alarms of 2 to test the robustness in poor radio signal conditions; 100K particles are used for SLAM 3



Simulation Results (cnt.)

- The performance of virtual source localization is measured by the Euclidean-distance-based mean optimal sub-pattern assignment (MOSPA) metric

- MOSPA error vs time for the two static assets



- The agent position is estimated with high accuracy and the virtual source map is inferred with a low MOSPA error!

Conclusion

- Localization with ECDs
  - controlled the WiFi driver and extracted the CSI measurements from 35 WiFi channels within the channel coherence time
  - mitigated the impacts of processing impairments using signal processing techniques

- Multipath-assisted Localization
  - derived a statistical model for multipath-assisted SLAM
  - developed a multistatic SLAM messaging algorithm
  - evaluated the performance of the developed technique numerically

Way Forward

- Localization with ECDs
  - develop ranging and localization algorithms using ECDs
  - evaluate the performance of the localization system based on ECDs
- Multipath-assisted Localization
  - compare the developed multi-path assisted SLAM approach with existing algorithms for SLAM
  - perform experiments for multipath-assisted SLAM using different sensing technologies, e.g., UWB or millimeter wave radios
- Resource management and asset deployment
  - develop context-aware optimization and control methods for efficient resource utilization and deployment of mobile assets

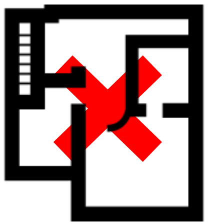
An Infrastructure-Free Localization System for Firefighters

Anthony Rowe
Associate Professor
Electrical and Computer Engineering Department
Carnegie Mellon University

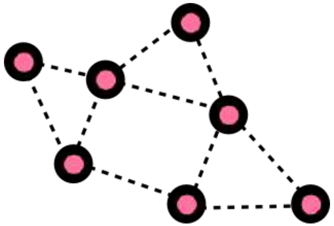
Indoor Localization Platform Goals

Hardware

No prior infrastructure

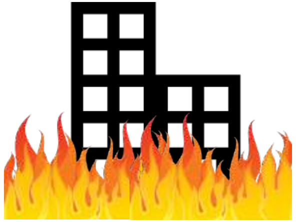


Ad-hoc wireless connectivity



Deployment

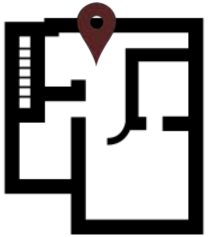
Restricted perimeter



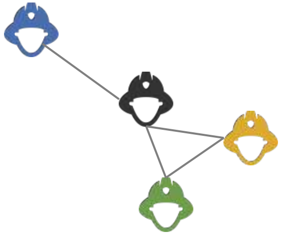
No user-effort

Location algorithm

Absolute location and orientation

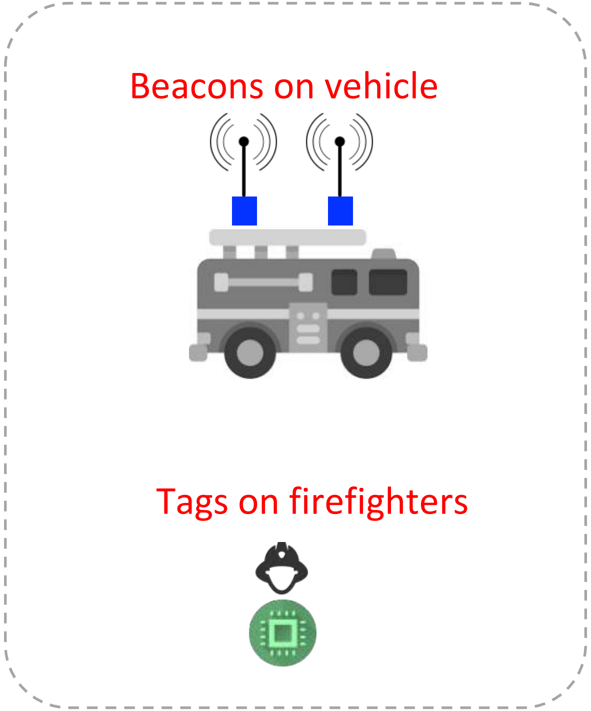


Relative location

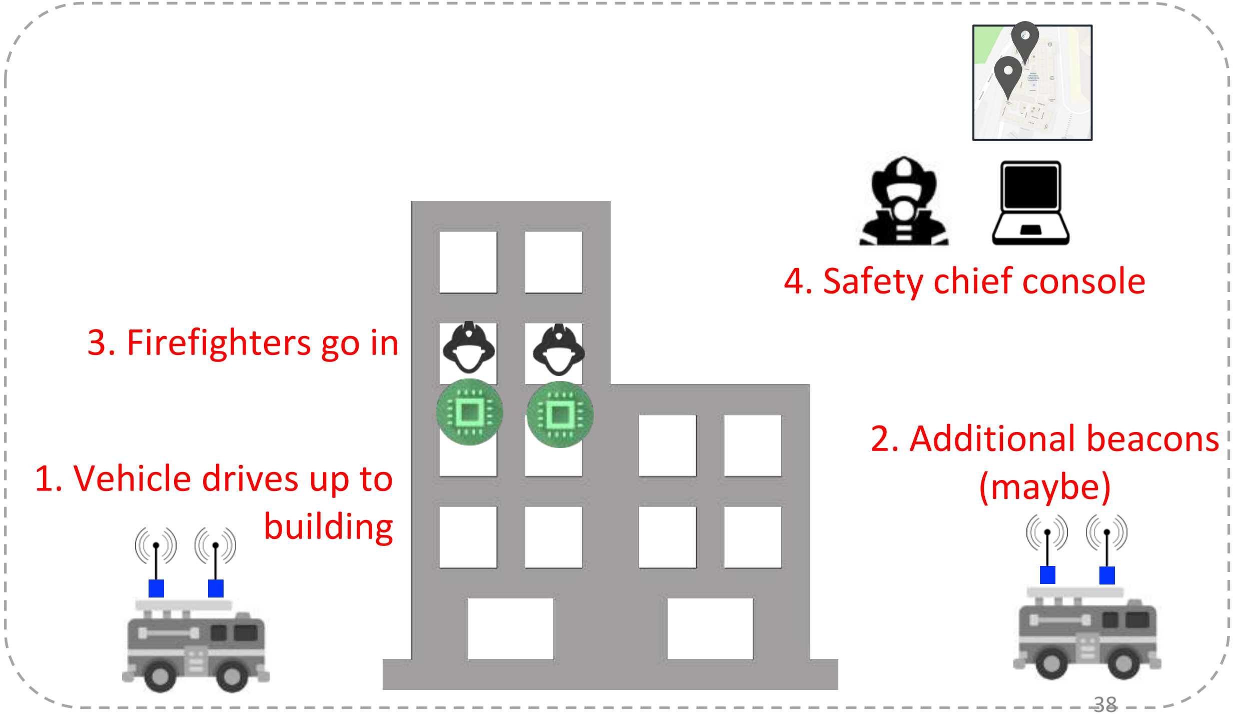


Our approach

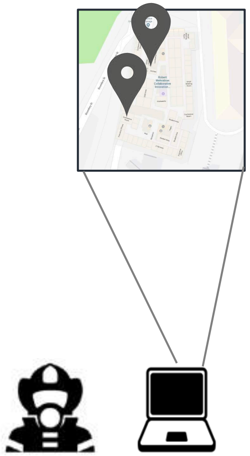
Pre-install



On-site



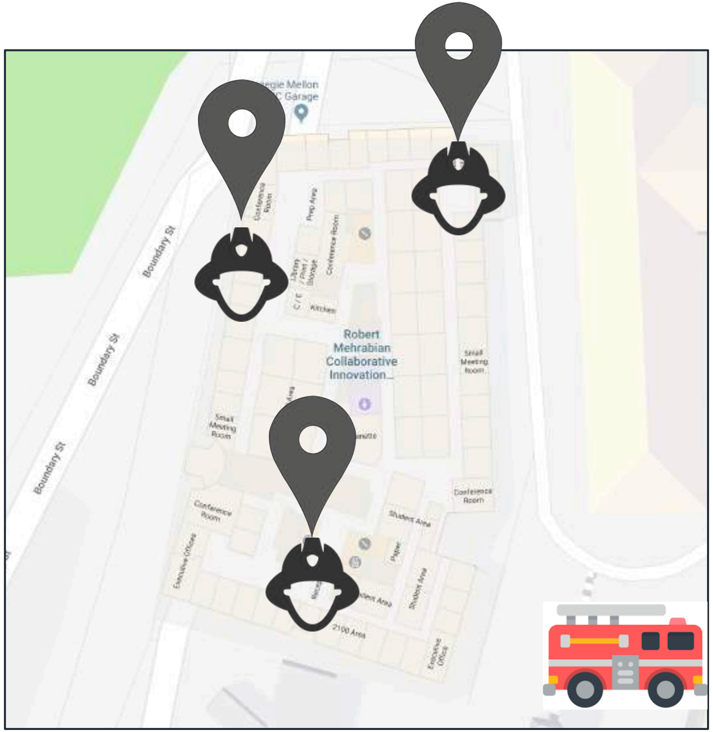
Location Application Scenarios



Location inference

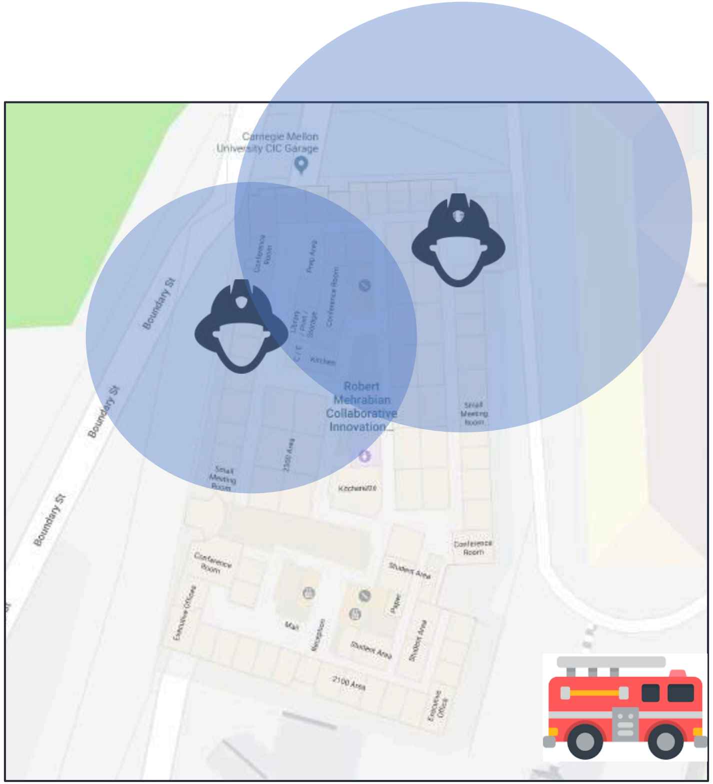
on safety chief console

Scenario 1



Absolute location of firefighters on map

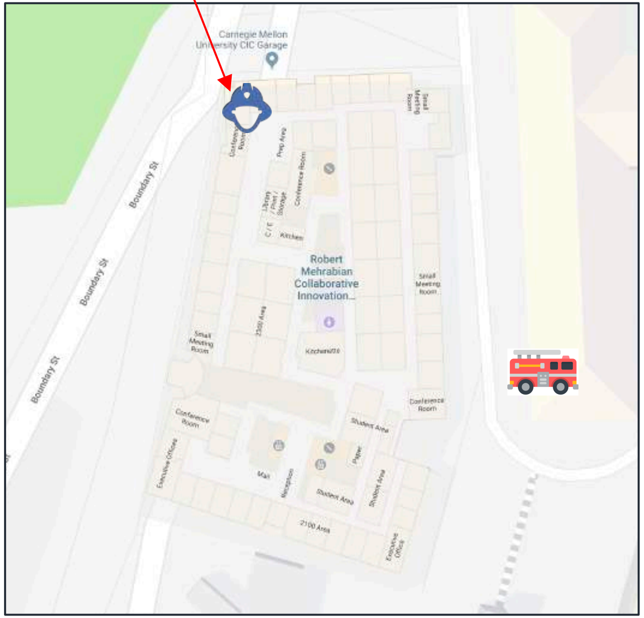
Scenario 2



- Absolute locations on map is uncertain
- Relative locations has high confidence

Scenario 3

Unknown location

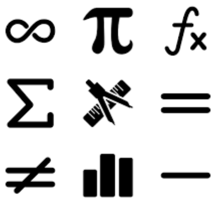


Location identified

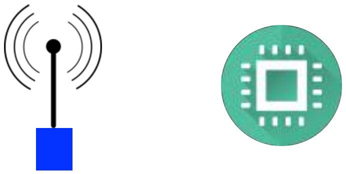
Known locations

System Components

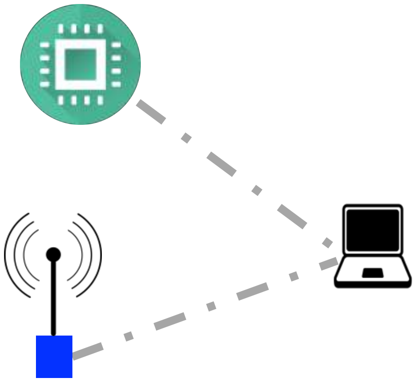
Location Solver



Sensors

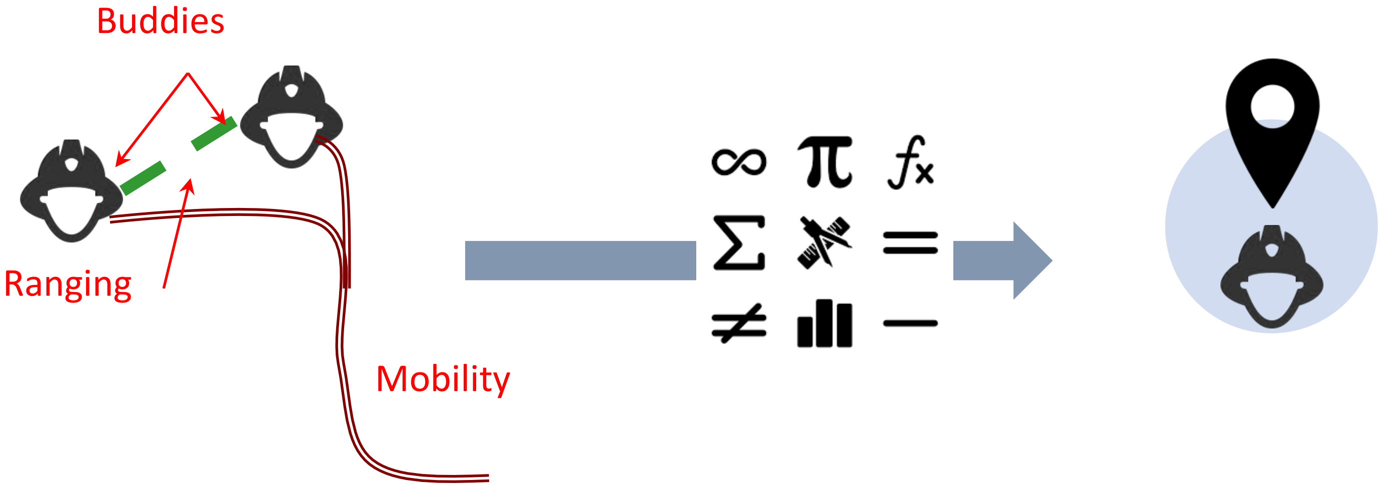


Communication

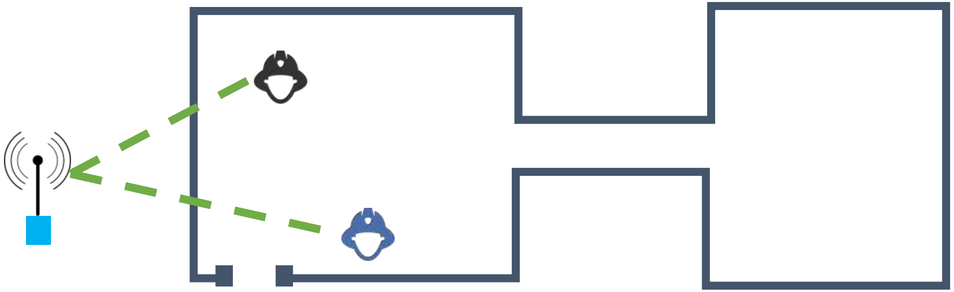


Location Solving Approach

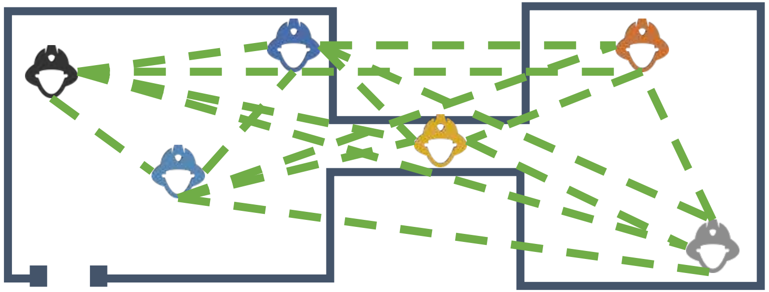
Utilize **ranges** between firefighters and beacons, fused with **mobility** (inertial measurement data) to track location



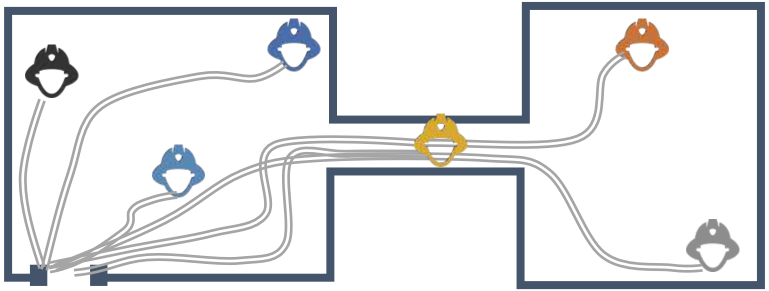
Sensor Inputs



Range to beacons provides absolute positioning

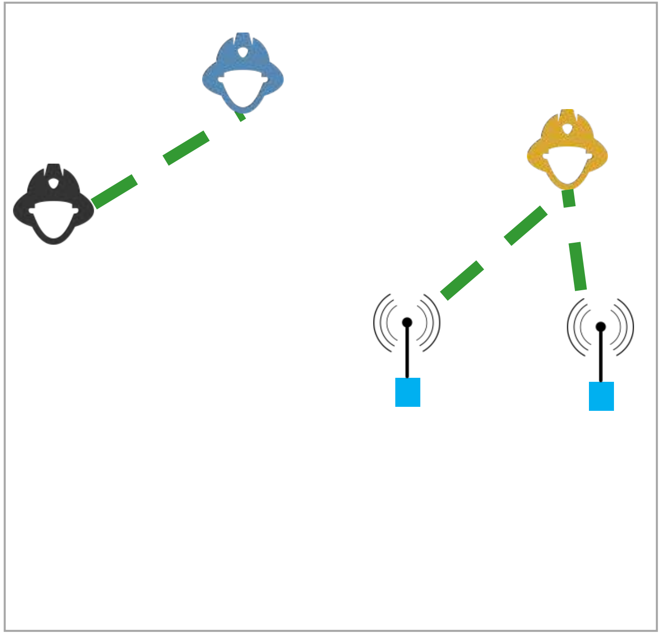


Range between firefighters provides relative positioning

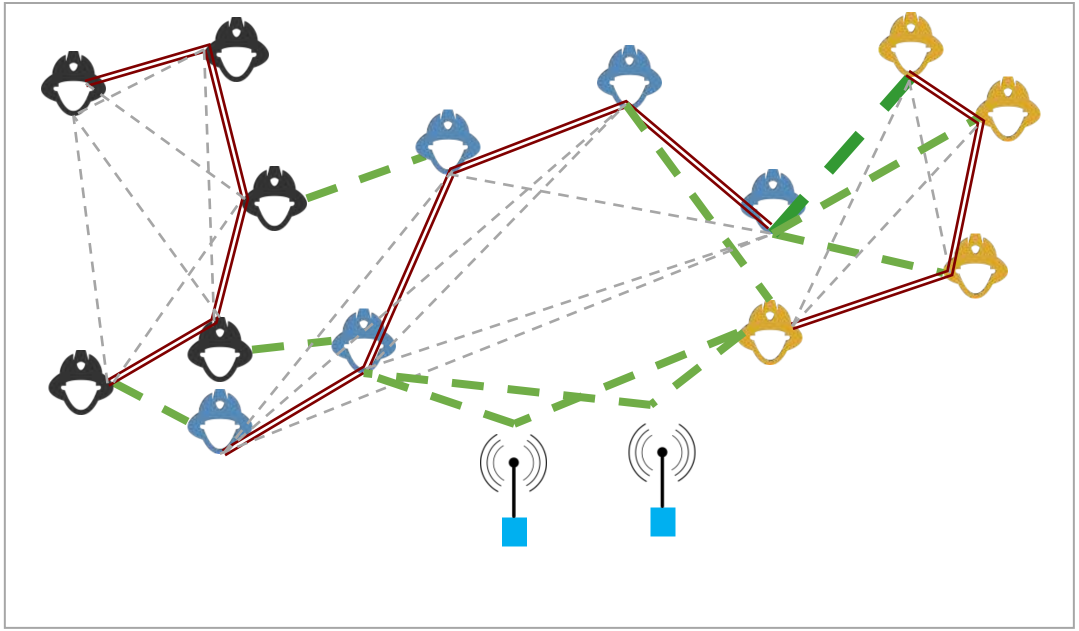


Inertial sensors provide tracking with **Mobility**

Temporal and Spatial Diversity



A Snapshot: Not Solvable

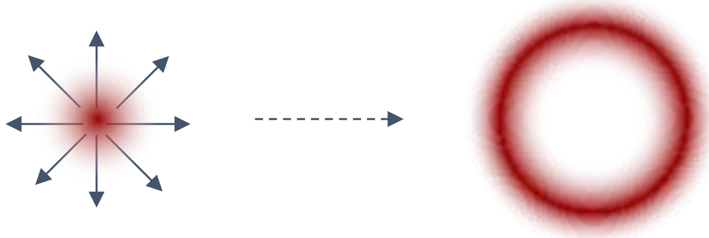


Snapshot Over Time: Solvable!

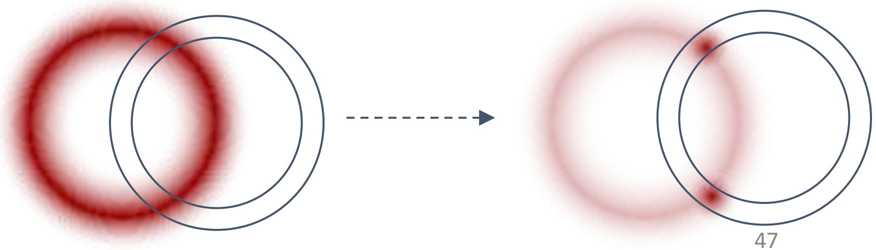
Sensor Fusion

1. Initial belief of location

1. Update belief with motion update from **Mobility**



1. Update weight of particles based on **range** measurement



Heterogenous Sensing

- Device-to-device ranging
- Inertial Measurement Unit
- Visual Tracking
- Sensor driven IMU calibration / training

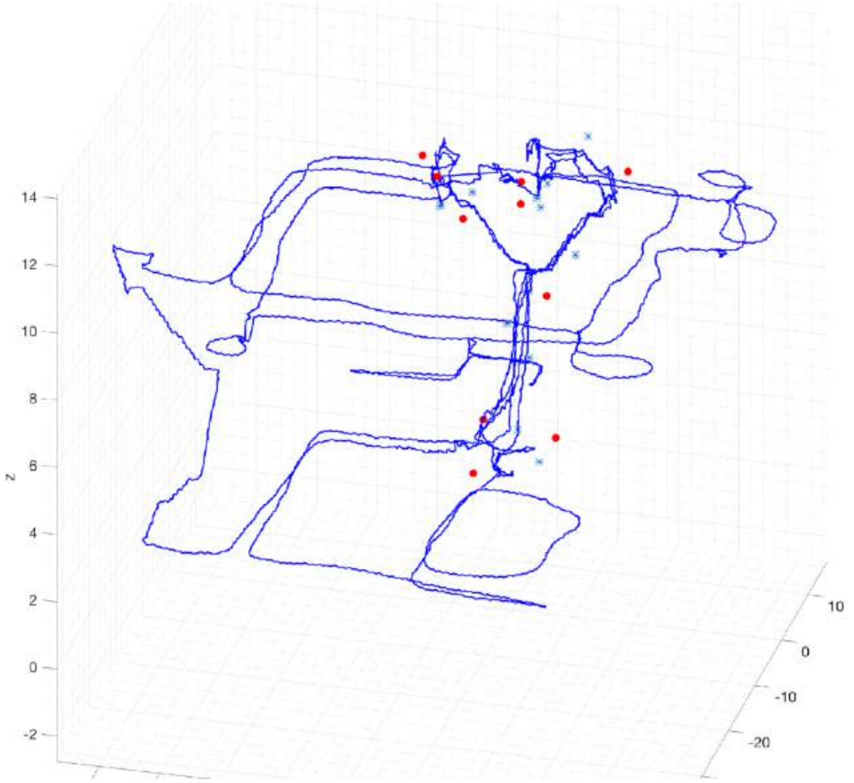
	IMU Dead Reckoning	Peer-to-Peer Ranging	Beacons (fixed but unknown)	Laser Scanner (single user)
Class 1	X			
Class 2	X	X		
Class 3	X	X	X	
Stage 4	X	X	X	X

Algorithmic Goal: Approach that spans these classes with a sensitivity analysis in terms of performance

Microsoft Indoor Localization Competition

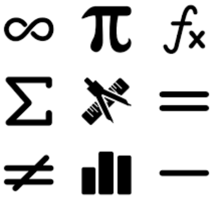
Competition Results:
1st Place!
27cm accuracy in 3D

Also won Best Demo!

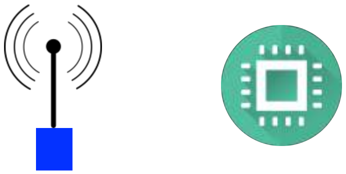


System Components

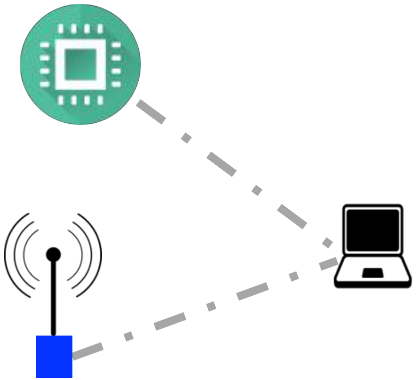
Location Solver



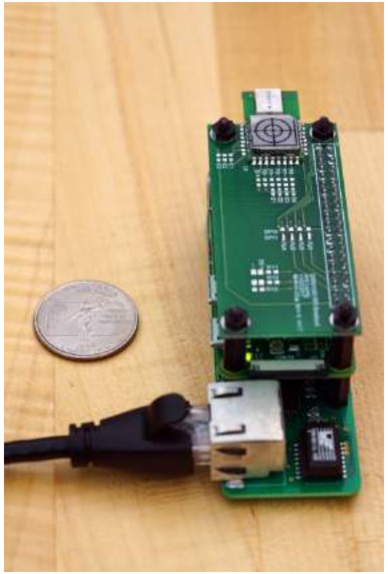
Sensors



Communication



Prototype



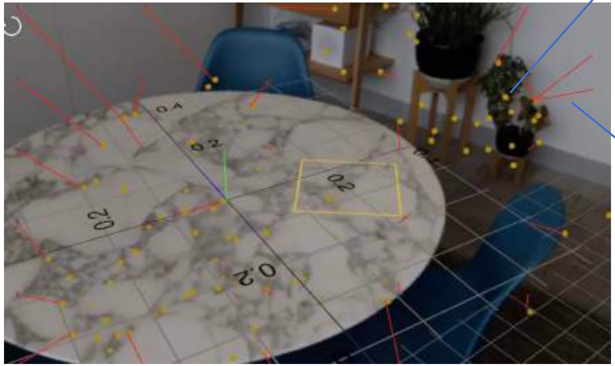
Beacon

Tag

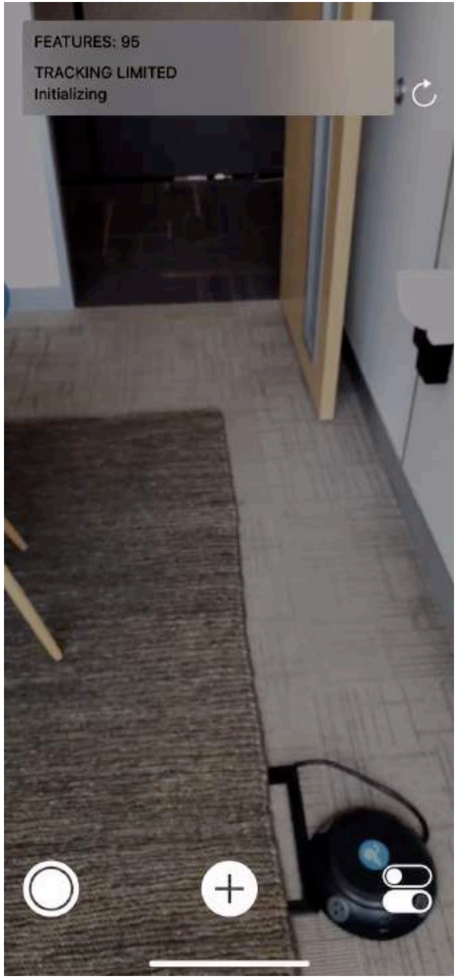
Visual Inertial Odometry

- Optical Feature Tracking
- Inertial Measurement
- Well tuned!

Feature Points



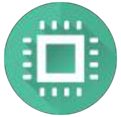
Motion Vector



Hardware Components

- LoRa (Long Range < 1 GHz Communication)
- UWB (Ranging Radio)
- Air Pressure Sensors
- Inertial Measurement

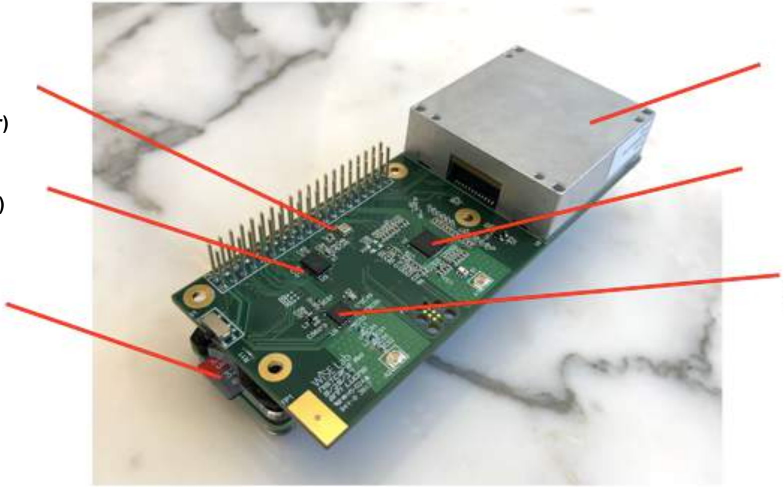
- GPS
- LoRa (Long Range < 1 GHz Communication)
- UWB (Ranging Radio)
- Air Pressure Sensors



(1) Ingress Beacons

(2) Airpack Transponder

Testbed v1


BME680
(Bosch Air
Pressure Sensor)
BNO080
(Bosch 9DOF IMU)
RPI 0 W
ADIS16488
(Tactical IMU)
DecaWave DW1000
(UWB Range Radio)
SX1280
(Narrowband ToF)

Testbed v2

LoRa Gateway

GPS

BME680 (Bosch Air Pressure Sensor)

BNO080 (Bosch 9DOF IMU)

Raspberry Pi

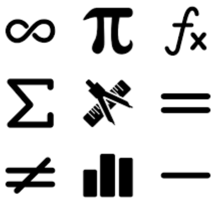
SX1280 (Narrowband ToF)

ADIS16488 (Tactical IMU)

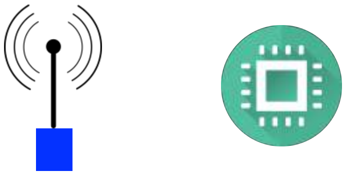
LoRa Transceiver

System Components

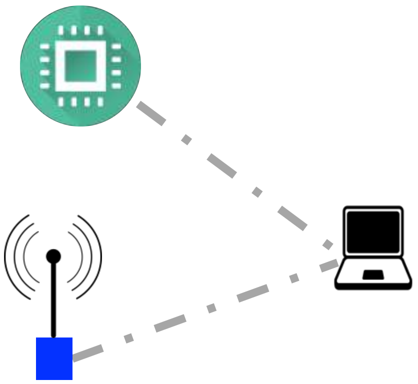
Location Solver



Sensors



Communication



Low-Power Wide-Area Networking (LPWAN)

LoRa

sigfox

lte ADVANCED

NB-IoT

INGENU simply genius

Why LPWAN?

