First Responder Indoor Location Using LTE Direct Mode Operations

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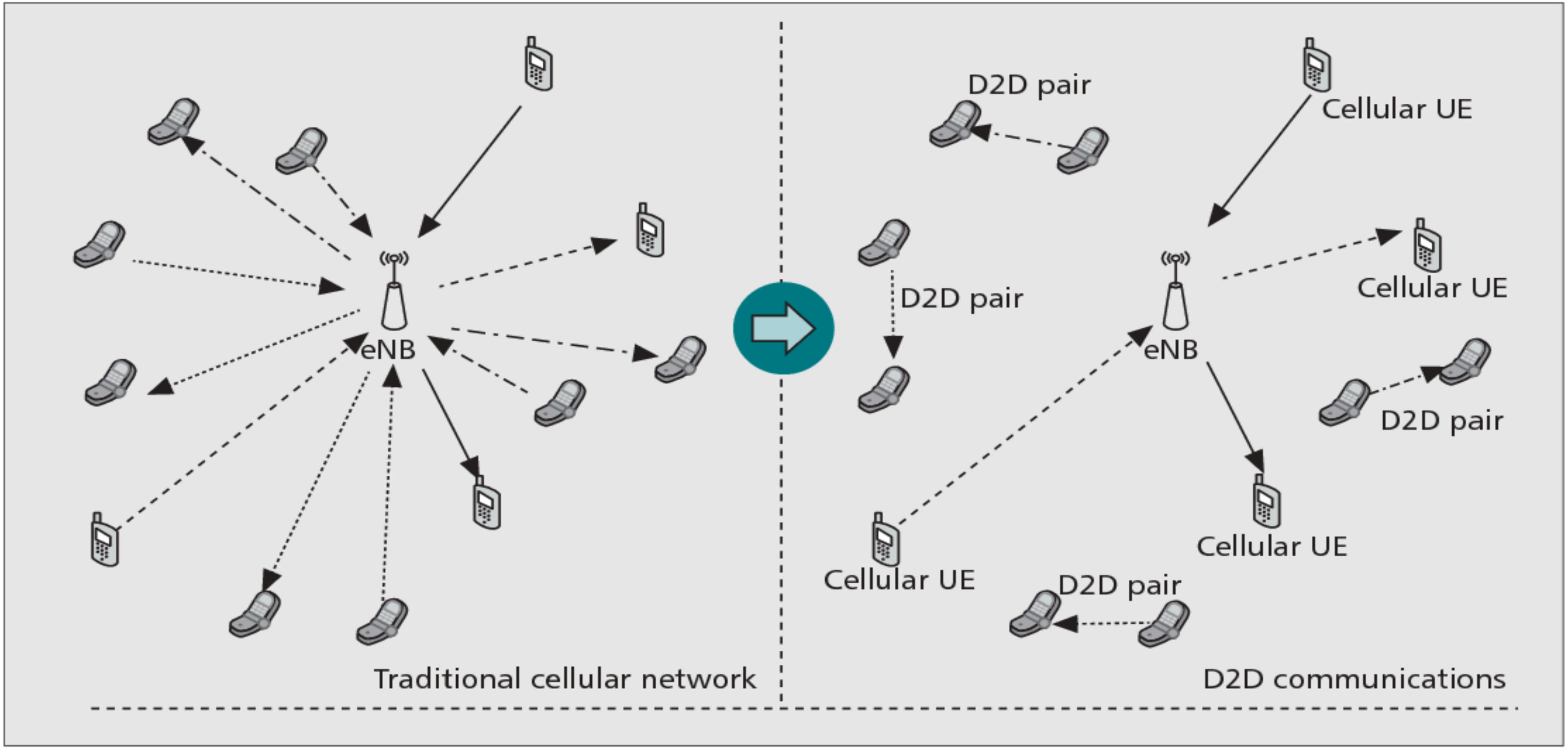
Acronym Glossary

- ALI = Automatic Location Identification
- BFS/DFS = Breadth First Search/ Depth First Search
- BT = Bluetooth
- CNN = Convolutional Neural Network
- COPSS = Content-Oriented Publish/Subscribe System
- D2D = Device-to-Device
- DS = Deployable System
- DTN = Delay Tolerant Networking
- EKF = Extended Kalman Filter
- EPC = Evolved Packet Core
- FC = Fully Connected
- FoV = Field of Vision
- FRG = Family Readiness Group
- GNSS = Global Navigation Satellite System
- HR = Hyper Reality
- ICN = Information Centric Network
- IMU = Inertial Measurement Unit
- INS = Inertial Navigation System
- IVR = Interactive Voice Response
- LiDAR = Light Detection and Ranging
- LOS = Line-of-Sight
- LSTM = Long-Short Term Memory
- MF = Multicast Firewall
- NDN = Named Data Networking
- OLED = Organic Light- Emitting Diodes
- PDR = Pedestrian Dead Reckoning
- Pub/Sub = Publish/ Subscribe
- PVA = Position, Velocity, and Attitude
- RBF = Radial Basis Function
- RSSI = Received Signal Strength Indicator
- RX = Receive/ Receiver
- SA = Situational Awareness
- SIFT = Scale Invariant Transform Feature
- SLAM = Simultaneous Localization and Mapping
- SVM = Support Vector Machine
- TDOA = Time Difference of Arrival
- TOA = Time of Arrival
- TX = Transmit/ Transmitter
- UAS = Unmanned Aerial System
- UKF = Unscented Kalman Filter
- USRP = Universal Software Radio Peripheral
- VM = Virtual Machine
- VNF = Virtual Network Functions
- ZARU = Zero Angular Rate Update
- ZUPT = Zero Velocity Update

OVERVIEW

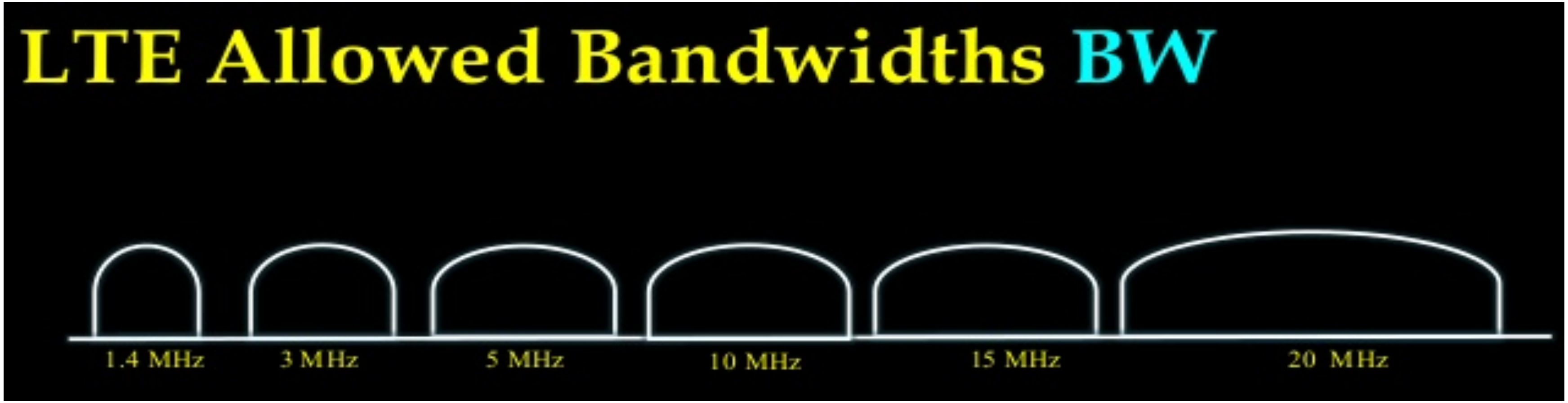
- Indoor location is important to first responders
- GPS signals are not available indoors
- LTE Direct Mode Proximity Service (ProSe) for voice communication – mission critical
- We piggy-back location service on LTE ProSe voice communication links
- Incorporate Building Information Modeling (BIM) onto location & display – critical building info (doors, windows, fire escapes)


eNB
Traditional cellular network
D2D pair
Cellular UE
Cellular UE
D2D pair
eNB
D2D pair
Cellular UE
Cellular UE
D2D pair
D2D communications

OBJECTIVES

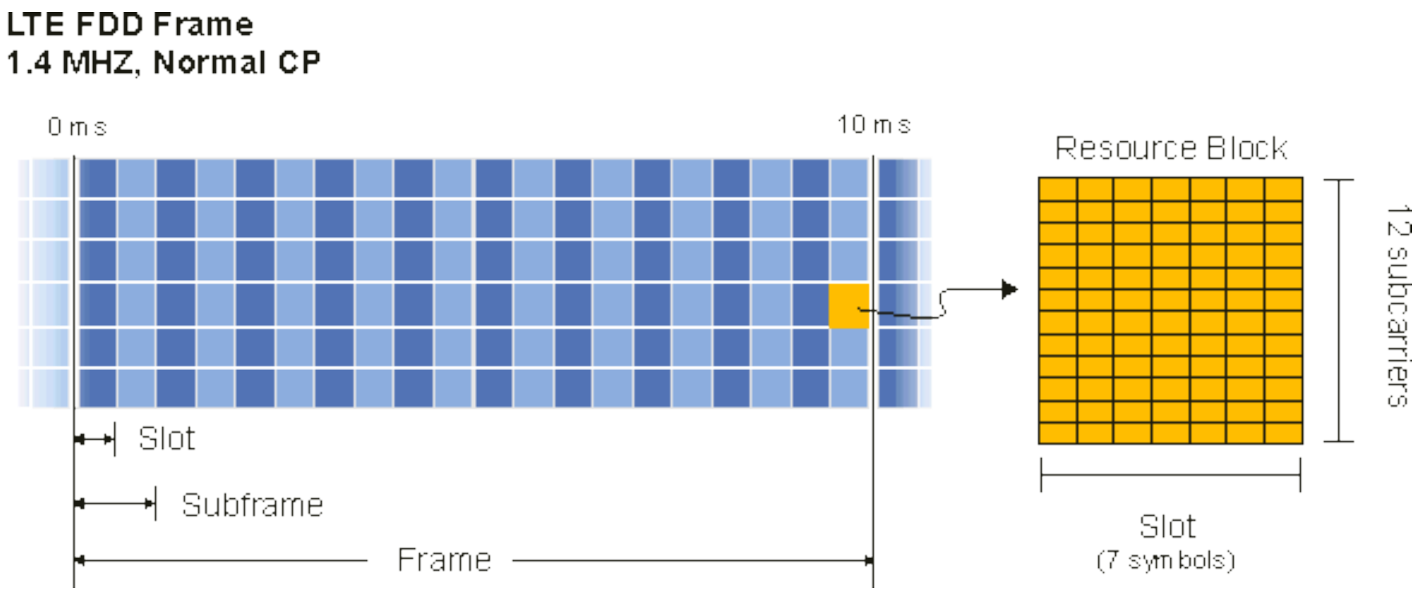
- Form an *ad hoc* ProSe network that establishes D2D direct communication among UEs
- Measure ranging signal TOA among UEs
- Use the dTDOA algorithm to find locations of all users
- Extract critical information from Building Information Modeling (BIM) data base
- Display all user locations on building layout with critical information (doors, windows, etc.)
- Test on USRP software defined radios

LTE BW


LTE Allowed Bandwidths BW
1.4 MHz
3 MHz
5 MHz
10 MHz
15 MHz
20 MHz

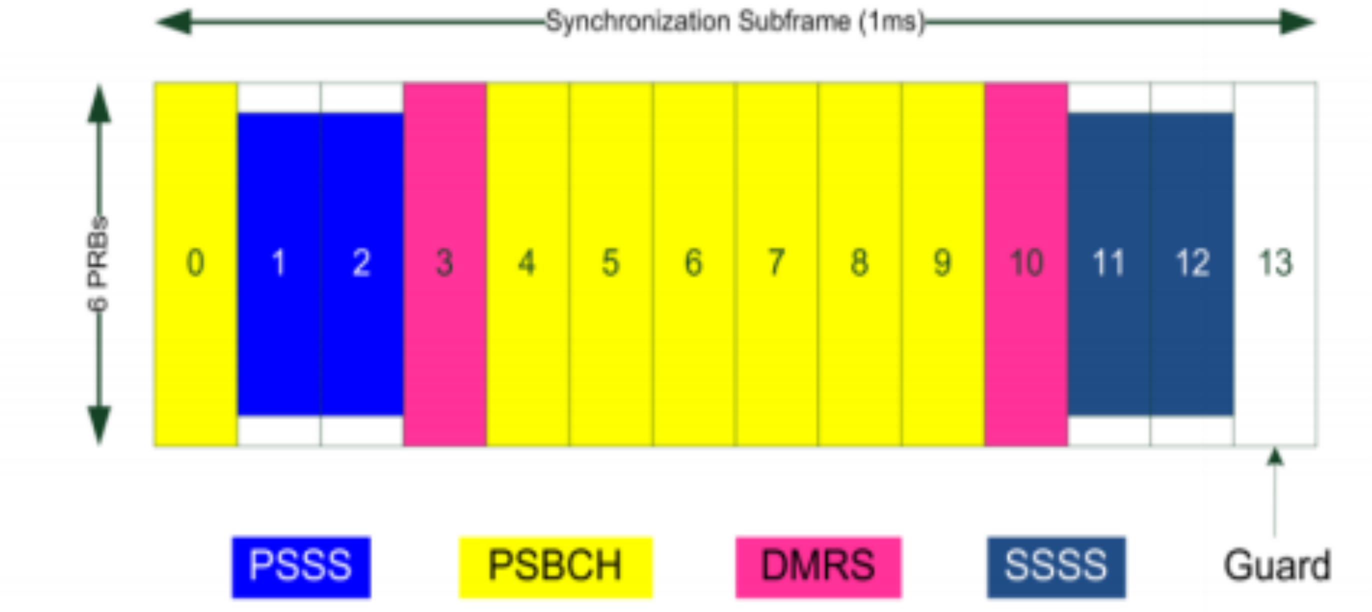
Measuring TOAs

- Use LTE resource blocks (PSS/SSS/PRS)

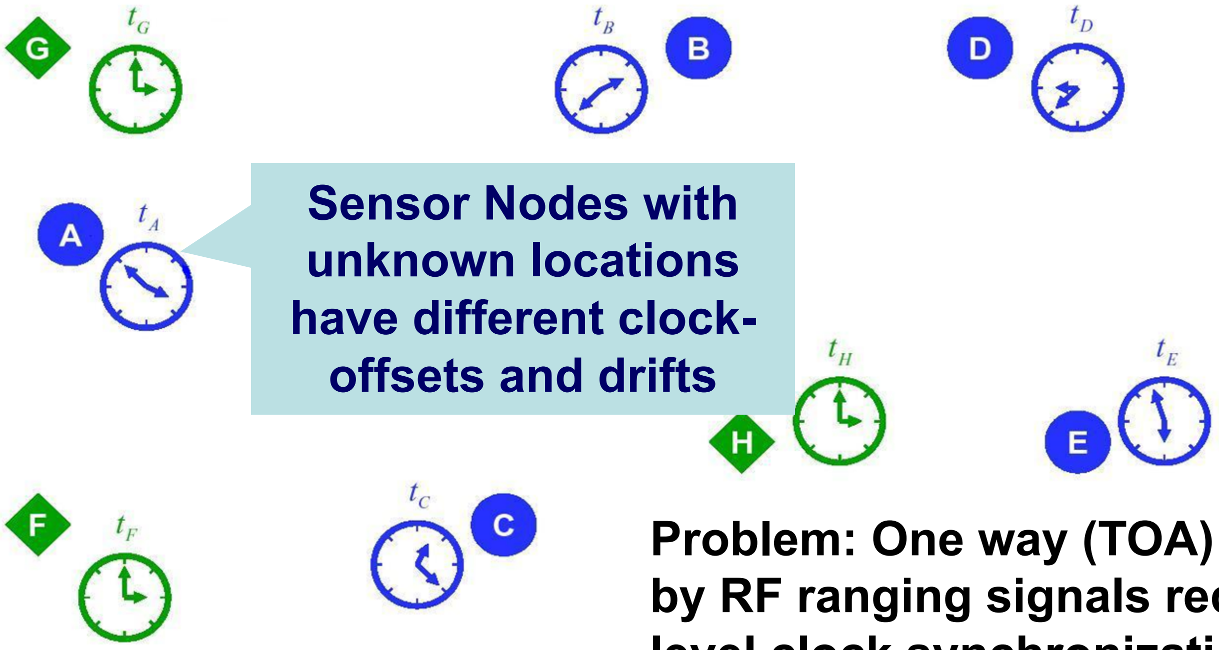


Measuring TOAs

- Use LTE resource blocks (PSS/SSS/PRS)



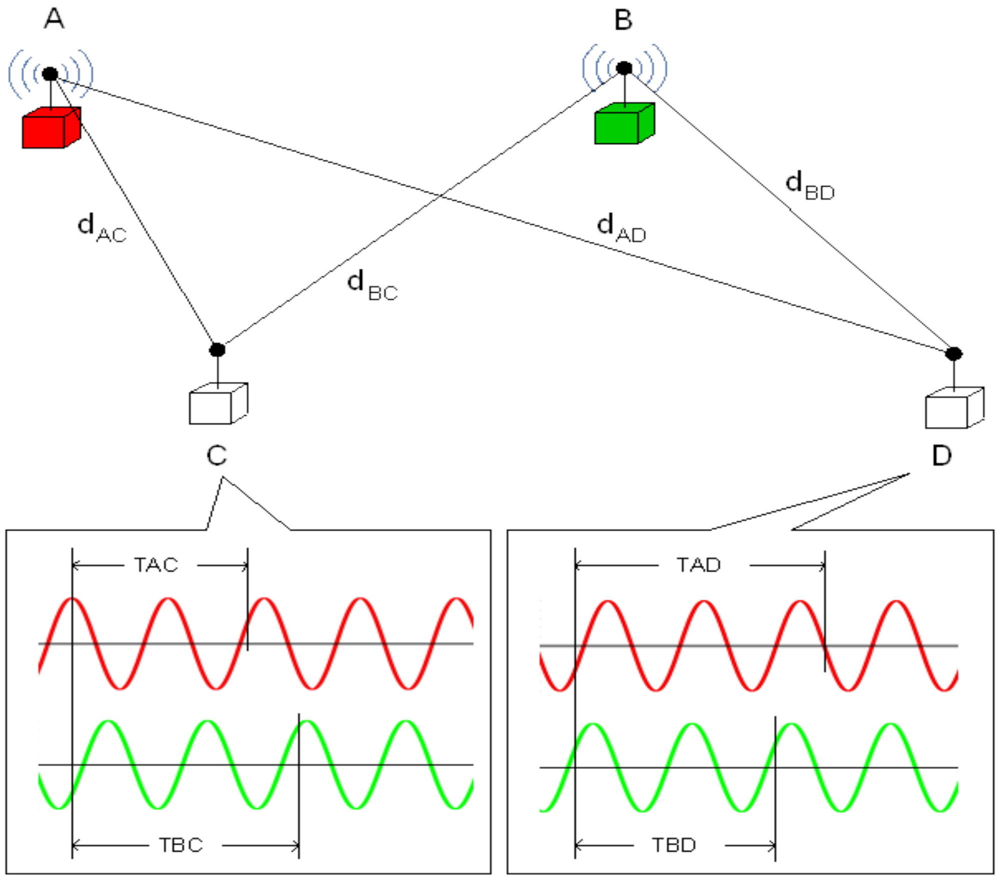
The dTDOA Algorithm



Problem: One way (TOA) and (TDOA) by RF ranging signals requires nanosecond-level clock synchronization to reach meter-level positioning precision

The dTDOA Algorithm

- It takes two Tx and two Rx to get a dTDOA equation
- Tx do not need to be synchronized
- TOAs are measured with local unsynchronized clocks



The dTDOA Algorithm

Transmitted signal from the mth sensor and received at the ith sensor:

$$s_m(t - t_m - t_{mi} - \mathrm{D}t_i)$$

t_m Unknown transmission start time

$t_{mi} = d_{mi}/c$ Unknown propagation delay

$\mathrm{D}t_i$ Unknown clock offset of the ith sensor

$t_i^m = t_m + d_{mi}/c + \mathrm{D}t_i$ Delay at sensor i

The dTDOA Algorithm

Transmitted signal from the *m*th sensor and received at the *i*th sensor:

$$s_m(t - t_m - t_{mi} - \mathrm{D}t_i)$$

t_m Unknown transmission start time

$t_{mi} = d_{mi}/c$ Unknown propagation delay

$\mathrm{D}t_i$ Unknown clock offset of the *i*th sensor

$t_i^m = t_m + d_{mi}/c + \mathrm{D}t_i$ Delay at sensor *i*

The dTDOA Algorithm

- Two Tx and two Rx:

$$t_C^A = t_A + \frac{d_{AC}}{c} + \mathrm{D}t_C \qquad t_D^A = t_A + \frac{d_{AD}}{c} + \mathrm{D}t_D$$

$$t_C^B = t_B + \frac{d_{BC}}{c} + \mathrm{D}t_C \qquad t_D^B = t_B + \frac{d_{BD}}{c} + \mathrm{D}t_D$$