LoRa

Sub-GHz ISM band
chirp spread-spectrum (CSS)

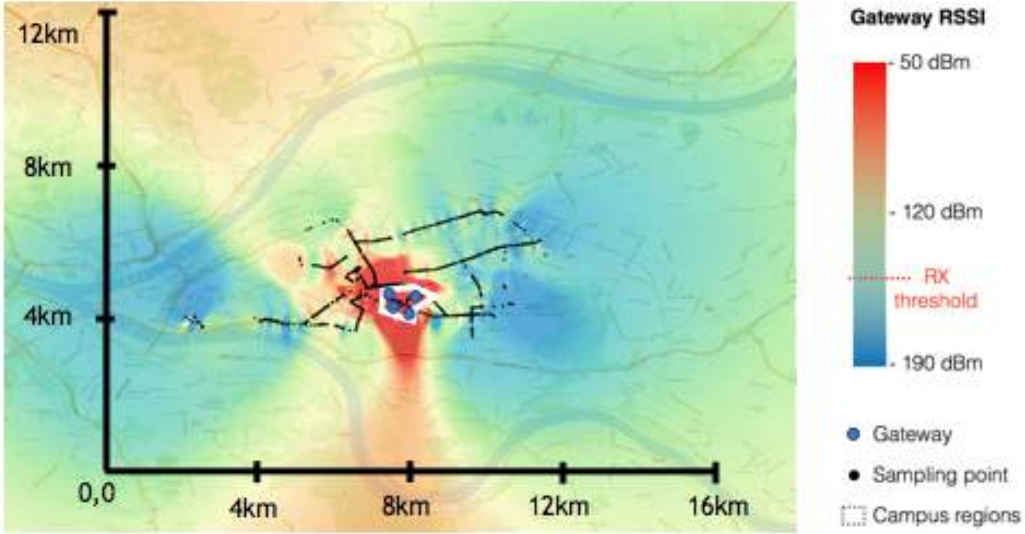
10km range in line-of-sight

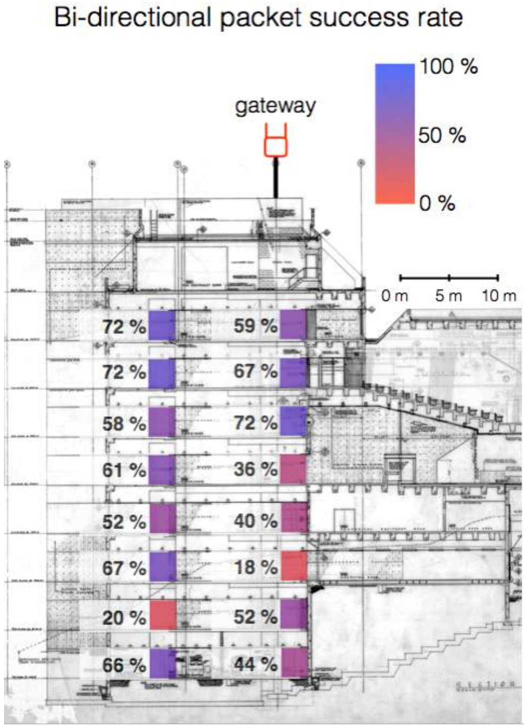
Low data rate
(0.25 kbps – 27 kbps)

5+ year battery life

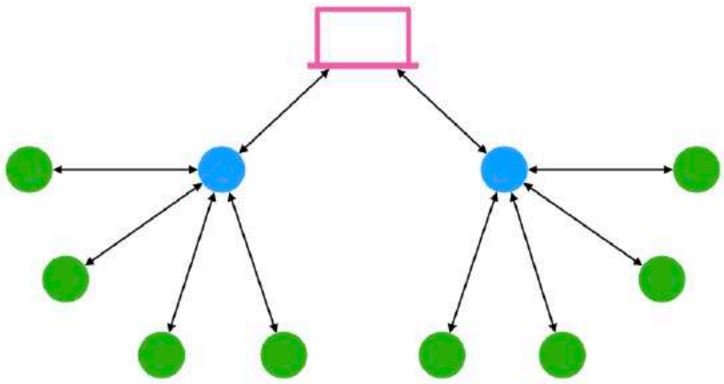
Thousands of devices
per gateway

LoRa Coverage

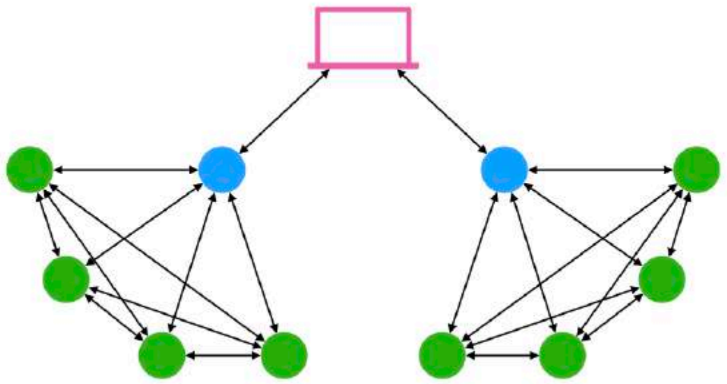




LPWAN Mesh



Traditional star topology

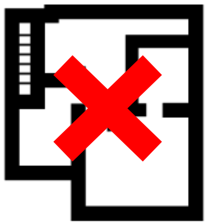


Mesh network
- Extended coverage
- Increased reliability

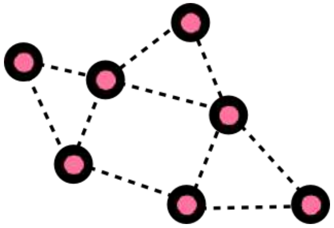
Indoor Localization Platform Goals

Hardware

No prior infrastructure

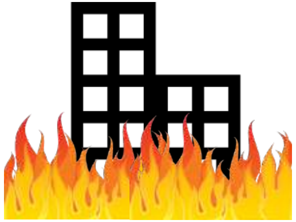


Ad-hoc wireless connectivity



Deployment

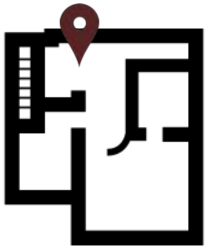
Restricted perimeter



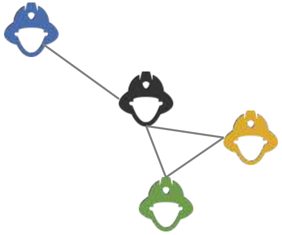
No user-effort

Location algorithm

Absolute location and orientation



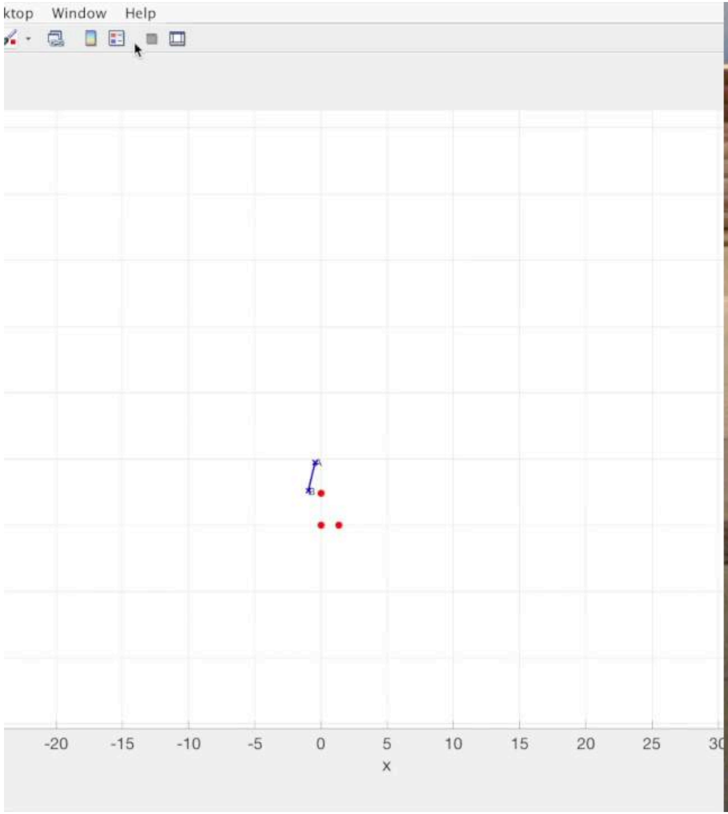
Relative location

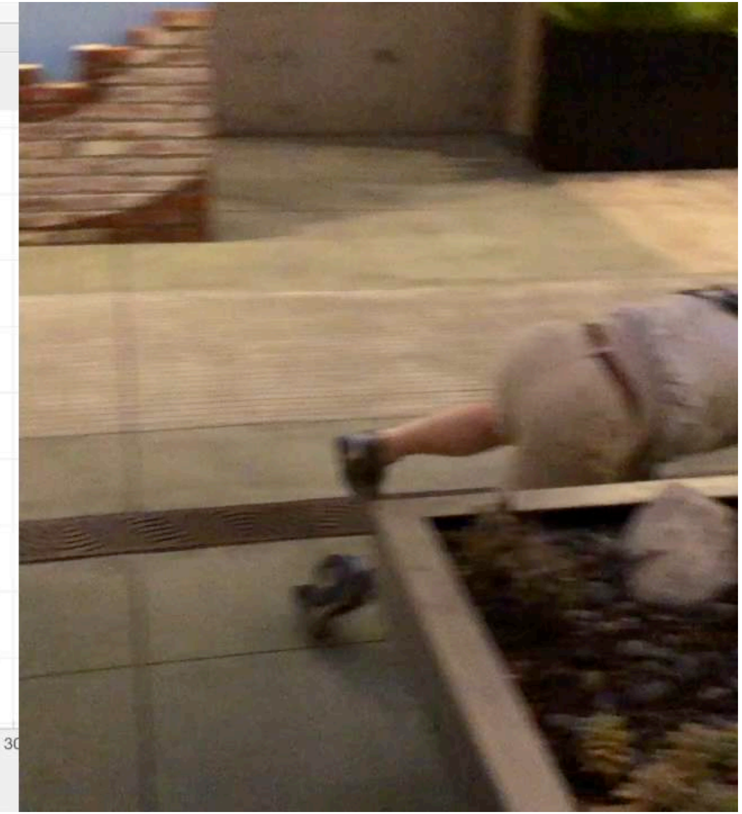


Demo

1. Three ingress beacons are fixed
2. Two volunteers with tags are mobile and walk around
3. Computer shows locations of the volunteers

Video





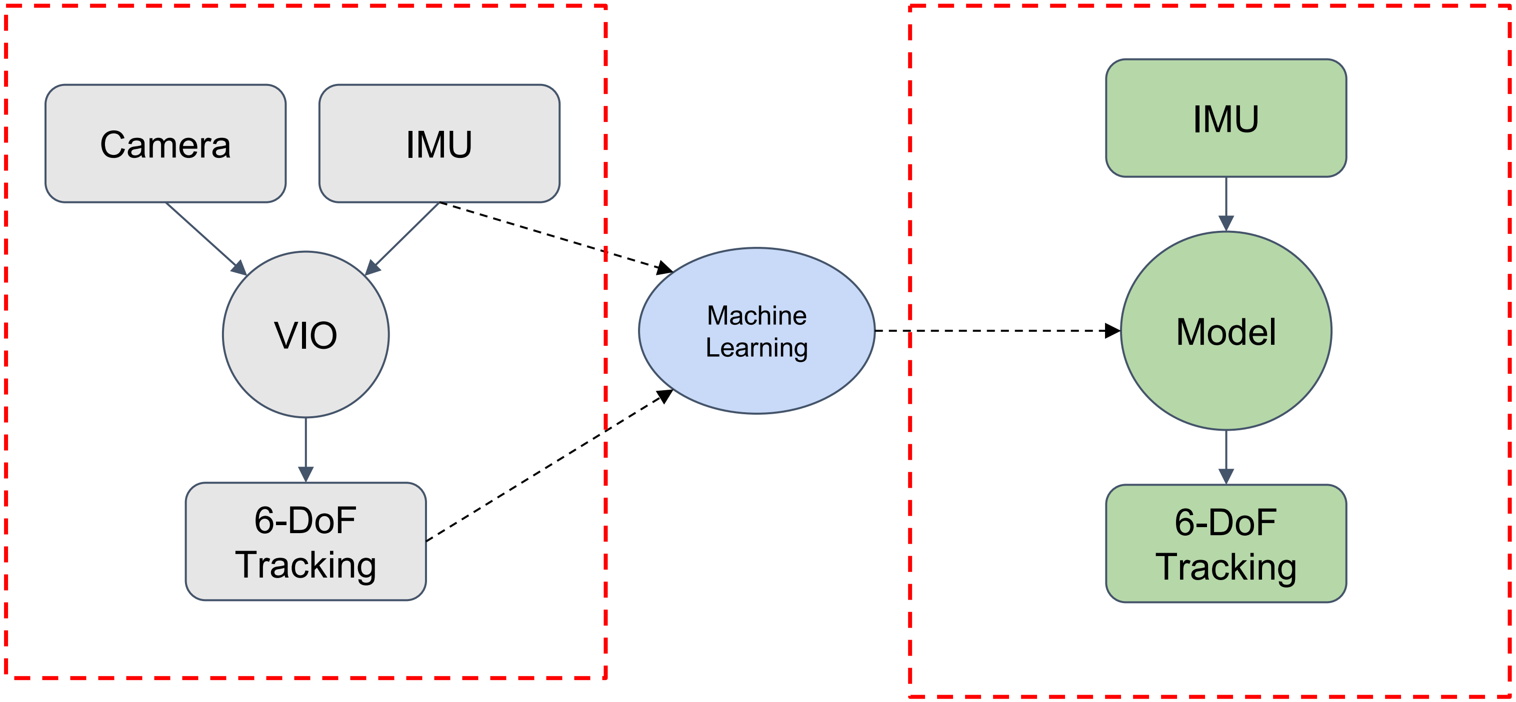
Next Steps

- Field Testing
- Robust enclosure added to SCBA
  - Study impact of placement
- Dealing with intermittent sensor data
  - Algorithmic development
- Lowering system cost through vio-based training

Field Testing

- Capture motion data set
  - Walking, running, crawling, climbing with SCBA in place
  - Multiple body locations
    - Top, middle, bottom of airpack
    - Front strap (good for police as well)
- Capture channel models in different types of smoke
  - Ultra Wide Band RF
  - Laser (multiple varieties)
  - Narrow-band RF

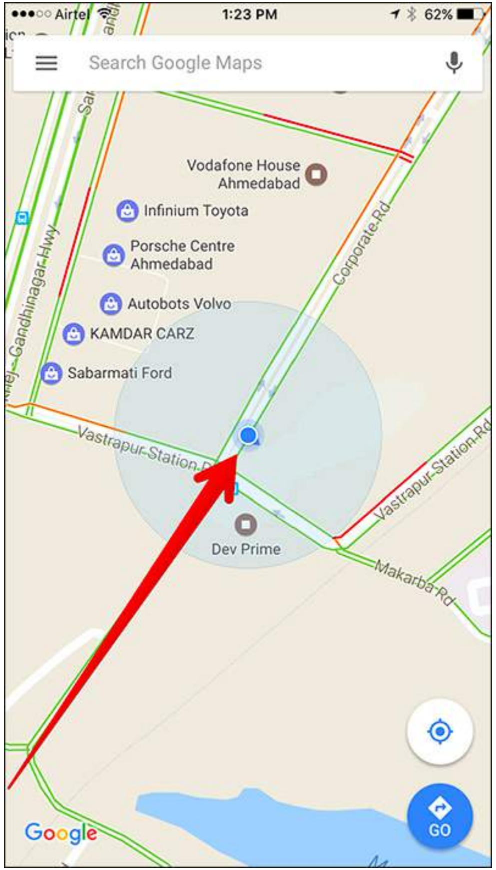
Automated learning of mobility model



Current system

Intermittent Data

- Model Sensor Uncertainty
  - IMU drift
  - RF Ranging Error
  - VIO drift
  - VIO failure in smoke
- Merge and reconstruct data
  - Upon contact with additional data sources like other search groups



Our Team


2200
AREA
2200
AREA
2300
AREA

Thank you!

uNavChip:
Ultimate Navigation Chip

Chip-Scale Personal Navigation System Integrating Deterministic Localization and Probabilistic Signals of Opportunity

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University of California, Irvine

2018 PSCR Public Safety Broadband Stakeholder Meeting
San Diego Convention Center

Team Members

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Team:	
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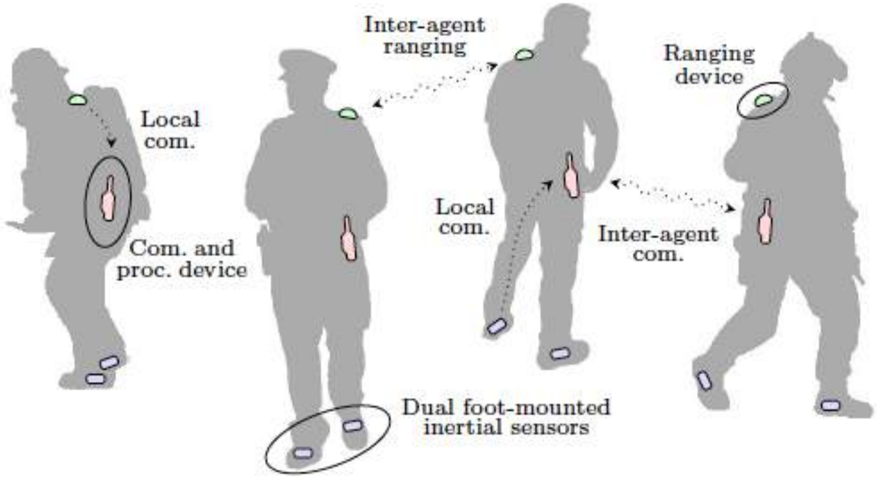
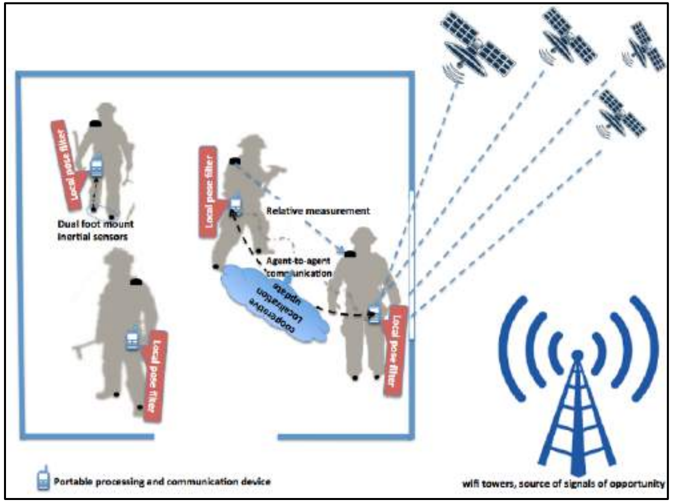
The Problem Statement



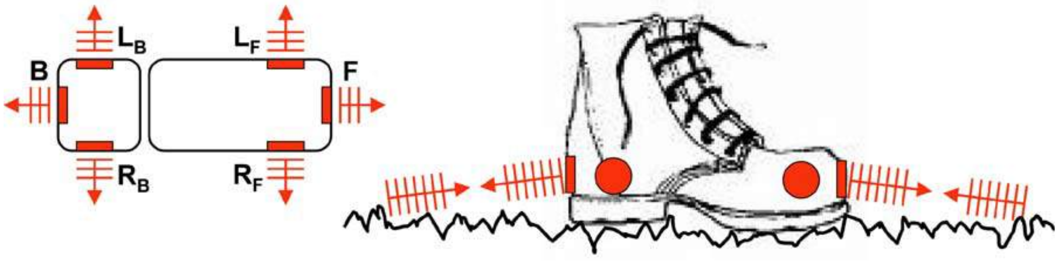


- Localization + Communication
- Situation awareness, coordination, support
- Localization w/o any infrastructure

Our Approach

- Deterministic + Probabilistic + Cooperative

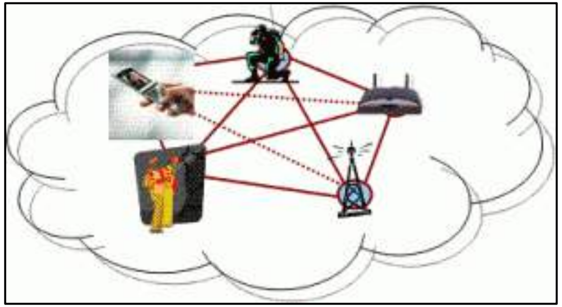
Deterministic

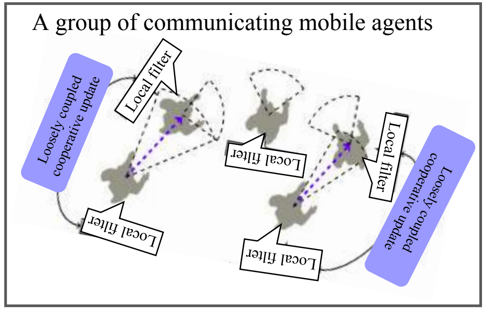


- **Inertial navigation**
- **Foot-to-foot ranging**
- **Zero-velocity-update (ZUPT)**

Probabilistic

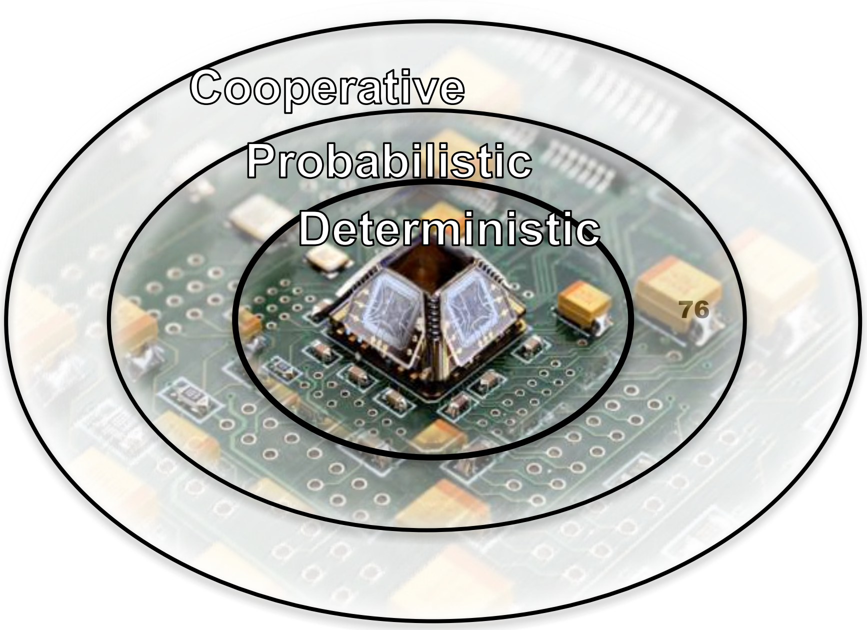
- **Cloud of signals of opportunity**





- **Cooperative localization**

The Concept of *uNavChip*



- **Deterministic**
  Inertial measurement unit, clock, altimeter, proximity sensor

- **Probabilistic**
  Authenticate external signals of opportunity

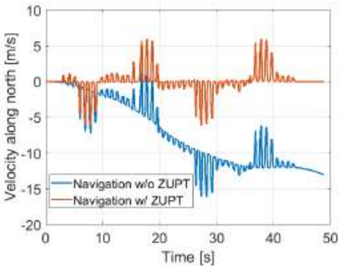
- **Cooperative**
  Detect external signals of opportunity

- Provide maximum autonomy, security, precision

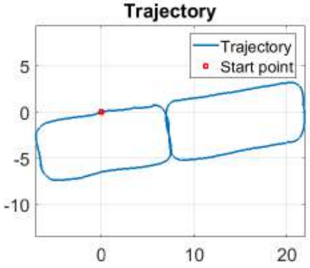
Deterministic Approach

Deterministic

Free vs. ZUPT-aided Navigation

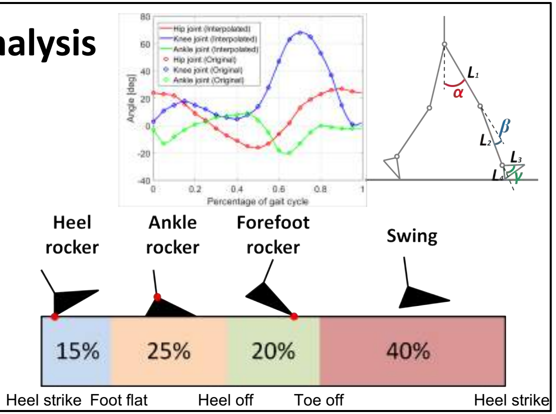


Navigation time	48 s
Error w/o ZUPT	360 m
Error w/ ZUPT	0.31 m



ZUPT improves navigation accuracy

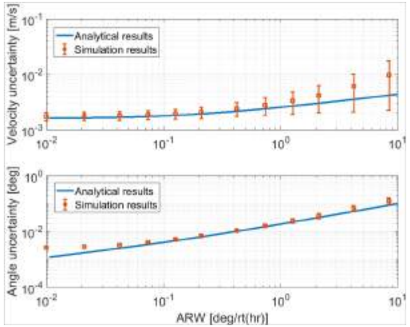
Gait Analysis

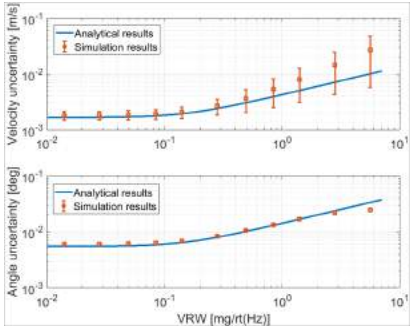


Effects of IMU errors in ZUPT

IMU grade	ZUPT off	ZUPT on
Consumer	192 m	0.87 m
Tactical	1.79 m	0.031 m
Inertial	0.019 m	0.015 m

- Navigation time: 54 s
- Trajectory length: 75 m

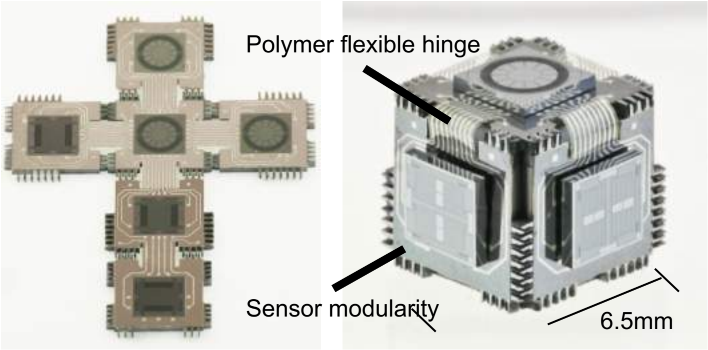


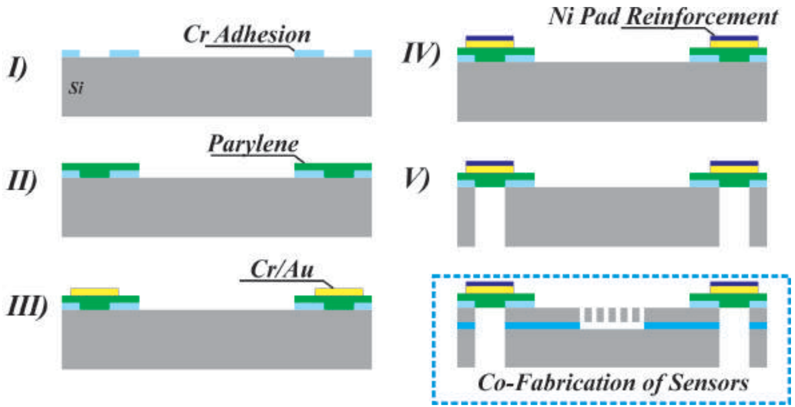


Better IMU performance is still needed even with ZUPT algorithm

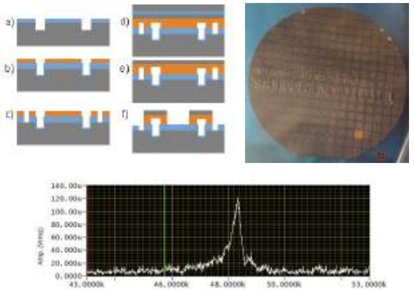
Prototyping of *uNavChip*

Deterministic

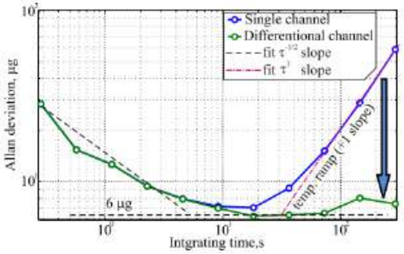




Ultrasonic Ranger (CMUT)

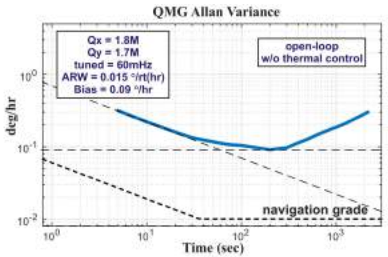


Accelerometer



Zotov, Sergei A., et al. "High quality factor resonant MEMS accelerometer with continuous thermal compensation." *IEEE Sensors Journal* 15.9 (2015): 5045-5052.

Gyroscpe



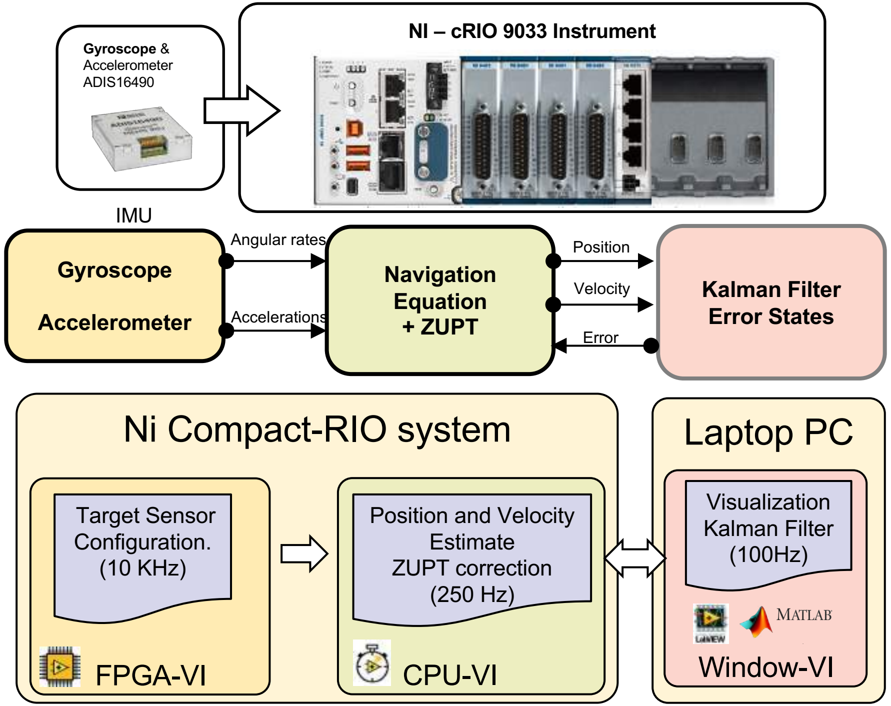
Askari, S., Asadian, M., Kakavand, K., and Shkel, AM. "Near-Navigation Grade Quad Mass Gyroscope with Q-factor Limited by Thermo-Elastic Damping", Hilton Head 2016

Platform for field demonstration

Deterministic

Commercial localization platforms

Selection and implementation of hardware



Multi-sensor localization electronic platform

Signals of opportunity

- Graduate students: K. Shamaei & A. Abdallah

Cellular Signals

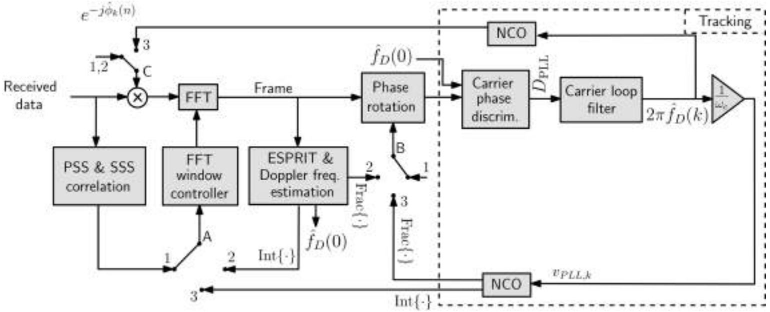
CDMA frequncy bands	U.S. operators	LTE frequncy bands
1930 – 1990 MHz 869 – 894 MHz	AT&T	717 – 728 MHz 734 – 746 MHz 869 – 894 MHz 1930 – 1990 MHz 2350 – 2360 MHz
1930 – 1990 MHz 2110 – 2155 MHz	T-Mobile	2110 – 2170 MHz 729 – 746 MHz
2110 – 2170 MHz	Sprint	814 – 849 MHz 1850 – 1915 MHz 2496 – 2690 MHz
2120 – 2170 MHz	Verizon	746 – 756 MHz

Digital Television Signals

U.S. frequncy bands
54 – 88 MHz
174 – 216 MHz
470 – 890 MHz

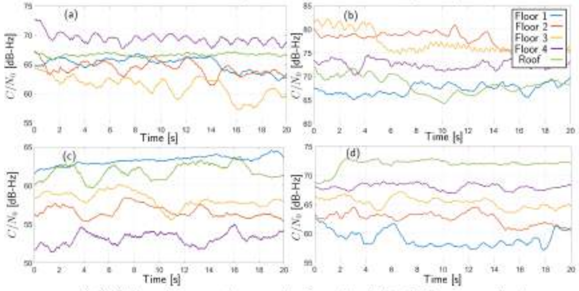
WiFi Signals

U.S. frequncy bands
2401 – 2473 MHz



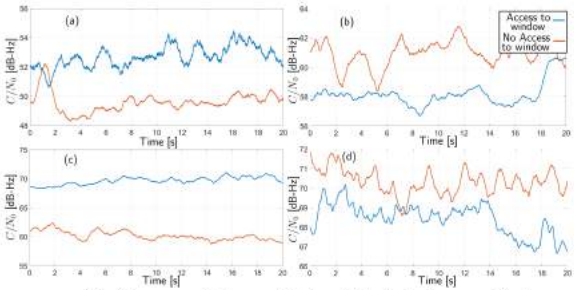
Carrier phase-based receiver structure for indoor navigation with LTE signals

Effect of the height on the received signal C/N_0



(a)–(d) represent the results for eNodeBs 1–4, respectively.

Effect of the room structure on the received signal C/N_0



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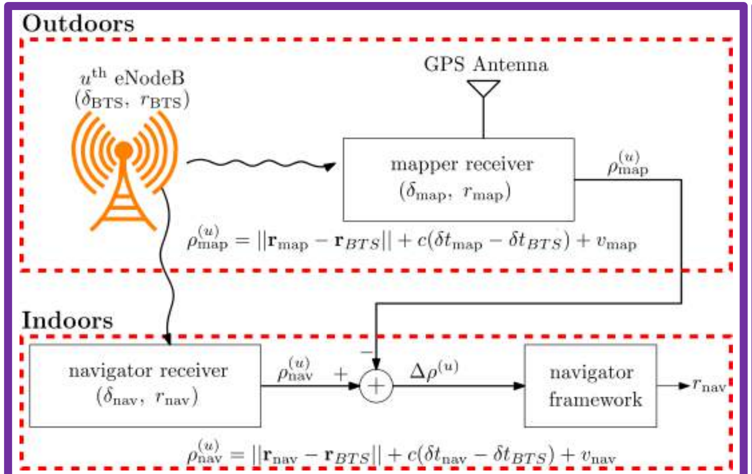
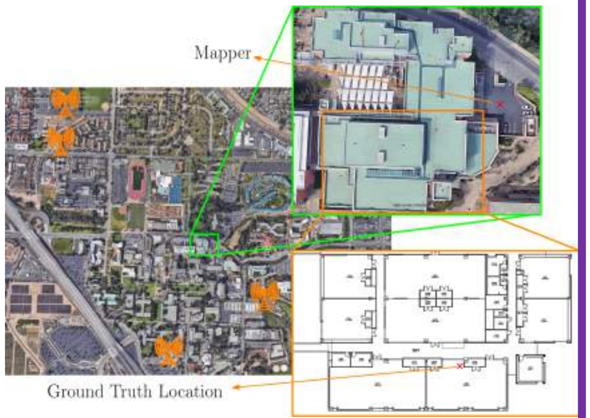
Signals of opportunity

Probabilistic



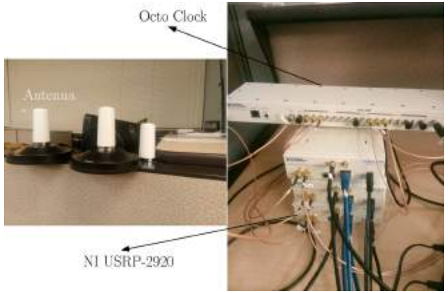
Mapper/Navigator framework



Environmental layout

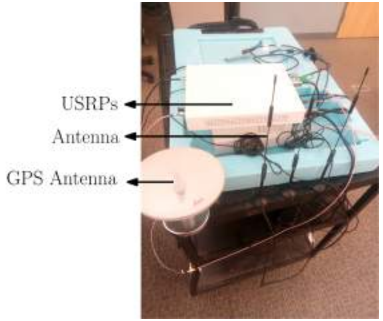
Experimental setup:

(a) Navigator



Experimental setup:

(b) Mapper



Signals of opportunity

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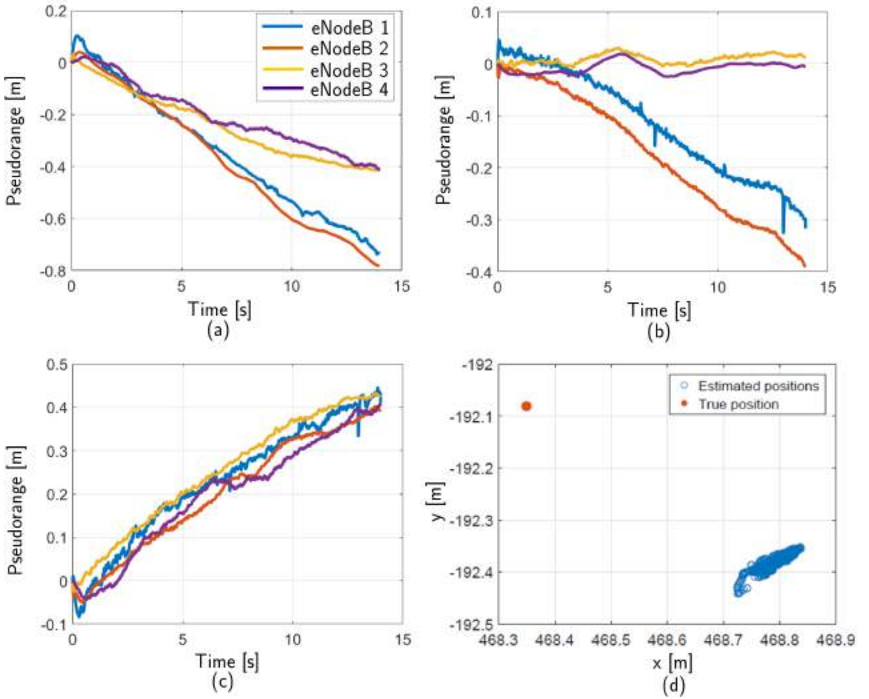
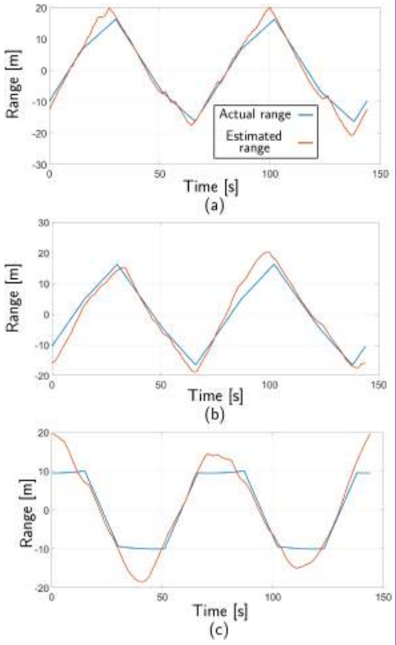
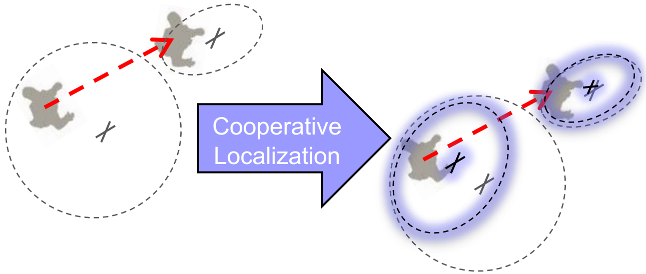


Experimental results: (a) mapper, (b) navigator, (c) difference, and (d) estimated position vs. true positions (assuming perfect synchronization between mapper and navigator)



Actual and estimated ranges: (a) – (c) show the results for eNodeBs 1-3, respectively

Cooperative Localization

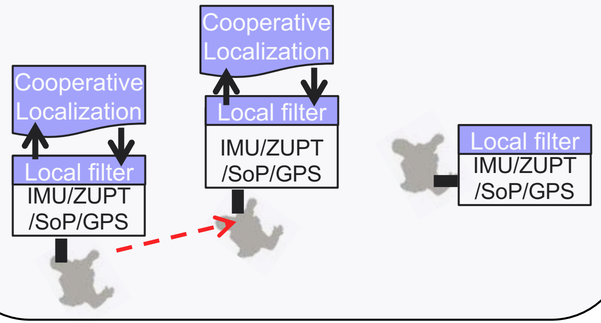


$$\hat{\boldsymbol{x}}_i^+ = \hat{\boldsymbol{x}}_i^- + \boldsymbol{K}_x\left(r - \sqrt{(\hat{x}_i^- - \hat{x}_j^-)^2 + (\hat{y}_i^- - \hat{y}_j^-)^2}\right)$$

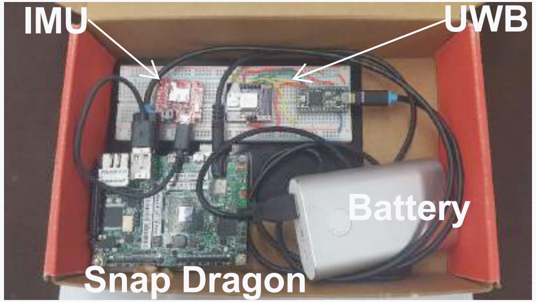
$$\boldsymbol{P}^- = \begin{bmatrix} \boldsymbol{P}_i^- & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{P}_j^- \end{bmatrix} \longrightarrow \boldsymbol{P}^+ = \begin{bmatrix} \boldsymbol{P}_i^+ & \boldsymbol{P}_{ij}^+ \\ \boldsymbol{P}_{ji}^+ & \boldsymbol{P}_j^+ \end{bmatrix}$$

- **Challenge**: - strong correlations that cannot be ignored
  - limited communication
- **Objective**: - Communicate time = relative measurement time
- **Solution**: - upper-bound the join covariance
  - estimate unknown correlations

Algorithm level



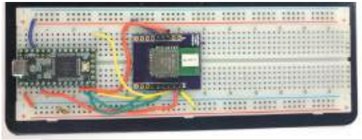
Hardware



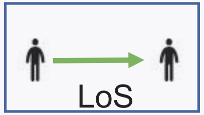
Cooperative localization

Cooperative

UWB

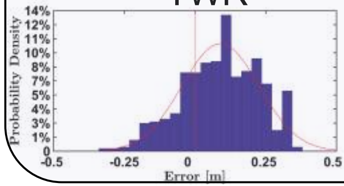


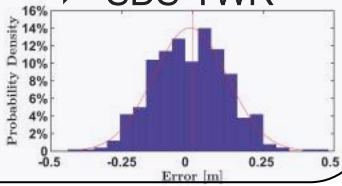
- ➢ Ranging sensor
- ➢ Communication module

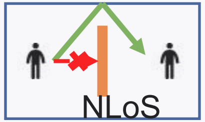


- *Single-sided TWR*
- *Symmetric double-sided TWR*

TWR → SDS-TWR

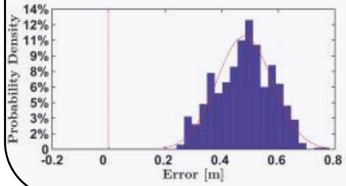


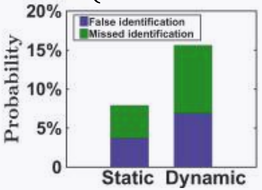




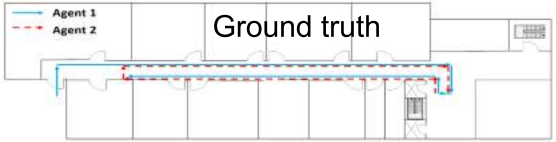
NLoS Identification:

$$P_{RX} - P_{FR} \begin{cases} \geq P_{PI} & \text{NLoS} \\ < P_{PI} & \text{LoS} \end{cases}$$

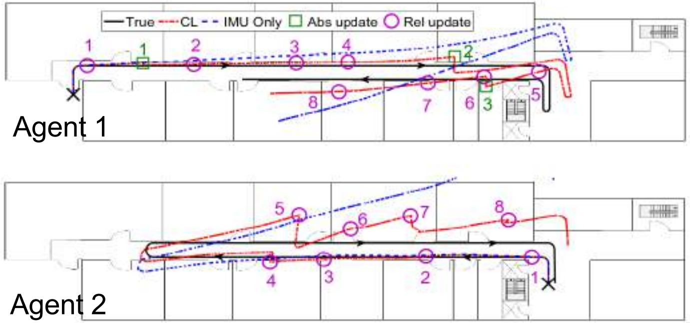




Experiment



Cooperative localization vs. IMU only



Expected Impact

- *uNavChip*
  - a single-chip integrating deterministic, probabilistic, cooperative capabilities
- Miniaturized Personal Navigation Technology for GPS-challenged environment
- Achieve the localization accuracy on the level of 1 meter
- Hours of operation with the level of accuracy

Acknowledgements

This work was performed under the following financial assistance award 70NANB17H192 from U.S. Department of Commerce, National Institute of Standards and Technology. Program Manager Jeb Benson.

Decimeter Accurate, Long Range Non-Line-of-Sight RF Localization Solution for Public Safety Applications

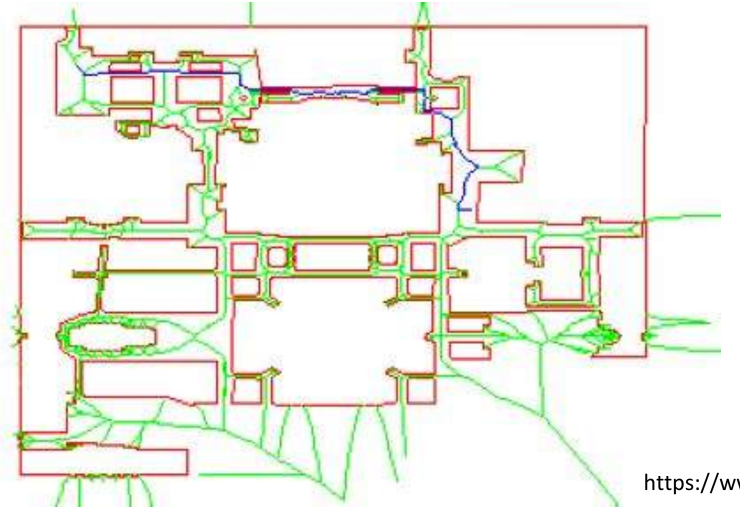
PI: Hun-Seok Kim

Department of Electrical and Computer Engineering
University of Michigan

Motivation

- LBS for public safety applications
  - First responder task path planning and tracking
  - Localization and tracking of things and people
    - Robots, packages, and workers in warehouses
    - Medicine, equipment, patients, and staff in hospitals
    - Emergency evacuation path planning / guidance

Image from http://scanonline.com/rtls/



https://www.cs.columbia.edu/~pblaer/projects/path_planner/

Indoor Localization Technologies

- Inertial measurement unit (IMU) based
  - Accelerometer and gyroscope for 6 degree-of-freedom measurement
  - Susceptible to error integration
- Computer vision based
  - Simultaneous localization and mapping (SLAM)
  - Sensitive to light conditions
  - Computationally demanding
- Radio frequency (RF) based
  - Non-line-of-sight operable
  - Faster measurement time
  - Challenges to obtain long range, decimeter accuracy indoors
- Sensor fusion
  - IMU + CV + RF: fusion with adaptive filter

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Existing RF Localization Solutions

- GPS
  - Covered area ✓
  - Accuracy ✗
  - Indoor usage ✗

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- GPS
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- WiFi / Bluetooth (RSSI-based)
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  - Indoor usage ✓
- Ultra-Wide Band (UWB, 802.15.4a)
  - Covered area ✗
  - Accuracy ✓
  - Indoor usage ✓

Requirements for Public Safety Apps

- Easily and quickly deployable infrastructure
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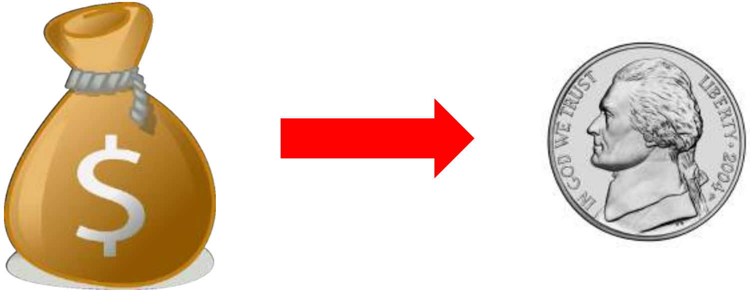
  - Long range (~100m) operable
  - Milli-second refresh rate, 10s of cm accuracy
- Ultra-low cost tags
  - To be ported on numerous IoT devices
  - Tracking of disposable tags



Requirements for Public Safety Apps

- Small form factor
  - Unobtrusive integration into IoT

Small

Requirements for Public Safety Apps

- Small form factor
  - Unobtrusive integration into IoT
- Low power consumption
  - Sustainable with a small coin-cell battery
  - No manual battery management

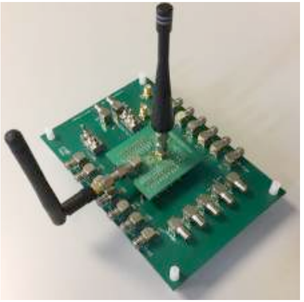
Small

Low-power

RF-Echo

- ~100 m distance for indoor localization
- Decimeter ranging accuracy (LOS/NLOS)
- Low-energy consumption tag: 18 μJ per fix

Tag



Tag with DC board

Anchor (USRP + Laptop) & tag

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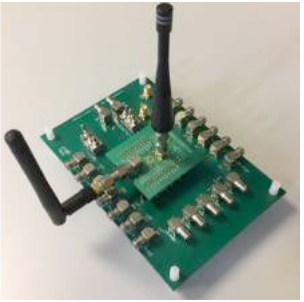
RF-Echo

- ~100 m distance for indoor localization
- Decimeter ranging accuracy (LOS/NLOS)
- Low-energy consumption tag: 18 µJ per fix
- Custom ASIC tag (180 nm technology)
- Anchor realized on USRP software defined radio

Tag



Tag with DC board

Anchor (USRP + Laptop) & tag

Time of Flight (ToF) Ranging

- Speed of light: c, Time of Flight (ToF): τ
- Distance: $d = c\tau$ → 30 cm with ToF of 1ns
- Transmit (TX) signal: $x(t)$
- Receive (RX) signal: $y(t)$
- Channel Impulse Response (CIR): $h(t)$
- $y(t) = x(t) * h(t)$

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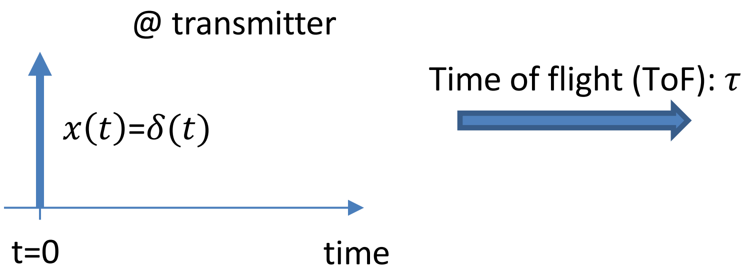

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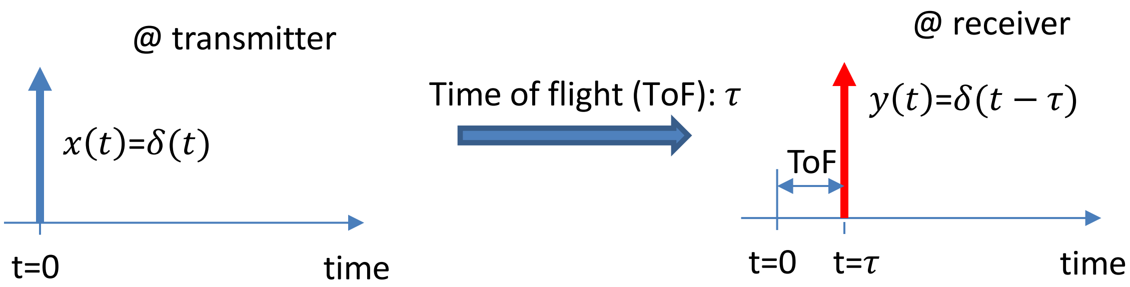

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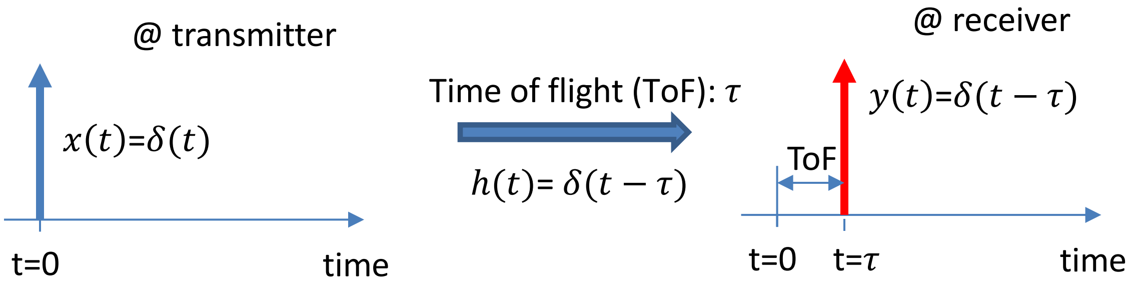

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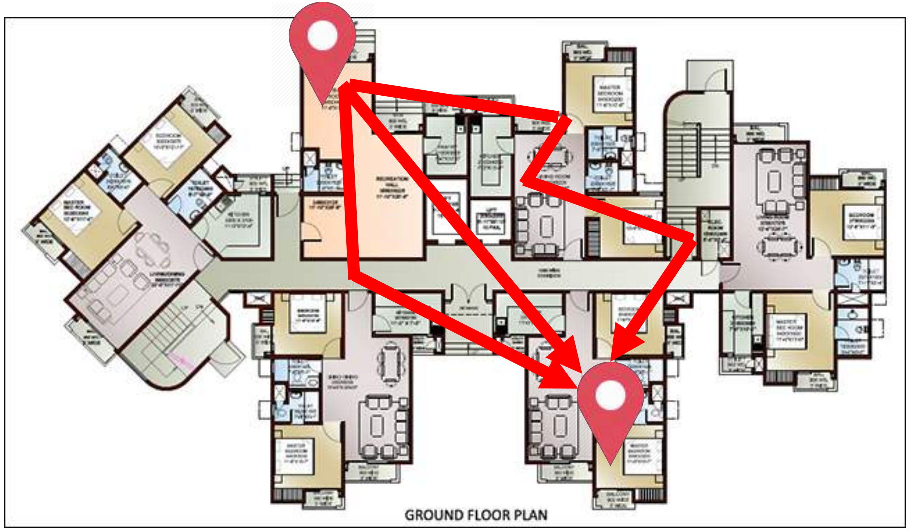
Time of Flight (ToF) Ranging

1 ns ToF ==
30 cm in distance

Indoor channel is **multi-path** rich



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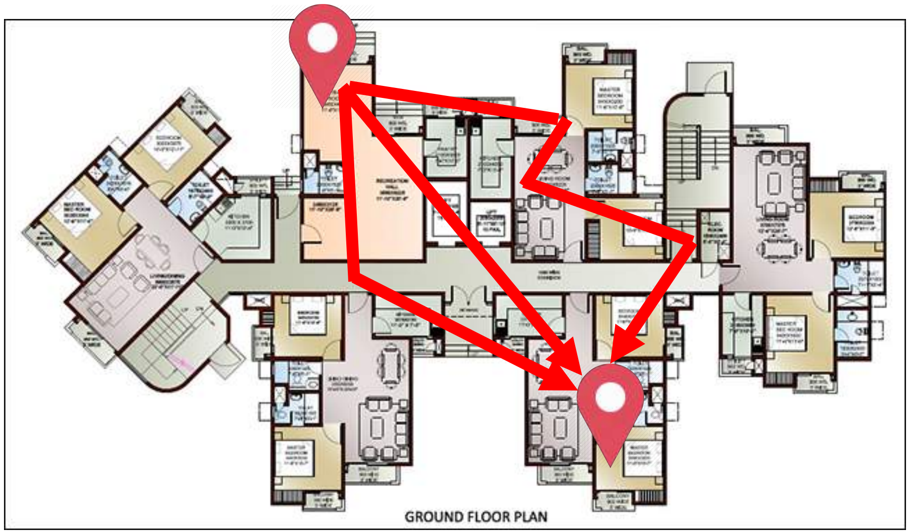
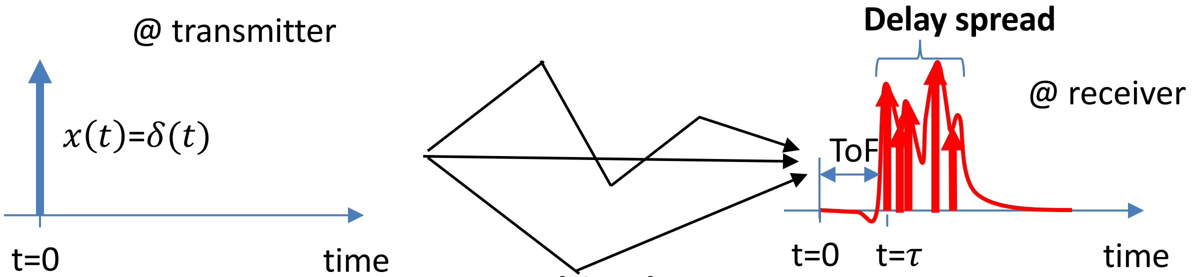
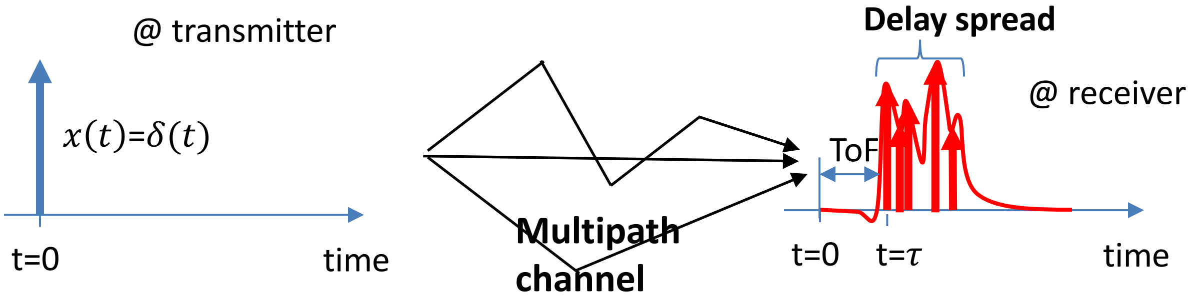




Ultra-Wide Bandwidth (UWB) Ranging

- Bandwidth = $\frac{1}{\text{Pulse Width}}$
- UWB: ultra-short pulses occupying an ultra-wide band
- UWB (> 1 GHz) pulse width << multi-path delay spread
- Observing RX signal directly reveals $h(t)$ and ToF



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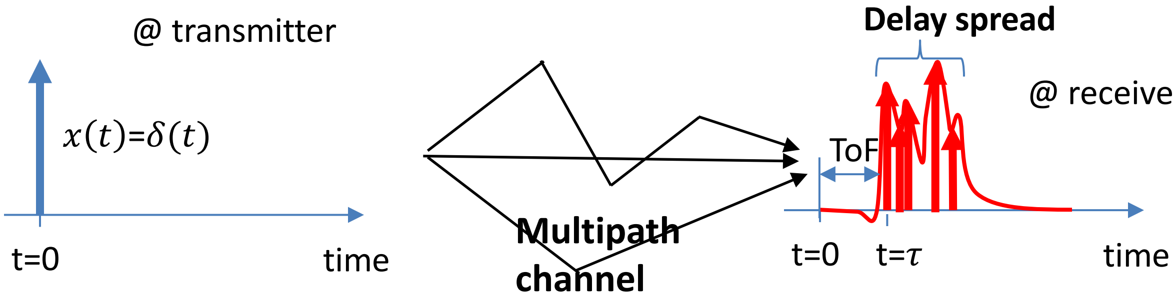
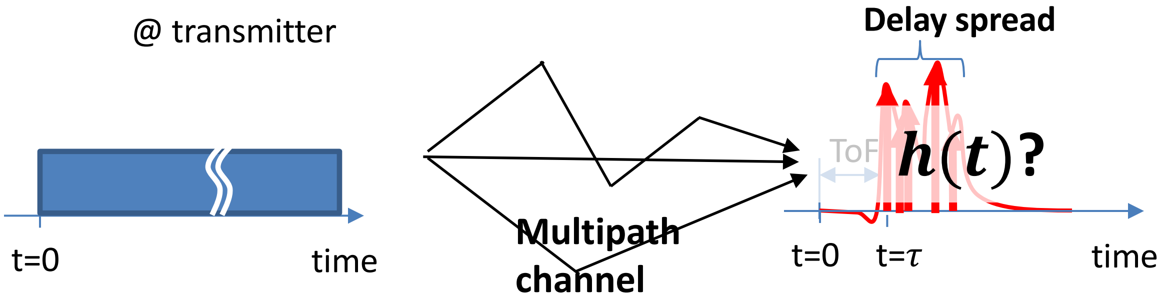
- UWB: ultra-short pulses occupying an ultra-wide band
- UWB (>1GHz) pulse width << multi-path delay spread
- Observing RX signal directly reveals $h(t)$ and ToF
- But … it requires
  - Precise time synchronization
  - High sampling rate ADC
  - Ultra-wide bandwidth



Narrow Bandwidth Ranging

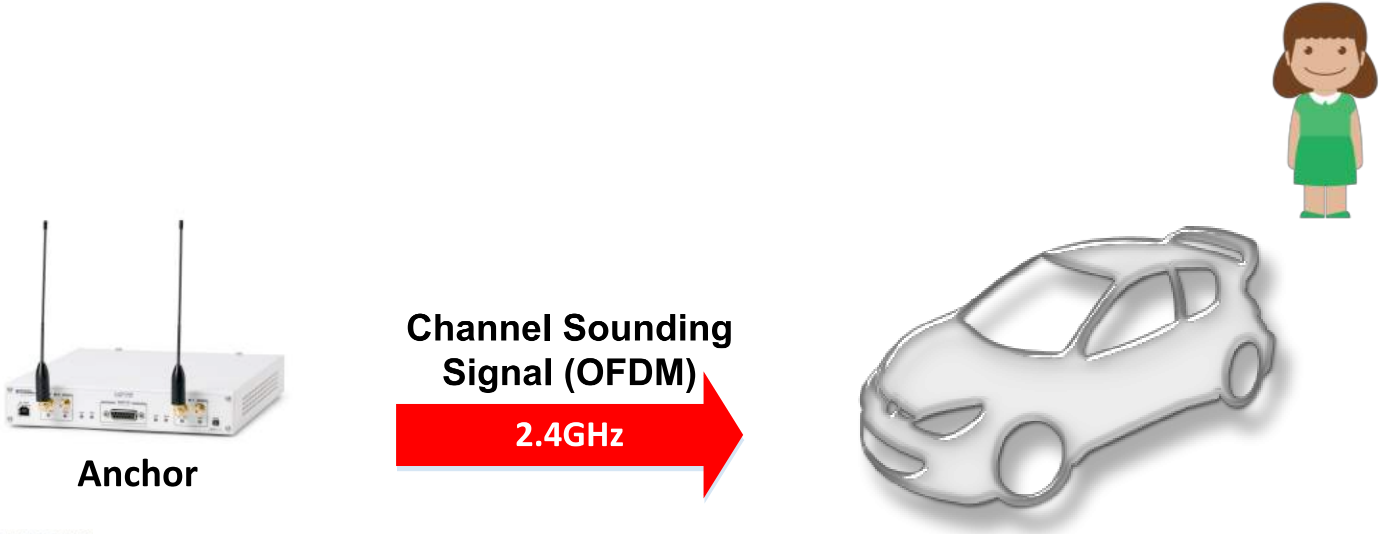
- Bandwidth = $\frac{1}{\text{Pulse Width}}$
- Bandwidth is a scarce resource!
- **Narrowband signal:**

  Pulse width >> Multi-path delay spread
- **Narrow bandwidth imposes fundamental limitation to accurately estimate CIR $h(t)$**



RF-Echo

- Operating Principle:
  - Round-trip Time-of-Flight (RToF)



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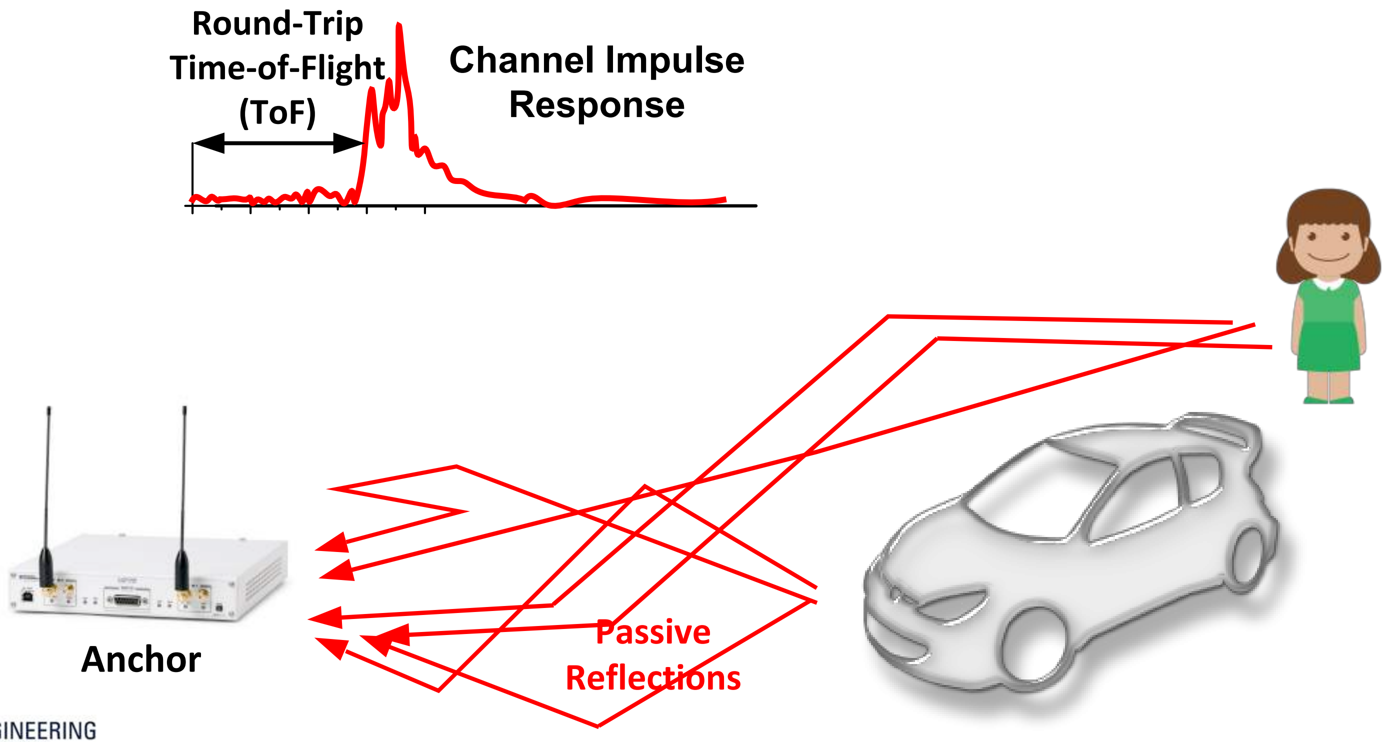
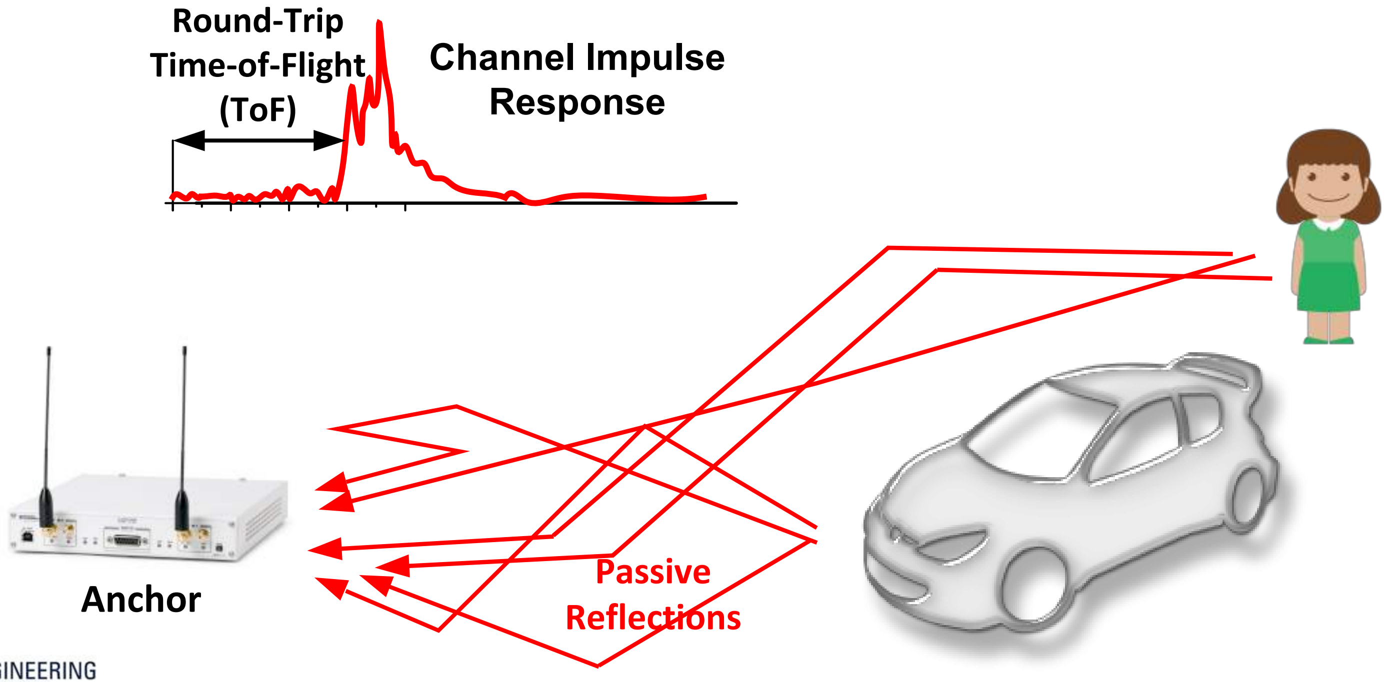


RF-Echo

- Operating Principle:
  - Round-trip Time-of-Flight (RToF)
  - Passive reflection: cannot distinguish target and non-targets



RF-Echo

- Operating Principle:
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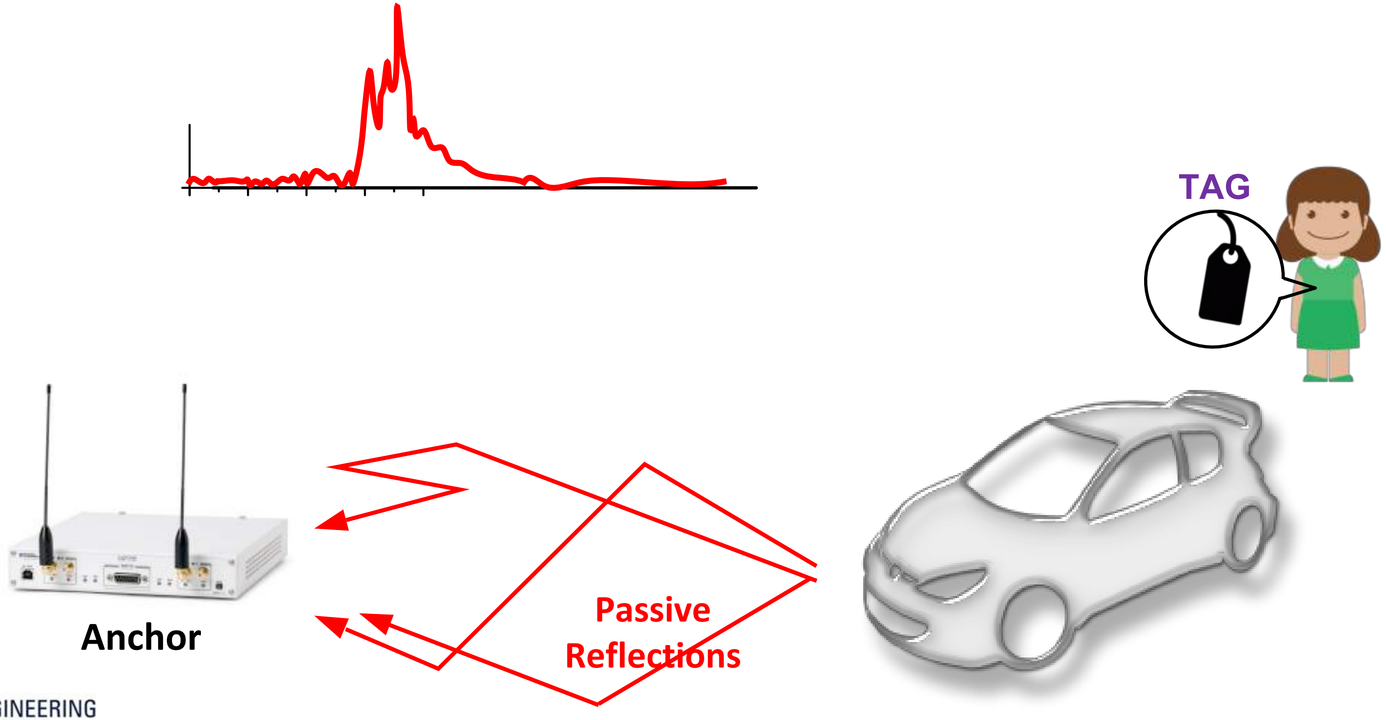
  - Introduce **active reflector tag with frequency conversion**