- Form the dTDOA (double difference):

$$t_{CD}^{AB} = t_{CD}^A - t_{CD}^B = (t_C^A - t_D^A) - (t_C^B - t_D^B)$$

$$= (d_{AC} - d_{AD} - d_{BC} + d_{BD})/c$$

- These equations are in terms of sensor locations

The dTDOA Algorithm

$$t_{CD}^{AB} = t_{CD}^{A} - t_{CD}^{B} = (t_{C}^{A} - t_{D}^{A}) - (t_{C}^{B} - t_{D}^{B})$$

$$= (d_{AC} - d_{AD} - d_{BC} + d_{BD})/c$$

- With *N* sensors, *N*(*N*-3)/2 independent equations
- In 2-D, 5 sensors → 5 independent equations

  6 sensors → 9 independent equations

  7 sensors → 14 independent equations
- Can only find relative locations
- Some sensors need to be “anchored”

Multipath Mitigation

- Multipath is a serious problem indoors
- Walls will attenuate LOS path amplitude
- Location computation depends on LOS paths
- There are many algorithms to mitigate problem of attenuated LOS path amplitude
- If LOS path amplitude is too weak, will not work
- Will start this work in July/August 2018

dTDOA Simulation

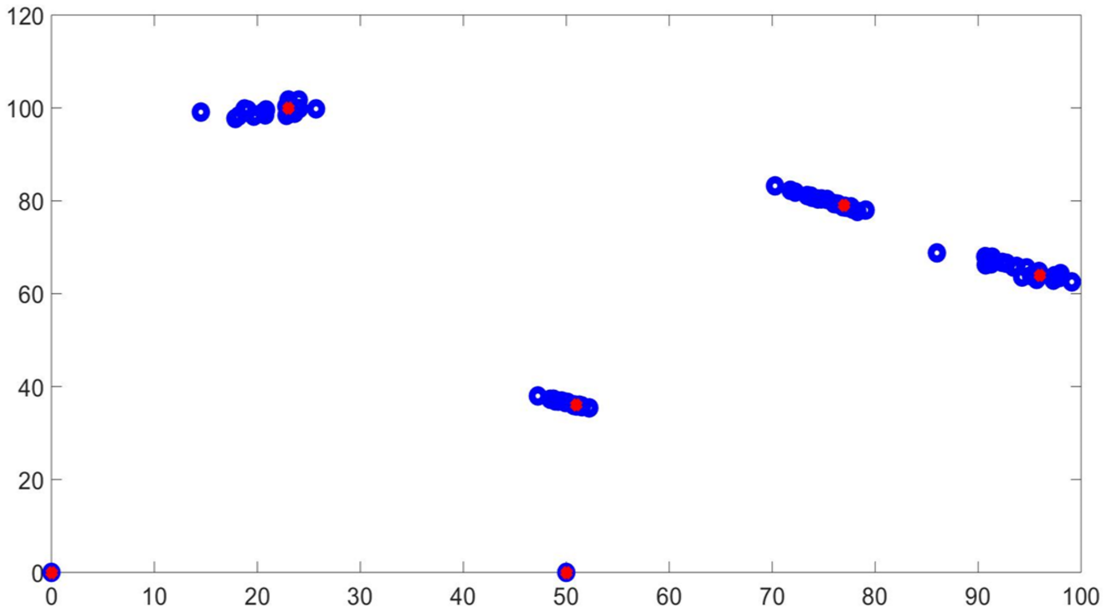
- Simulated 6 nodes in a 100mx100m 2D space
- Two nodes are fixed, with known locations
- Four nodes are at unknown locations
- Simulated noisy TOA measurements to come up with 9 independent dTDOA equations

$$t_{CD}^{AB} = (d_{AC} - d_{AD} - d_{BC} + d_{BD})/c$$

- Solved 8 unknowns using iterative Levenberg-Marquardt algorithm

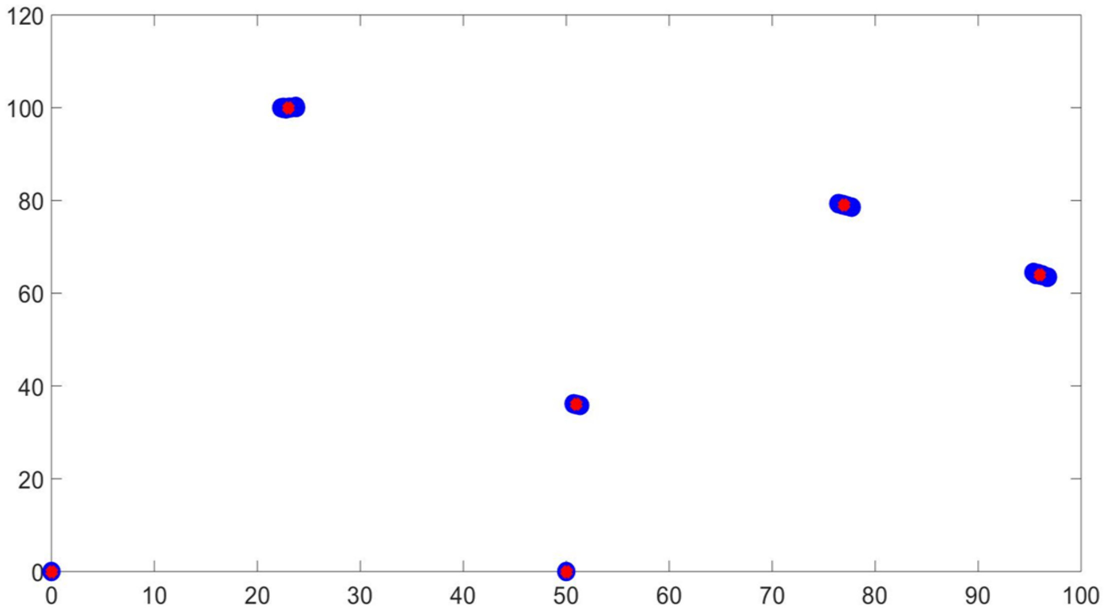
dTDOA Simulation

10 dB SNR



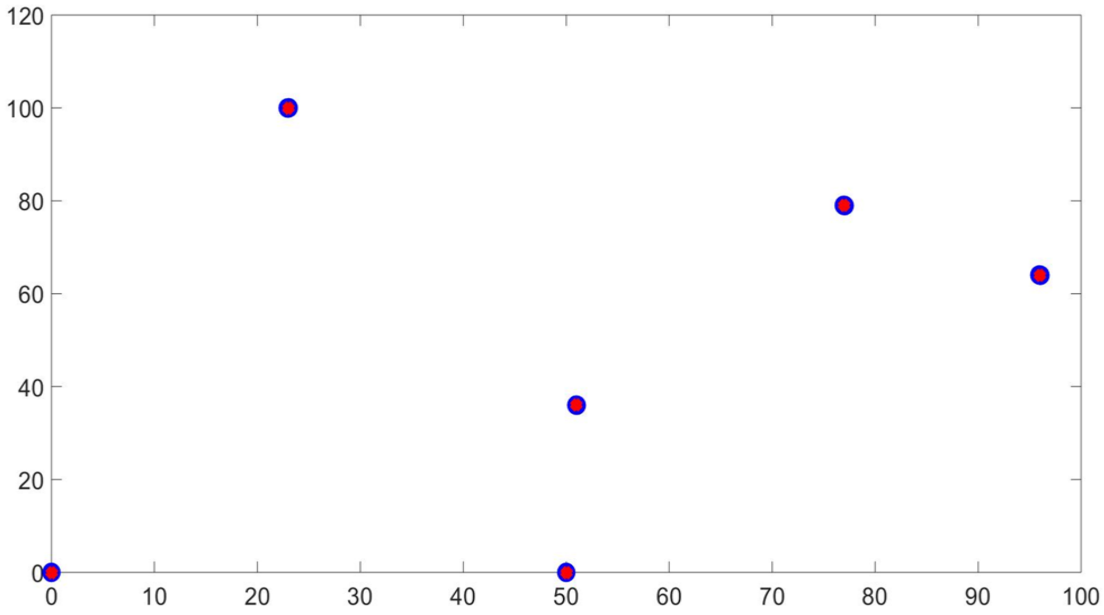
dTDOA Simulation

20 dB SNR



dTDOA Simulation

30 dB SNR



BIM-related Research Work

Objectives:

• Investigate extraction of BIM (Building Information Modeling) data including building **geometric** and **semantic** information, and incorporate into the proposed location service.

• Develop a BIM– based **interactive 3D indoor model viewing method** for first responder use.

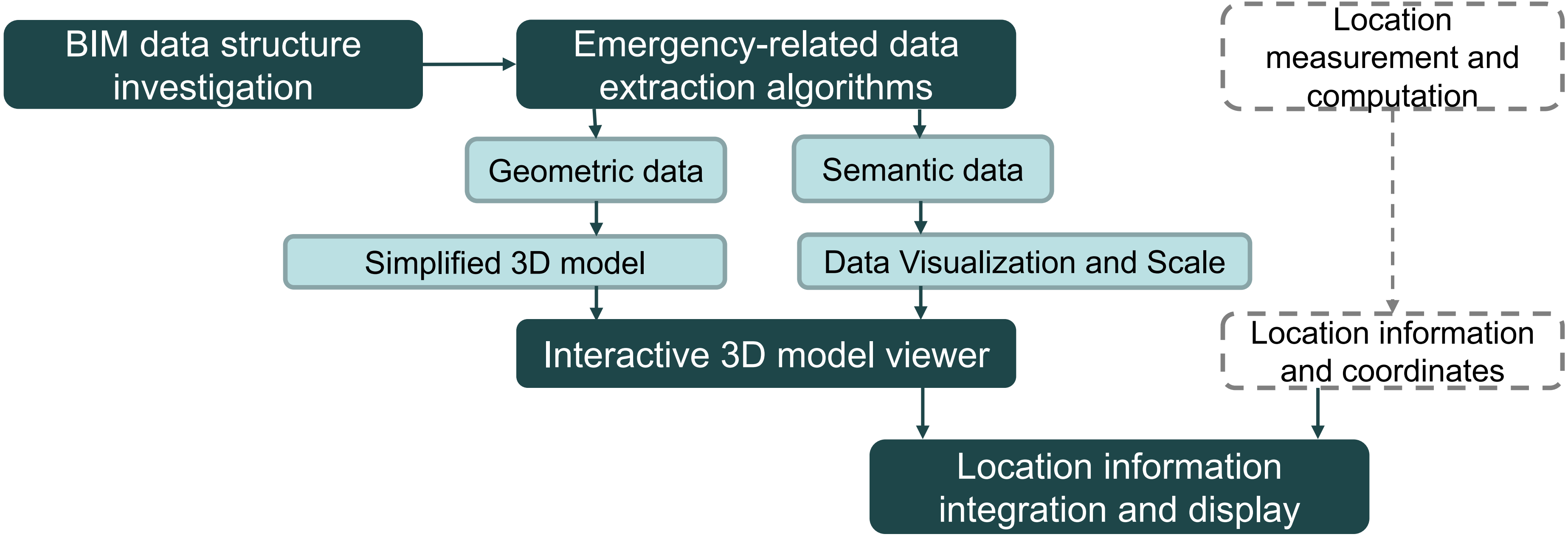
BIM-related Research Work

Context:

- **38%** architecture, engineering and construction users use BIM now, and it is expected to increase to **54%** in the next 3-5 years.

- **The unique feature of a BIM-compliant database** is that it contains **geometric** and **semantic information** of all building elements and fixtures, which would provide **3D mapping and visualization** and for **indoor emergency decision support**.

Approaches and Workflow

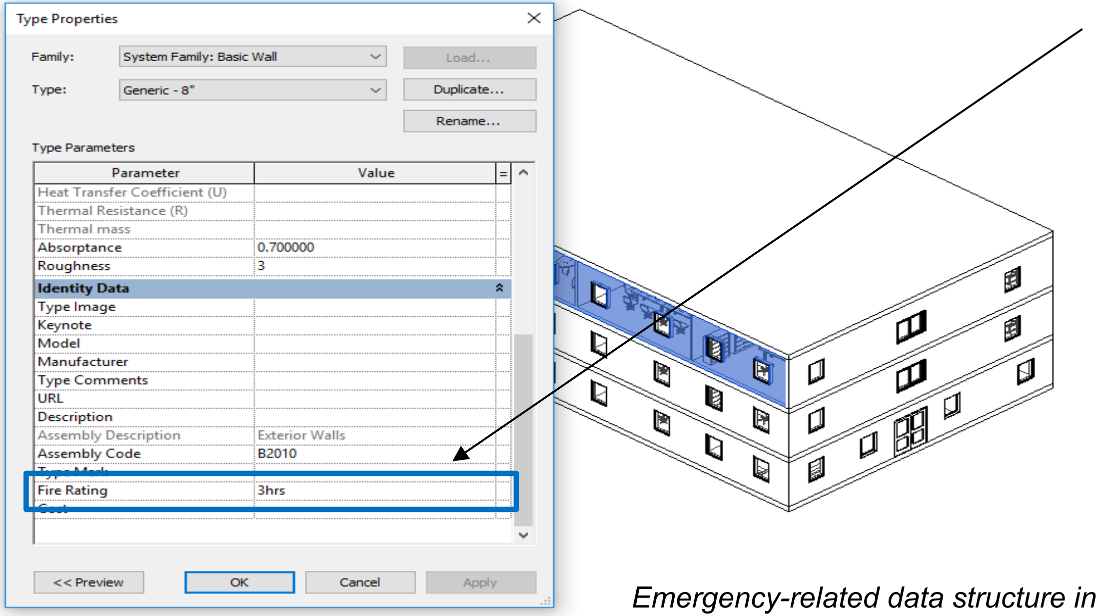


BIM Data Structure Investigation

- Took the International Fire Code, National Fire Protection Association Fire Code, and International Building Code
- Distilled a clear sense of how building egress-related elements and information are set and defined.

Element	Key Use	Building / Fire Code	BIM Structure
Smoke Barrier	Automatic activation during smoke to prevent smoke from spreading to other parts.	NFPA 105	Family type
Fire walls, Barriers, Partitions	Prevent fire spreading	NFPA 80	Instance of wall family type
Fire Doors	Fire evacuation. Kept closed other times.	SDI	Instance of door family type
Fire Alarms	To indicate the breakout of fire	NFPA 72	Family type
Automatic Sprinkler System	For suppressing fire.	NFPA 13	Family type
Portable fire extinguisher	Placed in several places in a building and aid in putting out the fire	NFPA 10	Family type
Smoke and heat vents	Vents prevent the smoke from building up in the building and cause added problems in evacuation.	NFPA 204	Instance of vent family type
Carbon dioxide fire extinguishing system	Uses carbon dioxide for extinguishing purposes	NFPA 12	Instance of plumbing system family
Halon 1301 fire extinguishing system	Halon based fire extinguisher.	NFPA 12A	Instance of plumbing system family
Stand pipe system	Can be combined with automatic sprinkler system or can be used alone for suppressing fire.	NFPA 14	Family type
Deflagration venting	Provided only in the exterior of walls and roofs where place for providing normal vents is not available.	IBC	Instance of vent family type
Egress doors	Evacuation access doorways	IFC section 1010	Instance of door family type
Egress windows	Helps in evacuation		Instance of window family type
Egress Ramps	Helps in evacuation	IFC section 1012, ICC A117.1	Instance of ramp family type
Stairways	Stairways are an important element when it comes to fire evacuation.	IBC	Family
Exit signs Internally and externally illuminated	Helps in effective evacuation and to find out the exit	NFPA 101	Instance
Egress path markings	Helps to guide people to the exit.	IFC sec 1025	Instance
Types of doors	Thickness, width and other details provide a good detail at the time of evacuation	IBC	Family type
Types of windows	Thickness, width and other details provide a good detail at the time of evacuation	IBC	Family type
Room tags, room dimensions	For providing details on types of rooms and information in it.	IBC	Family type

BIM Data Structure Investigation

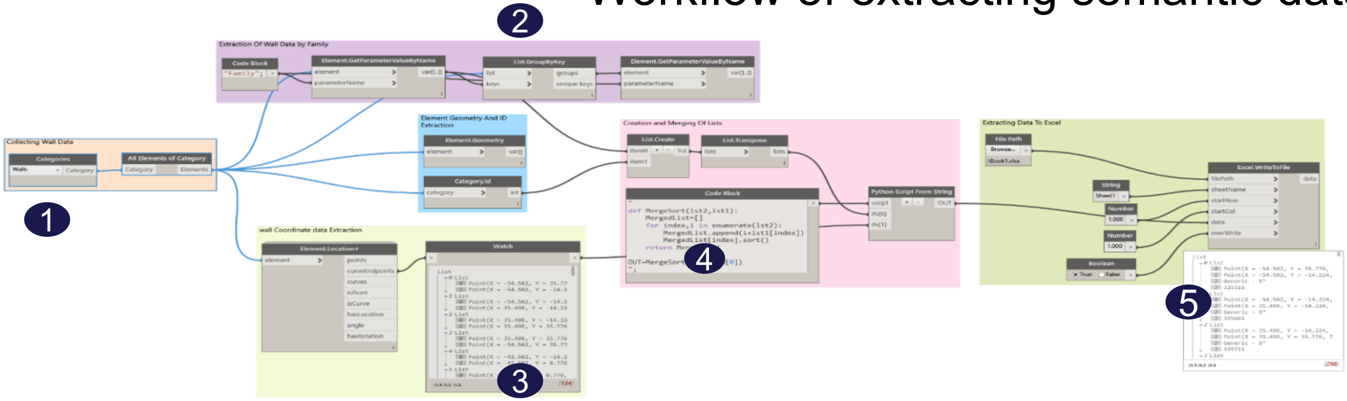


Fire rating hours are structured in wall-type-properties/identity data

Emergency-related data structure in BIM-compliance dataset

Emergency-Related Data Extraction

Workflow of extracting semantic data



Example of building wall extraction

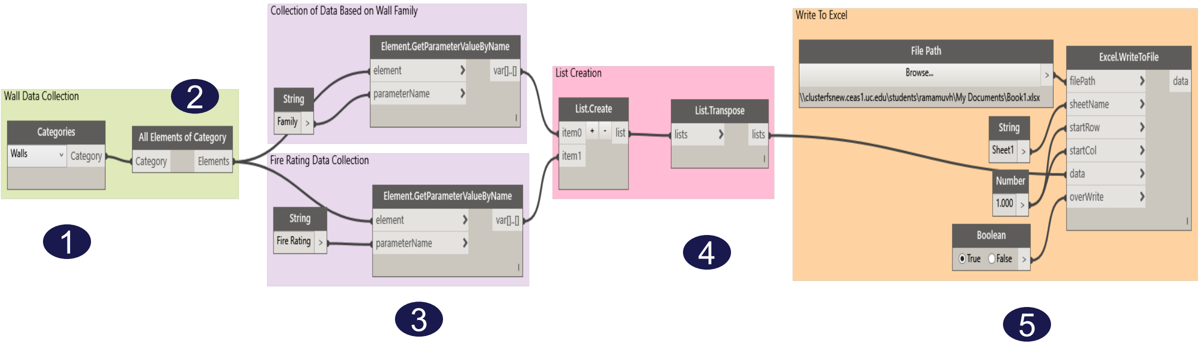
D	E
Wall Type:	Element ID:
Generic - 8"	325516
Generic - 8"	325661
Generic - 8"	325715
Generic - 8"	325767
Interior - 5 1/2" Partition (1-hr)	326034
Interior - 5 1/2" Partition (1-hr)	326066
Interior - 5 1/2" Partition (1-hr)	326306
Interior - 5 1/2" Partition (1-hr)	326663
Interior - 5 1/2" Partition (1-hr)	326783

Extracted building wall list

1. The **Categories** node is used to select the Wall (element) whose data has to be extracted.
2. **All Elements Of Category** node selects all the elements of the selected categories that are present in the current Revit file.
3. **Element Get parameter value by name** uses a string input (wall type and element ID) and extracts all data correspond to the selected element.
4. A list of all the elements' data is created using the **List Create** node.
5. **File Path** node is used for the data file type selection and output.