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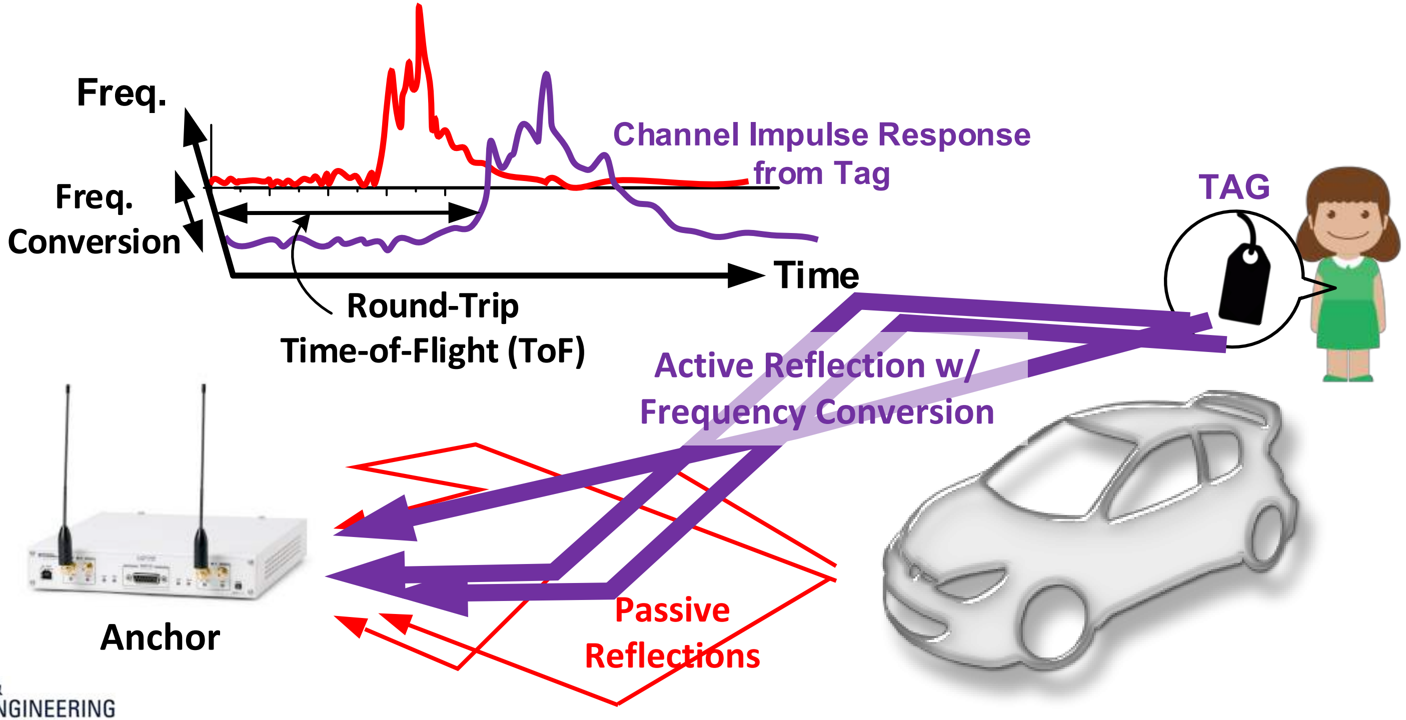
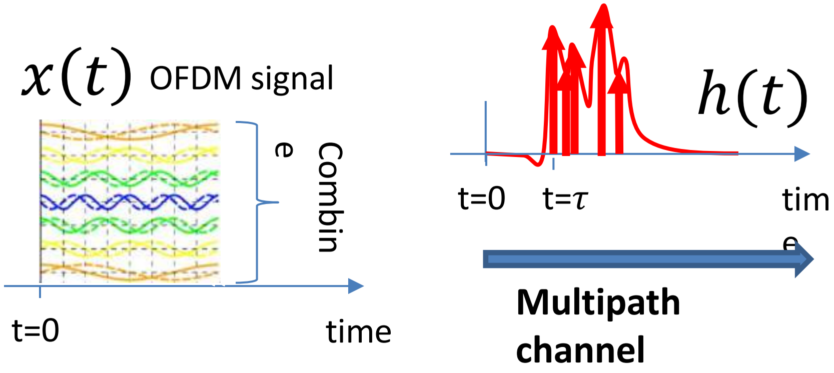


RF-Echo

- Operating Principle :
  - Round-trip Time-of-Flight (RToF)
  - Introduce **active reflector tag with frequency conversion**
    - Full-duplex tag: **simultaneous TX and RX**
    - Increase ranging distance by **active signal amplification** at tag
    - Tag reflection has **different frequency from passive reflection**
    - All analog tag design: **deterministic tag processing delay** without timing ambiguity

OFDM based Channel Impulse Response Estimation

- We propose using **OFDM** (Orthogonal Frequency Division Multiplexing) **for channel sounding signal**



$$y(t) = x(t) * h(t)$$

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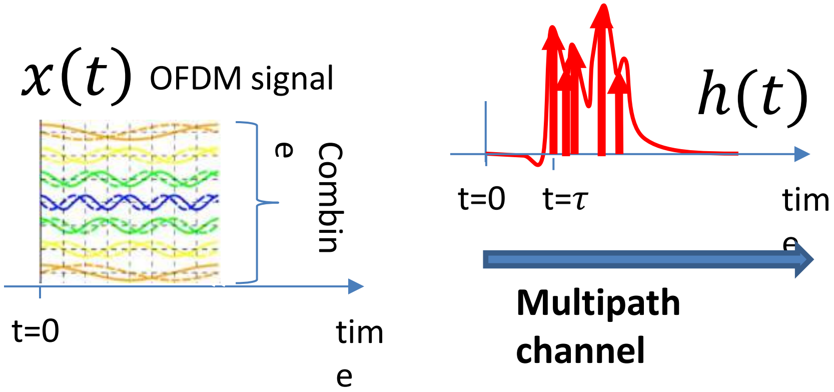

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- **OFDM does not have inter-carrier interference**

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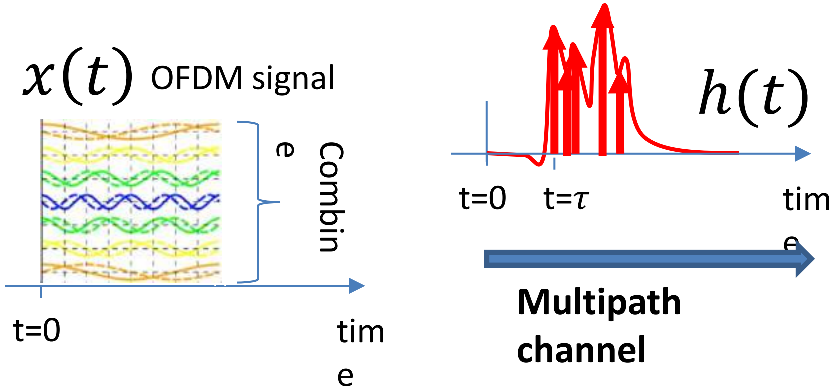
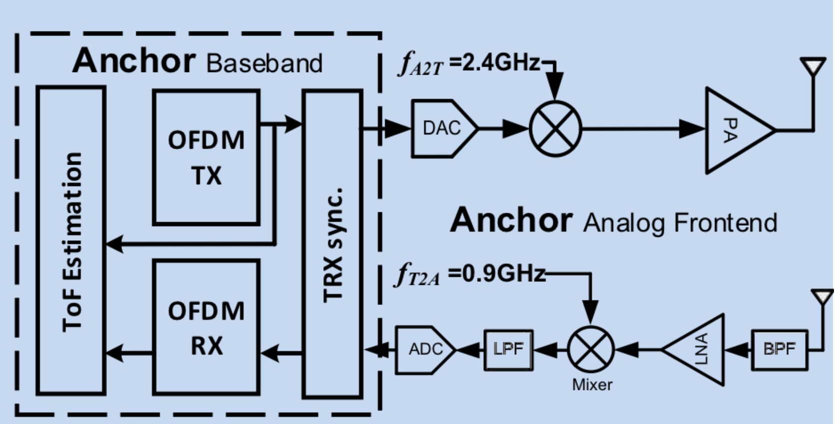


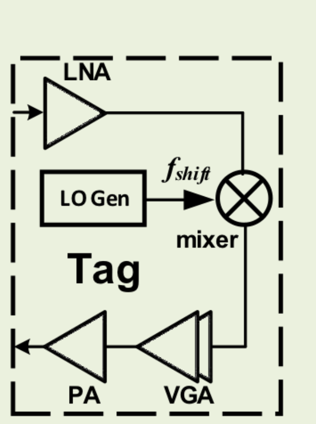
$$y(t) = x(t) * h(t)$$

- **OFDM does not have inter-carrier interference**
- **Estimate $h(t)$ in frequency domain**
  - $y(t) = x(t) * h(t) \leftrightarrow Y(f) = X(f)H(f)$
  - $\boldsymbol{H(f) = Y(f)/X(f)}$
  - $\boldsymbol{h(t)} = IFFT(\boldsymbol{H(f)})$

RF-Echo System Datapath

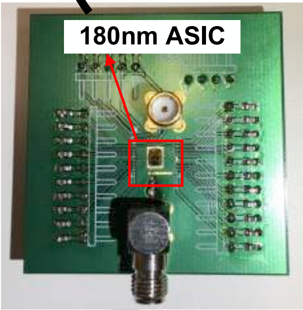


High TX power, good RX sensitivity



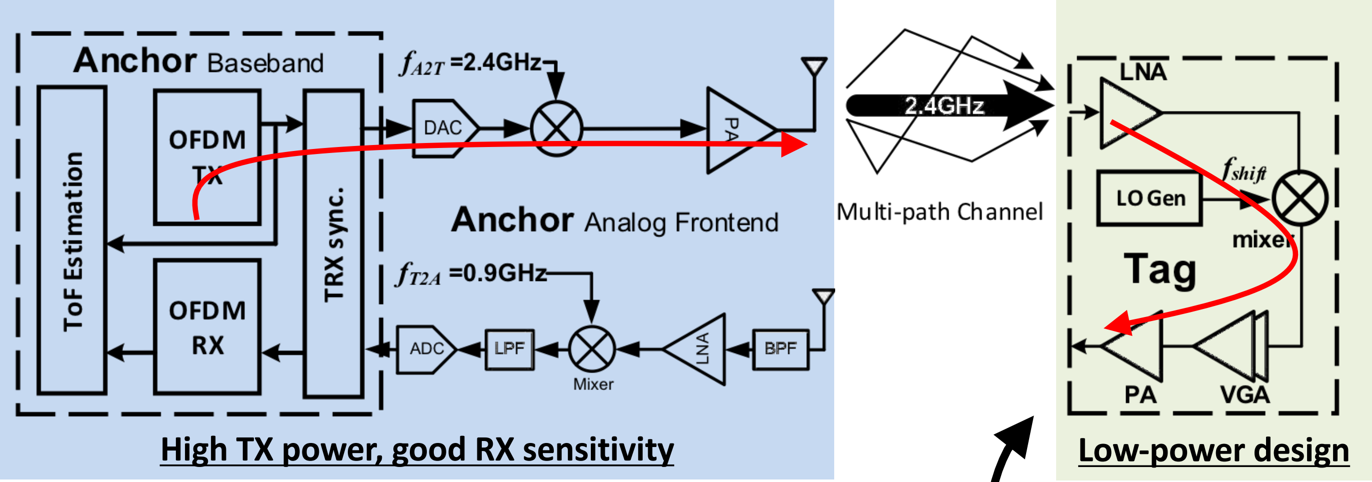
Low-power design

USRP X310 + Laptop

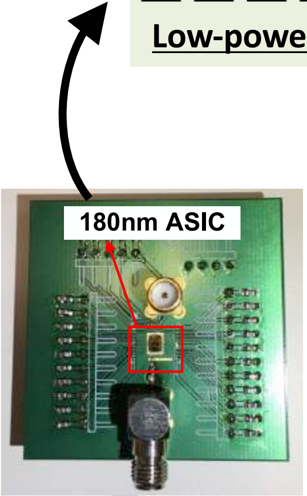


Tag

RF-Echo System Datapath



USRP X310 + Laptop



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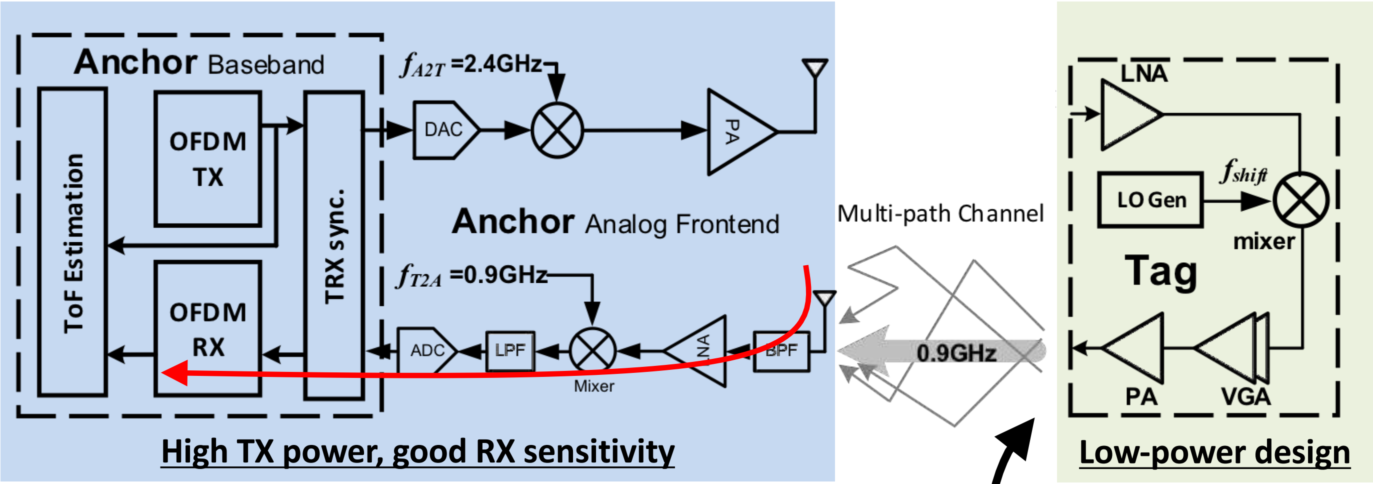
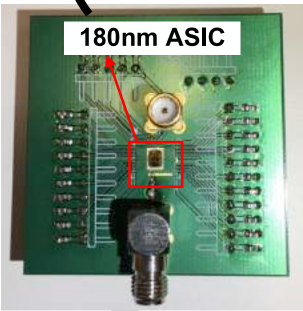


USRP X310 + Laptop



Tag

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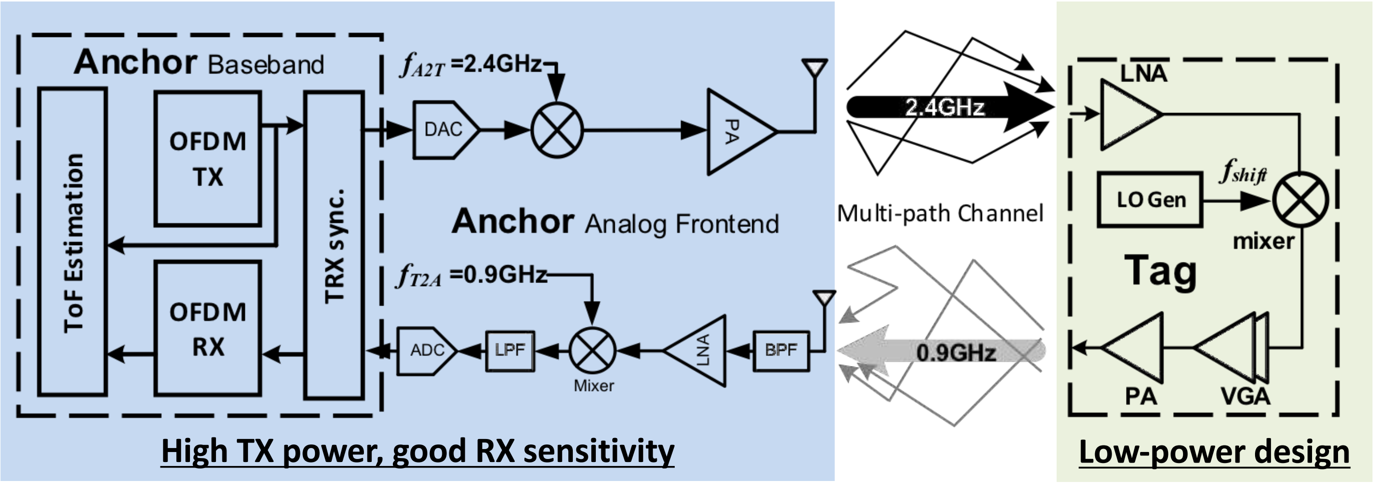

- Reflection scheme
  - Self-timing alignment of TX & RX at the anchor
  - No need for clock sync. between anchor and tag
  - Low-power, low-cost ASIC tag design
    - No RF Phase-Lock-Loop (PLL), No crystal

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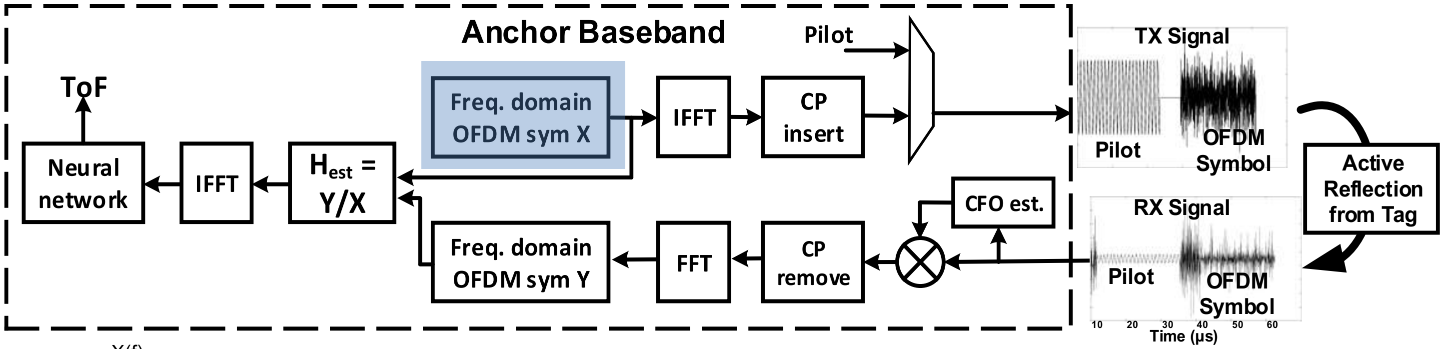
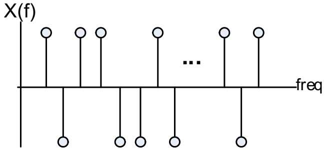
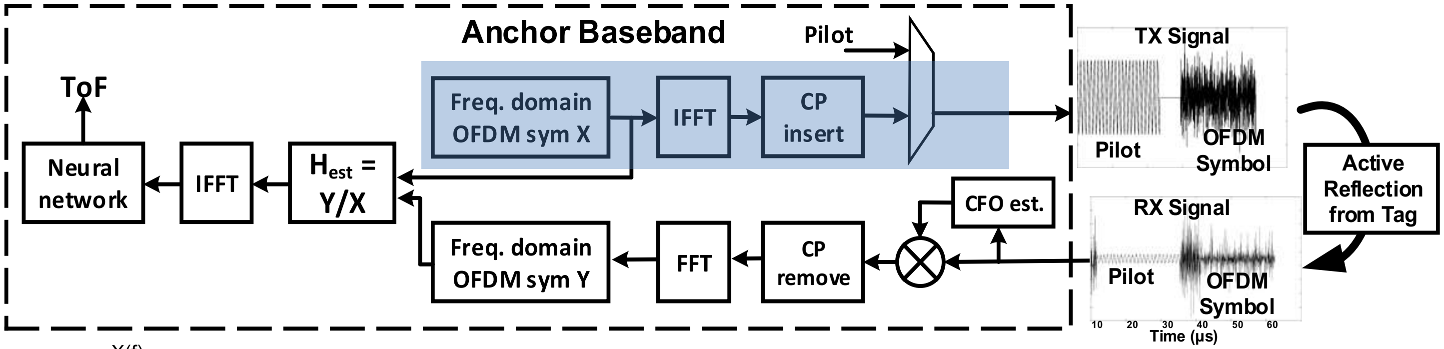
RF-Echo System Datapath

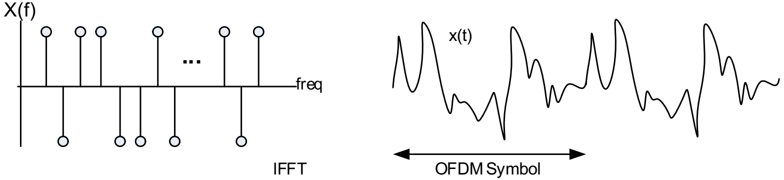




IFFT

RF-Echo System Datapath





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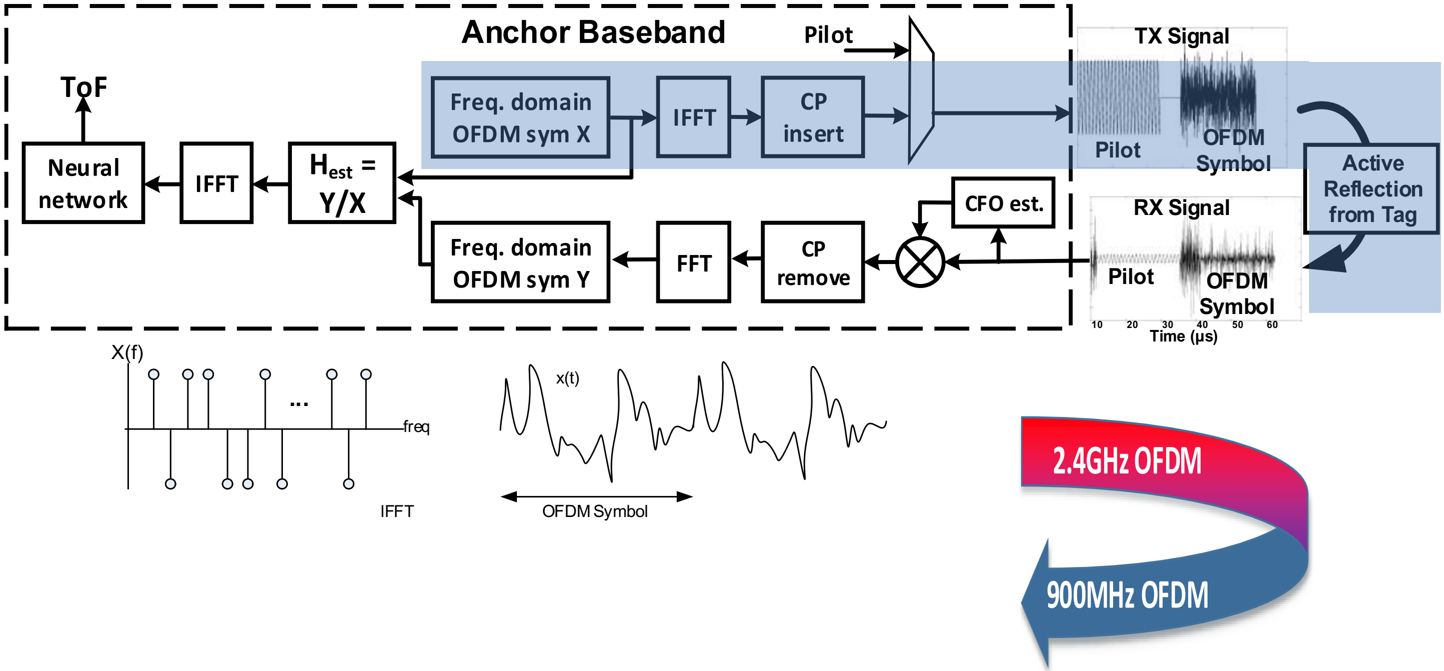

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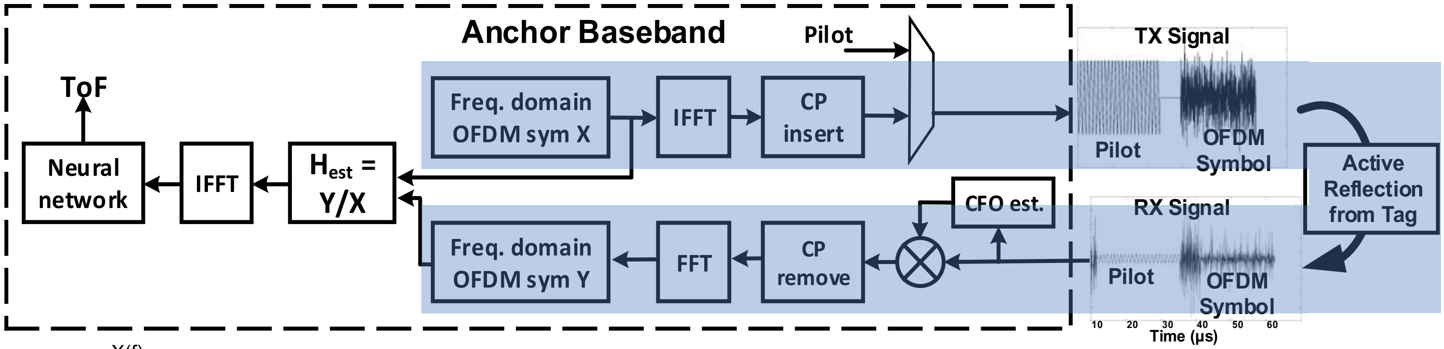

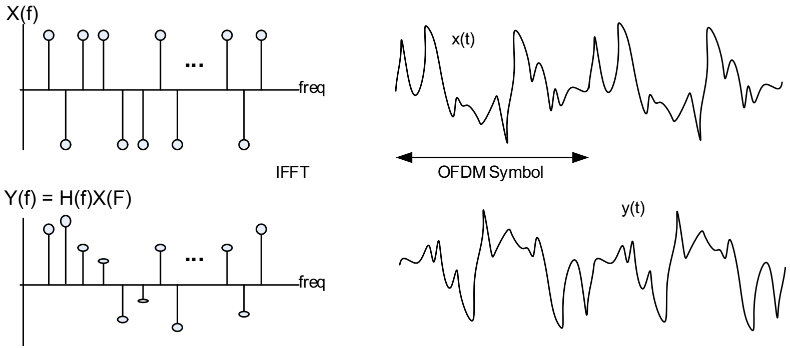

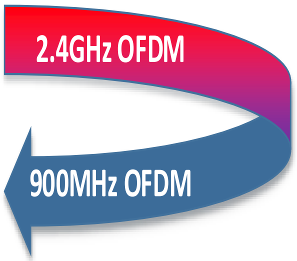

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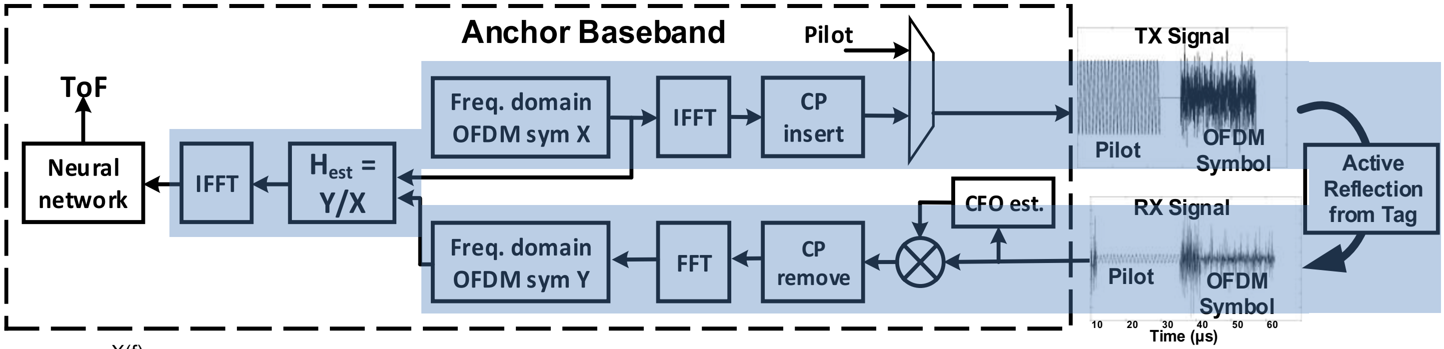
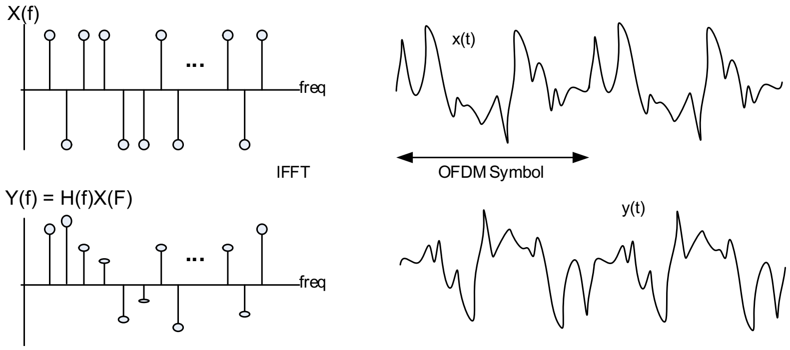
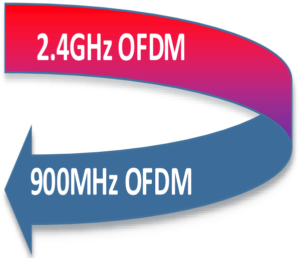


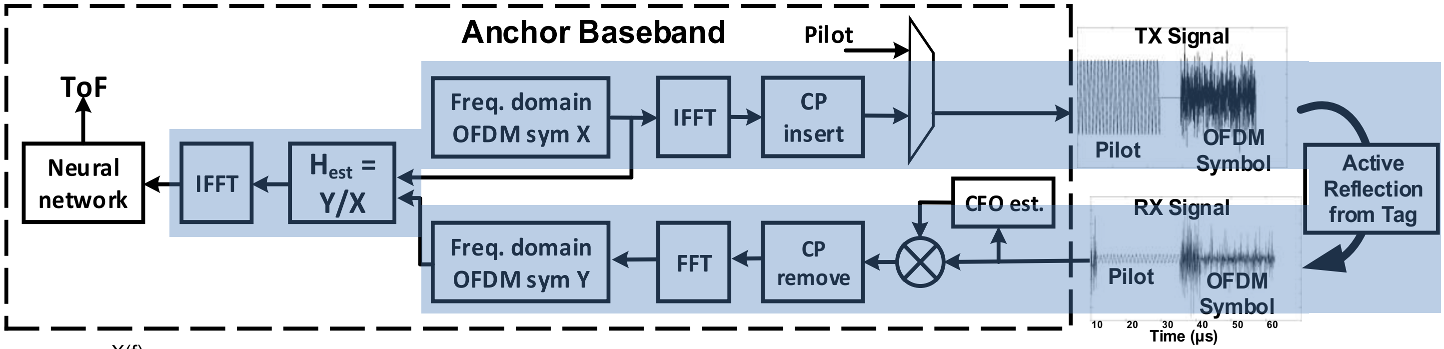


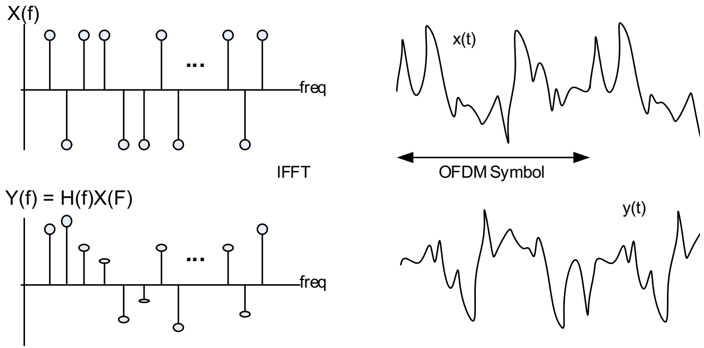


Freq. domain CIR
H(f) = Y(f)/X(f)

IFFT

RF-Echo System Datapath





Freq. domain CIR
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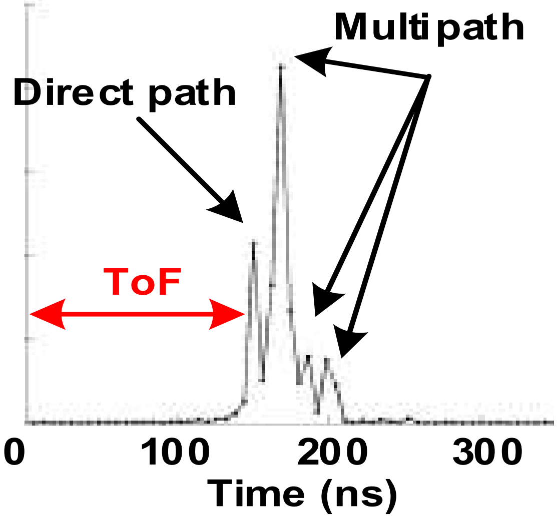
IFFT

Time-domain CIR
$h(t)$



Range, Bandwidth, Accuracy

- Ranging accuracy vs Signal bandwidth

$$Distance\ resolution \propto \frac{1}{BW}$$

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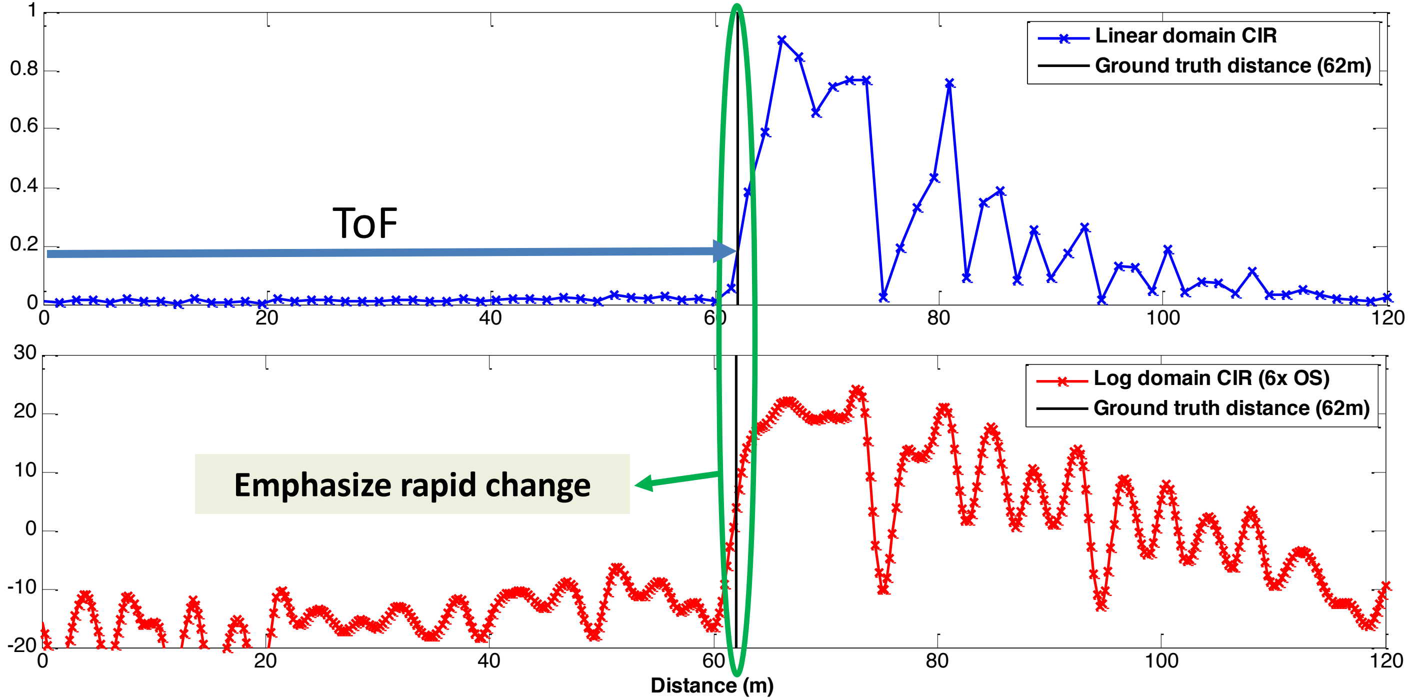
How to get decimeter (10 cm) accuracy with only 80MHz?

Neural Network ToF Estimation

- Log domain channel impulse response (CIR) interpolation for training
  - ToF estimation = rising edge detection



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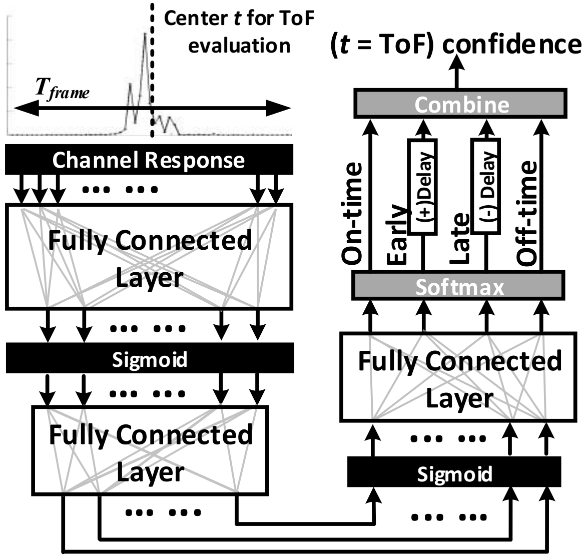
  - Trained neural network to identify CIR rising edge timing



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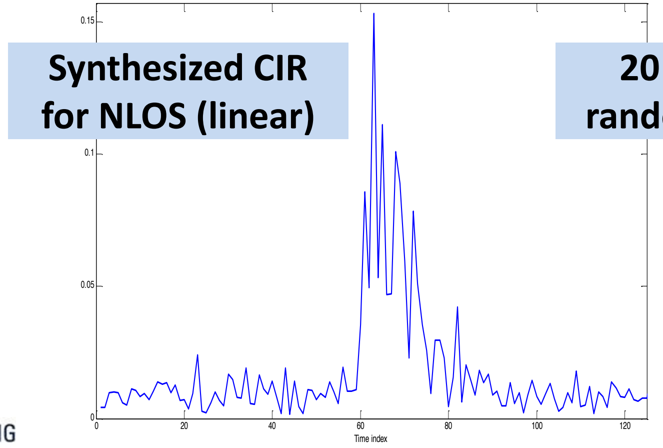

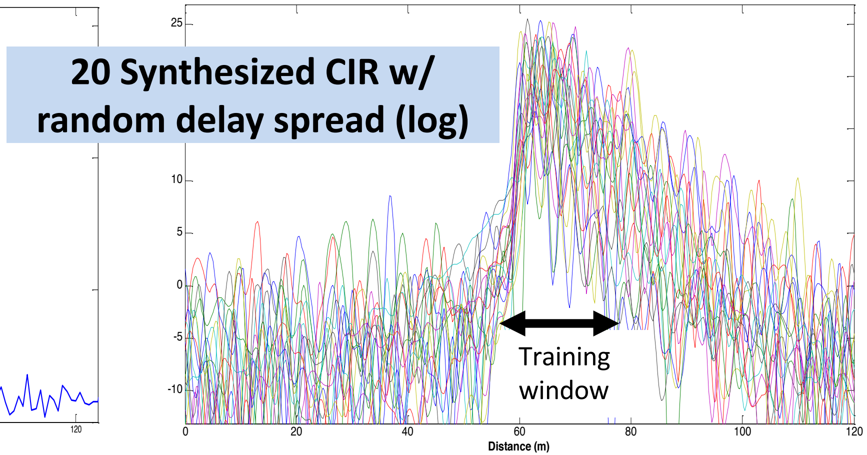

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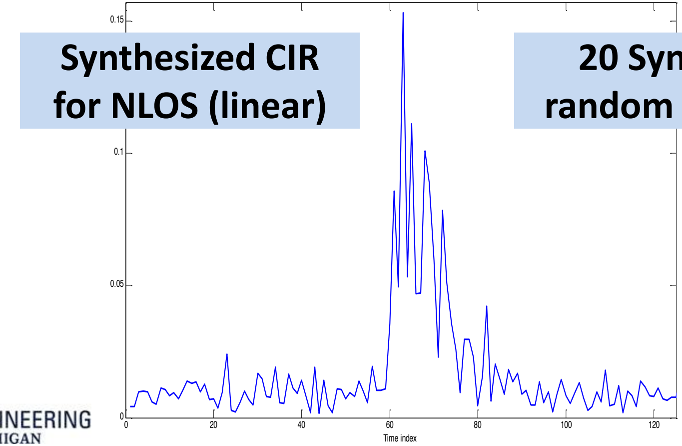
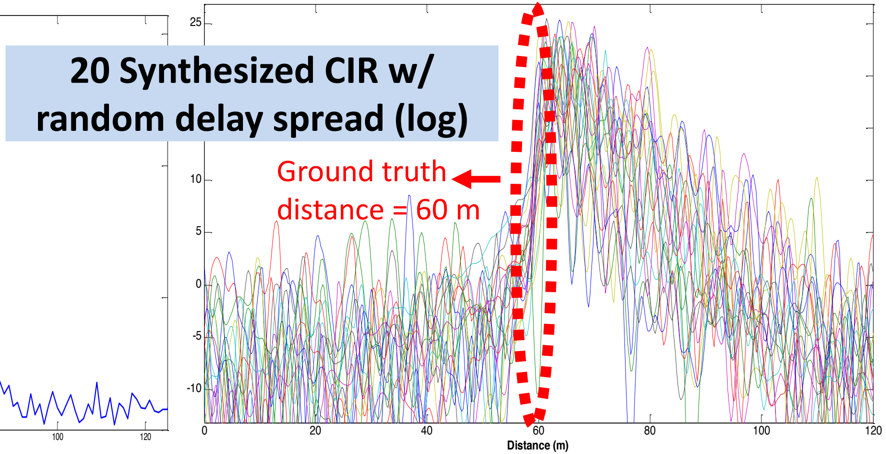
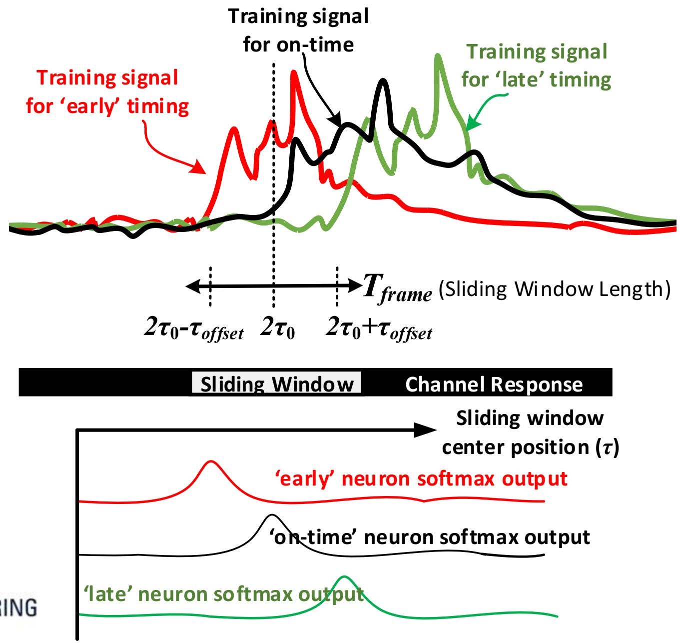




Enhancement for Machine Learning

- Bootstrap aggregating method
  - Multiple neural networks for early, on-time, late model training



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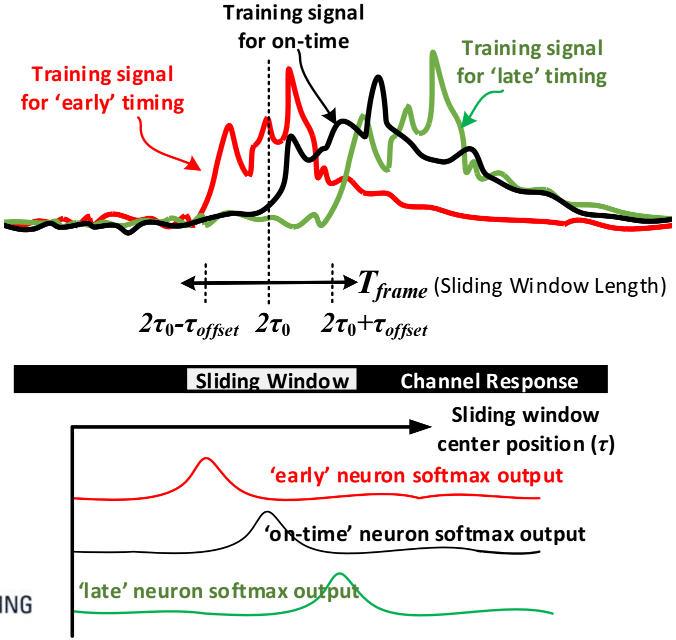
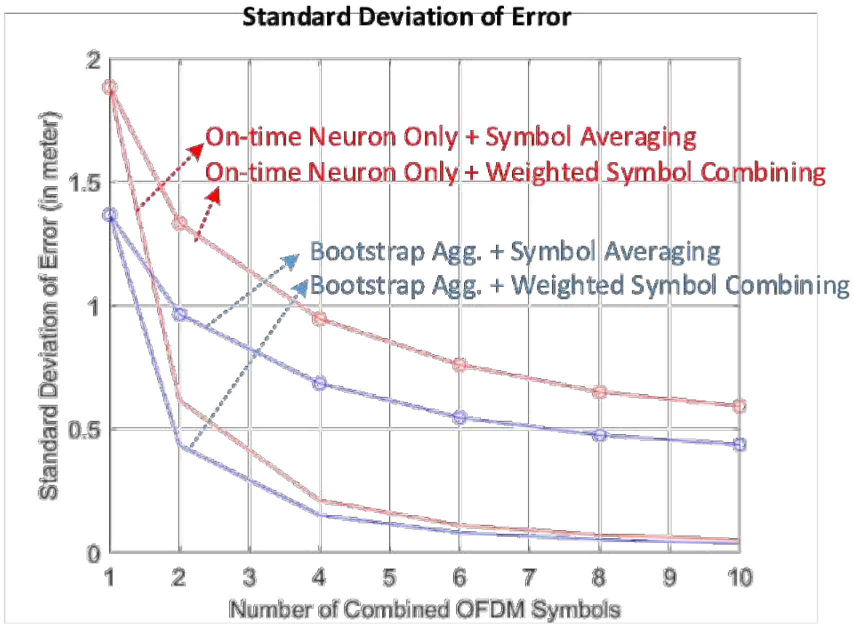
Enhancement for Machine Learning

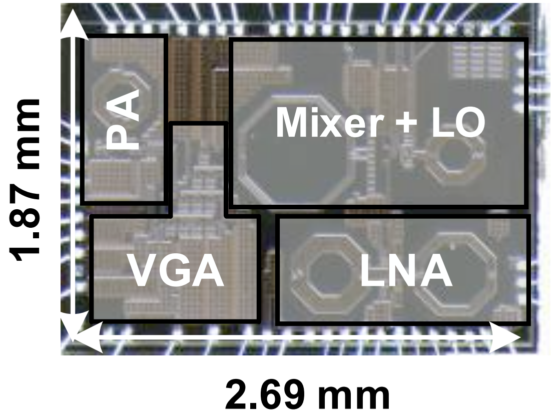
- Bootstrap aggregating method
  - Multiple neural networks for early, on-time, late model training
- Symbol Combining
  - Coherent symbol combining to enhance SNR
  - Neural network weighted symbol combining

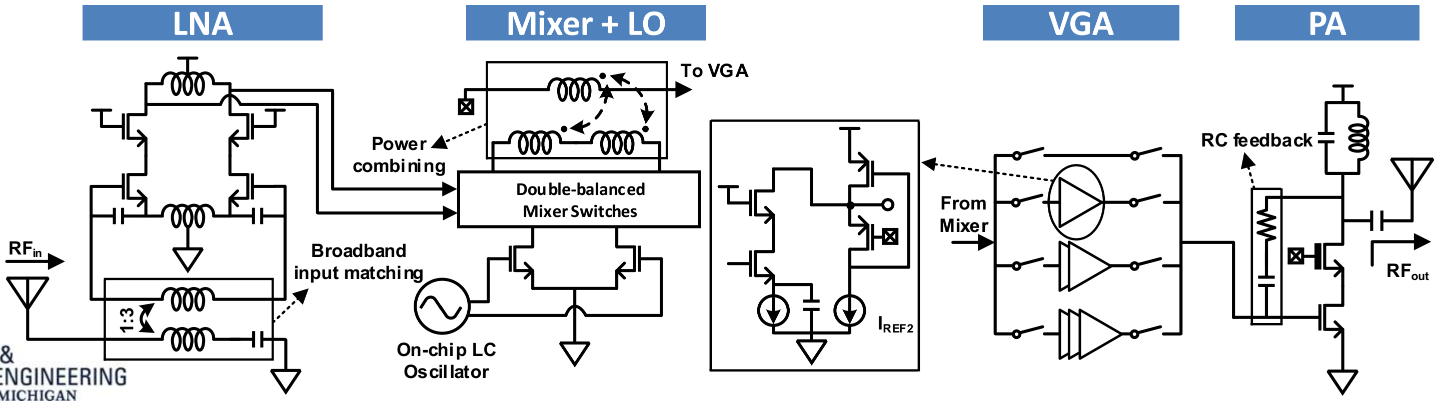




Low-Power ASIC Tag Design

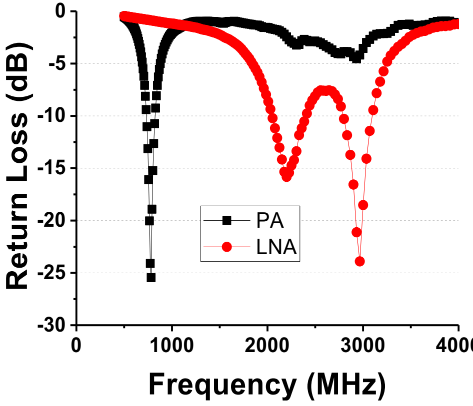
- Tag ASIC in TSMC 180 nm
- Low-cost simple tag design
  - Crystal-less, PLL-free
  - Phase noise → LC oscillator
- Analog-only design
  - No DSP circuitry, deterministic delay
- Large dynamic range

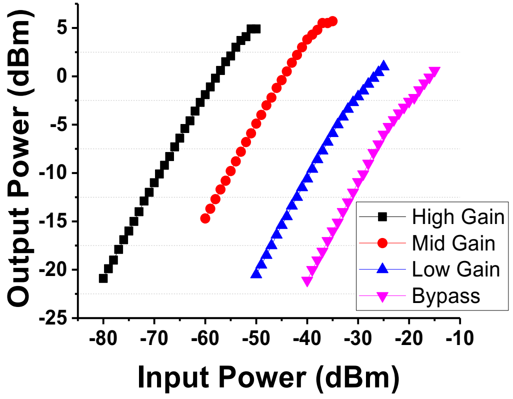


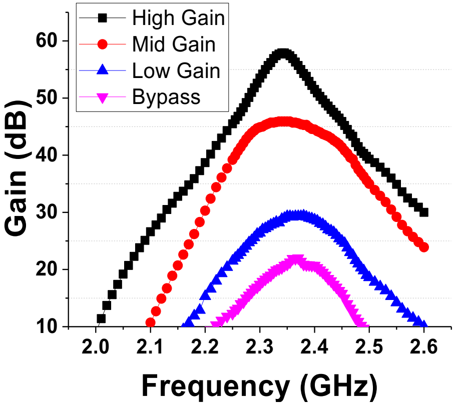


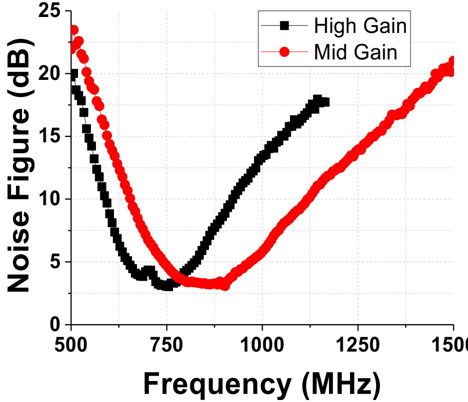
Tag ASIC Evaluation Results

- ASIC tag performance
  - Large dynamic range (20 – 60 dB adjustable gain)
  - Good linearity to ~ 0 dBm output power
  - 62.8 mW total power consumption



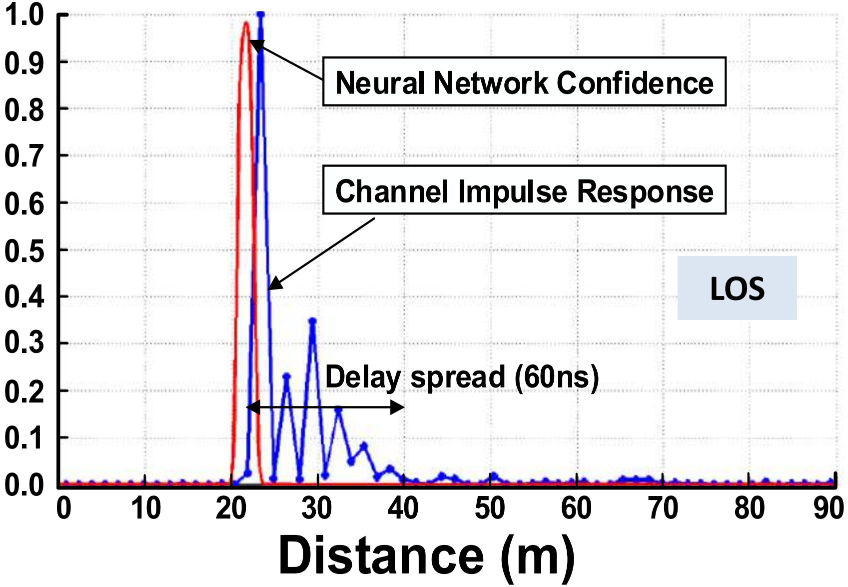


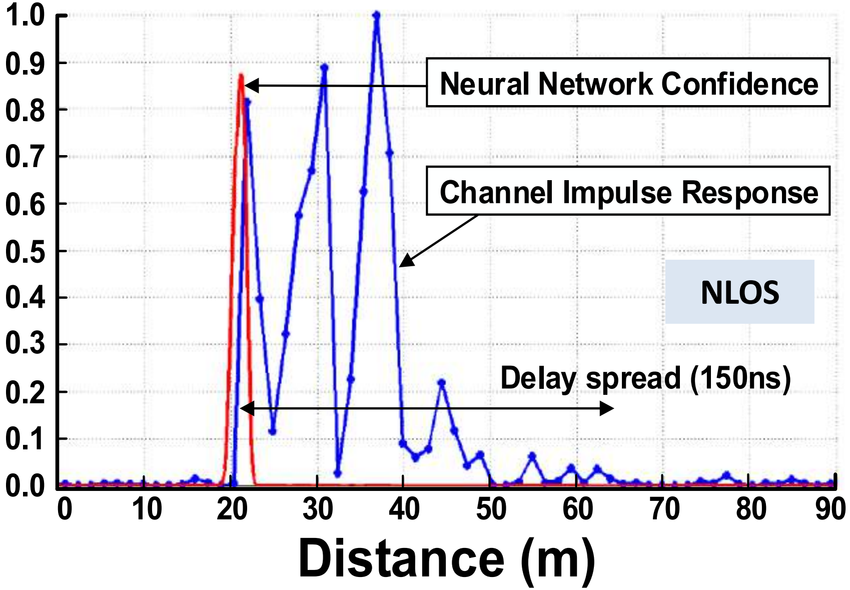




Evaluation Results

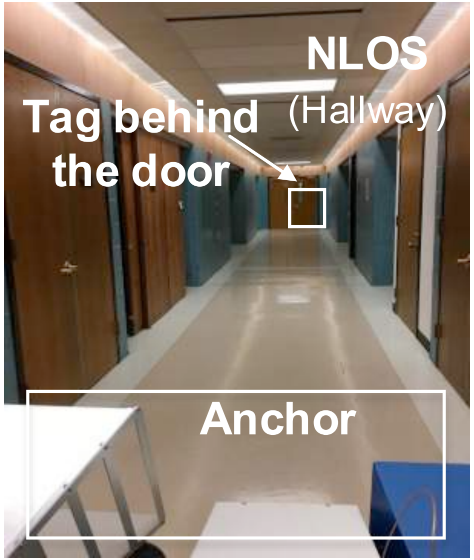
- Neural network ToF estimation
  - Measured LOS/NLOS Channel Impulse Response (CIR)

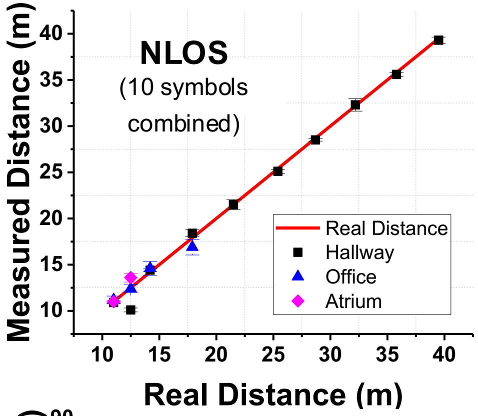


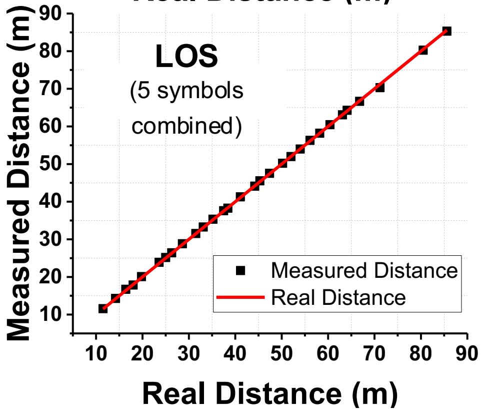


Evaluation Results

- 1D NLOS / LOS evaluation
  - NLOS test in multipath-light, multipath-rich environment







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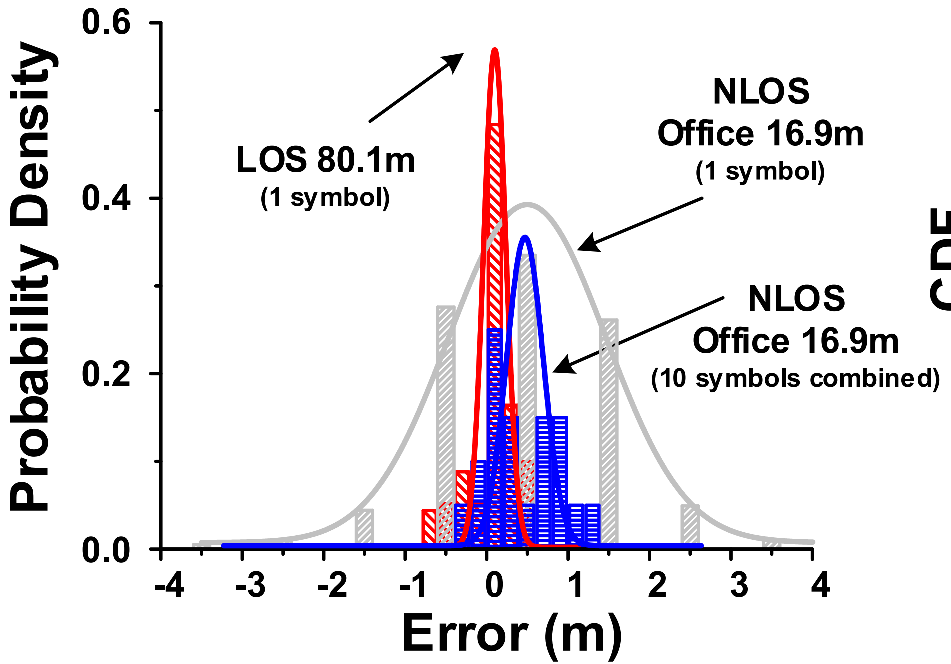
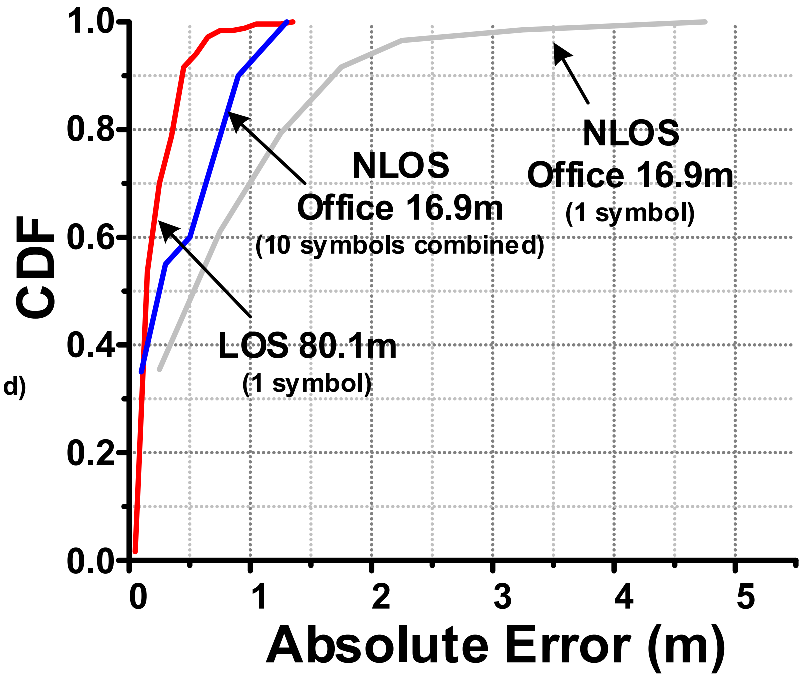
Evaluation Results

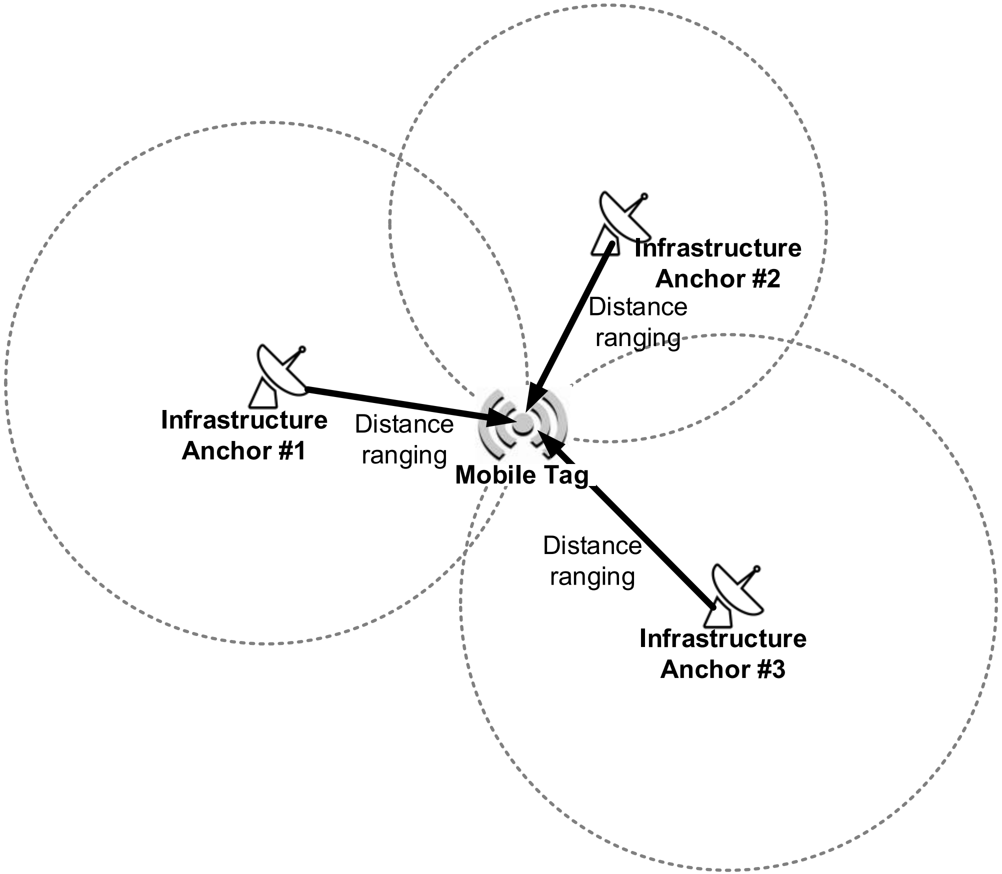
- Accuracy improvement via neural network weighted symbol combing





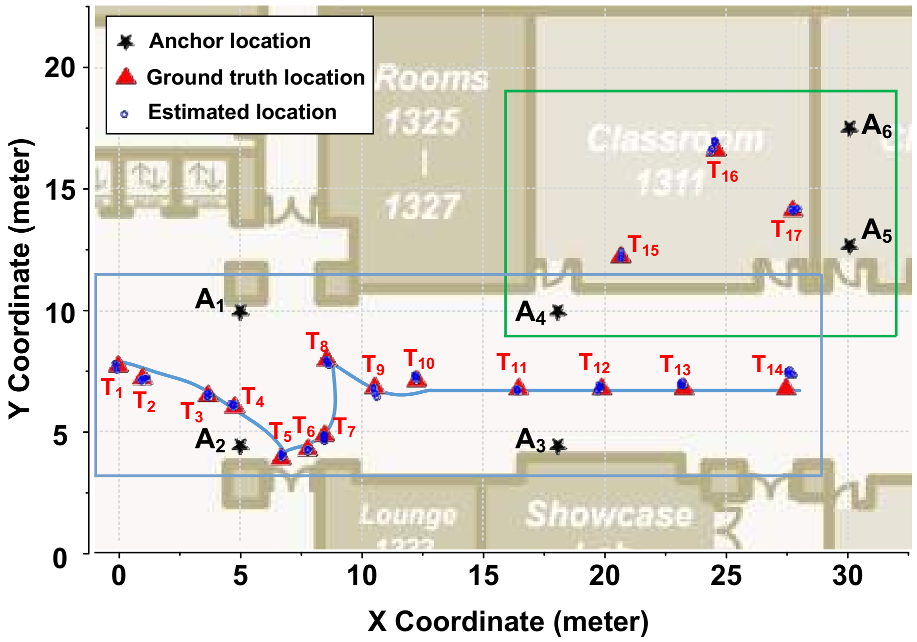
Triangularization for 2D/3D Localization

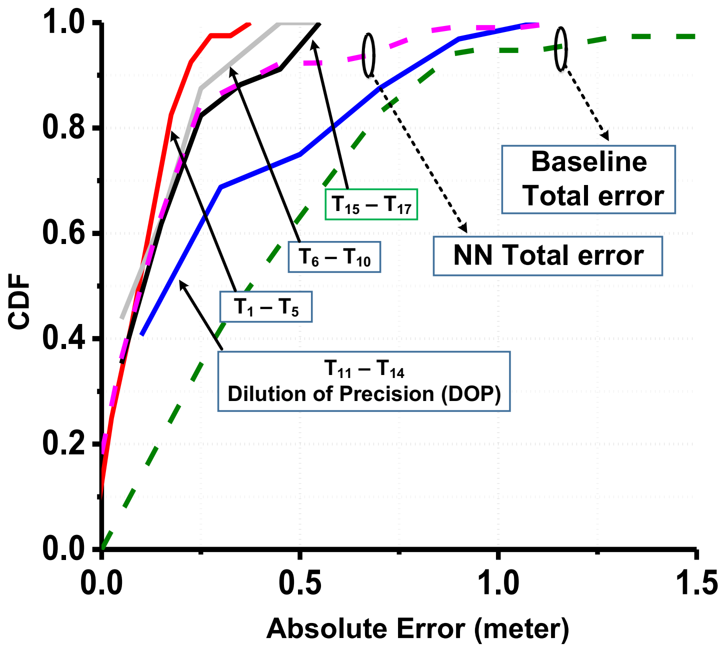
- For triangularization, ranging results from at least 3 anchors are combined



Evaluation Results

- 2D evaluation results in an Univ. of Michigan building
- Walls made of bricks and thick concrete





Comparison Table

- AISC Tag + Neural network ToF estimation

System	Technology	LOS Accuracy	NLOS Accuracy	Testing Dimension	Tag Power	System Bandwidth	Signal Type	Time per Fix	Energy per Fix
WiTrack	FMCW ToF	31 cm (90 %)	40 cm (90 %)	LOS: 3-11 m NLOS: 6 x 5 m^2	No Tag	1.69 GHz	FMCW	> 2.5 ms	N/A
Harmonium	UWB TDoA	31 cm (90 %)	42 cm (90 %)	LOS/NLOS: 4.6 x 7.2 x 2.7 m^3	75 mW	3.5 GHz	Impulse	52 ms	3900 µJ
Ubicarse	SAR + Motion sensor	39 cm (median)	59 cm (median)	LOS/NLOS: 15 x 15 m^2	N/A	N/A	WiFi	100 ms	N/A
Tagoram	RFID SAR	12 cm (median)	N/A	LOS: 1 x 2 m^2	Passive	6 MHz (UHF)	UHF RFID	> 33 ms	N/A
Chronos	802.11 WiFi + Band-stiching	14.1 cm (median)	20.7 cm (median)	LOS/NLOS: 20 x 20 m^2	1.6 W	20 MHz x 35 ch.	OFDM	84 ms	1.34 x 10^5 µJ
RF-Echo	**ASIC Active reflection + Neural network**	**26 cm (90 %)**	**46 cm (90 %)**	**LOS: 7 x 90 m^2** **NLOS: 30 x 20 m^2**	**62.8 mW**	**80 MHz**	**OFDM**	**20 µs per sym.**	**18 µJ 10 sym.**