Emergency-Related Data Extraction

Workflow of extracting semantic data



Example of building wall's fire rating extraction

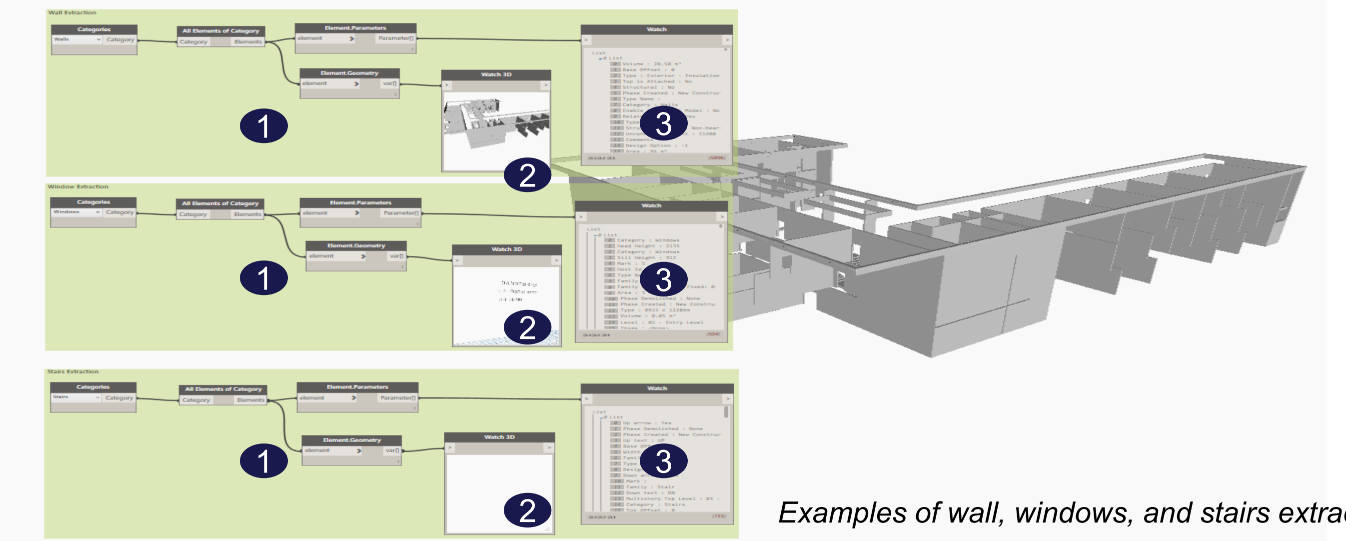
B	C
Wall Type:	Fire Rating
Generic - 8"	2HR
Generic - 8"	2HR
Generic - 8"	2HR
Generic - 8"	2HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR
Interior - 5 1/2" Partition (1-hr)	1HR

Extracted fire rating hour list

1. The **Categories** node is used to select the Wall (element) whose data has to be extracted.
2. **All Elements Of Category** node selects all the elements of the selected categories that are present in the current Revit file.
3. **Element Get parameter value by name** uses a string input (Fire Rating) and extracts all data corresponding to the selected element.
4. A list of all the elements' data is created using the **List Create** node.
5. **File Path** node is used for the data file type selection and output.

Emergency-Related Data Extraction

Workflow of extracting geometric data

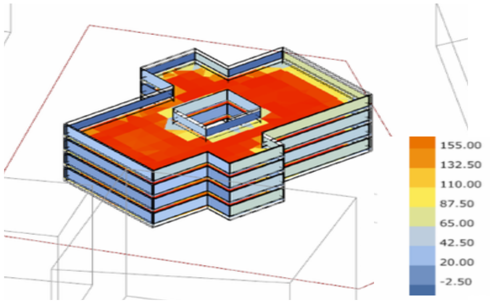


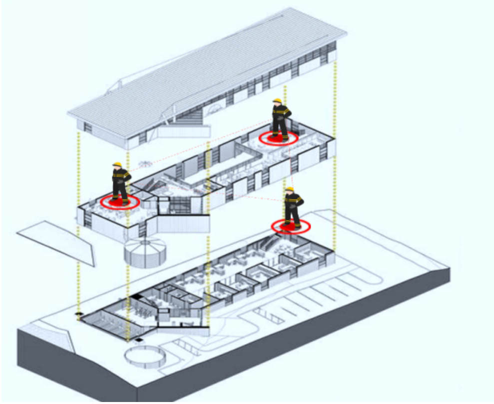
Examples of wall, windows, and stairs extraction

1. Geometry Walls, Windows and Stairs can be extracted by selecting the elements using the **Categories**, **All Elements of Category** and then running it after connecting it to the **Element Geometry** node.
2. Generate **Simplified Selected 3D Model**.
3. **Element Parameter** gives details such as volume, height, type of the selected elements.

Remaining Work and Methods

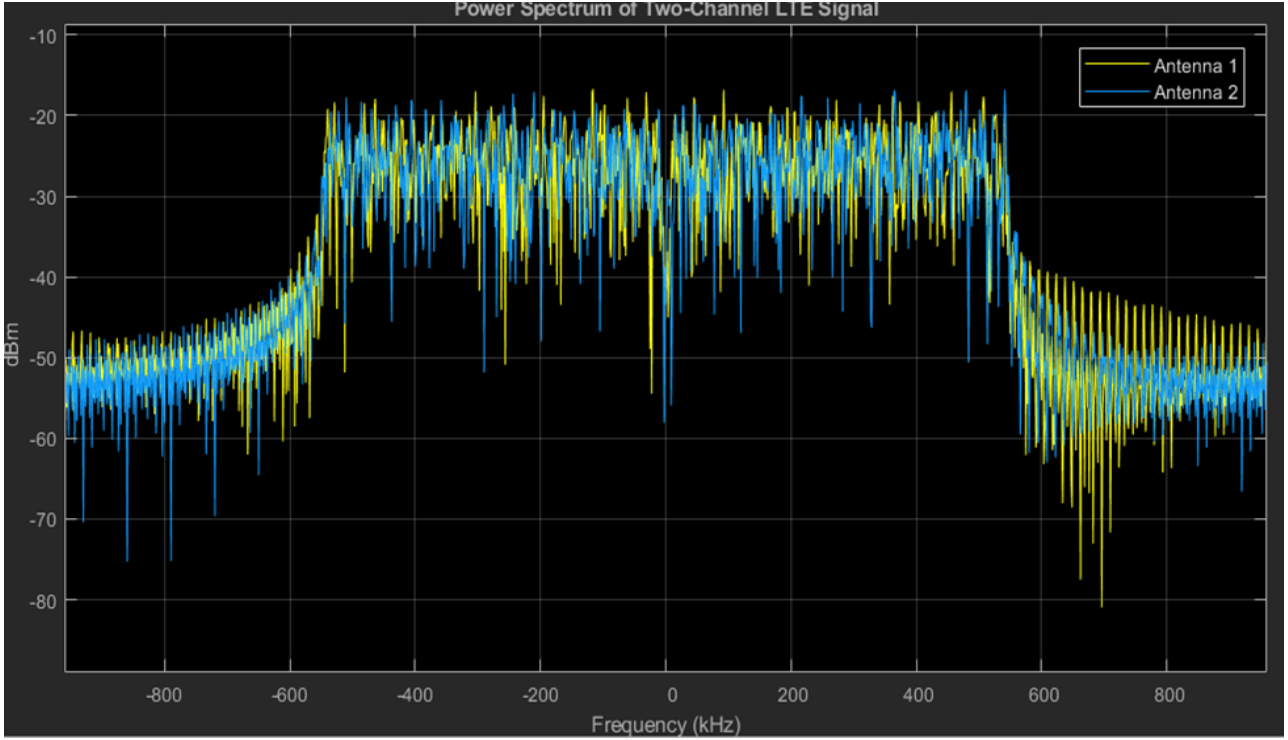
- Integrate semantic and geometric data into an interactive 3D model.
  - Using the pseudo coloring method to reveal the key emergency-related semantic information, e.g., highlight fire doors and operable windows; apply different false colors on wall's fire rating hours.
- Overlay real-time location on 3D model viewer.
  - Setting up shared global coordinating system
  - Using existing cloud platforms (e.g., Autodesk Forge) to perform data integration and presentation.



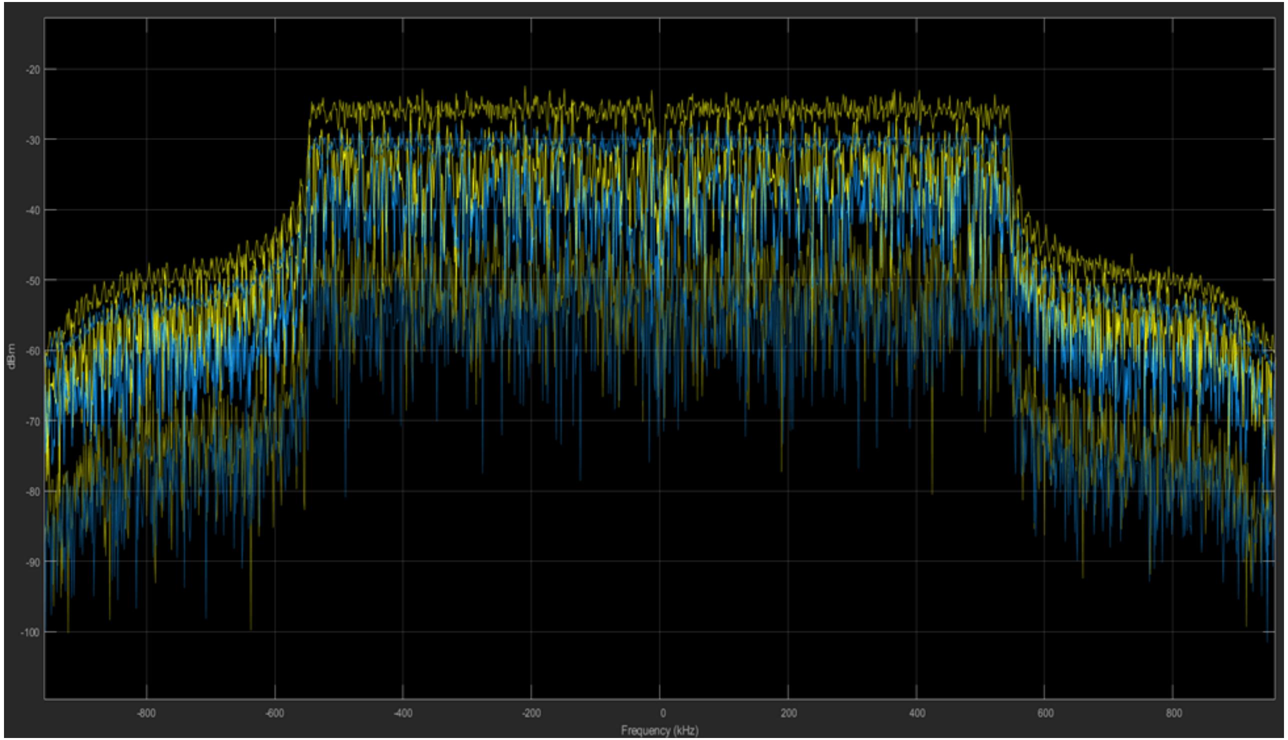


USRP Implementation

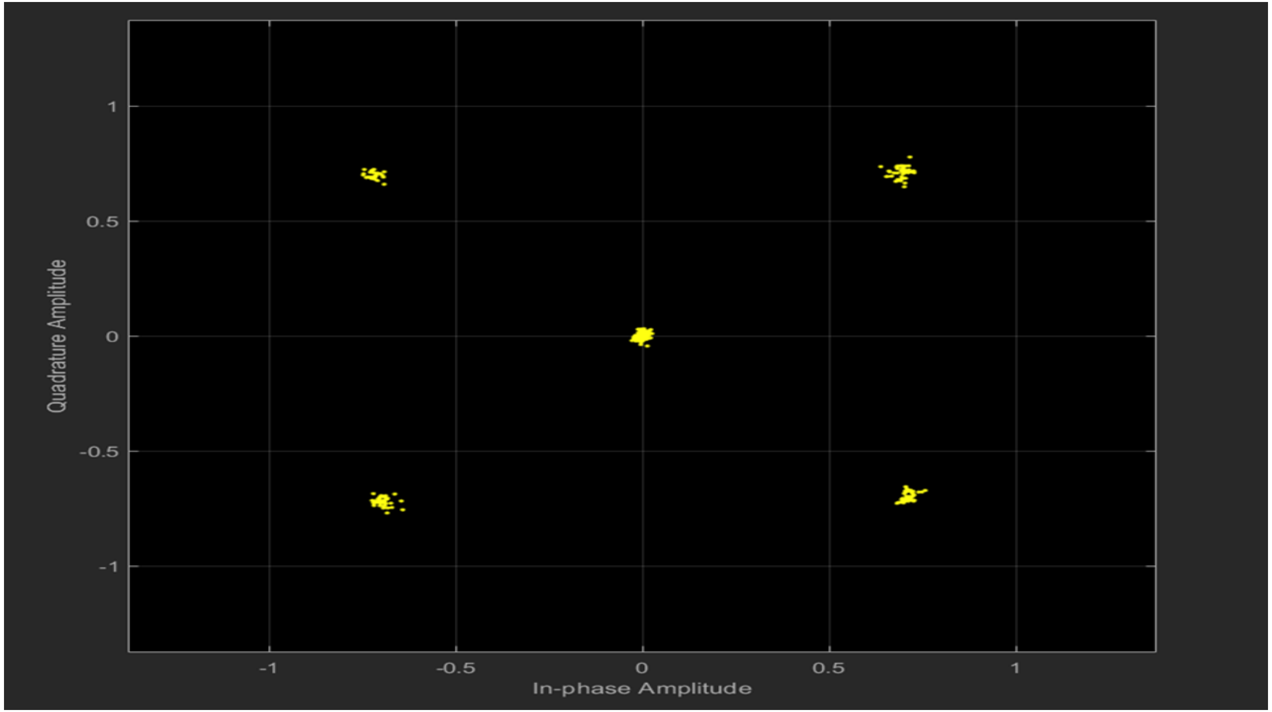
USRP Implementation



USRP Implementation



USRP Implementation



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Pervasive, Accurate and Reliable Location Based Services for Emergency Responders

Niki Trigoni, Andrew Markham (PIs)

Pedro Porto Buarque de Gusmão, Johan Wahlstrom (PDRAs)

Wei Wang, Yasin Almalioglou (PhD students)

Jamie Cousins (Hampshire Fire and Rescue Service)

Russell Smith (D.C. Fire & EMS Department)

Objective:

- To locate emergency responders in GPS denied environments

Emphasis:

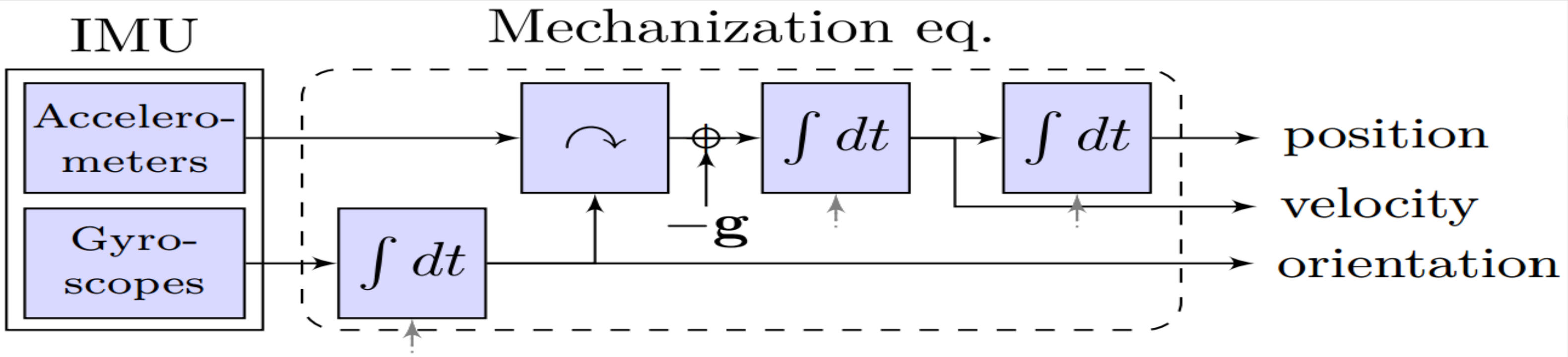
- Unique motion features and search patterns
- Unknown challenging environments

Three distinct approaches:

- Inertial
- Visual
- Magneto-inductive

1. Inertial Tracking

Inertial navigation

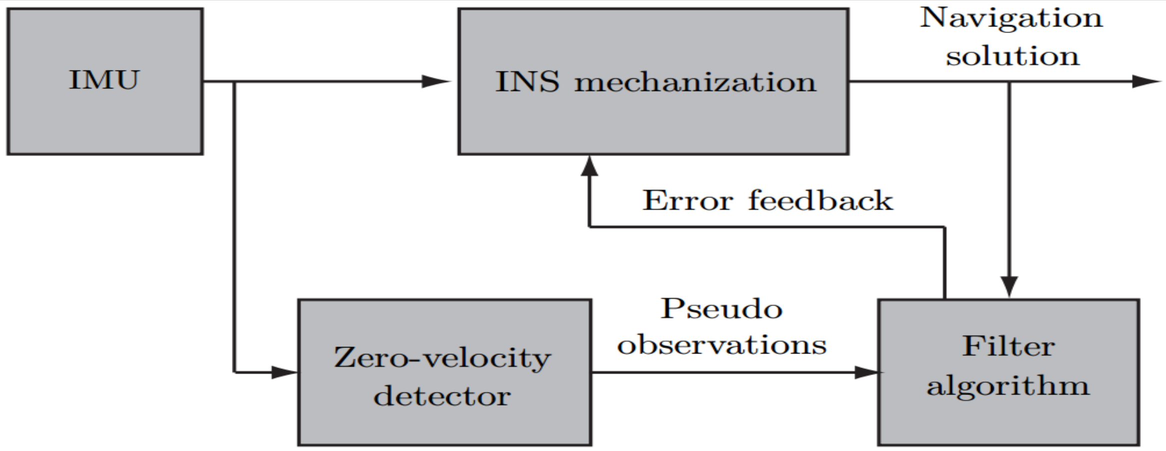


- Iterative algorithm → Requires initialization
- Cubic error growth; can be mitigated using motion model and maps

Foot-mounted inertial navigation

- Motion model: the foot is stationary at regular intervals

Zero-velocity updates



- Set zero velocity when the sensors indicate that the foot is stationary
- Breaks cubic error growth → Increases performance

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Firefighter motions

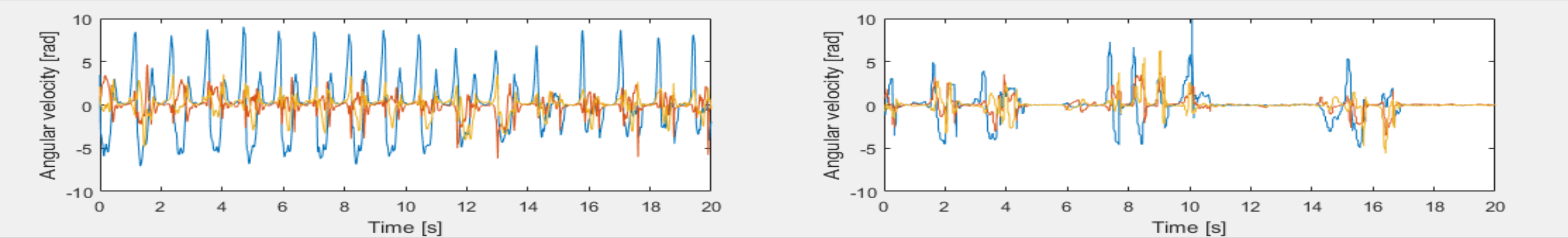
- The motion characteristics of firefighters are very different from those of civilians
- What is the impact on inertial tracking?