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Comparison Table

- Large operation dimension

System	Technology	LOS Accuracy	NLOS Accuracy	Testing Dimension	Tag Power	System Bandwidth	Signal Type	Time per Fix	Energy per Fix
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Comparison Table

- Low localization acquisition time

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Comparison Table

- Low-energy consumption tag

System	Technology	LOS Accuracy	NLOS Accuracy	Testing Dimension	Tag Power	System Bandwidth	Signal Type	Time per Fix	Energy per Fix
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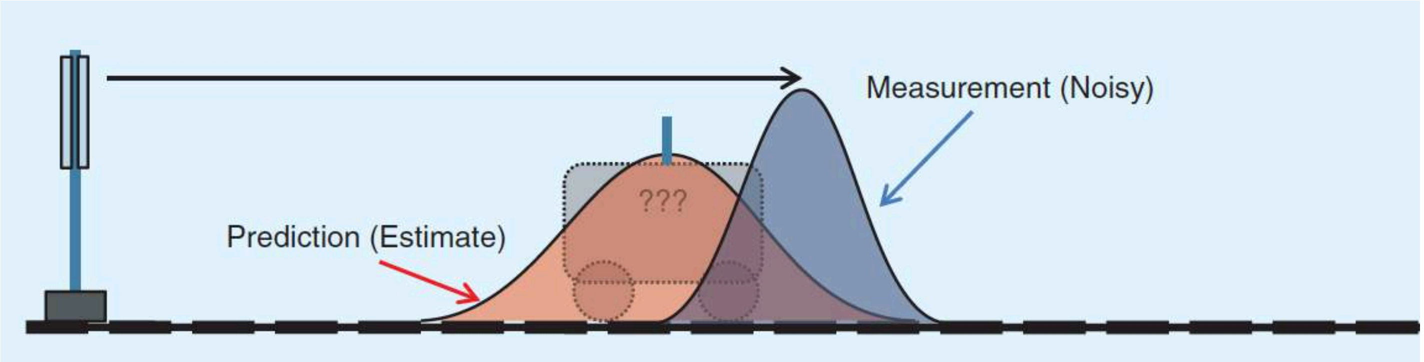
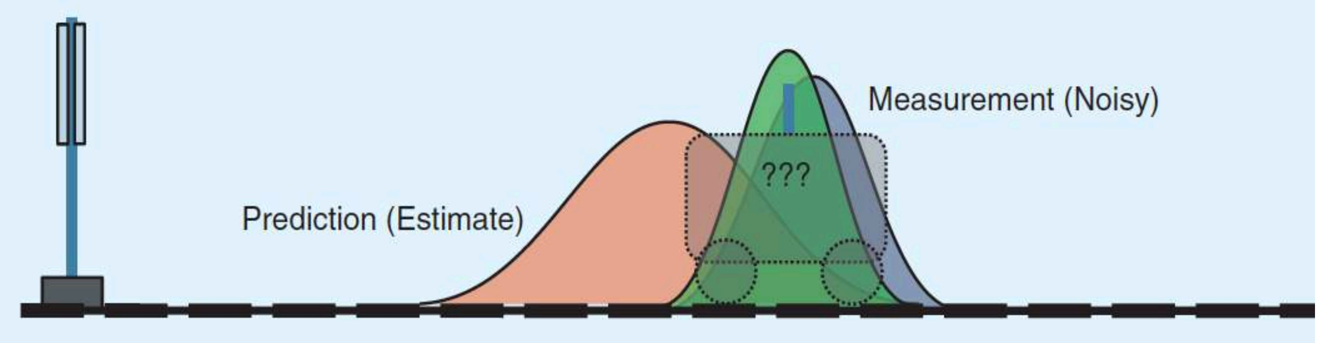
RF-Echo Enhancement: Adaptive Filtering



- Position prediction
  - Position of a tag can be predicted by previous position and latest motion vector of the tag
- Position measurement
  - Position of a tag can be measured by RF-Echo

[R. Faragher, IEEE SIGNAL PROCESSING MAGAZINE, 2012]

RF-Echo Enhancement: Adaptive Filtering

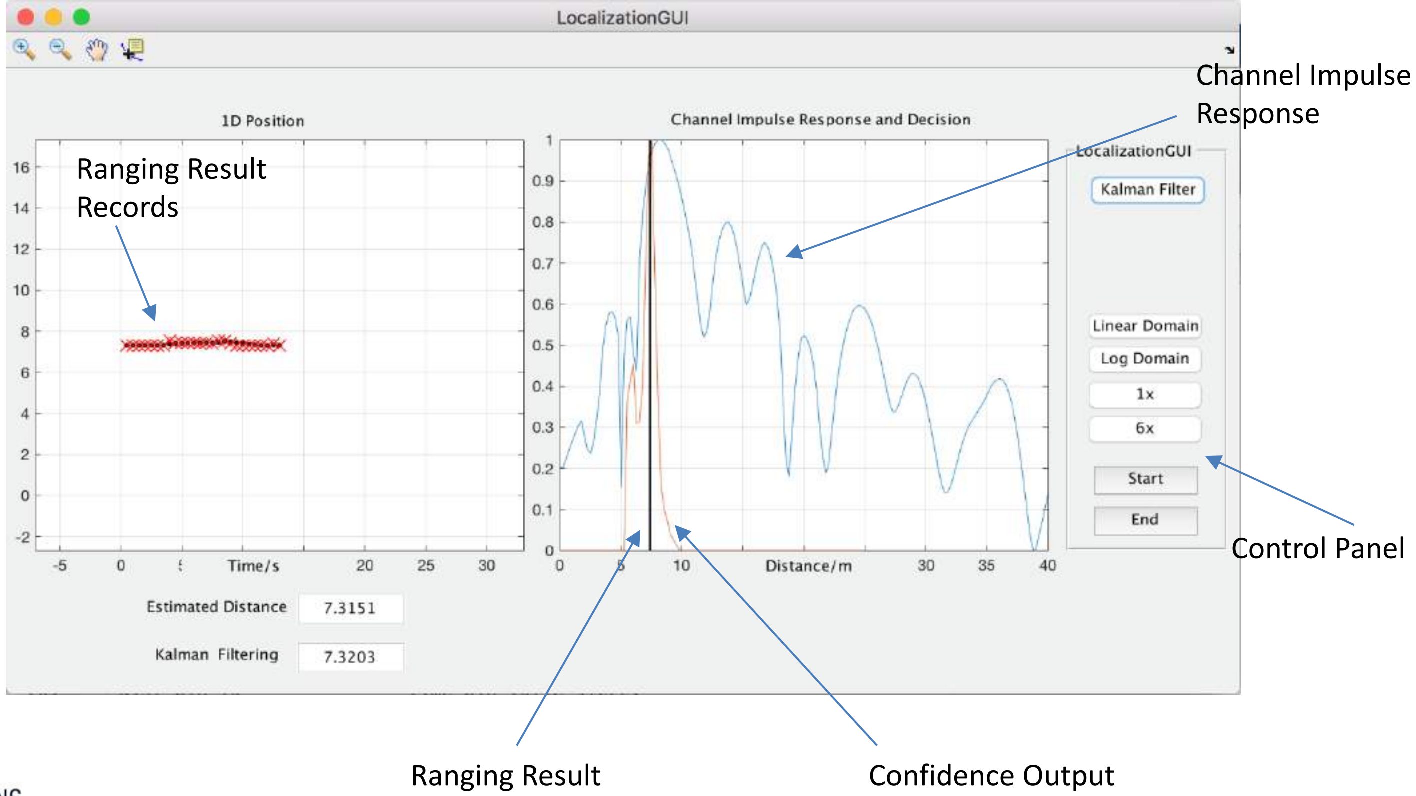


- Position prediction
  - Position of a tag can be predicted by previous position and latest motion vector of the tag
- Position measurement
  - Position of a tag can be measured by RF-Echo
- Adaptive filter combines prediction and measurement to get a more reliable localization output

[R. Faragher, IEEE SIGNAL PROCESSING MAGAZINE, 2012]

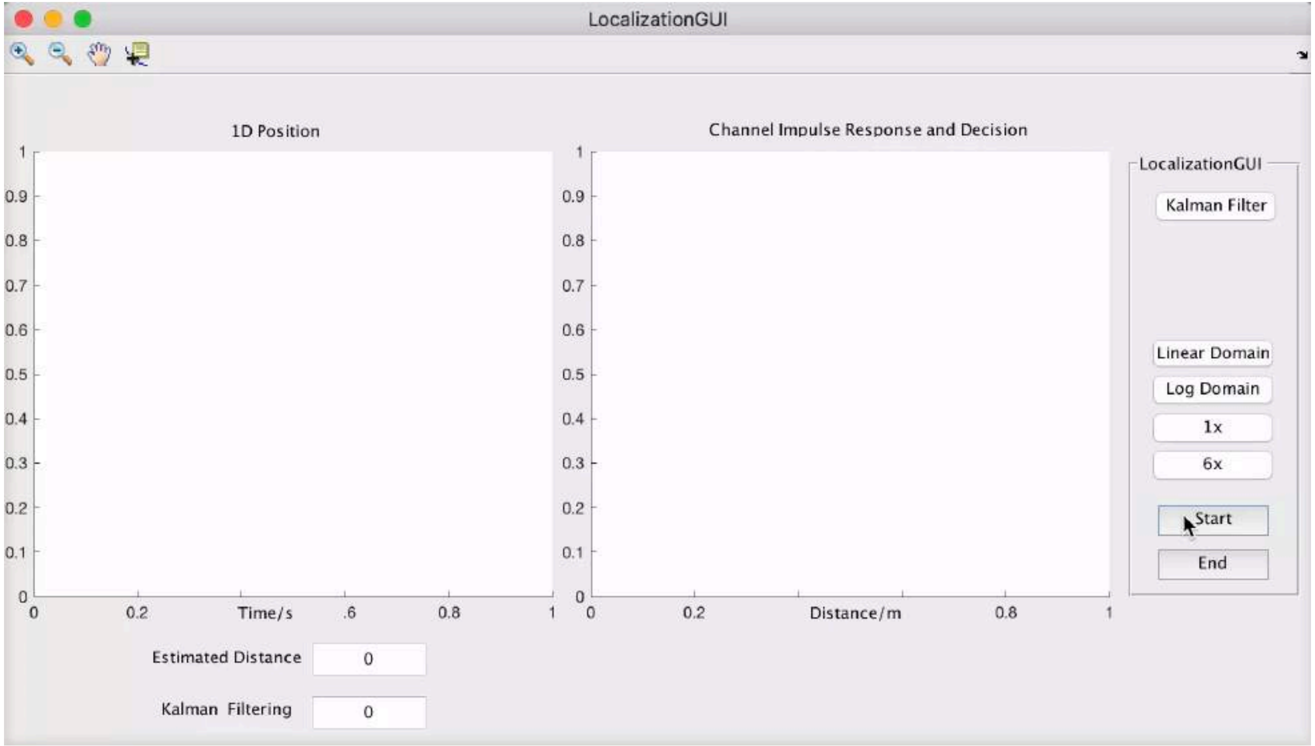
RF Echo Realtime Demo

- Demo system using USRP for both anchor and tag



RF Echo Realtime Demo

- Demo system using USRP for both anchor and tag



Year 2 Direction

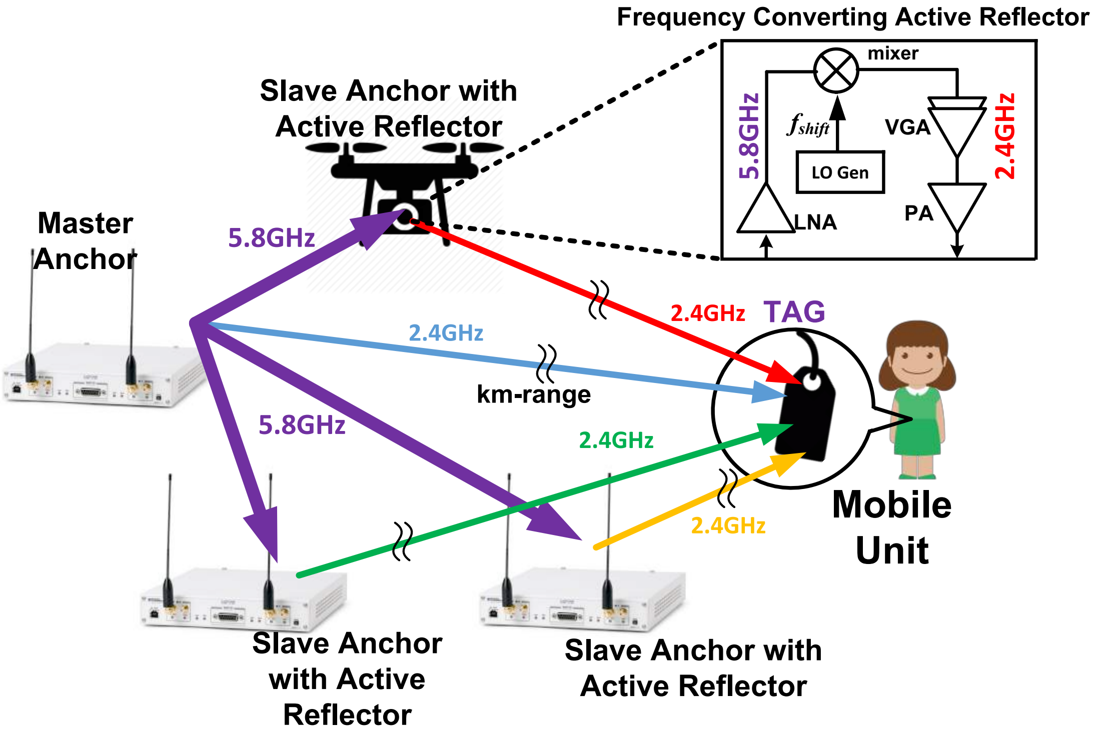
- RF-Echo limitations
  - Localization distance limited by tag transmit power
  - Each tag localized one-by-one sequentially
    - Scalability problem: tracking 100k tags in a large stadium?

Year 2 Direction

- RF-Echo limitations
  - Localization distance limited by tag transmit power
  - Each tag localized one-by-one sequentially
    - Scalability problem: tracking 100k tags in a large stadium?
- **Indoor Local Positioning System (iLPS)** in year 2
  - **Tags are RX only – similar to GPS receivers**
  - **Many tags can localize themselves concurrently**
  - **Localization together with safety information downlink comm.**
  - **Unlike RF-Echo, anchors perform full duplex active reflection**

iLPS

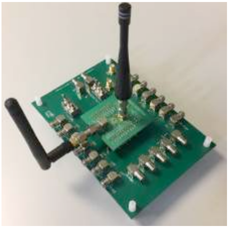
- Complements GPS for local public safety applications
- Anchors perform frequency conversion reflection
- Tags are RX only (like GPS receivers)
- Light infrastructure: no need to time-synchronize anchors
- Unlike GPS, iLPS is designed for indoor operations
- Compared to GPS: >10x faster, >10x energy efficiency, >10x accuracy



Conclusion

- RF-Echo (year 1)
  - ~100 m distance for indoor operation
  - Decimeter ranging accuracy (LOS/NLOS)
  - Low-energy consumption ASIC tag: 18 μJ per fix
- iLPS (year 2)
  - Complements GPS with 10x better accuracy, energy efficiency and speed
  - USRP based prototype is up and running → ASIC in 2nd half of 2018

Tag



Tag with DC board

Anchor (USRP + Laptop) & tag

Thank you!

Questions?

PSCR

INDOOR LOCALIZATION AND IMAGING USING RF SIGNALS AND COMPRESSIVE SENSING

Fabio da Silva – NIST Boulder

PSCR

Disclaimer

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately.

Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

*Please note, all information and data presented is preliminary/in-progress and subject to change.

Outline

- Motivation
- From 1D to 2D and 3D
- Review of Compressive Sensing
- Implementations
- NIST Model

PSCR

Motivation

Anatomy of an indoor location emergency

- Timeline:
  - Notification @ 6:13 pm
  - Deployment @ 6:26 pm
  - Critical point @ 6:47 pm

Source: M.Harris, “The Way Through the Flames,” in IEEE Spectrum, vol. 50, no. 9, pp. 30-35, September 2013. doi: 10.1109/MSPEC.2013.6587186

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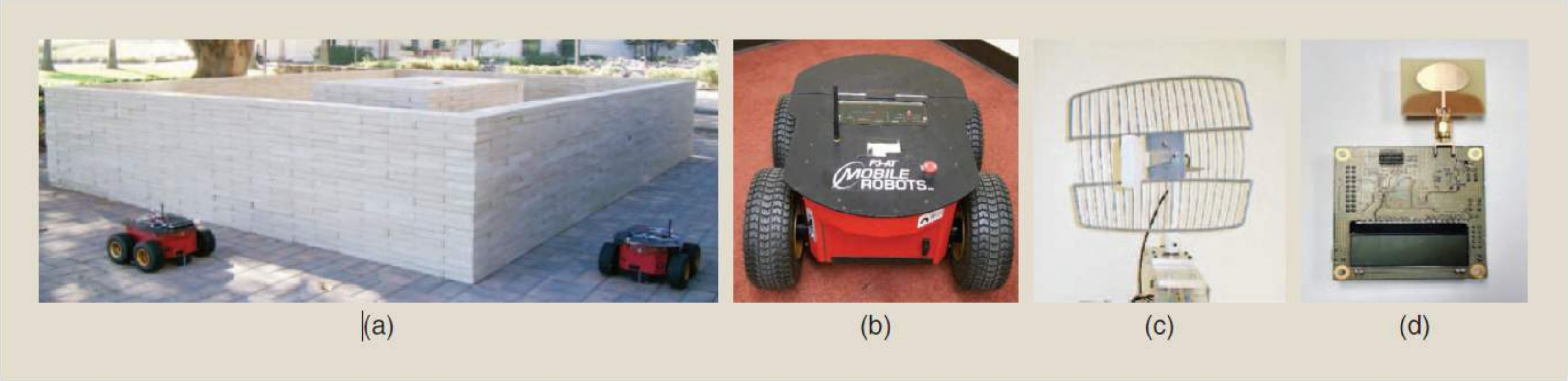
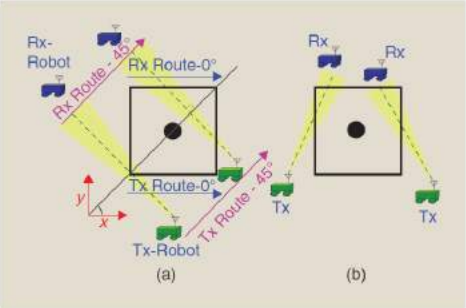
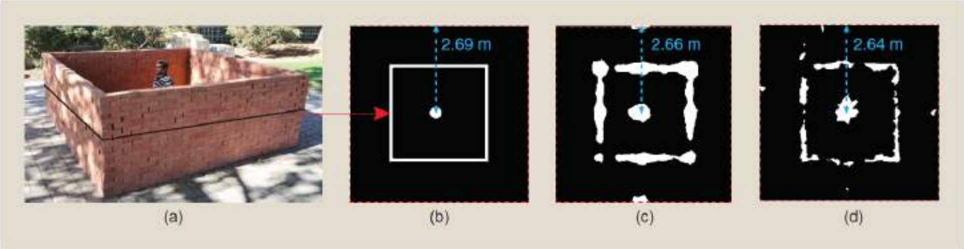
1D solution applied to 2D problems







Source: S. Depatia, C. R. Karanam and Y. Mostofi, "Robotic Through Wall-Imaging Radio-Frequency Imaging Possibilities with Unmanned Vehicles," in IEEE Antennas & Propagation Magazine, vol. 59, no. 5, pp 47-60, Oct 2017. doi: 10.1109/MAP.2017.2731302

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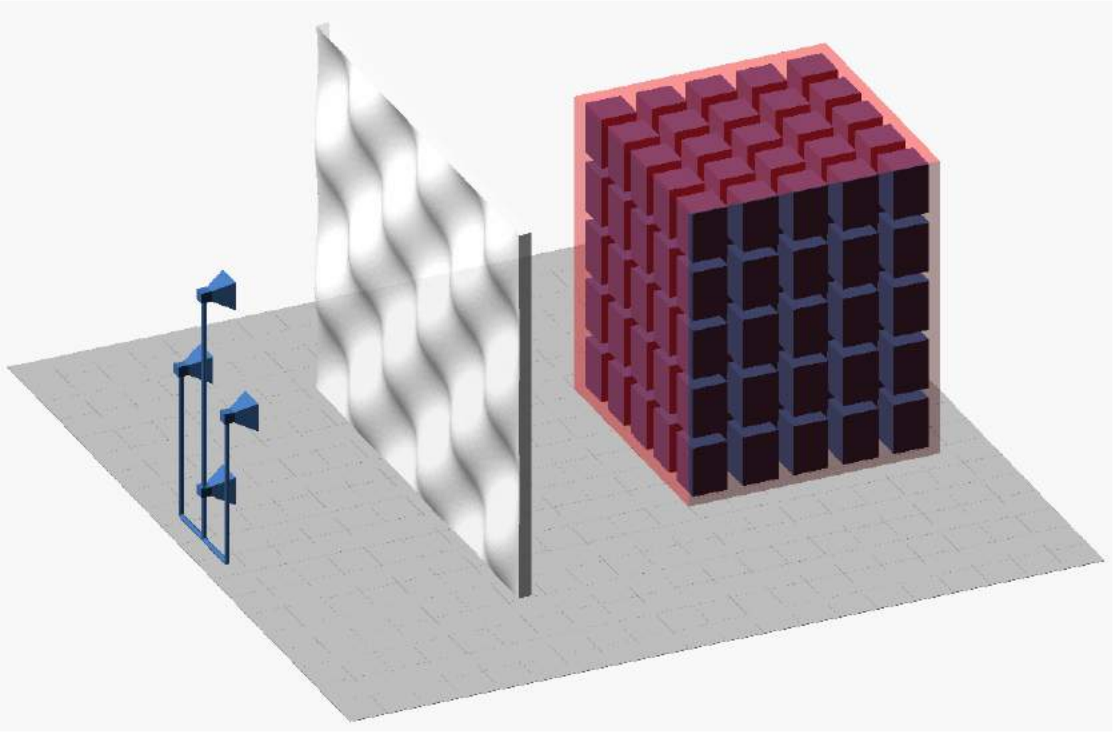
Compact solution using wave superposition and compressed sensing



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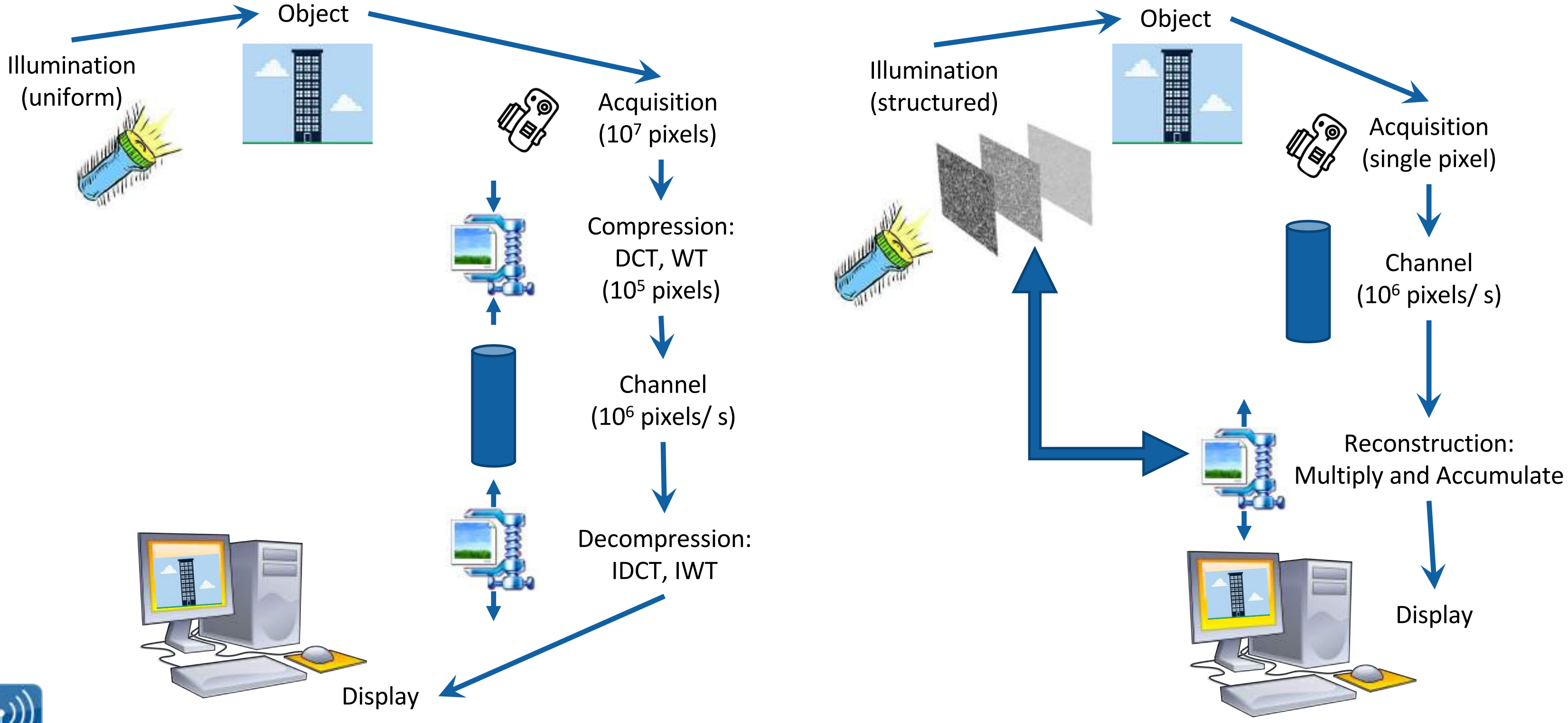
Review of Compressive Sensing

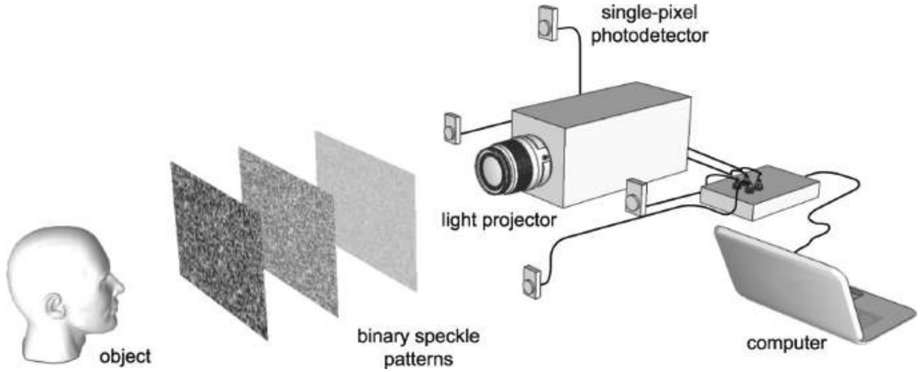
- General approach
    - Data model
    - Imaging model
- Cartoon description
- Goals of indoor localization with RF
- Implementations

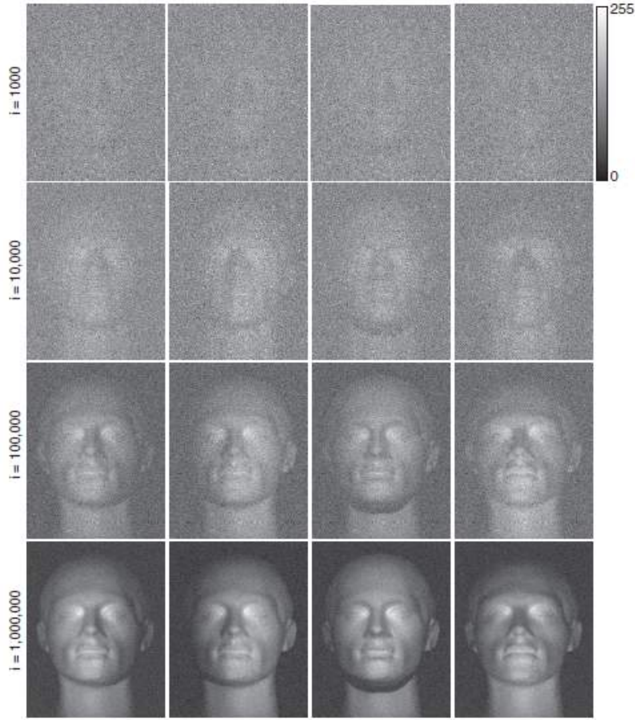
Review of Compressed Sensing: Data Model



PSCR

Review of Compressed Sensing: Imaging Model





Sun et al., Science **17**, 844 (2013).

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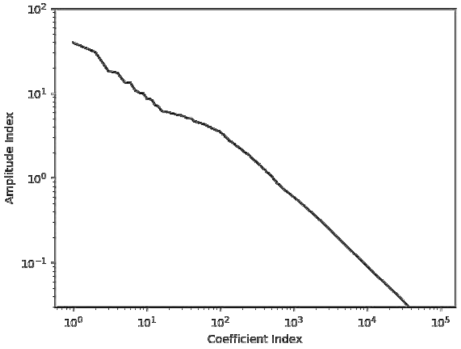
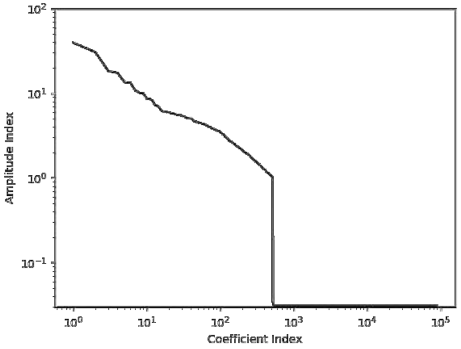
Cartoon Description: Sparsity

- N = 90,000 pixels (bases)

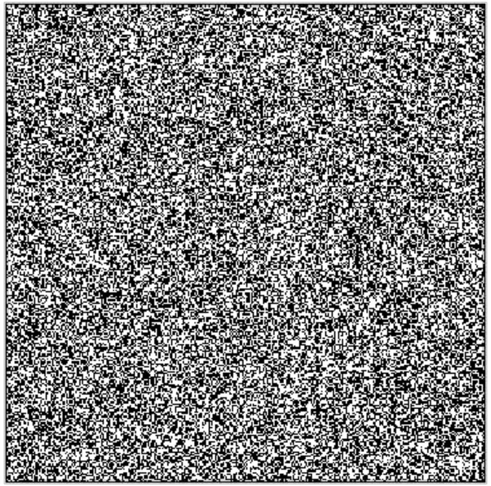


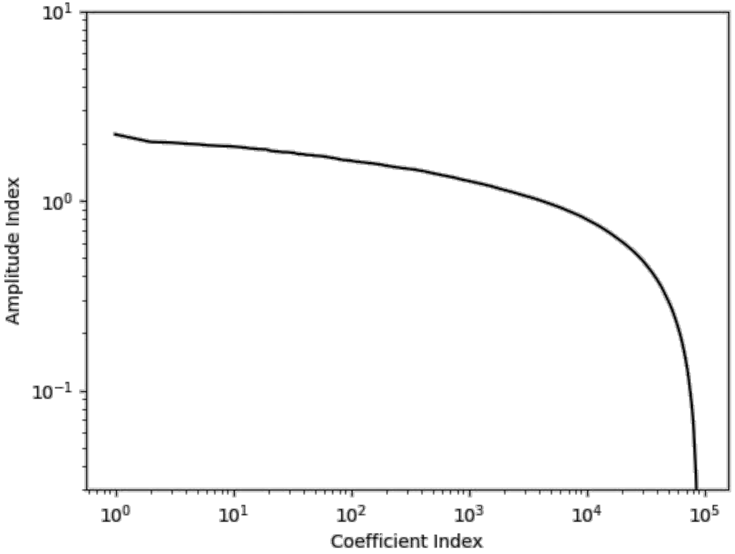
- N = 523 DCT bases



PSCR

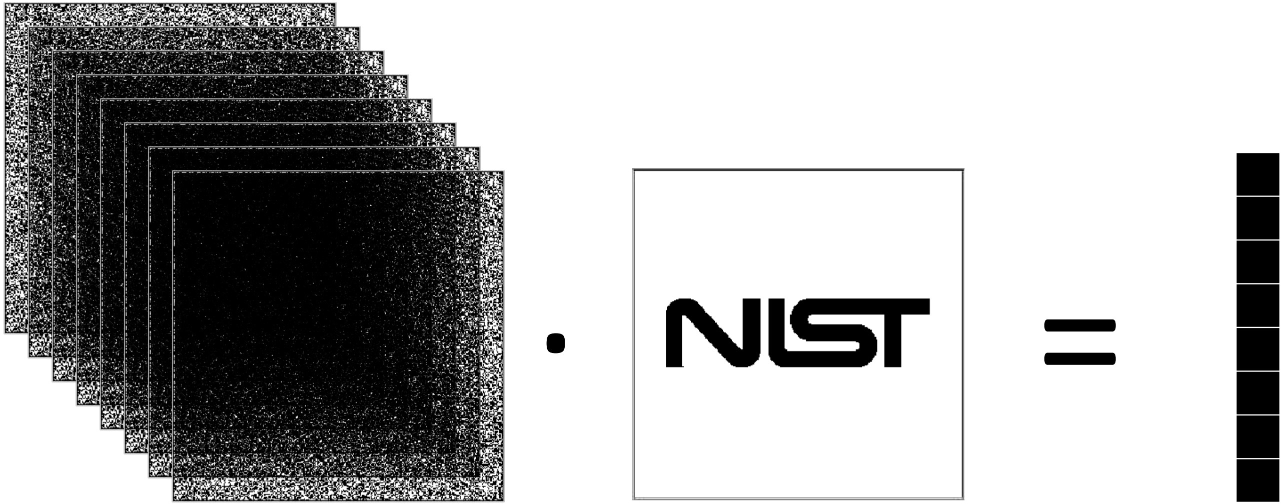
Cartoon Description: Coherence





PSCR

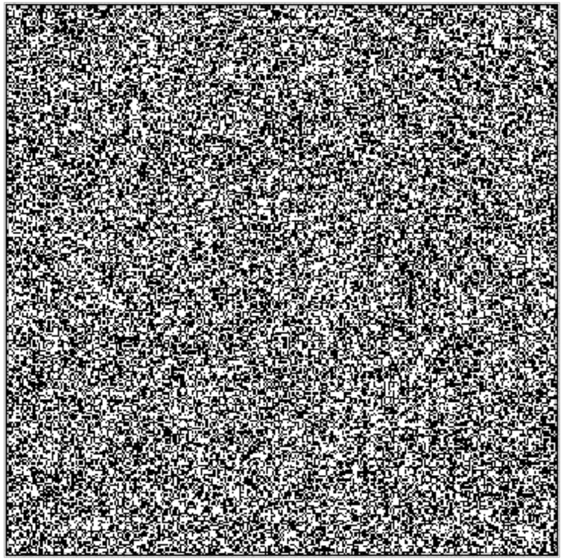
Cartoon Description: Sampling and Sensing



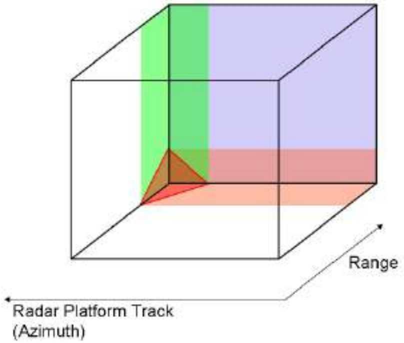
$$A \cdot x = y$$

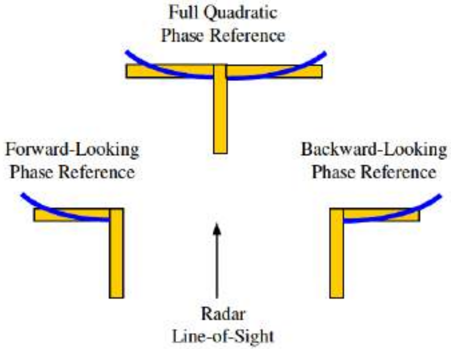
Goals for indoor localization with RF

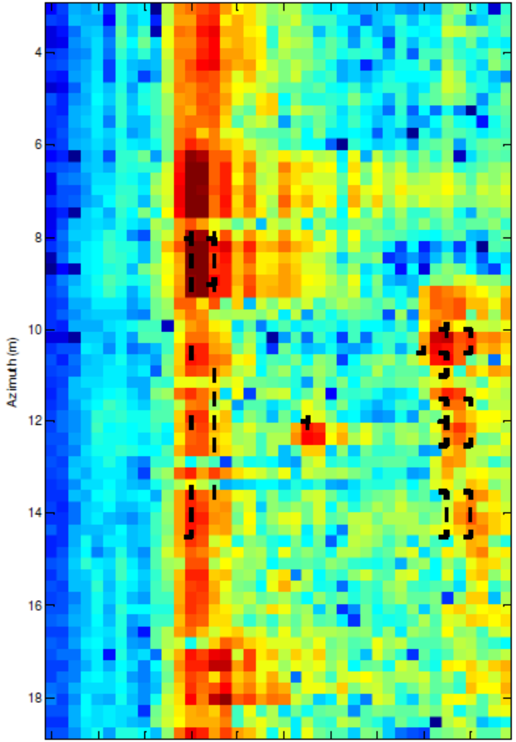
- How do we create random RF patterns?
- Can we get depth information?
- Can we make it real time?
- What can I resolve in space?
- How big can the range be?