Inertial navigation for firefighters

Gyroscope measurements

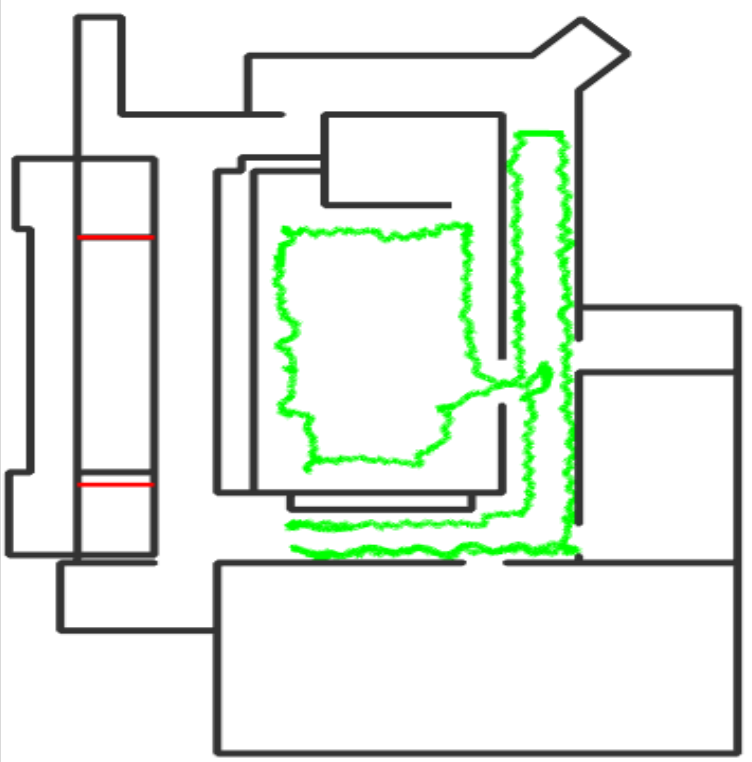
Normal walking

Firefighter search



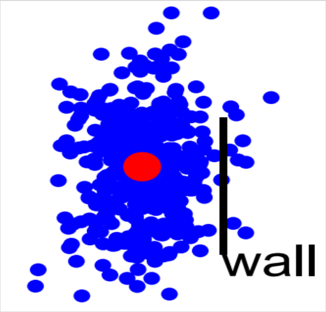
- Although the motions of firefighters are rather irregular, it was not necessary to change the algorithm for zero-velocity aided inertial navigation

Map information

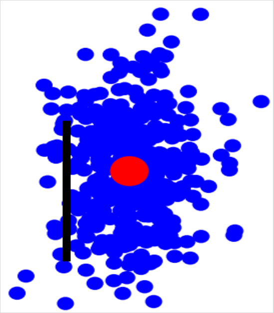


- Improve performance by constraining the motion of pedestrians

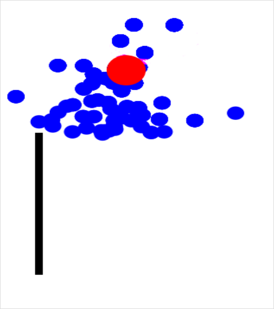
Particle-based implementations



Particle distribution



After propagating particles using inertial measurements

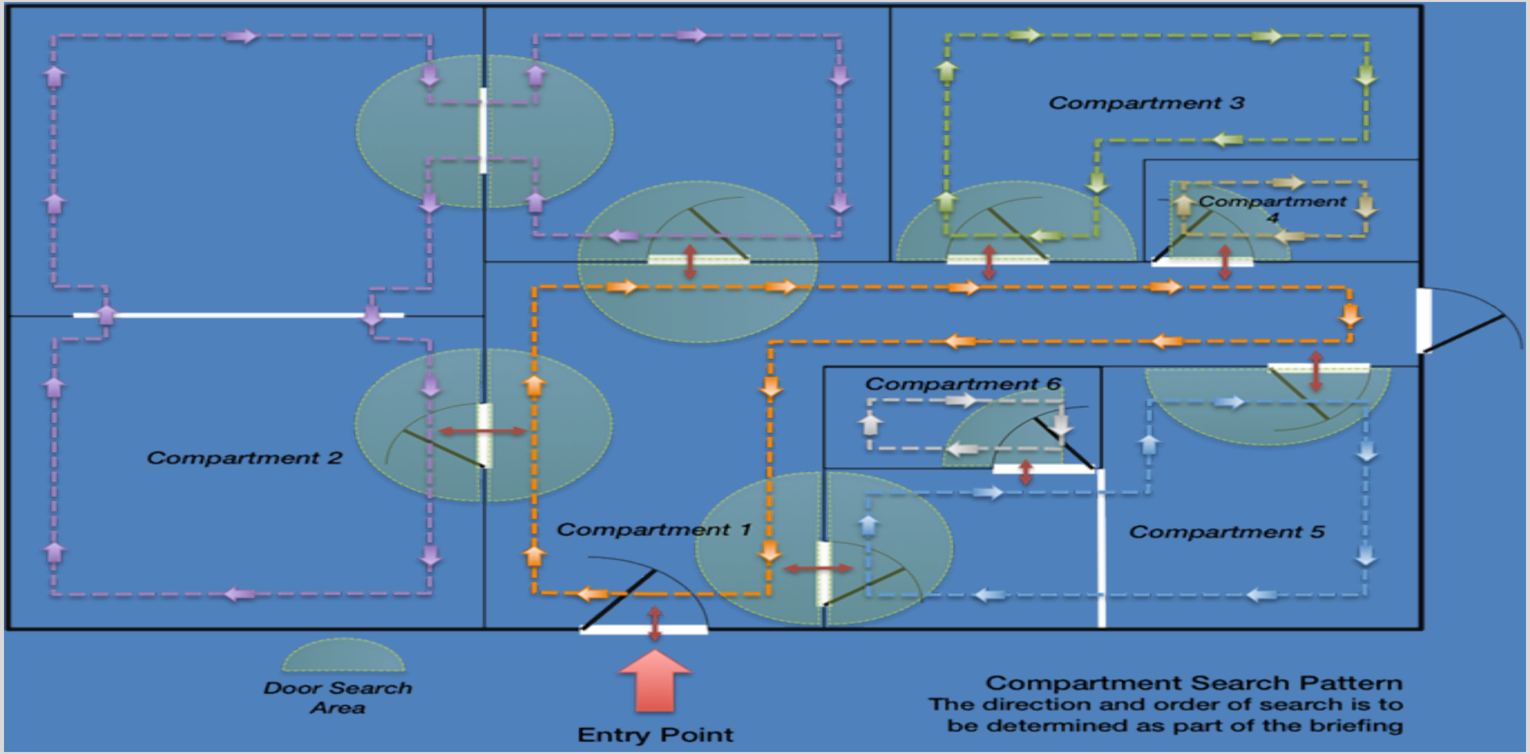


After eliminating particles that crossed the wall

- Likely navigation states can be represented using a set of samples, so-called particles
- Whenever a particle collides with a wall, it is eliminated

Remaining problems with map-aided inertial navigation

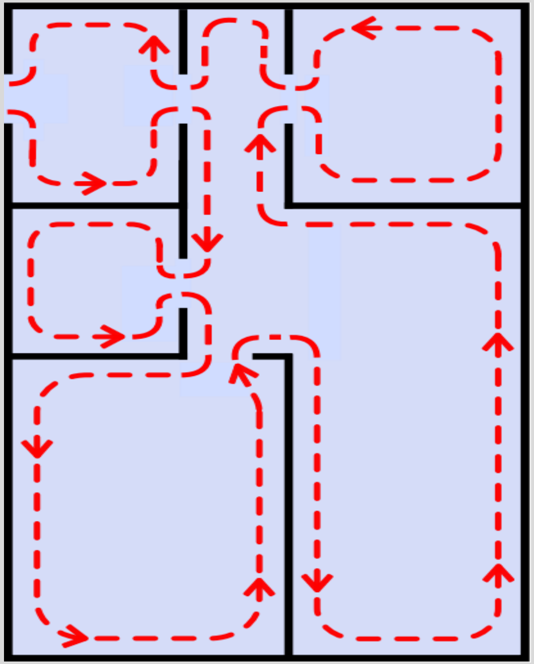
- The initial navigation state is unknown
- The filter may diverge; it is generally difficult to recover from this without access to position measurements



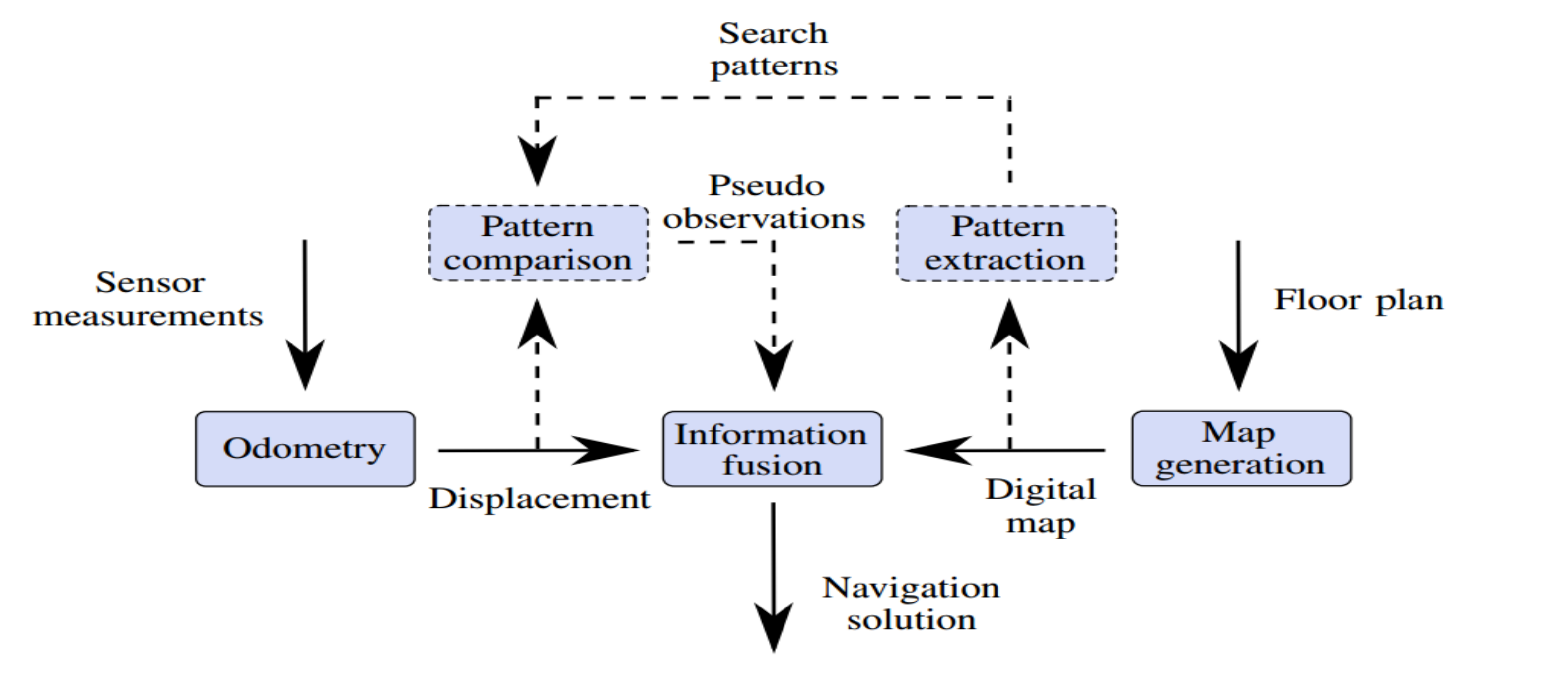
Courtesy of Jamie Cousins,
SM Research and Development

Left- and right-hand searches

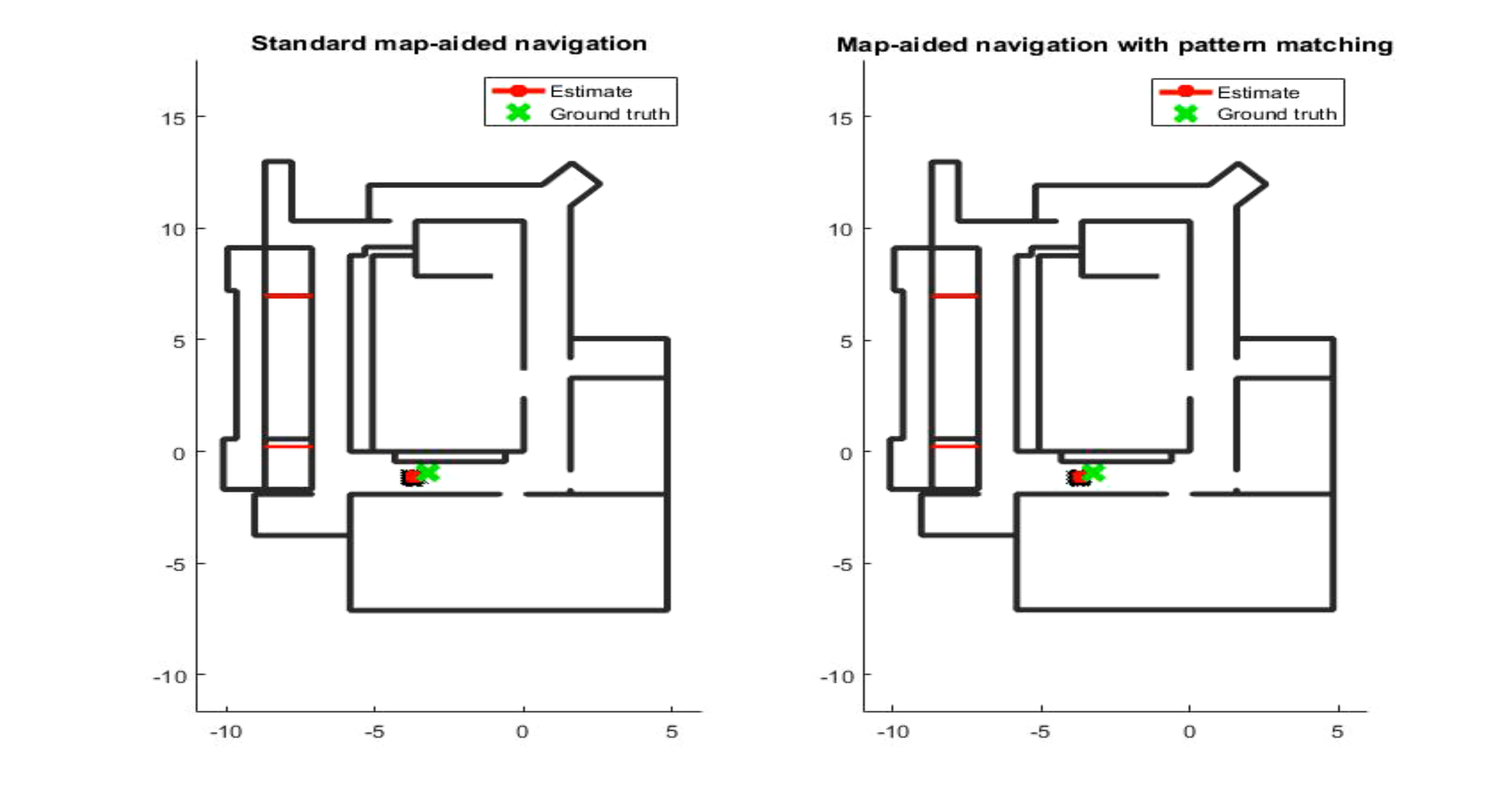
- Firefighters will often follow a left- or right-hand search pattern
- We propose to encapsulate this behavior in a motion model that can be incorporated into the navigation filter



Tracking with pattern matching



Navigation with knowledge of initial navigation state (no map info used)



Navigation with knowledge of initial position and orientation

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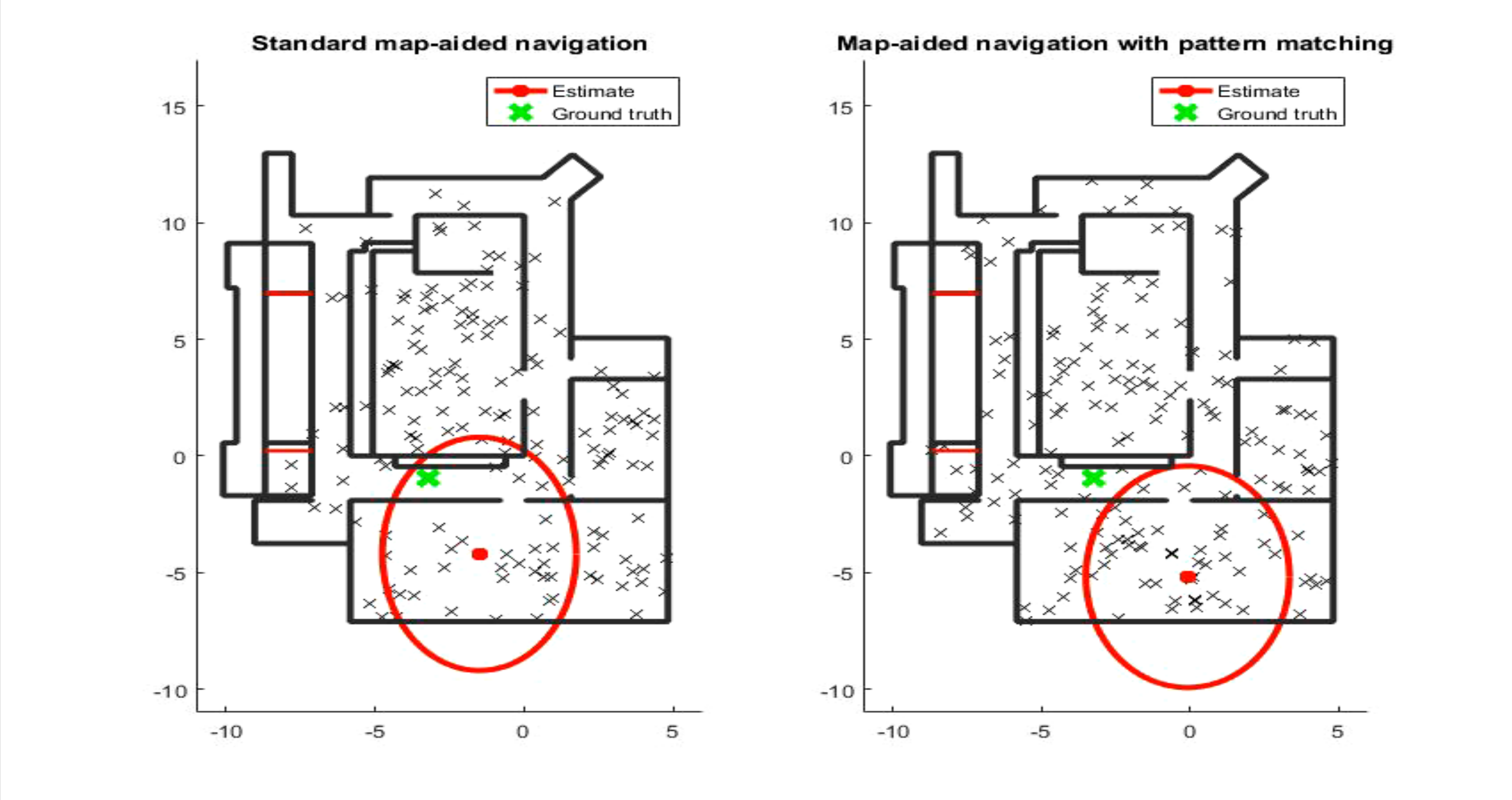

Navigation without knowledge of initial position and orientation

Inertial tracking – lessons learnt

- Zero velocity update with foot mounted sensors remains effective despite the characteristic slow walking style
- Inertial tracking is accurate and not affected by environmental conditions
- Maps are key to mitigating location drift
- Right/left hand search patterns can be leveraged to improve accuracy (esp. when start location is unknown)

2. Visual Tracking

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Visual tracking for firefighters

Real Conditions:

- Presence of dynamic objects.
- Feature-less walls and long corridors.
- Reflection.
- Abrupt motion.
- Abrupt changes in lighting conditions.
- Left-hand and right-hand searches reduce FoV.

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Analyzing the state-of-the-art algorithms under these conditions

- ORB-SLAM
- Semi Direct Visual Odometry (SVO)
- Direct Sparse Odometry (DSO)

ORB SLAM

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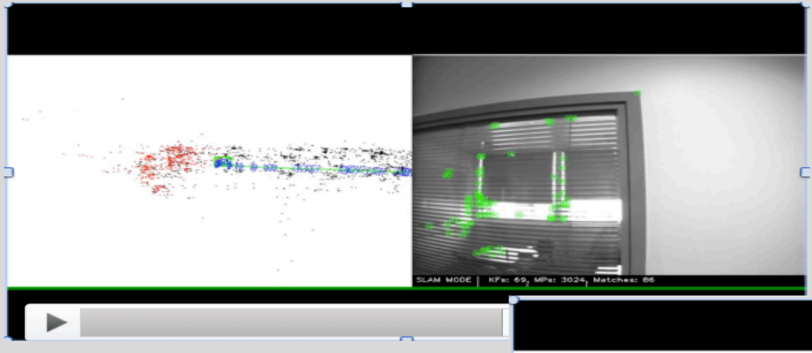
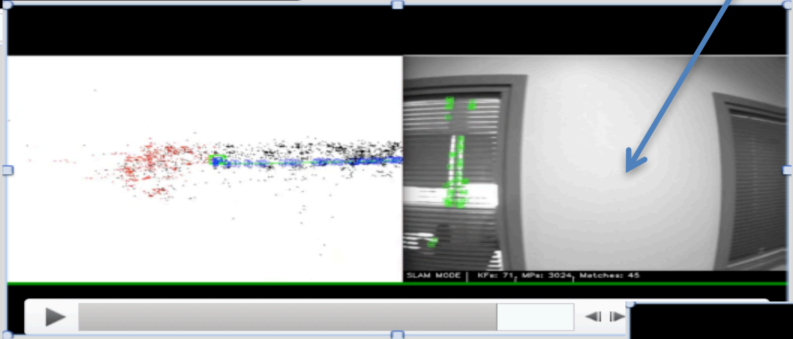
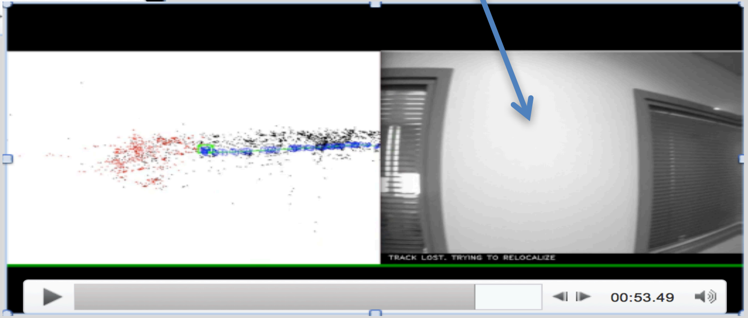


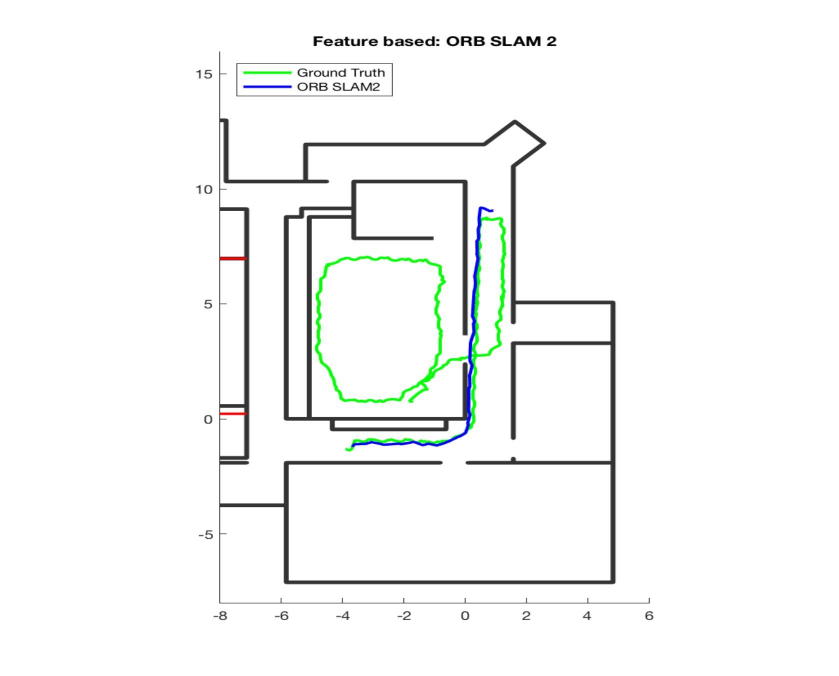




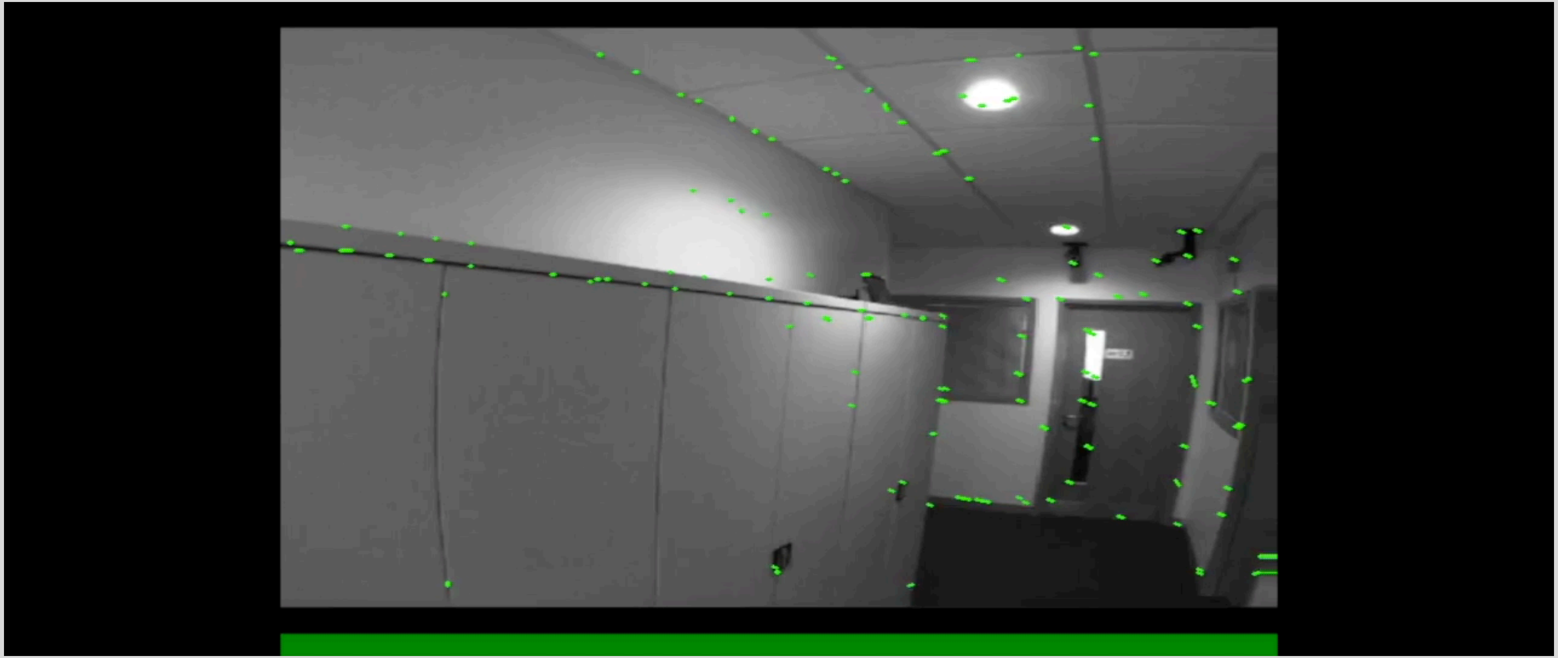
It loses tracking when the camera faces featureless scenes, e.g. white walls

ORB SLAM

- ORB-SLAM failed to track successfully as the fire figher did a U-turn at the end of the corridor
- It covered half of the trajectory and then failed



Semi-Direct Visual Odometry



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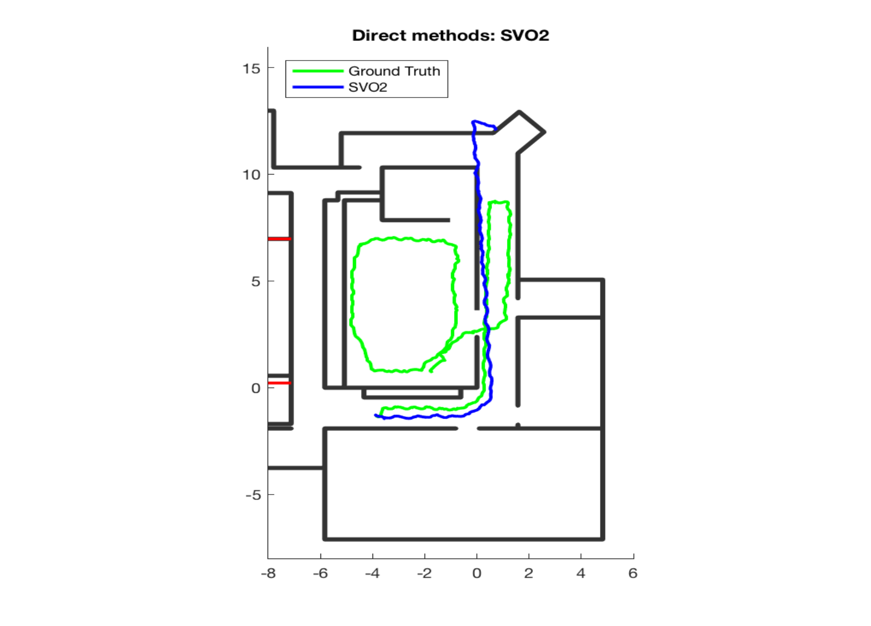
It also loses tracking when the frames include large featureless areas

Semi-Direct Visual Odometry

- Like ORB-SLAM, SVO failed to track successfully as the fire figher did a U-turn at the end of the corridor



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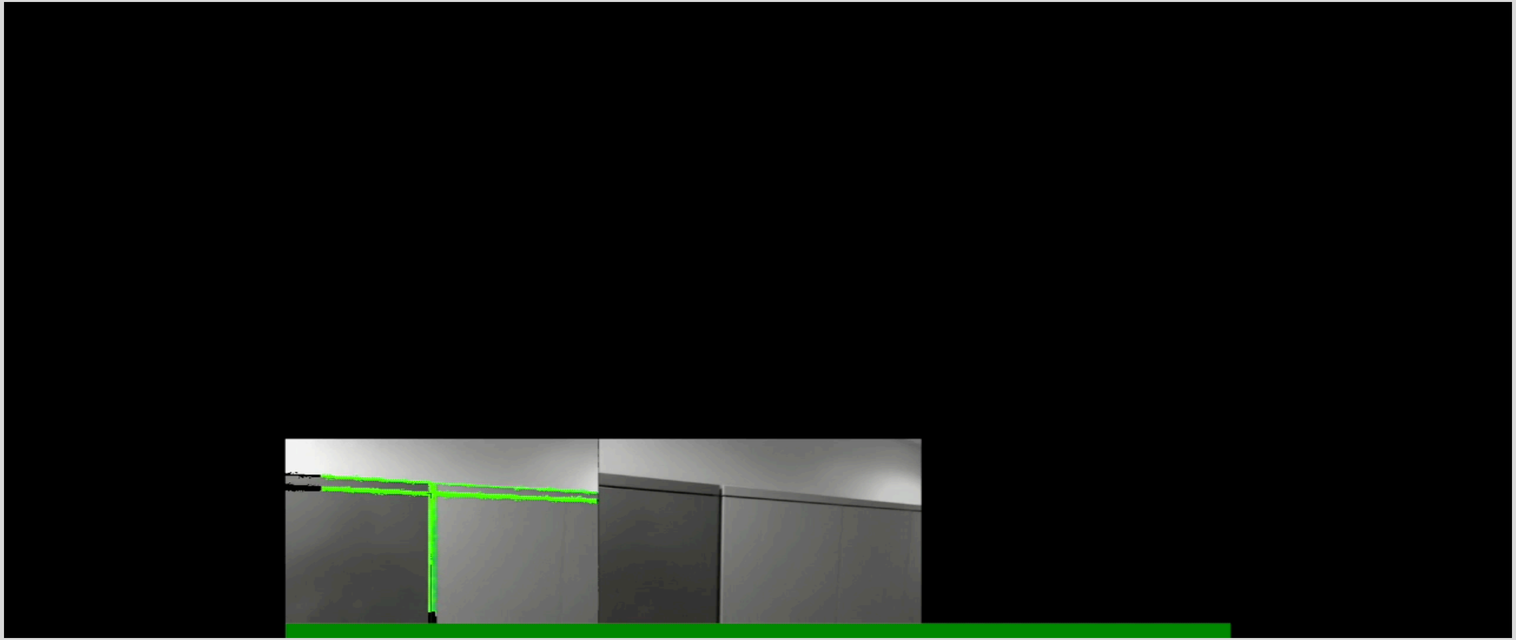
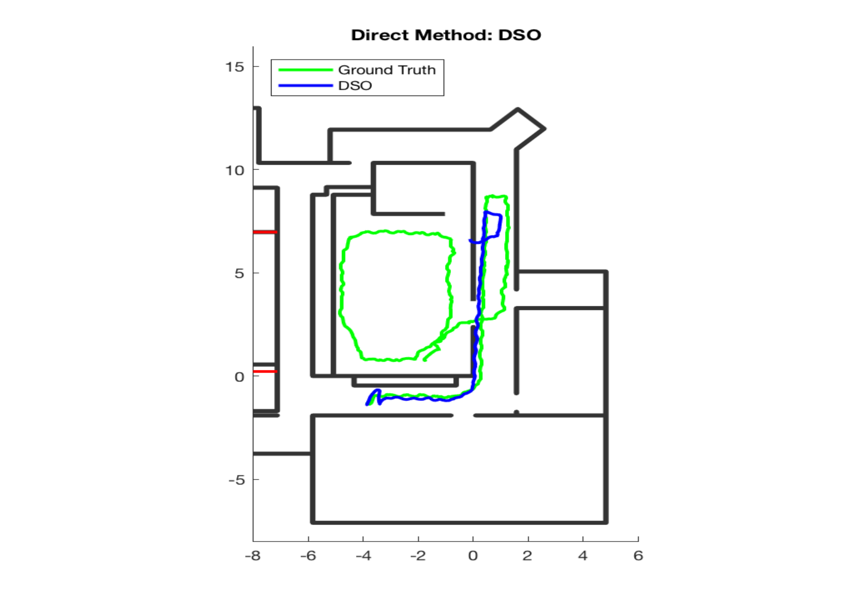
Direct Sparse Odometry

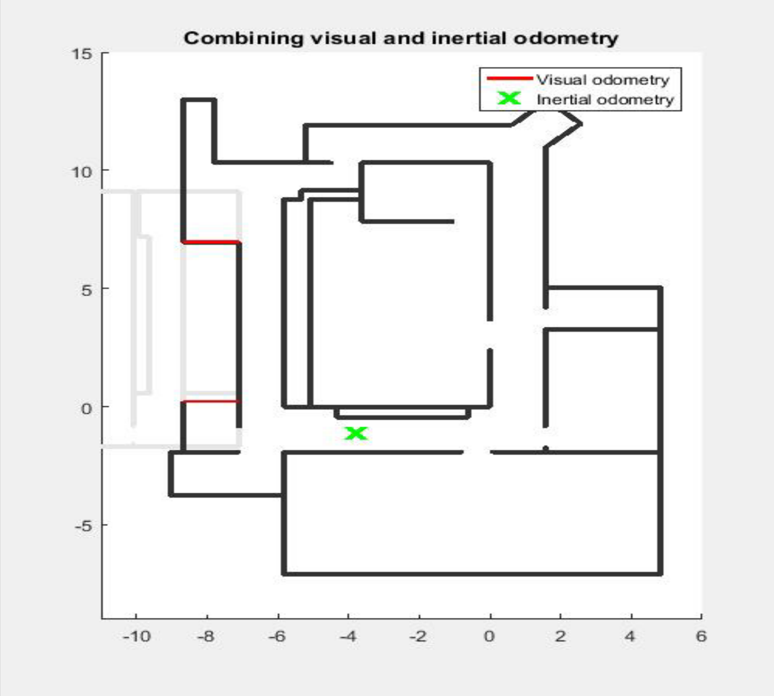


Direct Sparse Odometry

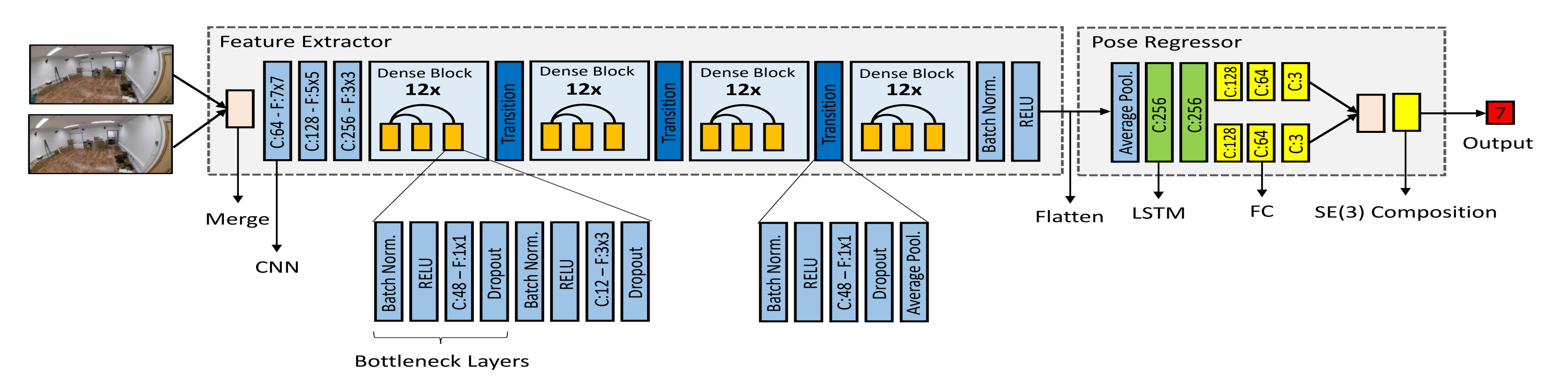
- Direct method with less constraints
- More robust to low gradients.
- Suggests a photometric calibration
- Scale Drift!