Implementations



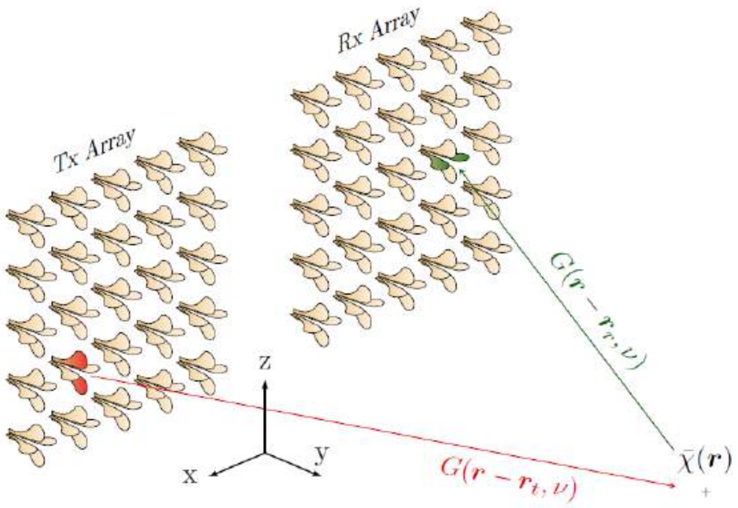




W. L. van Rossum, J.J. M. de Wit and R. G. Tan, "Radar Imaging of Building Interiors Using Sparse Reconstruction," 2012 9th European Radar Conference, Amsterdam, 2012, pp. 30-33. URL: http://ieeeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6450688&isnumber=6450609

Implementations

Computational polarimetric microwave imaging



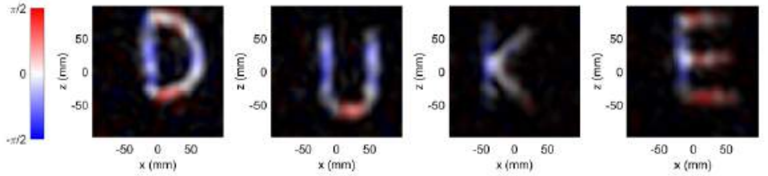
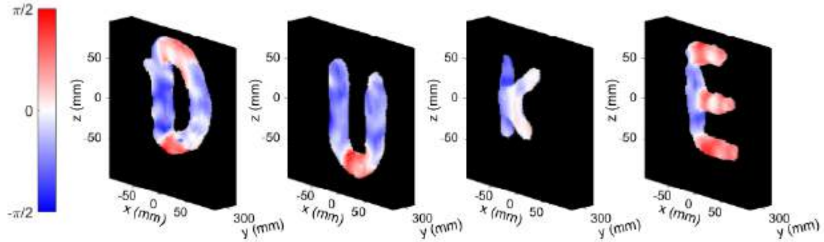


Fig. 13. Correlation of two co-polarized transverse components of $\hat{\chi}_{corr}$. The opacity of the figure corresponds to the magnitude of $\hat{\chi}_{corr}$ and the color coding of the phase of $\hat{\chi}_{corr}$.

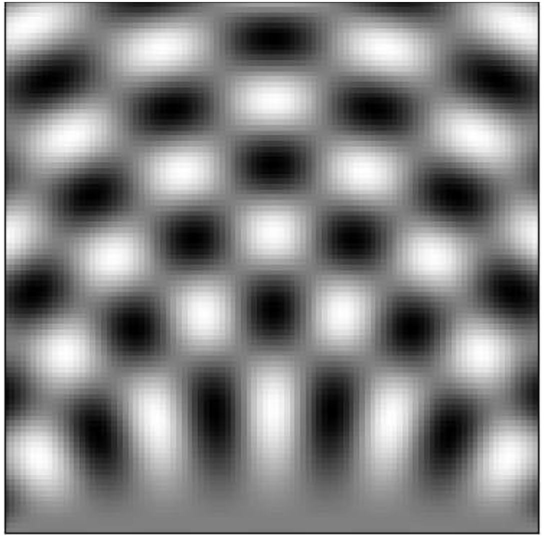


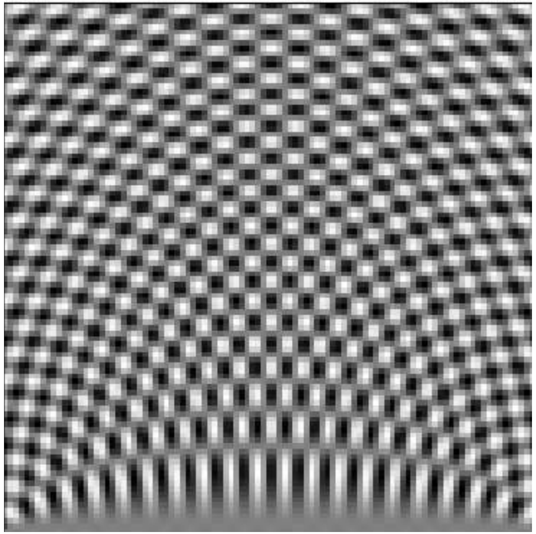
Thomas Fromenteze , Okan Yurduseven, Michael Boyarsky, Jonah Gollub, Daniel L. Marks, and David R. Smith, "Computational Polarimetric Microwave Imaging," Opt. Express **25**, 27488 (2017).

NIST Model

- Superposition patterns
- Pseudo random code pulses
- N transmitters and few receivers
- Results

NIST Model: Interference patterns





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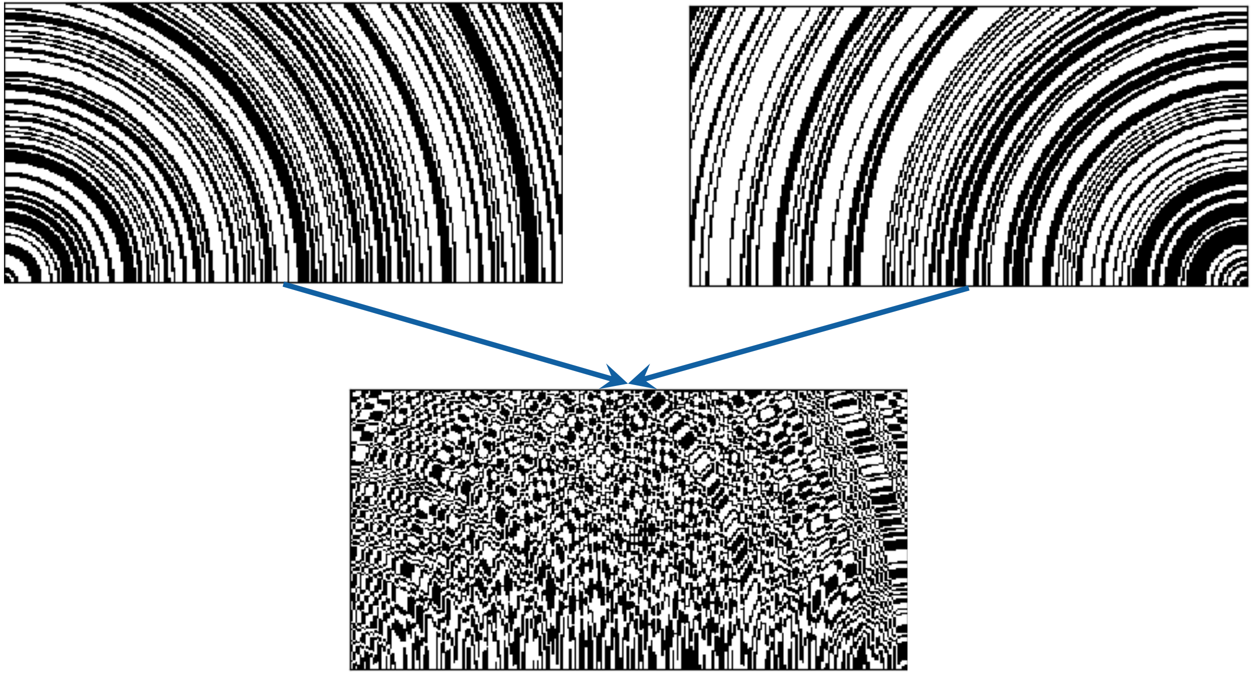
NIST Model: Pseudo-random code pulses



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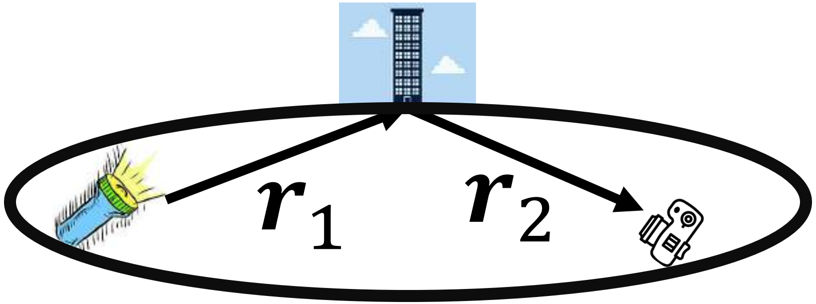
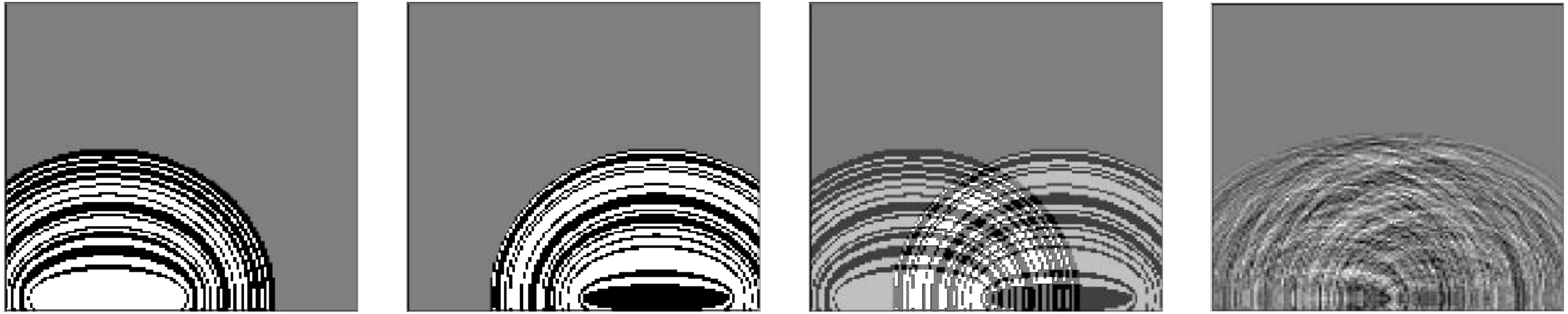
NIST Model: N Tx and 1 (One) Rx

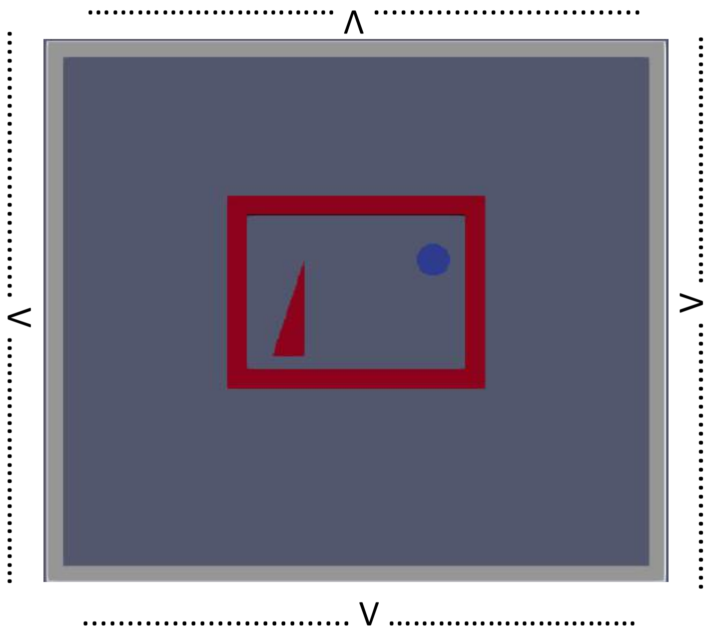


$$r_1 + r_2 = ct$$

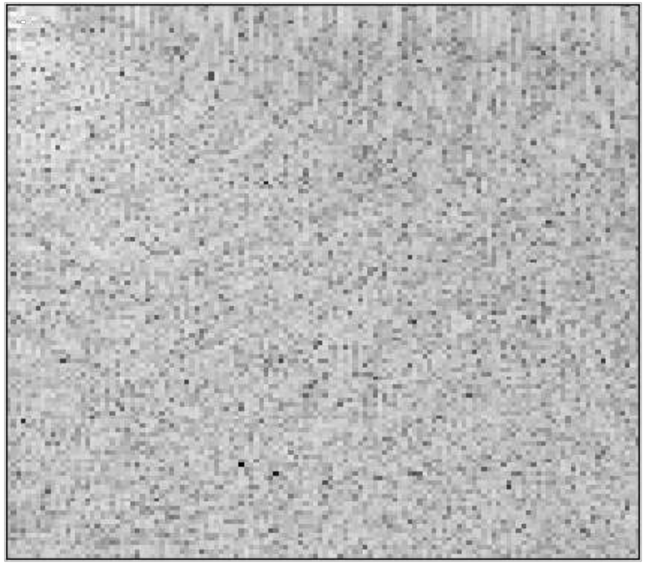


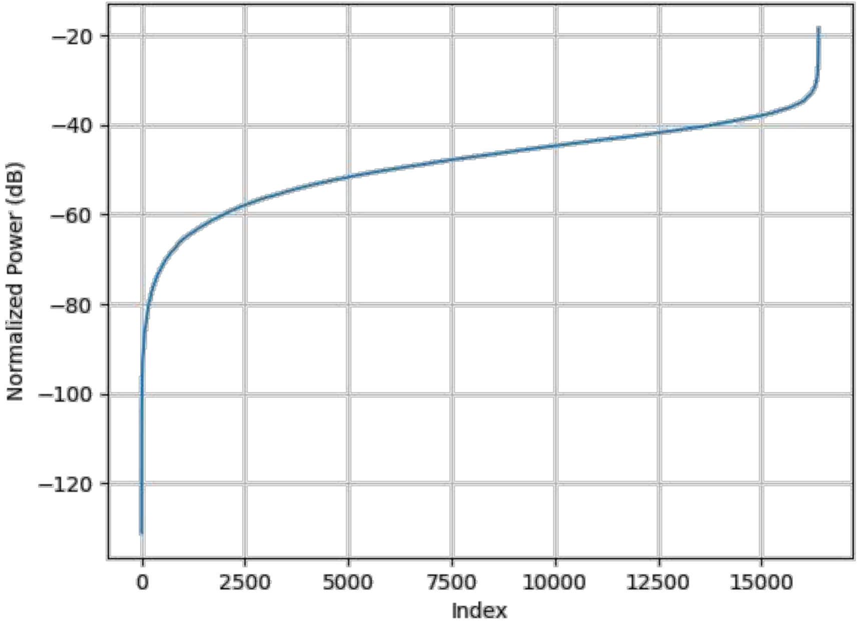
NIST Model: Simulation (no endorsement)

- FDTD full wave simulation with gprMax
- FDTD processing with NVIDIA
- Post processing with python™
- Package management done with ANACONDA
- Details:
  - $\Delta r = 2.5$ mm,
  - $\Delta t = 5.89664 \times 10^{-12}$ s,
  - 9.6 m × 8.4 m × 2.5 mm,
  - $\varepsilon_r = 1.5$.
- 128 Hertzian dipoles as transmitters.
- PR codes on gaussian pulses (BW=2.65 GHz).
- 1 receiver.
- 128 x 128 pixels.
- 8192 measurements.



NIST Model: Coherence





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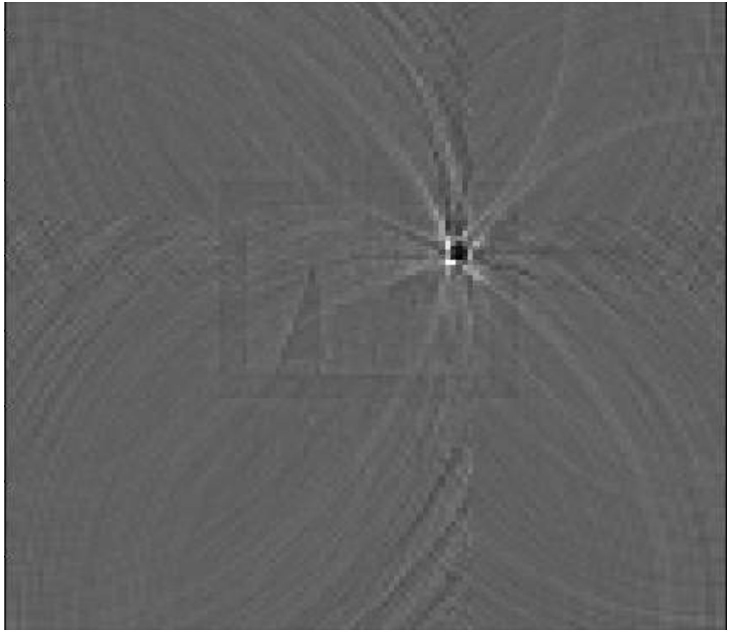
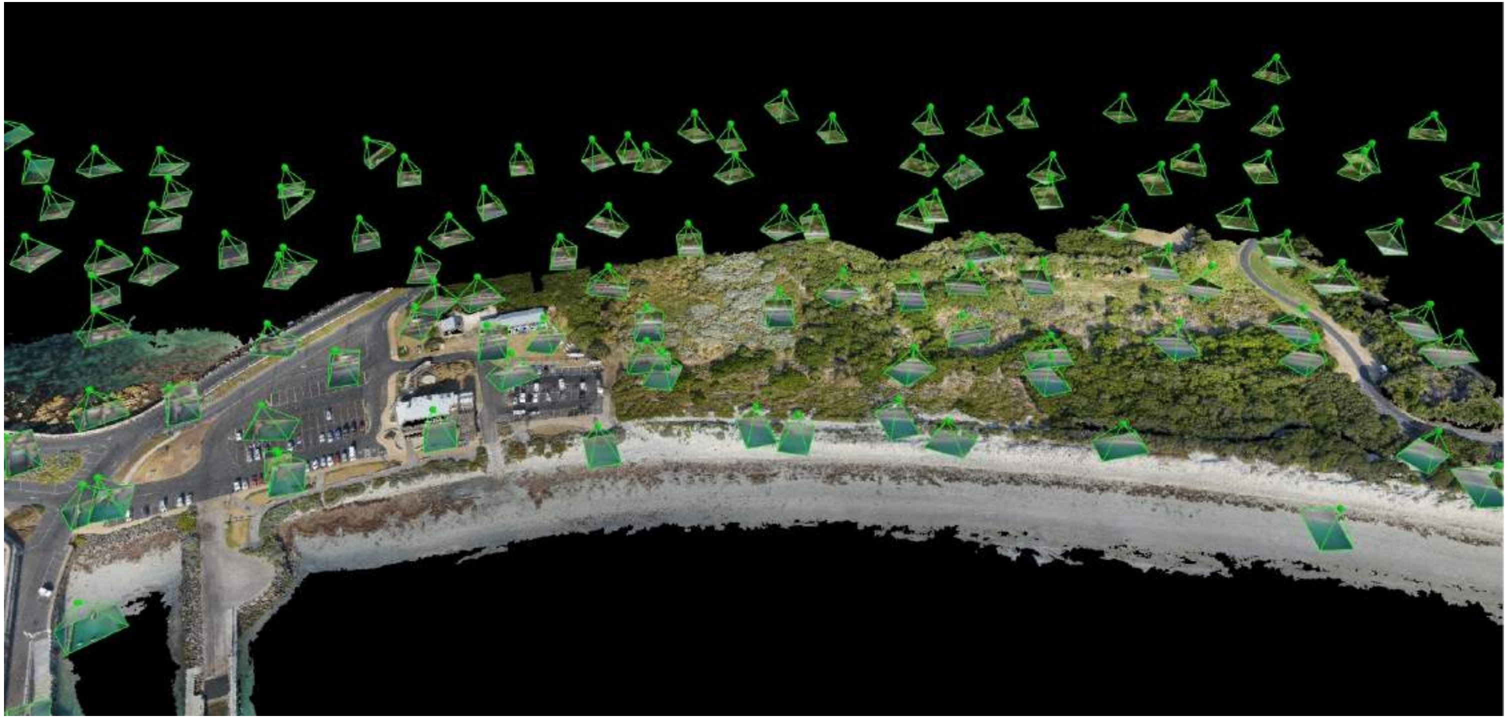
NIST Model: Preliminary results

- Results:
  - Sampling compression: 99.5 %,
  - Sensing compression : 90 %,
  - No prior knowledge of scene,
  - Multipath suppressed,
  - Depth info attained,
  - Sampling time: 3.86 µs,
  - No clock recovery needed.
- Challenges:
  - Shadows, blind spots
  - Delays,
  - …



Drone swarms

Lidar with drones



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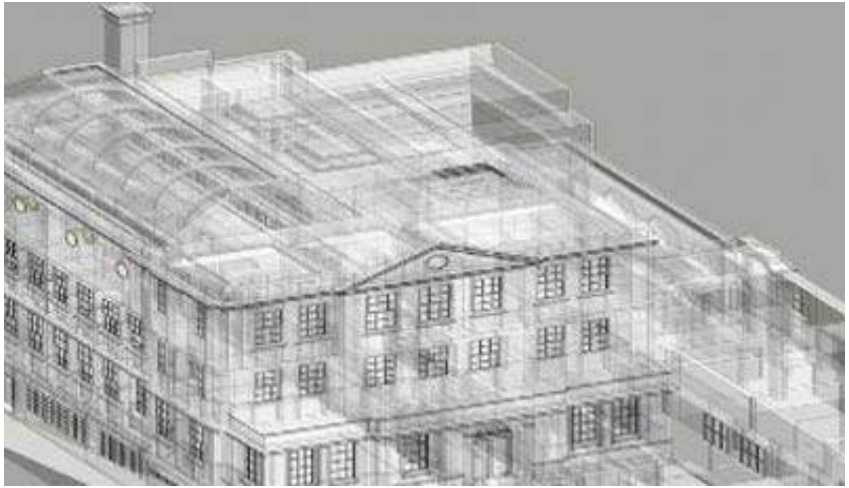
RF Lidar with drones




PSCR
THANK YOU
COLORADO SPRINGS
5

TRX First Responder Location and Mapping Services

Public Safety Innovation Accelerator Program

Carol Politi – President and CEO

Jeff Kunst – VP, Product and Business Development

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Suite 420
Greenbelt, MD 20770
(+1) 301-313-0053
info@trxsystems.com

TRX systems

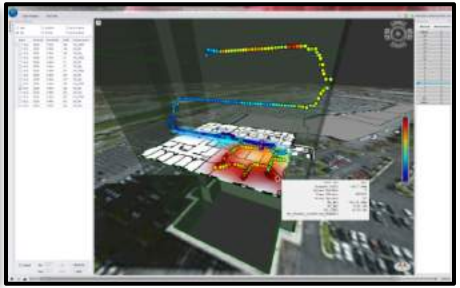
LOCATE. MAP. TRACK. INDOORS.

TRX Systems: 3D Mapping and Tracking

Ubiquitous Personnel Location and 3D Mapping:
Inside buildings, underground, in dense urban and GPS-denied areas

Events and Public Buildings

Critical Incident Response

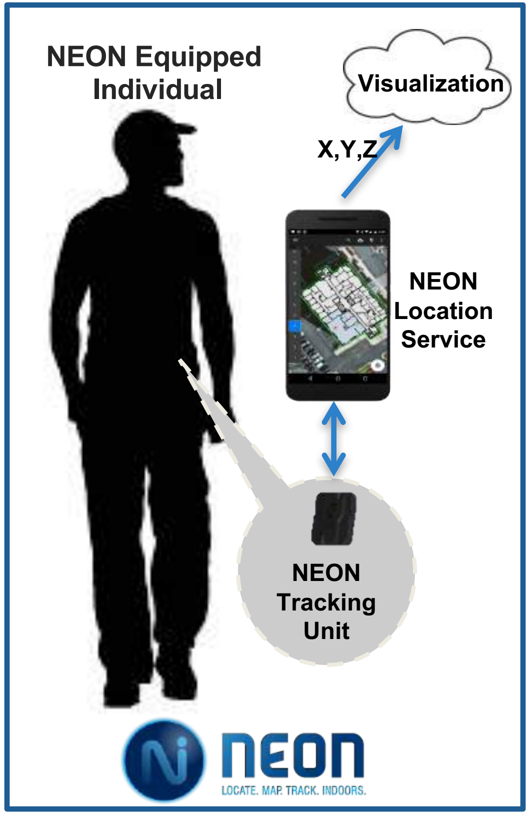


Network Coverage Validation

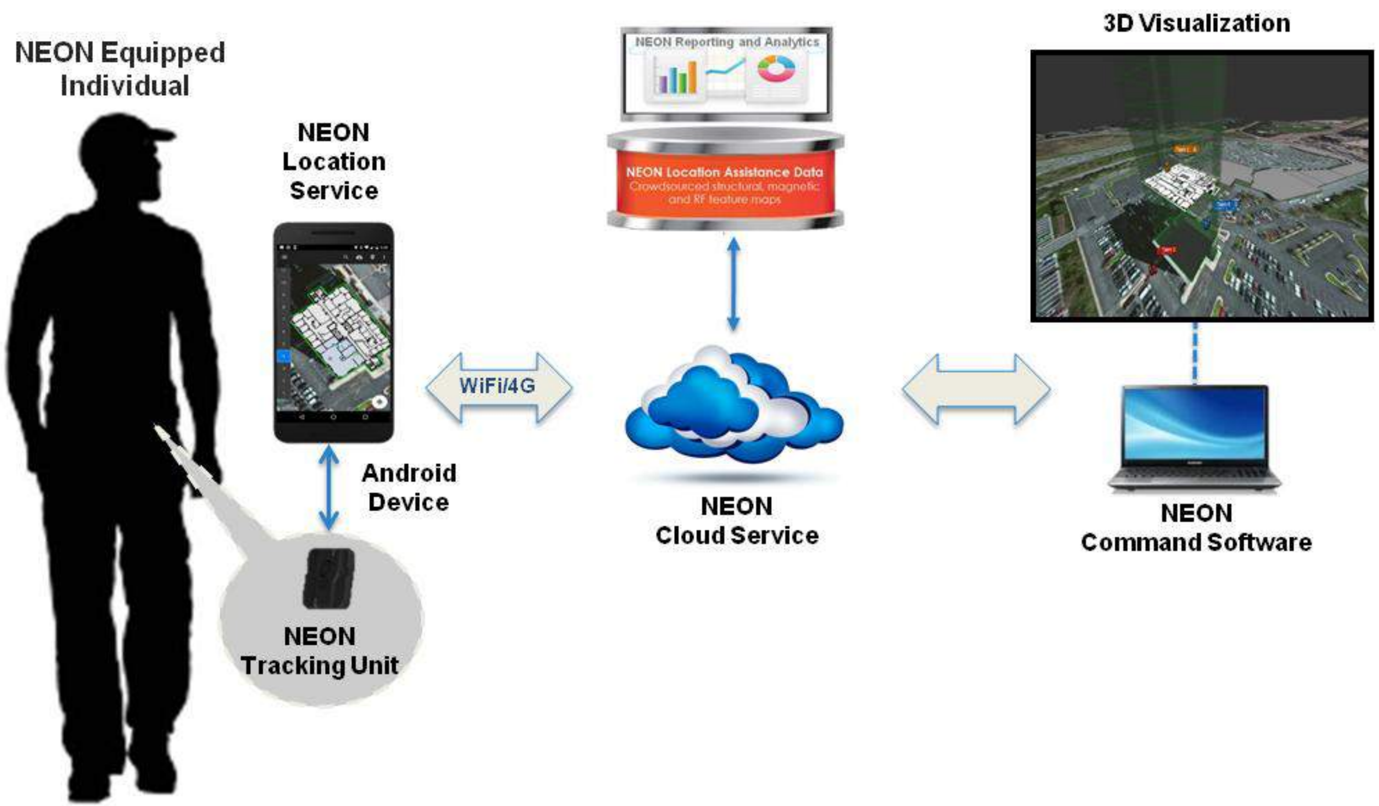
Industrial – Defense – Public Safety
Improves Safety, Command Awareness, and Operational Effectiveness

Personnel Tracker – Indoor & Outdoor Location

- Improves operational efficiency, command effectiveness, safety
- Real-time, 3D location calculated every step
- Sensor fusion, map and ranging technologies
- Android smart phone paired with NEON Tracking Unit
- API delivers lat/long, altitude, floor level, building data



NEON Personnel Tracker Solution



Recent NEON Deployments

SuperBowl LI Houston, TX	• Law enforcement, EMTs at Super Bowl LI in Houston • ~2M square feet and 7 levels of 3D tracking • Improved situational awareness & safety, reduced radio traffic
Immigration and Customs Checkpoint	• 24x7 situational awareness at large border checkpoint • 7 floors, indoor and outdoor 3D coverage • Integrated with Operations and Command Center
Active Violence Exercise Grand Central Terminal, NYC	• DHS first responder exercise in Grand Central Terminal involving NYPD, FDNY, and others • 3D situational awareness for remote command center
Radiation Mapping DARPA/DHS	• Tracking of law enforcement within transport hubs • Mapping radiation from low-cost, body worn detectors to support dirty bomb detection
2018 NBA All-Star Game Los Angeles, CA	• Safety and situational awareness for state and local police, fire and EMS personnel • NEON Location Service with API integrated with ATAK and WinTak for visualization

TRX PSIAP Program Goals

- Deliver robust, higher accuracy 3D location for first responders
  - Use wider array of location inputs and constraints
- Make available comprehensive map data sources and tools
  - Expand use of known and inferred building information
- Deliver easy to use 3D visualization
  - Enhance map databases to make them easy to modify, validate, synchronize

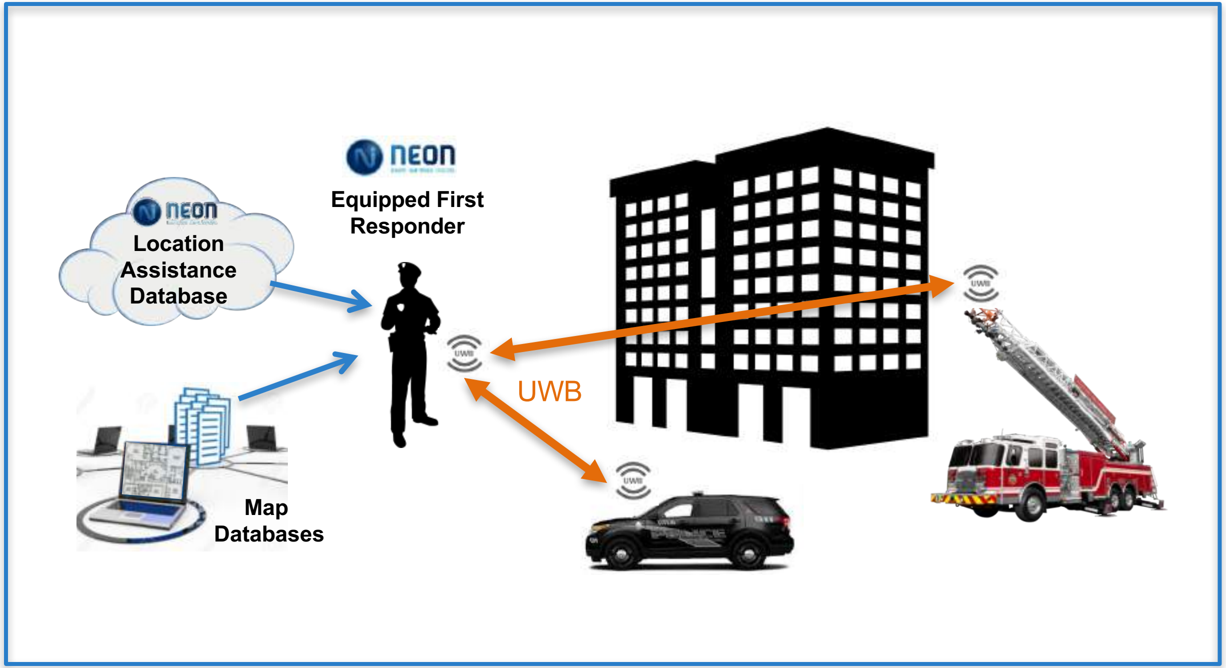
Year 1 Contributors

LOCATE. MAP. TRACK. INDOORS.

Arlington County Fire Department, VA

Harris County, TX Public Safety Technology Services

3D Location and Mapping – Year 1 Architecture



Targeted Use Cases: Tactical Law Enforcement & Fire Personnel

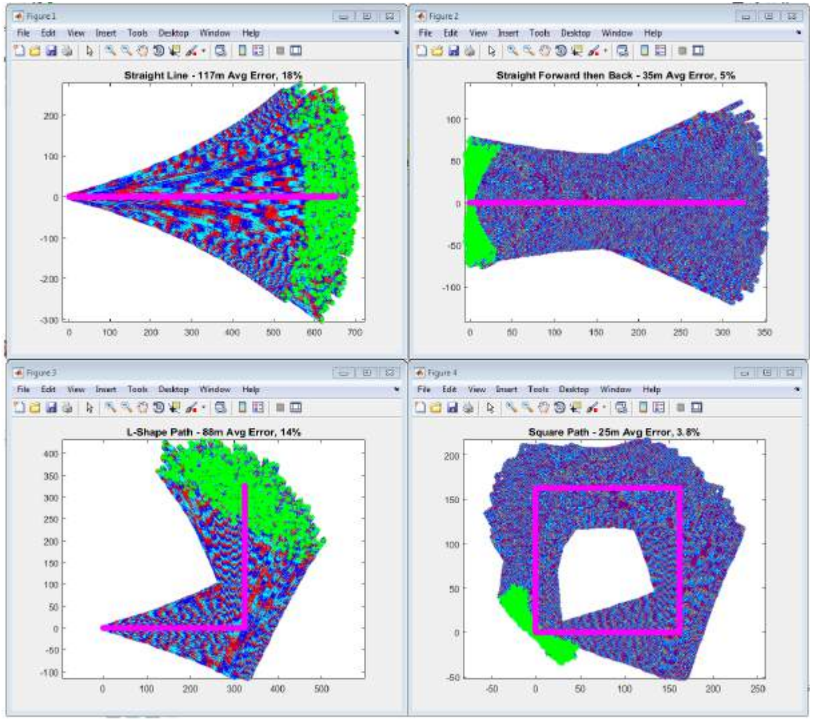
What technologies are being applied?