Visual + Inertial: Early Trials



Deep Learning Approach



Robust Visual Odometry (RVO)

Promising in terms of robustness to areas with few features; currently collecting data with the help of J. Cousins (Hampshire Fire Service) for training purposes

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Beyond the lab…

More realistic scenarios

Other modalities to be explored

Thermal

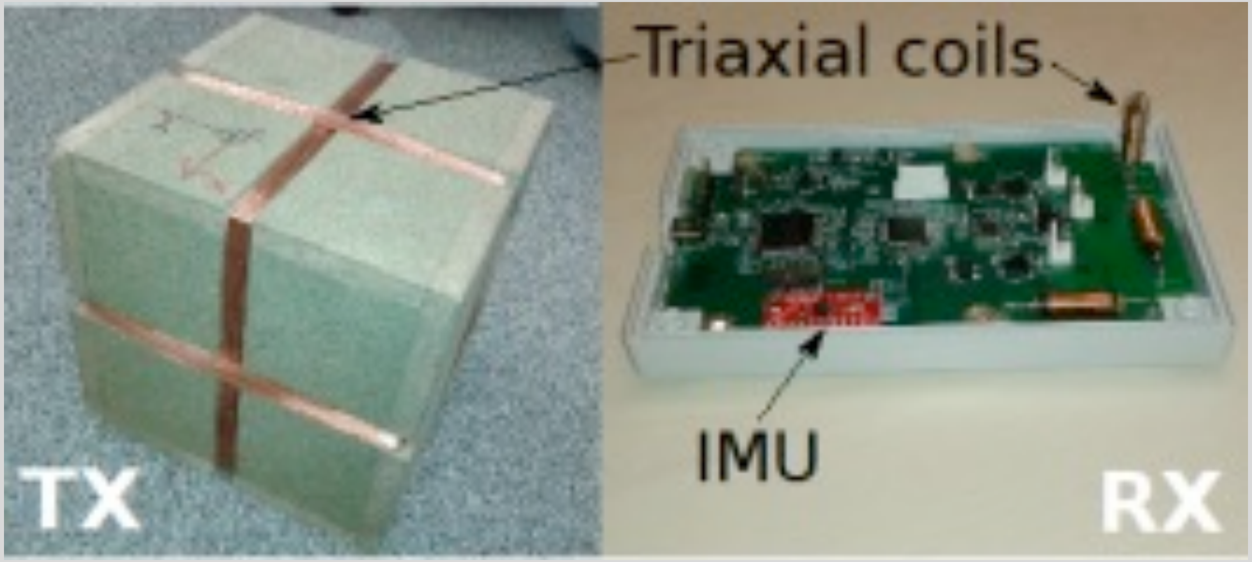
Depth

Visual tracking – lessons learnt

- Existing algorithms are not robust to "feature-less" environments and abrupt camera movements
- Fusing inertial and visual data can mitigate this problem
- Early work on a deep learning approach for visual odometry shows promise in terms of robustness to lack of visual features – still early stage

3. Magneto-Inductive Positioning

MI transmitter and receiver



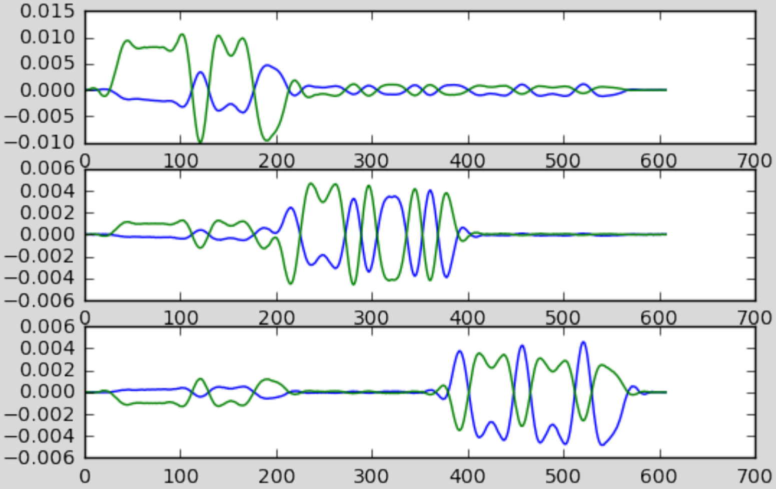
MI Positioning – The Good

- Low frequency modulated magnetic fields provide accurate 3-D positioning
- Unlike RF propagation, MI does not suffer from multipath
- In addition, it penetrates the majority of materials (concrete, soil, people, water, vegetation) without loss
- This leads to highly temporally stable field measurements
- *Single* transmitter provides 3-D positioning
- We can use physics based models to work out position and pose

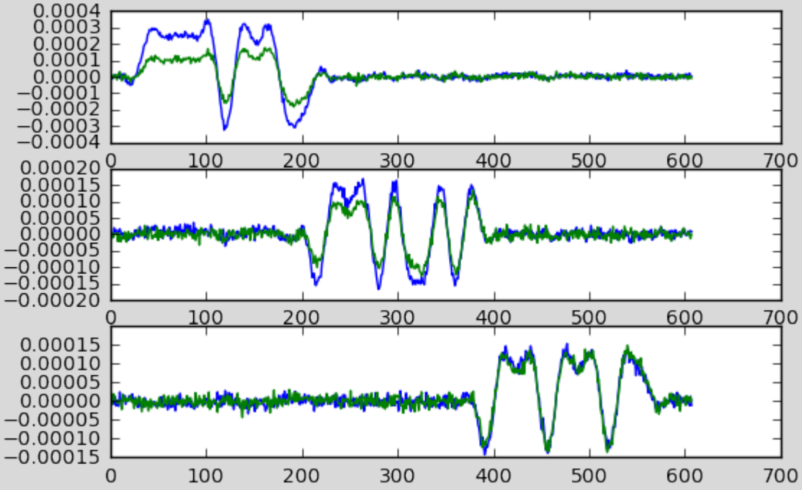
MI Positioning – The Bad

- Due to the near-field coupling, the evanescent fields decay following an inverse cube law
- This means that the signal received rapidly fades into noise with increasing distance

Rx at 3m

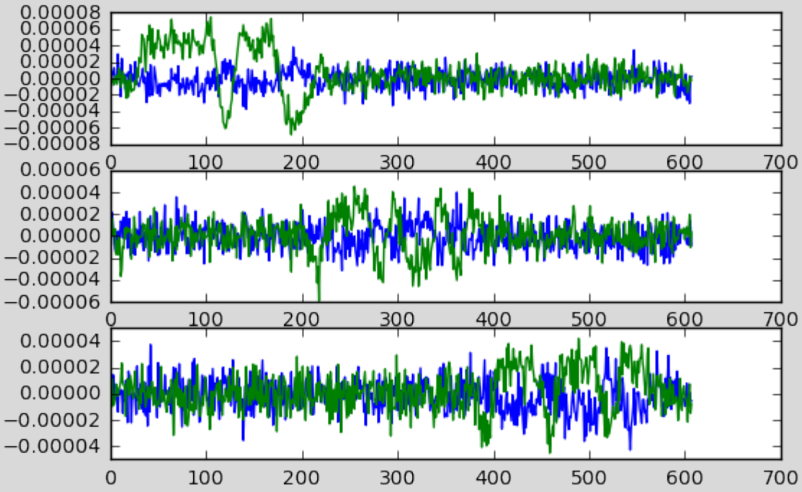

0.015
0.010
0.005
0.000
−0.005
−0.010
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
0
100
200
300
400
500
600
700

Rx at 10m



0.0004
0.0003
0.0002
0.0001
0.0000
−0.0001
−0.0002
−0.0003
−0.0004
0
100
200
300
400
500
600
700
0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
−0.00010
−0.00015
−0.00020
0
100
200
300
400
500
600
700
0.00015
0.00010
0.00005
0.00000
−0.00005
−0.00010
−0.00015
0
100
200
300
400
500
600
700

Rx at 20m



0.00008
0.00006
0.00004
0.00002
0.00000
−0.00002
−0.00004
−0.00006
−0.00008
0
100
200
300
400
500
600
700

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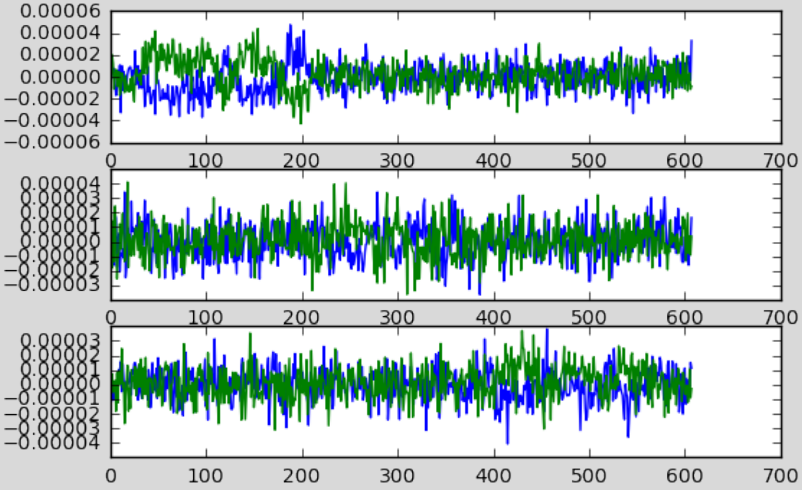
Rx at 30m

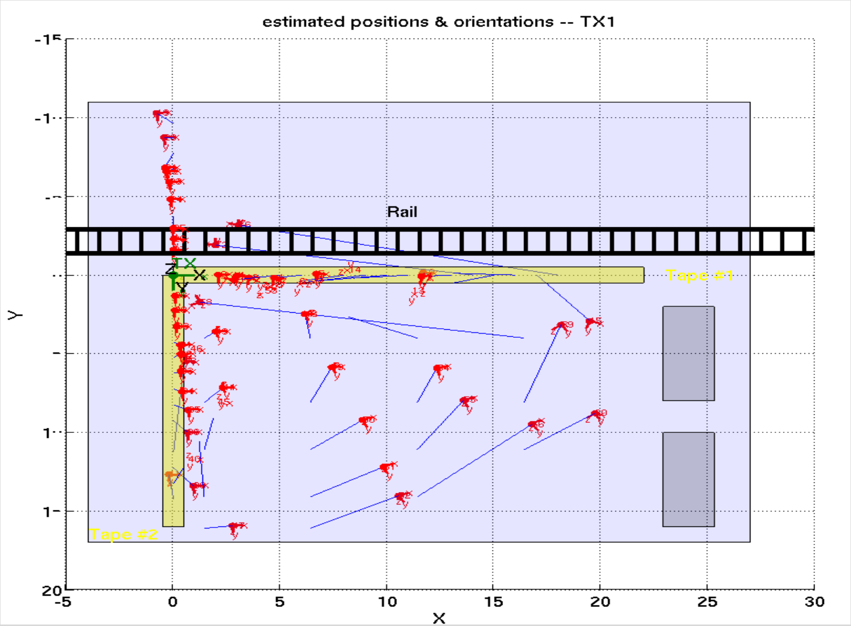


MI Positioning – The Ugly

- In ferrous metal free environments, signals perfectly obey physics model
- Along rail-ways or indoors, metal “bends” the field lines, distorting the derived locations
- We have come up with some techniques to reject these distortions, but the accuracy that they provide is not sufficient for this application

Distortion rejecting magneto-inductive three-dimensional localization (MagLoc), JSAC 2015

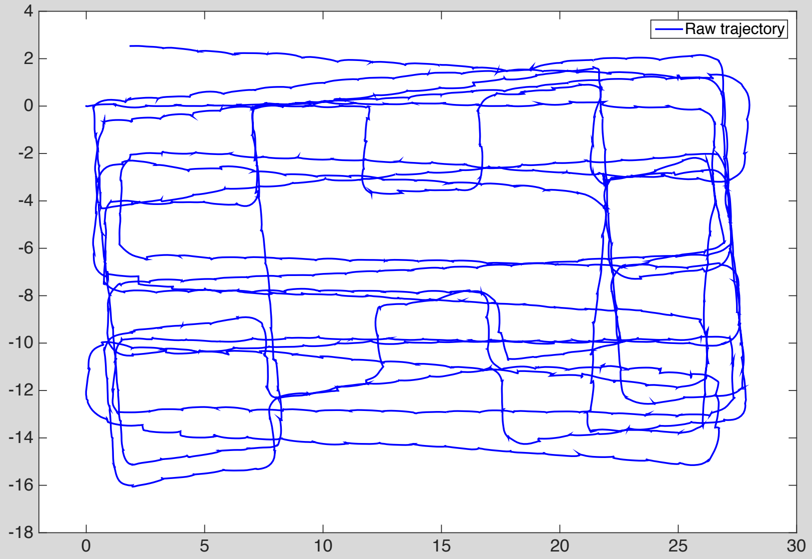
Example distortions



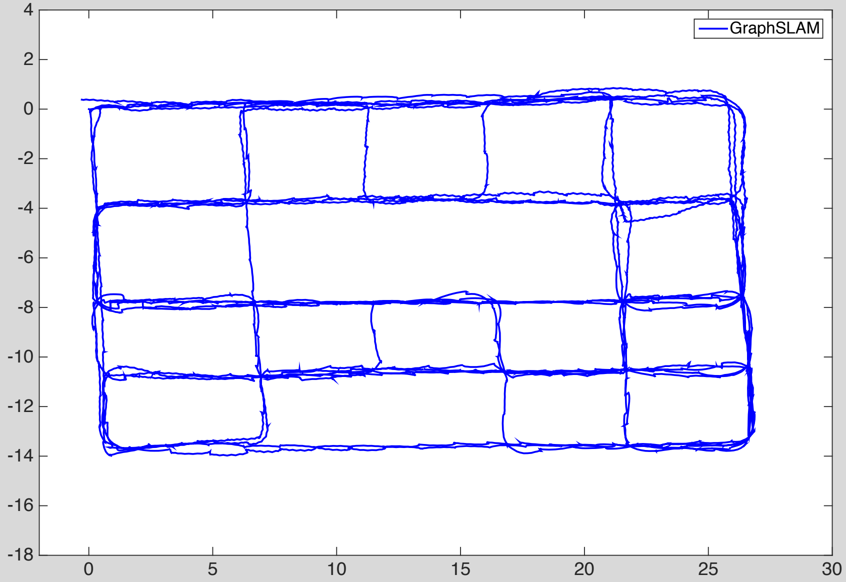
Distortions are constant and spatially discriminative

iMAG

- iMAG system uses robust SLAM to fuse:
  - inertial measurements (which suffer from drift)
  - magneto-inductive measurements (which suffer from distortion)
- These uncorrelated sources of error result in an accurate and robust positioning system



Inertial only



iMAG: Inertial with magnetic loop closures

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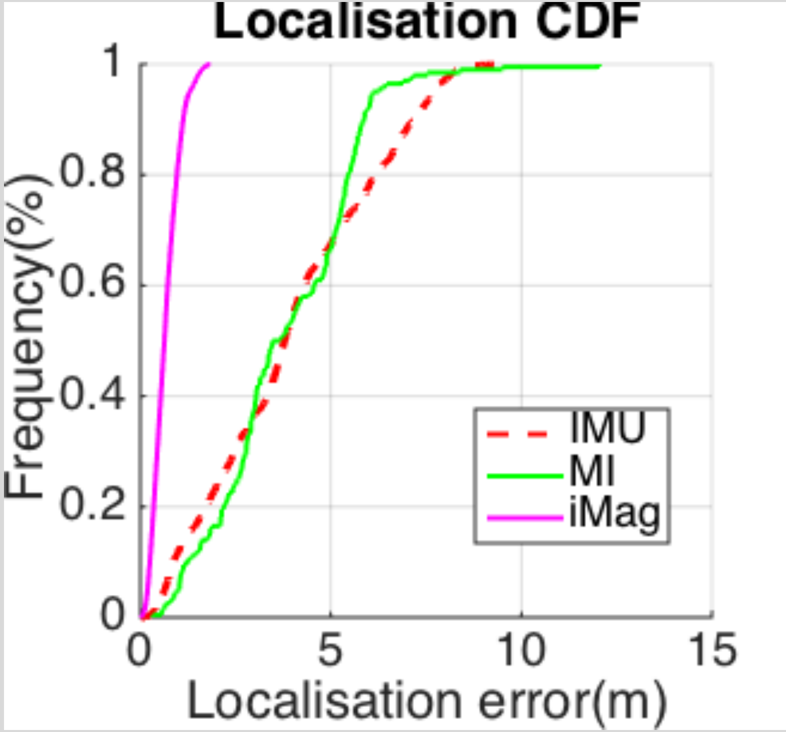

iMAG: Accurate and Rapidly Deployable Magneto-inductive localization: ICRA 2018

Deep learning approach to denoising MI signals

- We have been developing a weak signal extraction framework using deep learning
- The advantages are that we can synthesize an arbitrarily large dataset, corrupted by noise etc, to train our models
- Testing on real hardware is virtually identical to simulation

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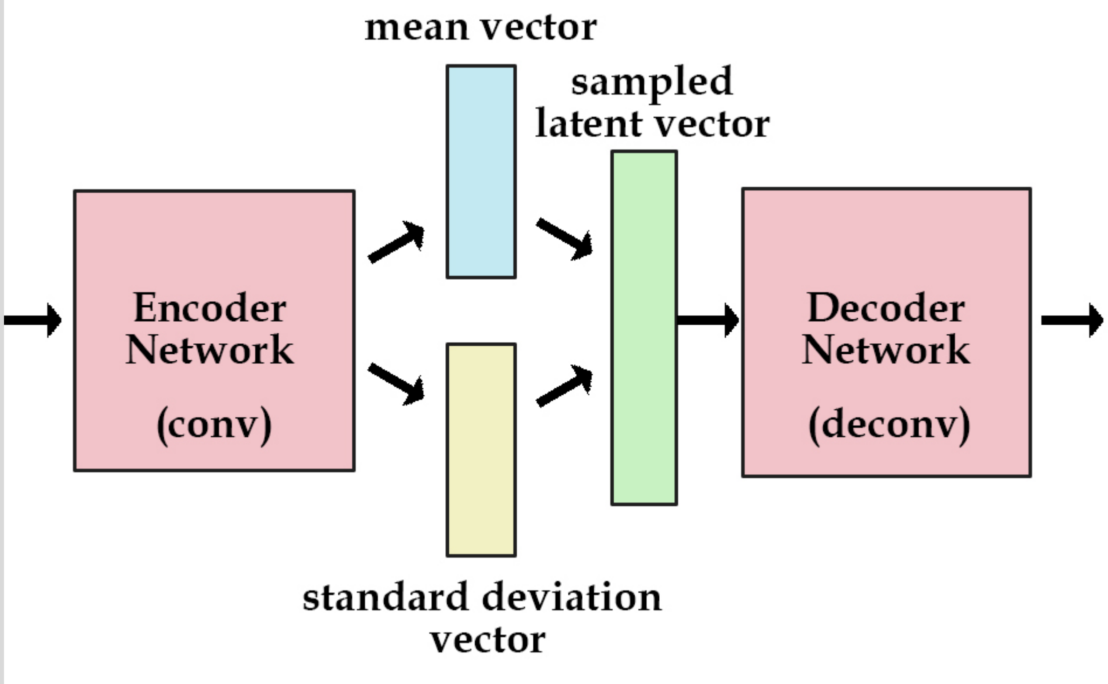
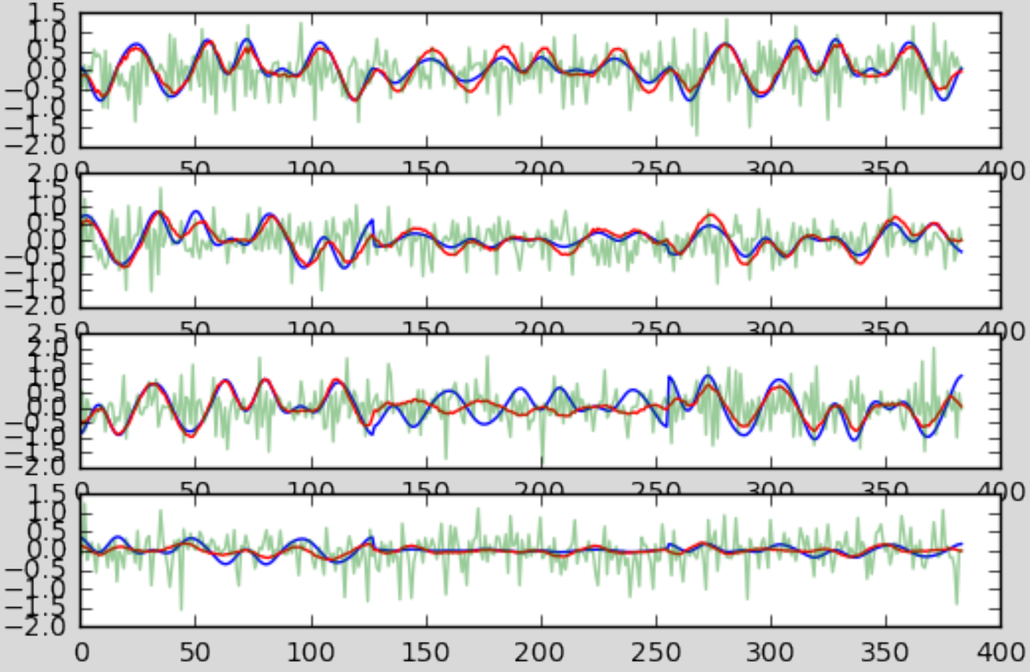
Architecture

Noisy signal



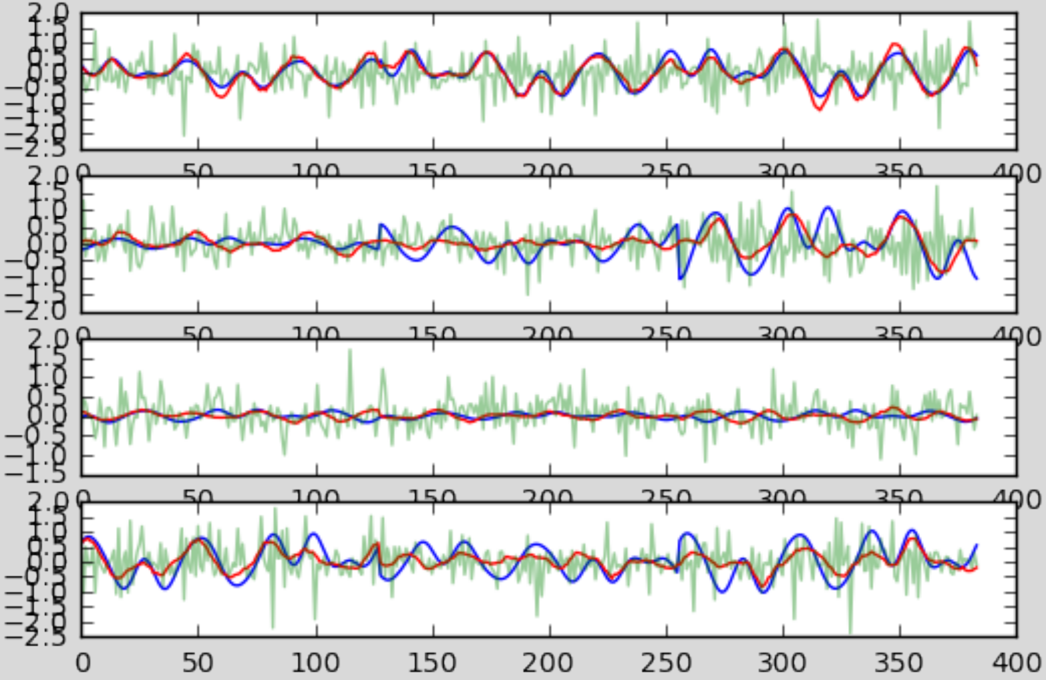
Clean signal

Results after 1 training epoch



Green: noisy signal
Blue: true signal
Red: reconstructed signal

Results after 2 training epochs



Green: noisy signal
Blue: true signal
Red: reconstructed signal

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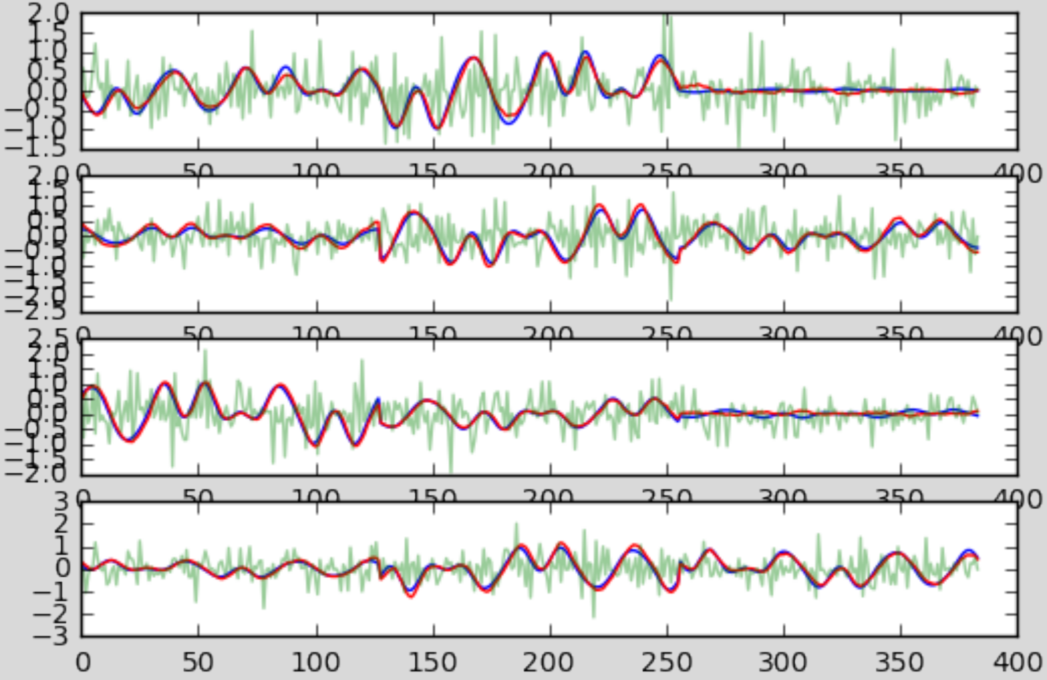
Results after 20 training epochs



Green: noisy signal

Blue: true signal

Red: reconstructed signal

MI positioning – lessons learnt

- Provides reliable distance measurements but at limited range
- Position estimates are distorted by metal structures
- Characteristic MI signal distortions ideal for loop closure
- Deep learning techniques can be used to extract weak signals

Conclusions

- Working with fire fighters has been key to
  - collecting realistic motion data
  - identifying limitations of existing techniques
  - understanding the pros and cons of different sensor modalities

- In Year 2,
  - we will continue to improve our positioning systems, putting them to the test in challenging scenarios
  - we will focus on robust fusion of various modalities

PSCR

PerfLoc Prize Competition for Development of Smartphone Indoor Localization Apps

Nader Moayeri, Chang Li, Lu Shi, and Ruizhi Chen

PSCR

Disclaimer

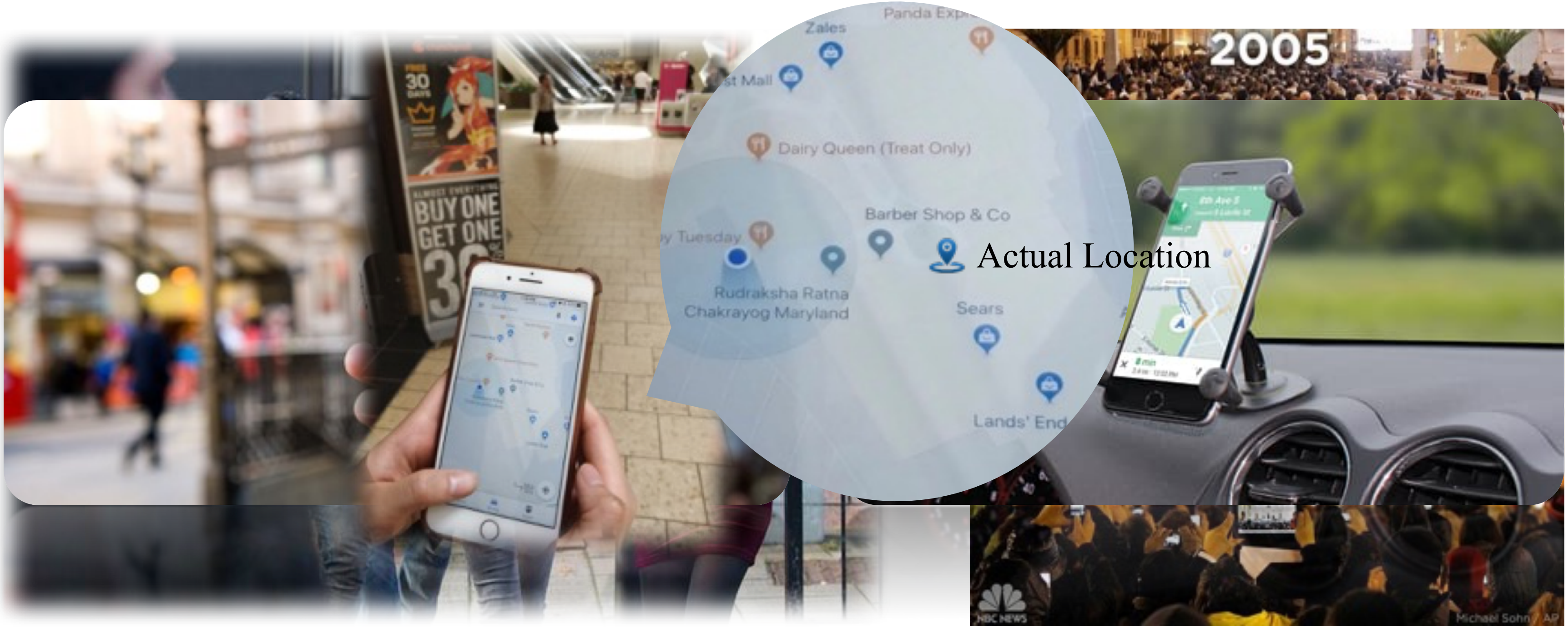
Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately.

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.

PSCR

Smartphone: Unrivaled King of Personal Mobile Devices



Indoor positioning and navigation still need work.
Smartphone navigation works well outdoors.

PerfLoc Prize Competition

- Create a level playing field for all to develop smartphone indoor localization apps.

Data Collection & Release → Over-the-Web Performance Evaluation → Live Test of Finalist Apps

1st place -	\$20,000
2nd place -	\$10,000
3rd place -	\$5,000

2018 IPIN Competition

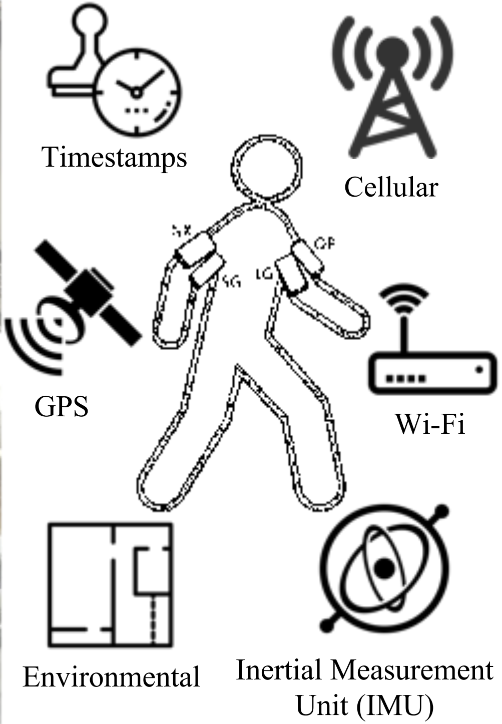
PSCR

Relevance to Public Safety

- Desirable: "first responders" need to work with whatever equipment they bring to the scene of an emergency.
- Public safety systems may use any building infrastructure available "opportunistically".

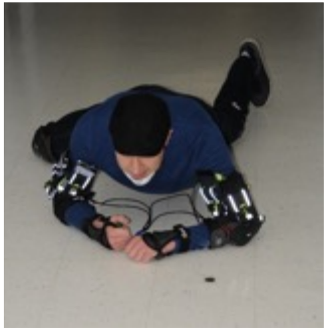
PSCR

About the Data



About the Data

Data Collection Campaign

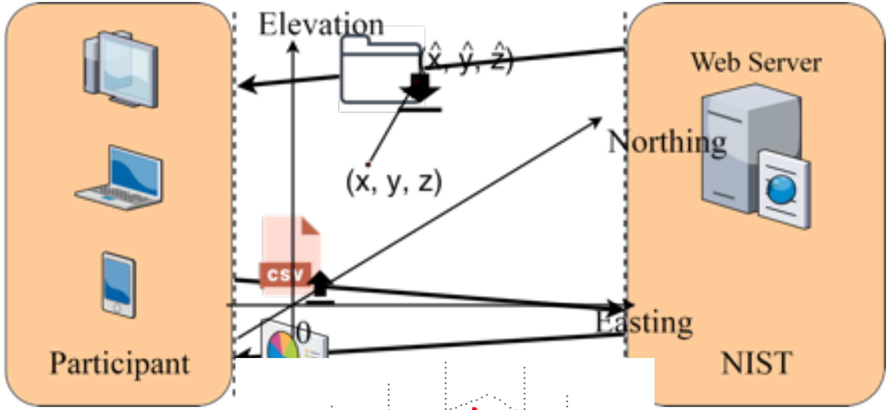



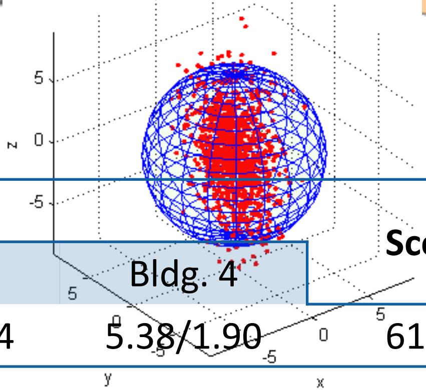

- Over 900 surveyed dots
- Total space more than 30,000 m^2
- 34 Test & Evaluation scenarios
- Supplemental data collection with additional 386 dots
- Training and test data sets

PSCR

Offline Evaluation of Algorithms

- NIST developed a web portal for PerfLoc.
- Participants need to upload 16,264 location estimates.
- Spherical Error 95% (SE95) is the performance metric.





SE95 / SE50 Performance (in meters)					Score
Overall	Bldg. 1	Bldg. 2	Bldg. 3	Bldg. 4	
6.29/2.04	5.44/1.64	7.04/2.84	6.26/2.24	5.38/1.90	61.70

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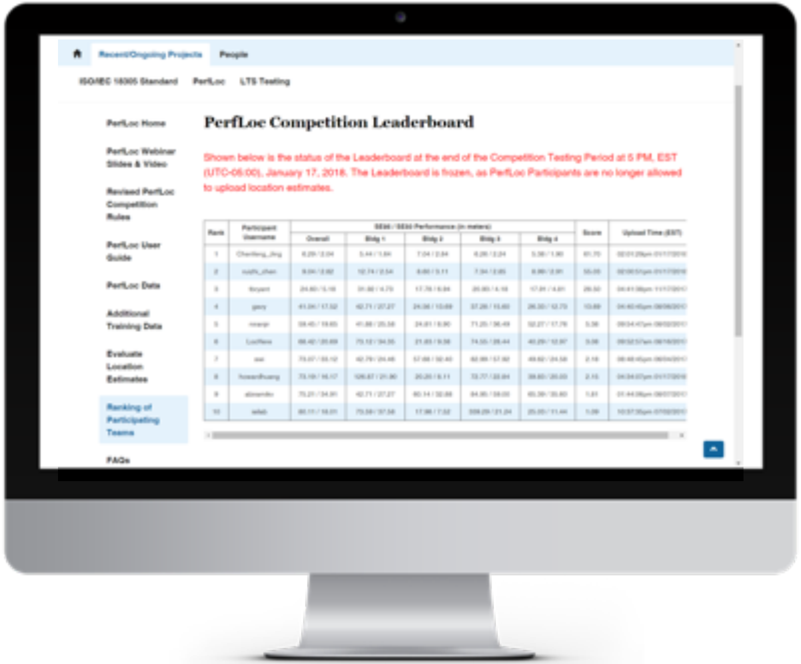
PerfLoc Leaderboard as of Jan. 17, 2018

Highlights

- 152 teams registered
- 16 teams uploaded
- Top team achieved overall SE95 of 6.29 meters.



https://perfloc.nist.gov/perfloc-ranking.php

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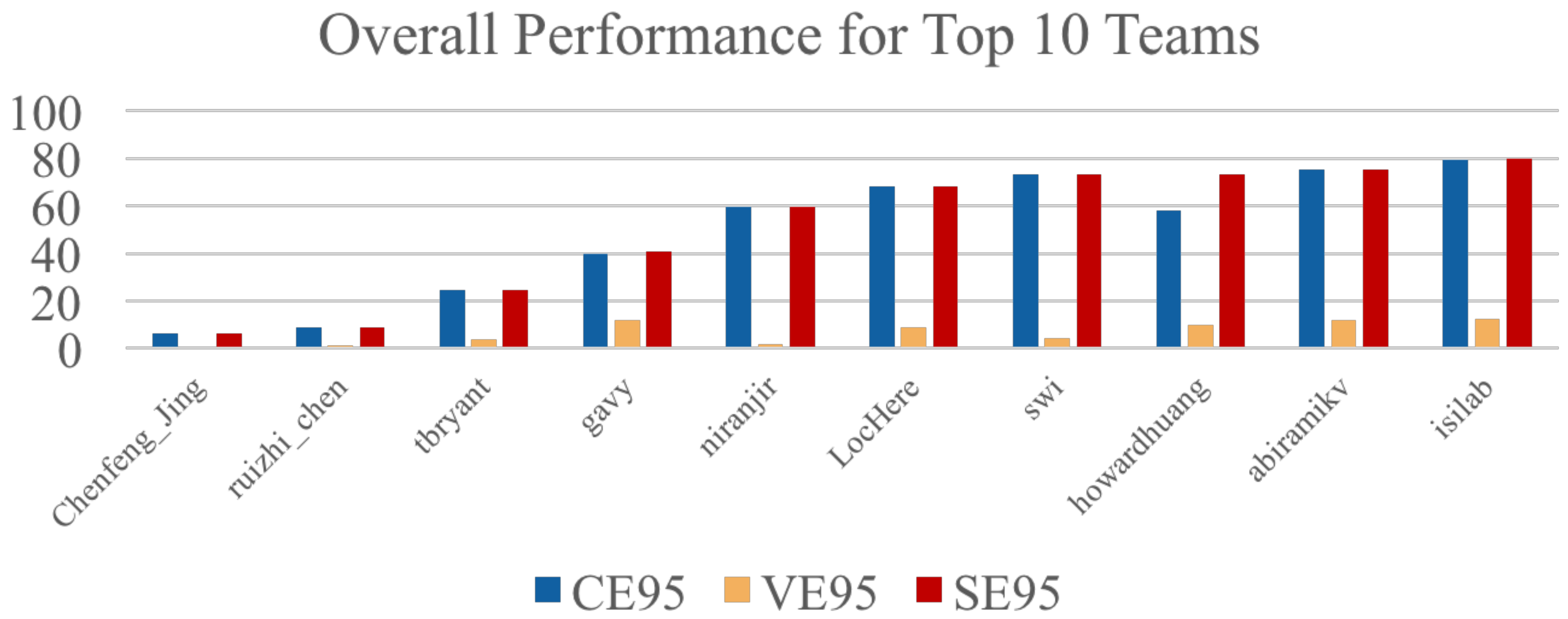
Performance of the Offline Evaluation



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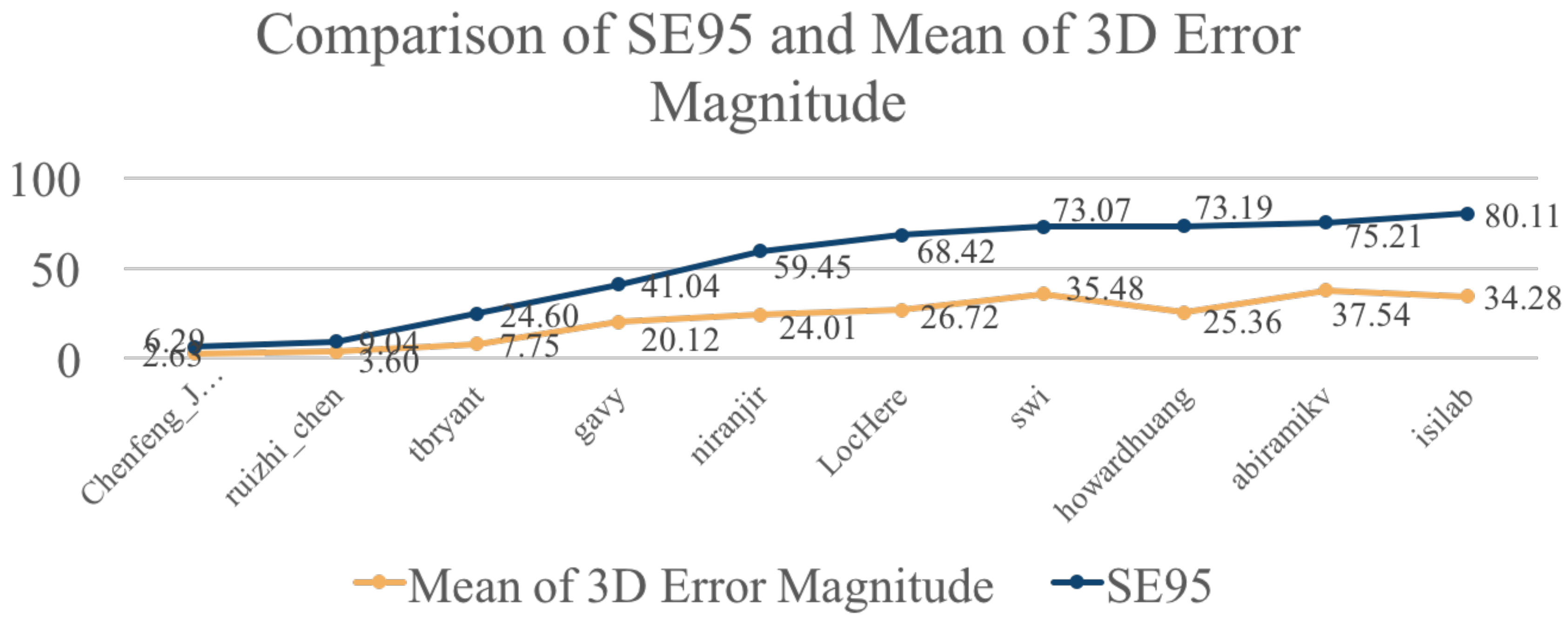
Performance of the Offline Evaluation