Algorithms fuse inertial sensor data, Bluetooth, UWB and Wi-Fi readings with inferred map and building data to deliver 3D location

	Initialization	Key parameters include start position, heading, user mounting location and gait; learned from GPS, beacons or manual input
	Sensor Fusion	Inertial sensors (gyro, accel, compass) plus pressure and other Android based sensors used to calculate movement in local frame
	Satellite and Terrain Data	Provides for placement of user in global frame with latitude, longitude and altitude above sea-level; allows for 3D visualization
	Building Data	Shape files give 3D construct for “floor level” tracking; learned data provides structural (stairs, entrances, elevator) constraints
	RF Signals	Learned RF (cellular, Wi-Fi, BT) data combined with structural data is geo-referenced to create 3D feature map stored in cloud
	Beacons	Ranging to optional UWB and/or BLE beacons provides high accuracy constraints where needed; can be dropped or placed

Inertial Sensor Fusion + Constraints

Inertial "dead reckoning" alone is infrastructure-free but accumulates error over distance travelled.



Inertial Dead Reckoning" Alone

NEON algorithms use intermittent GPS, map data, and UWB/BLE ranging to "constrain" inertial results and provide accurate 3D location

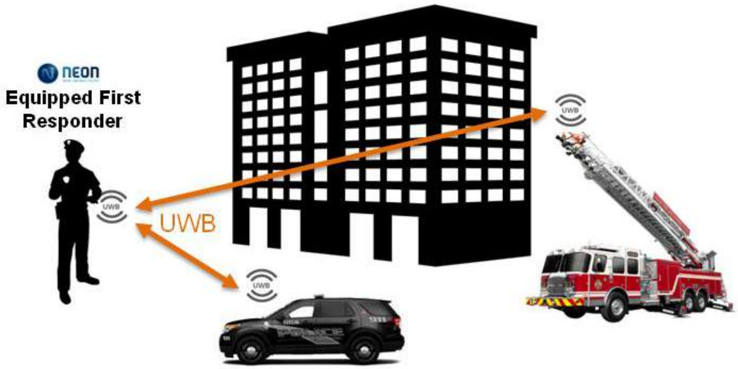
Year 1 Program Updates

Program Goals		Year 1 Program Activity
1. Deliver robust, higher accuracy 3D location for first responders	→	1. UWB-GPS beacon research, development and testing
2. Make available comprehensive map data sources and tools		2. Improved ease-of-use and features of pre-mapping tool
3. Deliver easy to use 3D visualization		3. Adding ability to model complex buildings
4. Test and validate with first responders		4. Completed initial testing with first responders

First Responder Initialization Enhancements

Program Goal #1: Deliver robust, higher accuracy 3D location

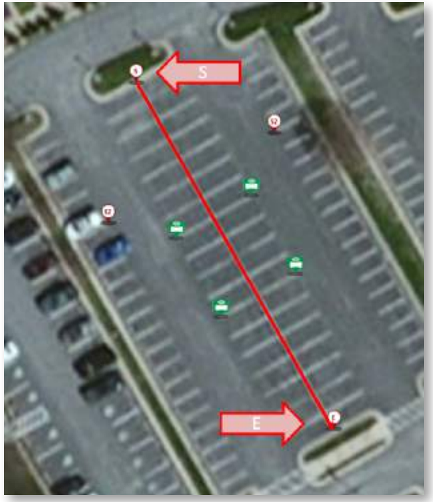
- Good initialization creating an accurate starting position and heading is important to achieving highest infrastructure-free accuracy
- GPS is a potential source of initialization but small devices – especially those held in a pocket - often provide poor GPS based position accuracy
- UWB provides highly accurate range data and is an excellent technology for initialization when available
- TRX researched and tested a combined GPS-UWB beacon for deployment on vehicles or dynamically on-site at an incident



Initialization: GPS-UWB Beacon Testing

GPS was evaluated as an automatic positioning source for UWB Beacons

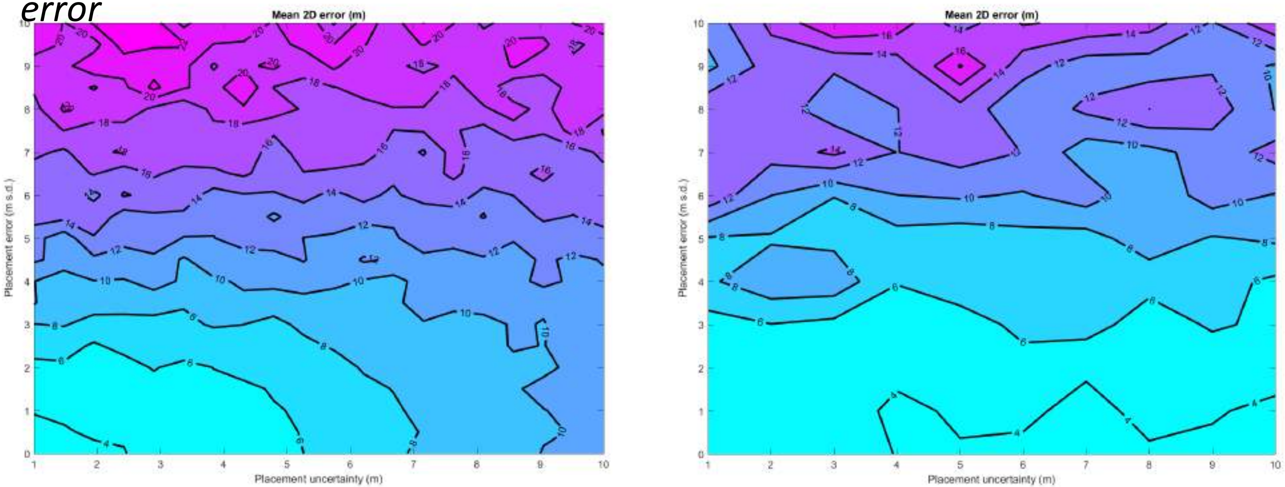
- Collected dataset using UWB anchors outside to simulate GPS anchor initialization



- Ran multiple tests with simulated first responders walking by 4 UWB beacons, in 2 different configurations

GPS-UWB Beacon Test Results

- Each log was reprocessed varying two different parameters
  1) The uncertainty in the reported location, in meters
  2) The delta of the actual location of the GPS receiver and its reported position
- A Monte Carlo experiment varied the reported location of the GPS receiver with Gaussian distribution with a specified standard deviation
- **Finding:** *a placement uncertainty less than 6 m with a placement error standard deviation less than 3 m is able to achieve a <6 m actual location error*



Mean 2D error (paths 1 and 2)

GPS Constraints – Challenges and Opportunities

- Initialization typically needed in close proximity to buildings where there are more complex RF multi-path environments
- GPS receivers provide many data parameters:
  - RMC: time, latitude, longitude, speed, …
  - GGA: fix quality, num satellites, HDOP, …
  - GSV: satellite elevation, satellite azimuth, …
- Multiple data parameters combined using statistical methods can be used to determine an estimate of the error distribution at any given time
- Multiple GPS receivers on a vehicle may allow for detection of multi-path and overall accuracy improvements of the UWB-GPS Beacons

Multiple GPS Receivers Testing

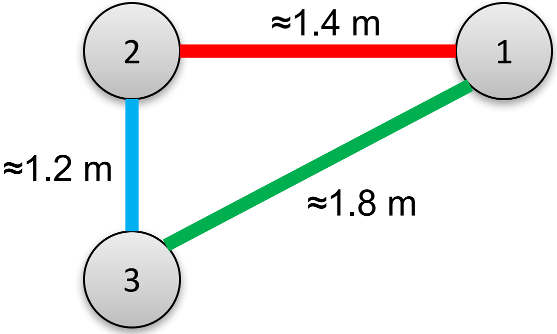
Hypothesis:

Multiple GPS receivers placed in a known configuration can be used to more accurately quantify GPS errors

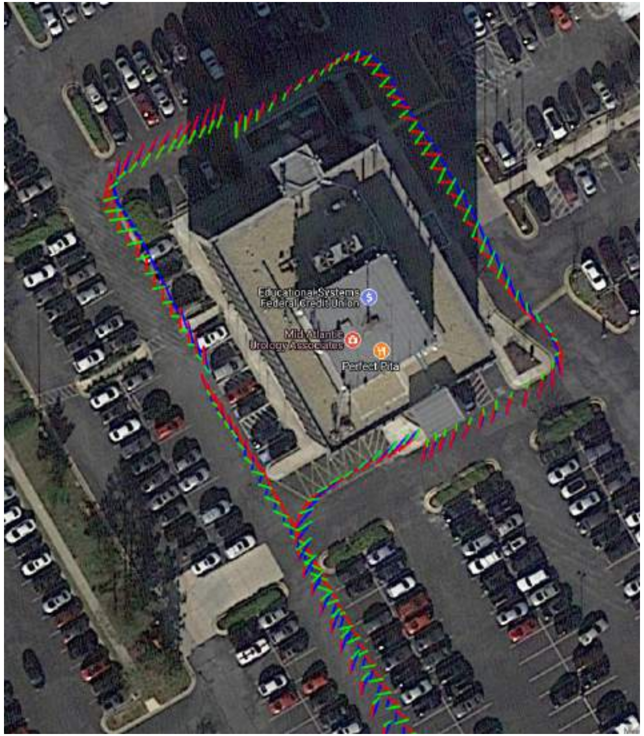
Test Configuration:

3 X GPS Receivers

Receivers placed in known configuration on vehicle roof

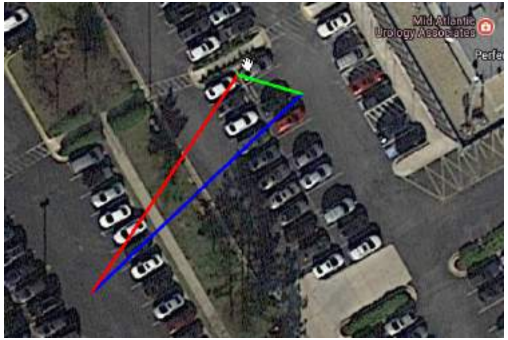


GPS Receiver Configuration

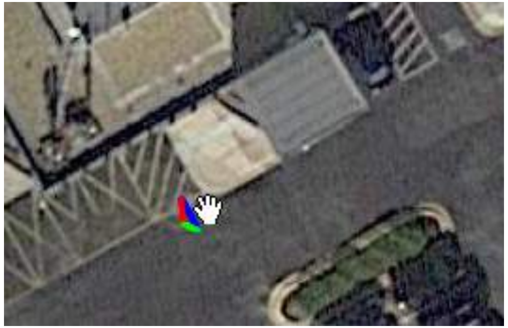


Sample Data Collection Through Parking Lot

Multiple GPS Receiver Results



Poor Fix Quality Result


Good Fix Quality Result

Error Estimation

Compare known configuration with measured configuration

Poor Fix Quality Result

- Nearby buildings: 2
- Directly between buildings
- Probable multipath issues

Good Fix Quality Result

- Nearby buildings: 1
- Approximately 25 % of sky view blocked

UWB-GPS Beacon Testing

Next Steps:

- Finalize prototype UWB-GPS Beacons for field testing
- Deploy and test with:
  - Arlington County, VA, Harris County, VA and MECC in Ohio

Arlington County Fire Department

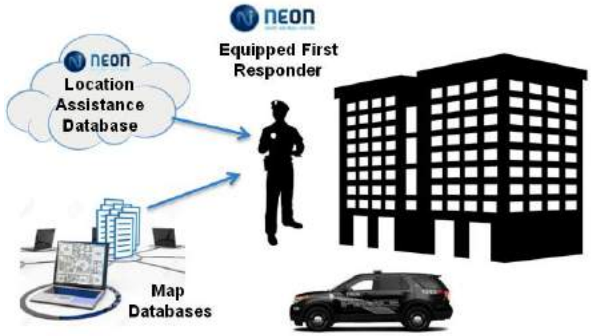
Harris County Public Safety Technology Services

Plain Township New Albany, OH

Premapping Enhancements – Map Data

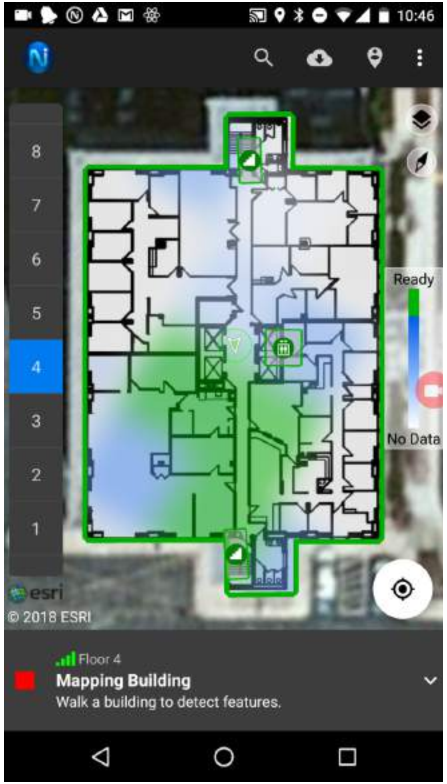
Program Goal #2: Make available map data sources and tools

- Map data provides valuable constraints that can improve location solution; also improves situational awareness
- Access to map data is limited so map data must be easy to import, generate and share
- “NEON Mapper” is a mobile app that allows for easy-to-use premapping of buildings and underground spaces from the handheld device
- *TRX expanded NEON Mapper allowing first responders to add preplan data directly from mobile device*



Creating Map Data - Premapping Enhancements

- Mapper is an Android app that discovers and enables placement of RF features, structural features and beacons
- Mapper with 3D shapefiles allows for creation of navigable 3D feature maps
- Updates dramatically improve ease-of-use
- Wi-Fi mapping redesigned to better handle mapping on building edges and outdoors.
  - Wi-Fi matching outdoors can improve location accuracy in urban environments, near buildings
- Shifted to geo-spatial database to simplify and speed up fingerprint queries



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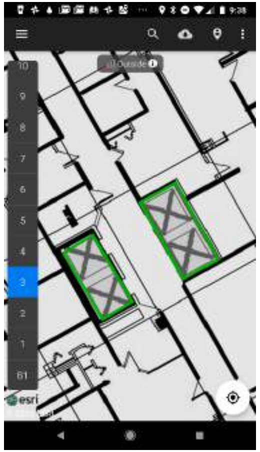
Wi-Fi and Structural Feature placement and learning

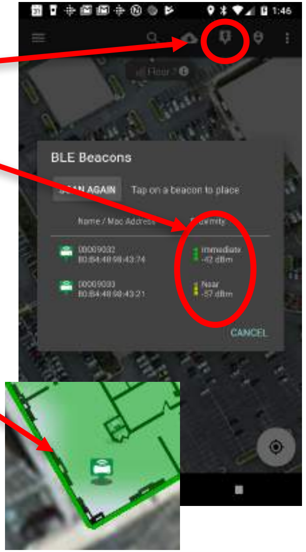


Walk facility to map Wi-Fi and structural features.

- Green indicates validated Wi-Fi map coverage, blue unvalidated data.
- Icons indicate discovered structural features and users can place these on the map

Simple Beacon placement

1. Tap BLE icon to scan beacon ID - *Signal strength of nearby beacons is displayed*
2. Select beacon and move map to put beacon icon at correct location.



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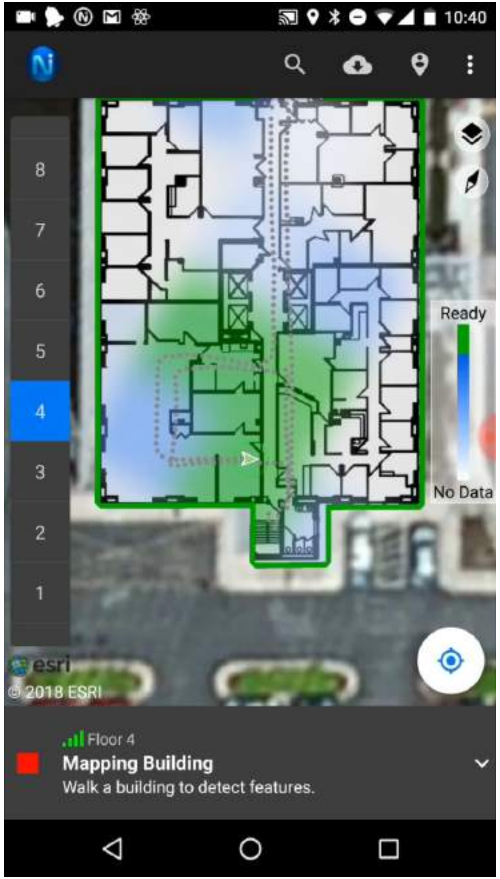
Creating Map Data - Premapping Enhancements

NEON Mapper Application video

- RF and Structural Feature Detection
- Allows placement of UWB and BLE beacons



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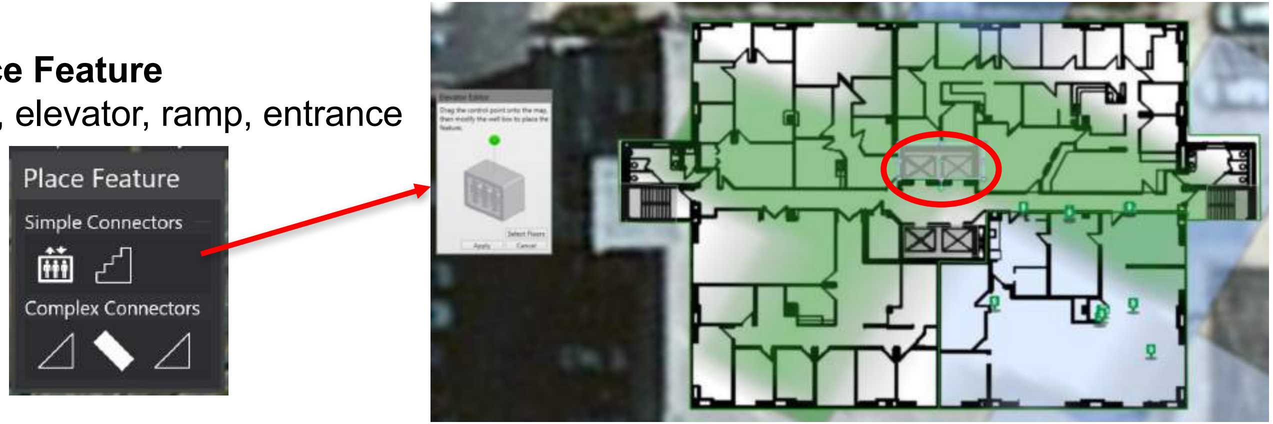
Program Goal #3: Deliver easy to use 3D mapping and visualization

Allows user to place structural features in NEON Command building editor

Place Feature
stair, elevator, ramp, entrance



- Simplifies accurate placement relative to floorplan
- Improves usability when several features are grouped together
- Command placed stair and elevator features provide a level of automated corrections – even without premapping at the facility

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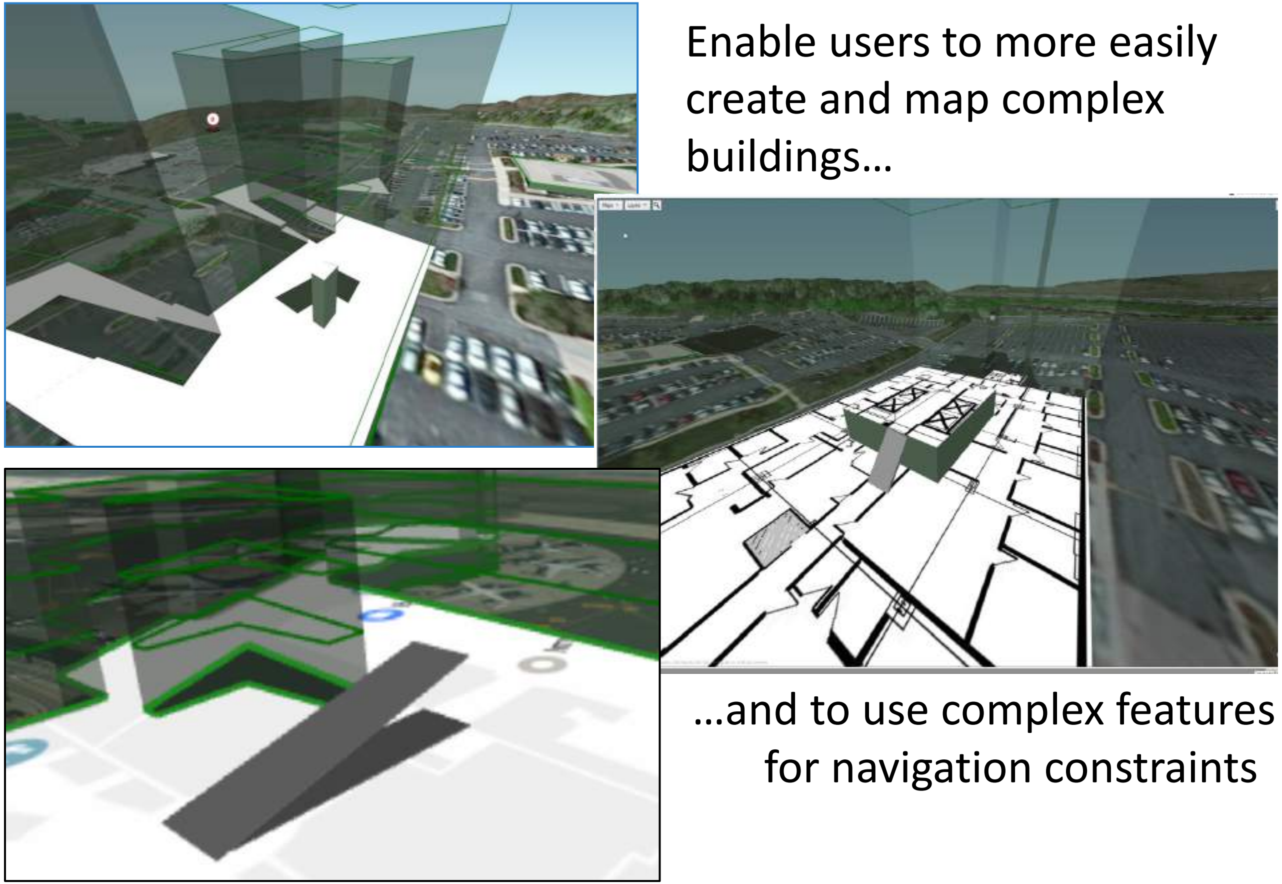
Creating Map Data - Command Building Editor



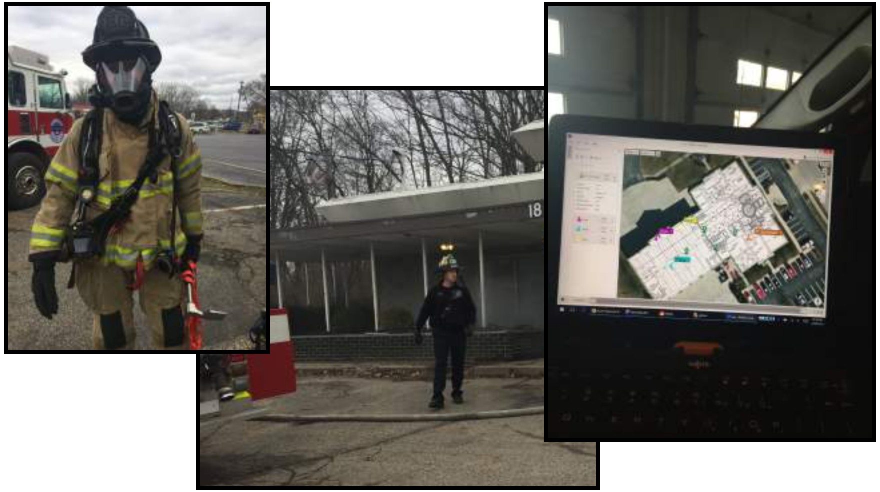
Enable users to more easily create and map complex buildings…

…and to use complex features for navigation constraints

Use Case Validation and Testing

Program Goal #4: feedback and initial testing with first responders

- Requirements, use case definition
- Training on the solution, new features
- Testing/trials with new features
- Usability assessments, gap analysis



Arlington County, VA
Fire Department

Harris County, TX Public
Safety Technology
Services

Plain Township
New Albany, OH
Fire Department

Mifflin Township
Gahanna, OH
Fire Department

Use Case Validation and Testing

Test Groups included 10 firefighters

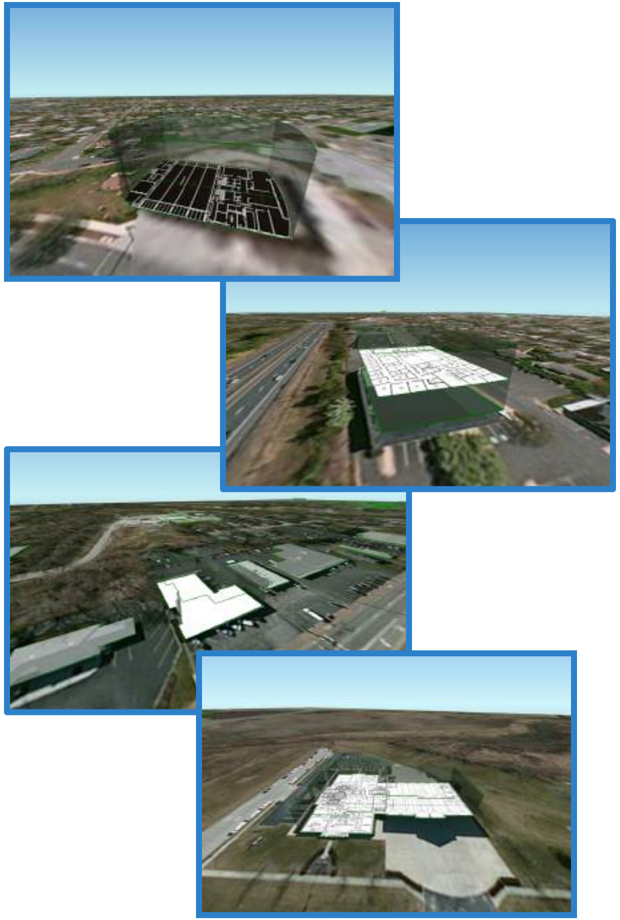
- 4 exercises; 10-15 minutes each
- >8000 location data points collected

Arlington County, VA Fire Dept:

- Simulated live fire incident
- Simulated active shooter
- GPS and simulated GPS-UWB beacons

Plain/Mifflin Townships Fire Depts:

- Simulated live fire incident
- GPS, UWB Sharing, and simulated drop beacons (2) inside the building



Use Case Validation and Testing

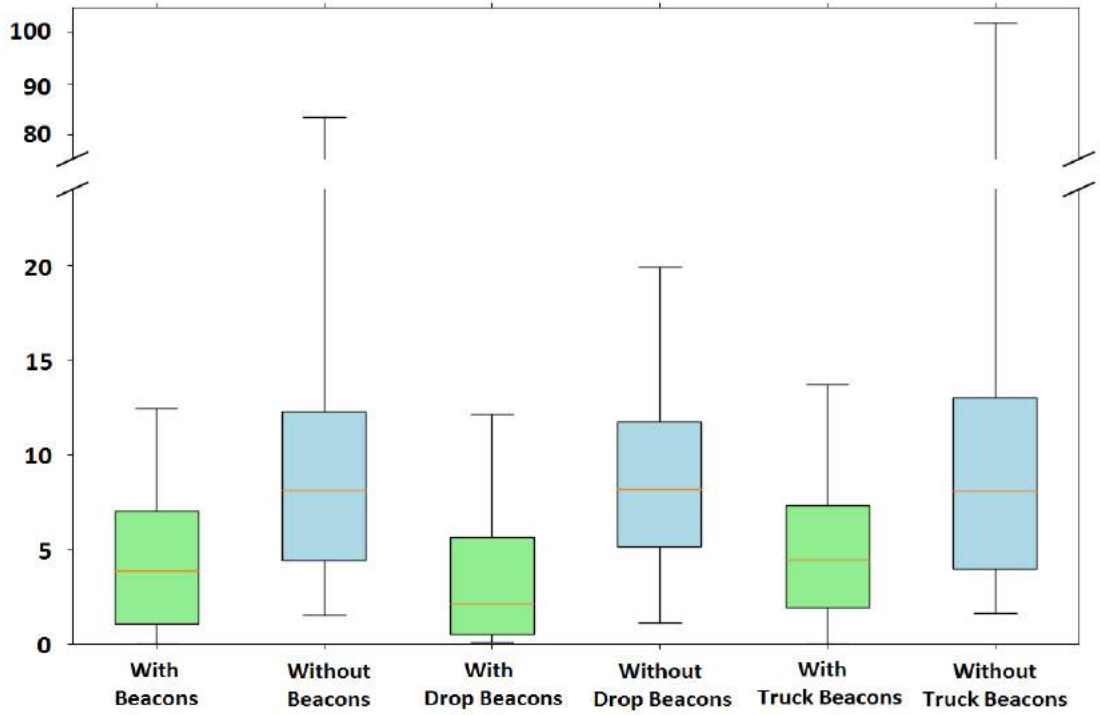
Difference between GPS and UWB initialization

Use Case Validation and Testing

NEON mapped feature constraints in action at Arlington County user testing

Use Case Validation and Testing

- Demonstrated that GPS devices carried in a pocket provide poor accuracy
- UWB for NEON initialization was much better than GPS alone
- UWB "dropped" inside was the best but this is not always feasible

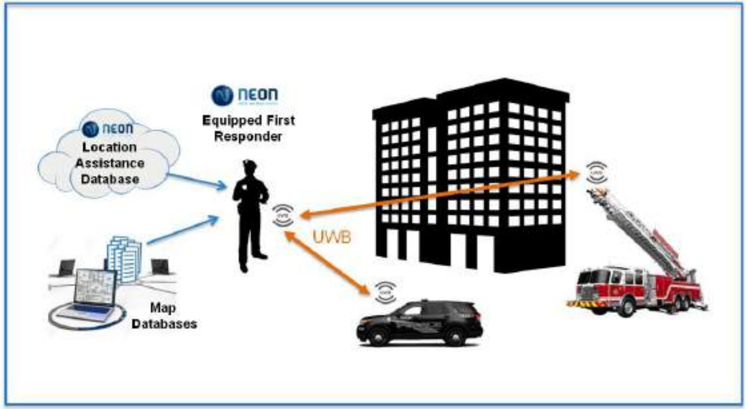


Use Case Validation and Testing

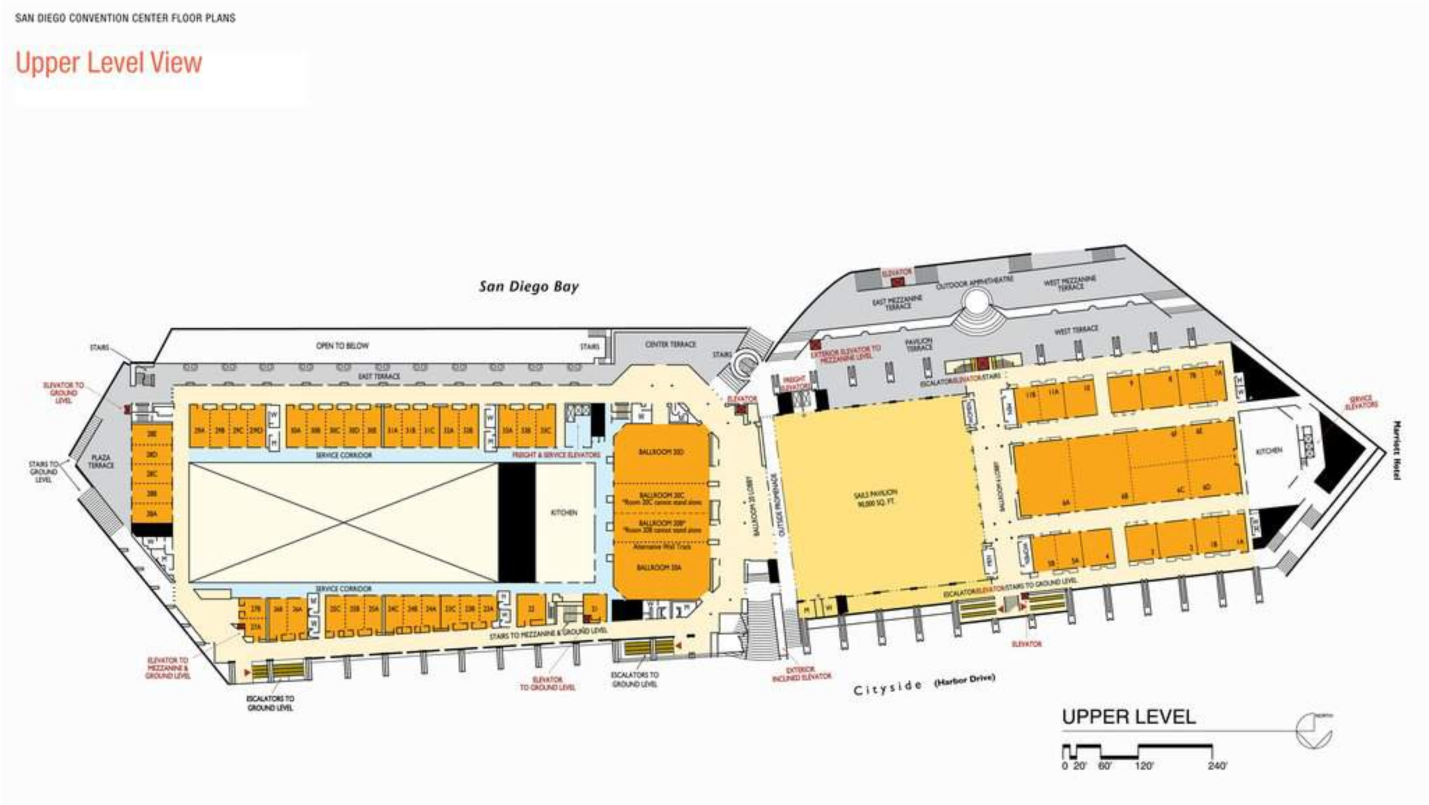
	With Beacons	Without Beacons	With Drop Beacons	Without Drop Beacons	With Truck Beacons	Without Truck Beacons
Average	4.7m	16.2m	3.8m	8.8m	5.3m	20.5m
Count	8327	8327	3026	3026	5301	5301
Standard Deviation	4.4m	25.8m	3.9m	5.2m	4.5m	31.4m
95% Confidence Interval	4.6m-4.8m	15.7m-16.8m	3.6m-3.9m	8.7m-9.0m	5.2m-5.4m	19.6m-21.3m

Year 2 Program Activities

- Expand UWB technology application for first responders
- Continue development of mapping tools to enable development of more dynamic navigable maps
- Incorporate feedback from the public safety community to enhance ease-of-use of mapping and visualization tools
- Build on baseline user testing to demonstrate full-scale tracking performance across applicable use cases



NEON Personnel Tracker Live Demo



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