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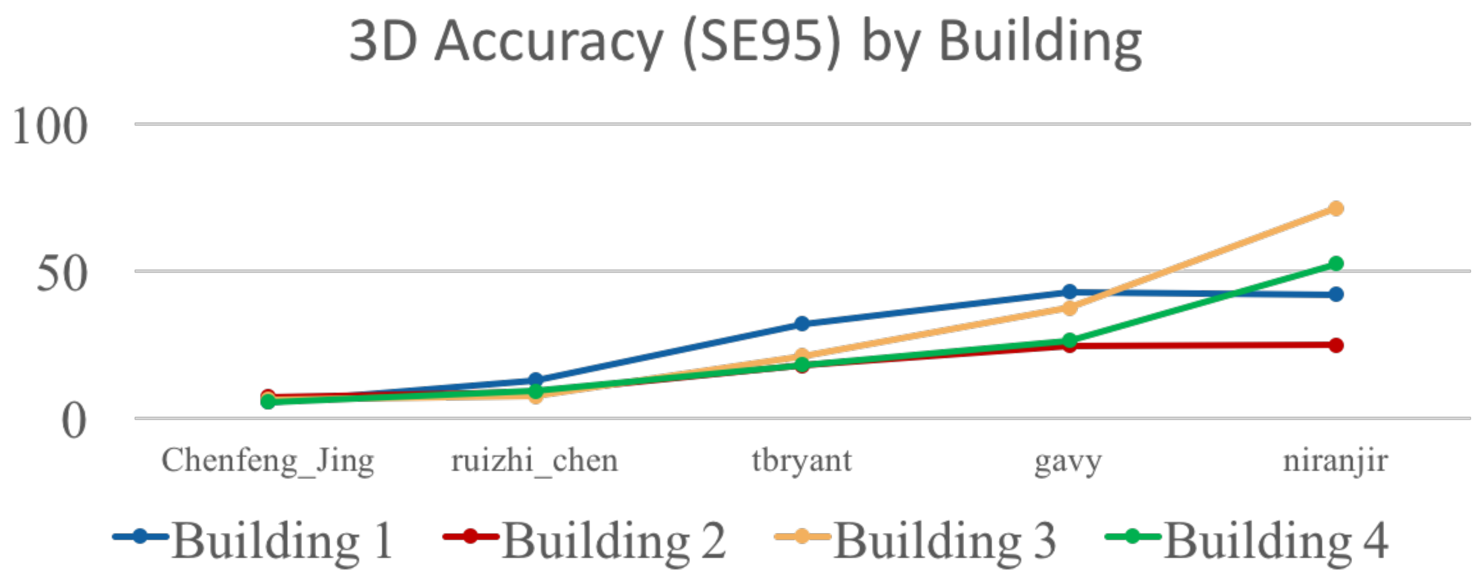
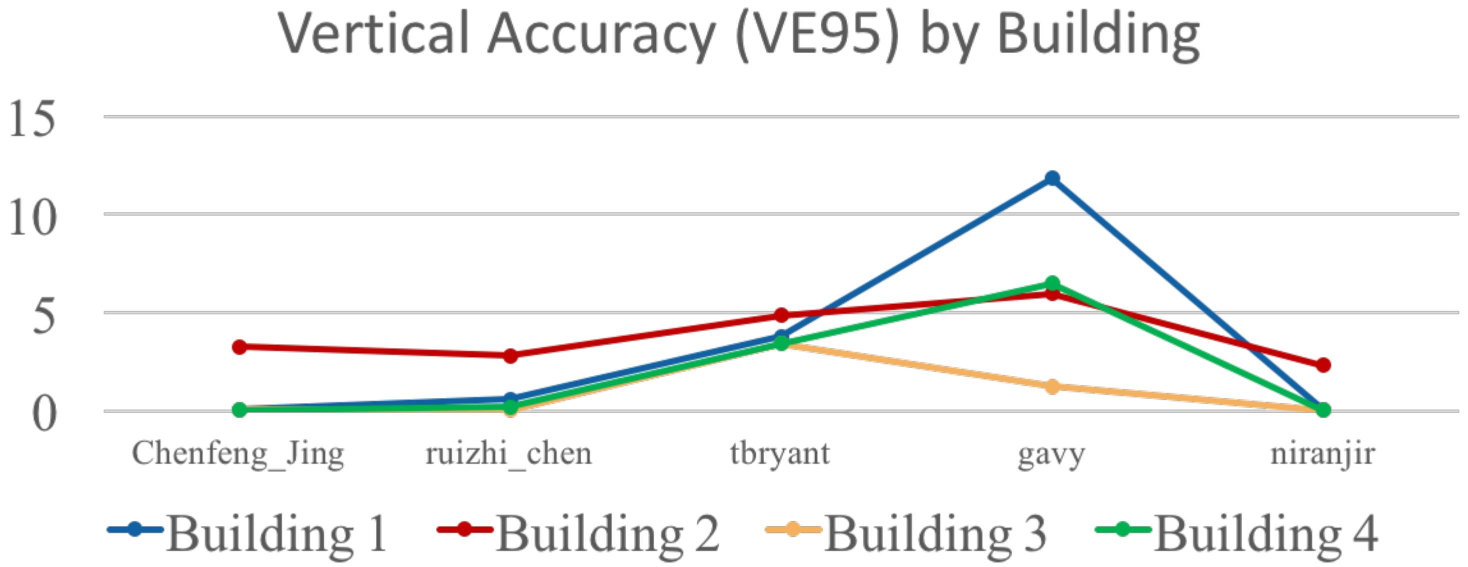
Performance of the Offline Evaluation

Building 2 and 4 yield lower 3D error than Building 1 and 3.



Performance of the Offline Evaluation

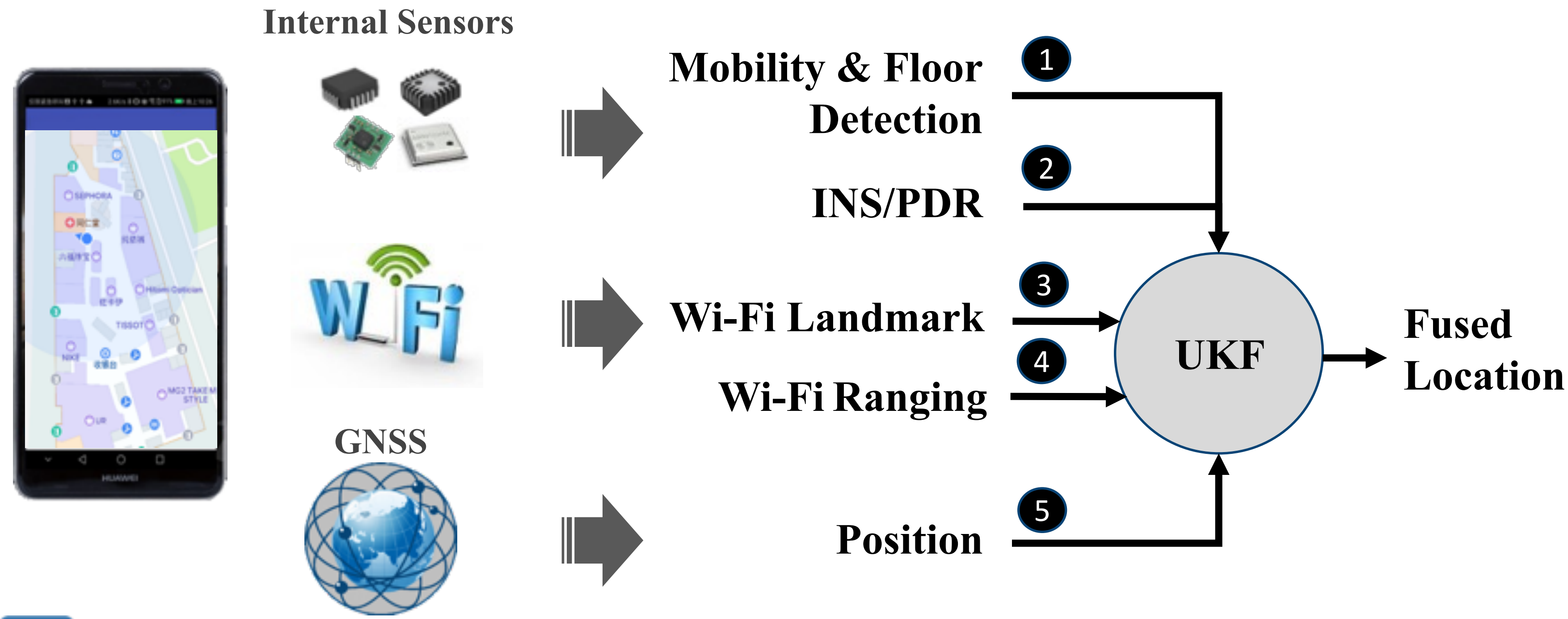
Building 3 and 4 yield lower vertical error than Building 1 and 2.



Smartphone Indoor Localization App Developed by the PerfLoc Winners

PSCR

Overview of the Real-Time Solution



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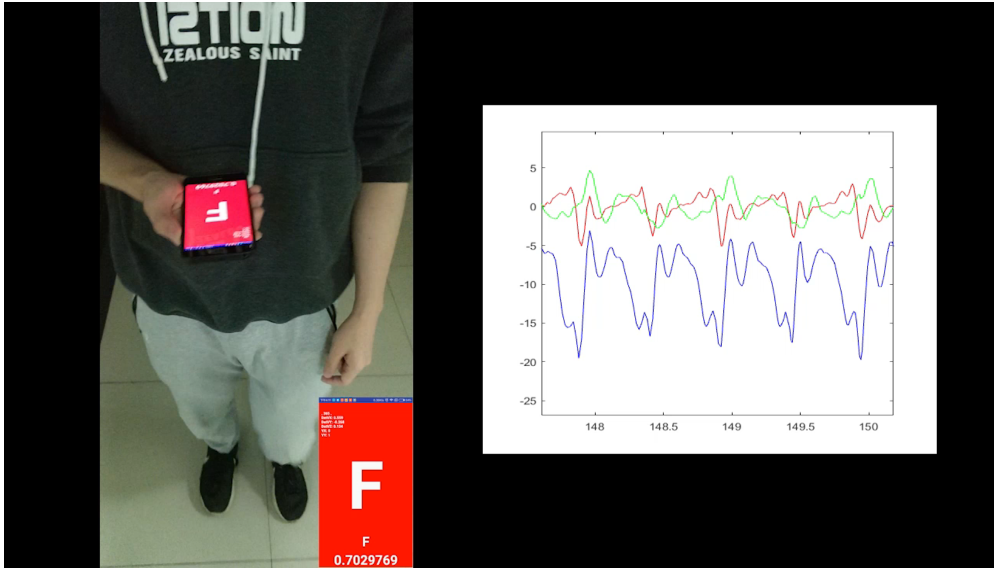
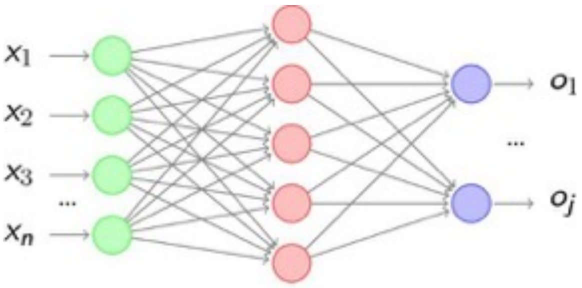
Mobility Detection

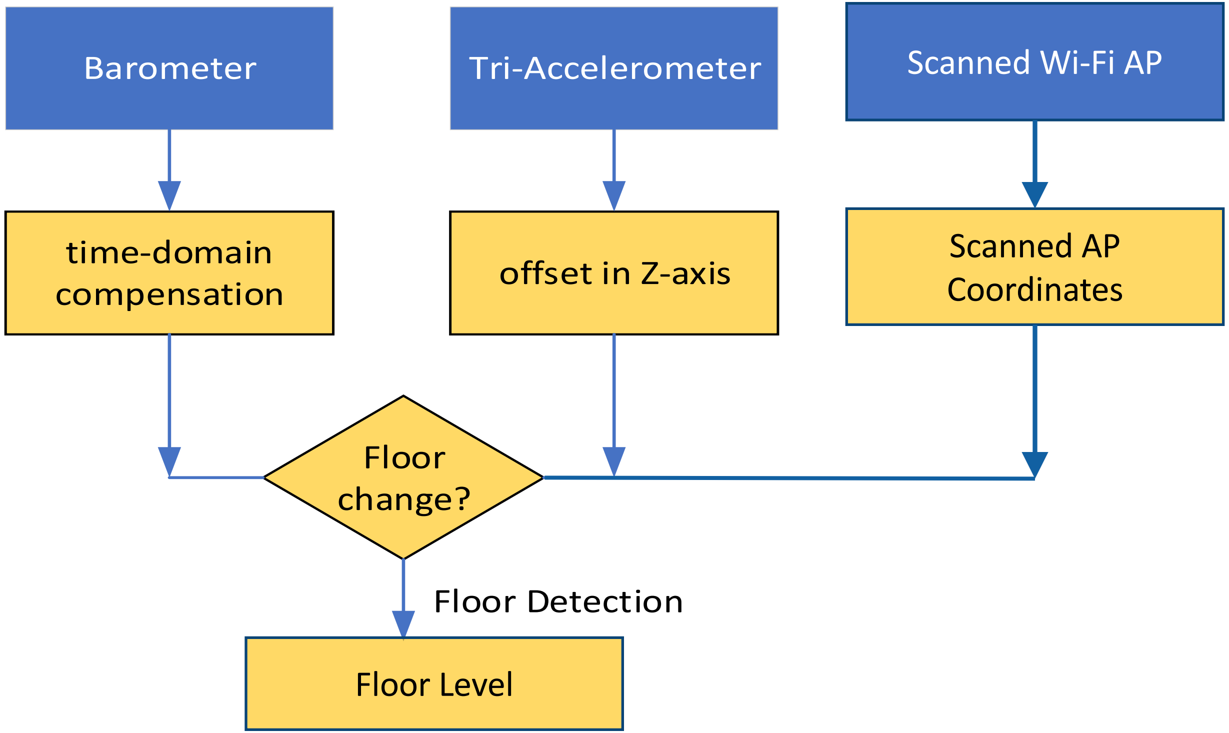


Walking Mode Recognition

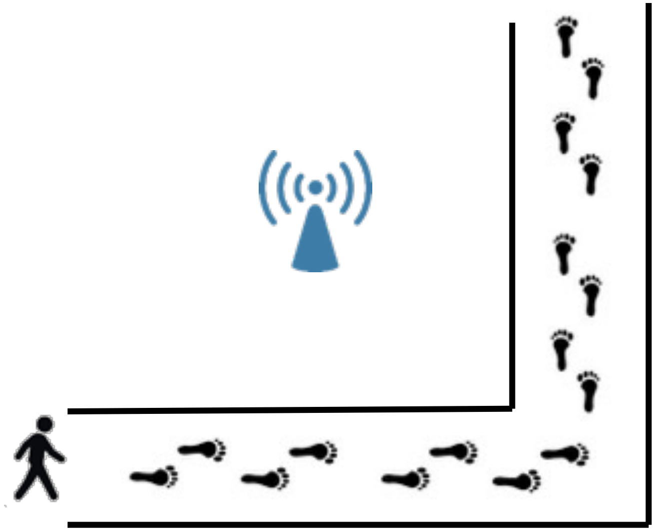


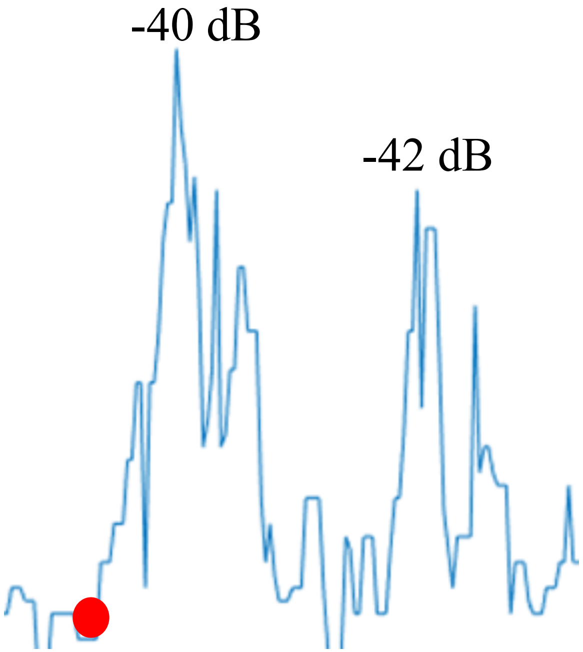
Neural Network Classifier

Floor Detection



Wi-Fi Landmark





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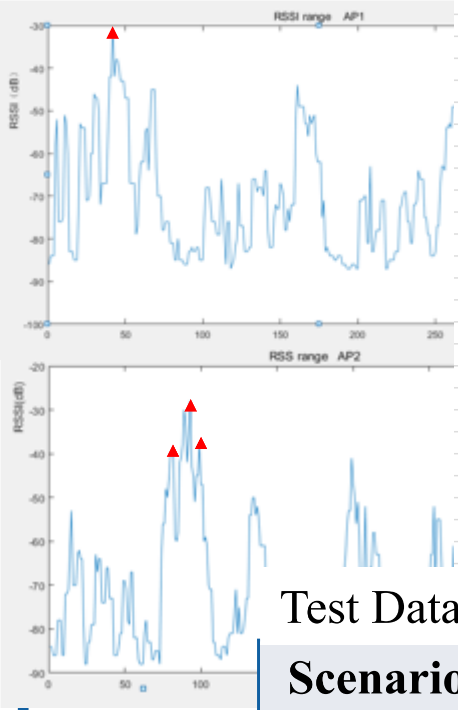
Wi-Fi Landmark



AP number	RSS(MAX)	coordinates (AP) (m)		timestamp	coordinates(calculated by PDR)(m)		error(m)
1	-42	162934.2465	381339.9211	1454963241	162935.3359	381339.3556	1.2274
2	-43	162953.1536	381330.3731	1454964639	162953.4676	381331.8834	1.5426
3	-34	162934.2335	381354.5615	1454964589	162934.861	381350.5744	4.0362
6	-38	162953.1606	381349.8826	1454964622	162950.6824	381347.5118	3.4296
8	-37	162934.2762	381392.3553	1454964512	162933.4226	381388.8062	3.6503
9	-38	162934.2577	381374.0544	1454964532	162935.4695	381376.8167	3.0164
10	-29	162953.1625	381368.1638	1454962830	162958.2101	381372.3222	6.5399
11	-39	162953.1951	381402.3158	1454962756	162952.2162	381400.3408	2.2043
12	-30	162953.1557	381315.7389	1454964669	162953.5621	381316.6704	1.0163
14	-35	162943.8878	381294.9223	1454963121	162941.5998	381295.0325	2.2906
15	-42	162953.1795	381384.0319	1454962786	162949.1876	381382.264	4.3658
17	-40	162934.2708	381344.7529	1454962931	162935.7206	381344.6252	1.4554
18	-39	162934.2514	381330.1096	1454962988	162934.2869	381326.0103	4.0994
19	-29	162953.1495	381343.772	1454964200	162958.3884	381342.9631	5.3009
20	-28	162934.2722	381367.9114	1454963348	162939.0407	381369.1853	4.9357
21	-38	162953.1631	381324.222	1454964147	162954.1596	381330.7295	6.5834
22	-37	162934.3023	381393.5173	1454963507	162936.0025	381401.0397	7.7122
23	-35	162953.199	381374.232	1454963398	162951.0944	381375.0546	2.2597
24	-38	162934.2824	381378.8915	1454964283	162933.1704	381378.5961	1.1505
25	-39	162953.1831	381358.3818	1454964229	162952.8019	381360.8438	2.4913
27	-35	162934.2441	381315.4808	1454963011	162934.9815	381315.1418	0.8116
28	-39	162953.2125	381393.7532	1454964375	162950.8828	381400.1424	6.8006
29	-36	162944.5796	381402.777	1454964395	162940.6871	381401.021	4.2702
30	-31	162934.2454	381294.9344	1454963054	162930.7108	381294.3825	3.5774
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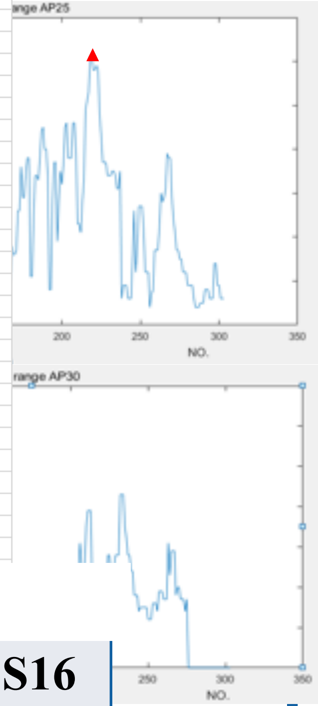
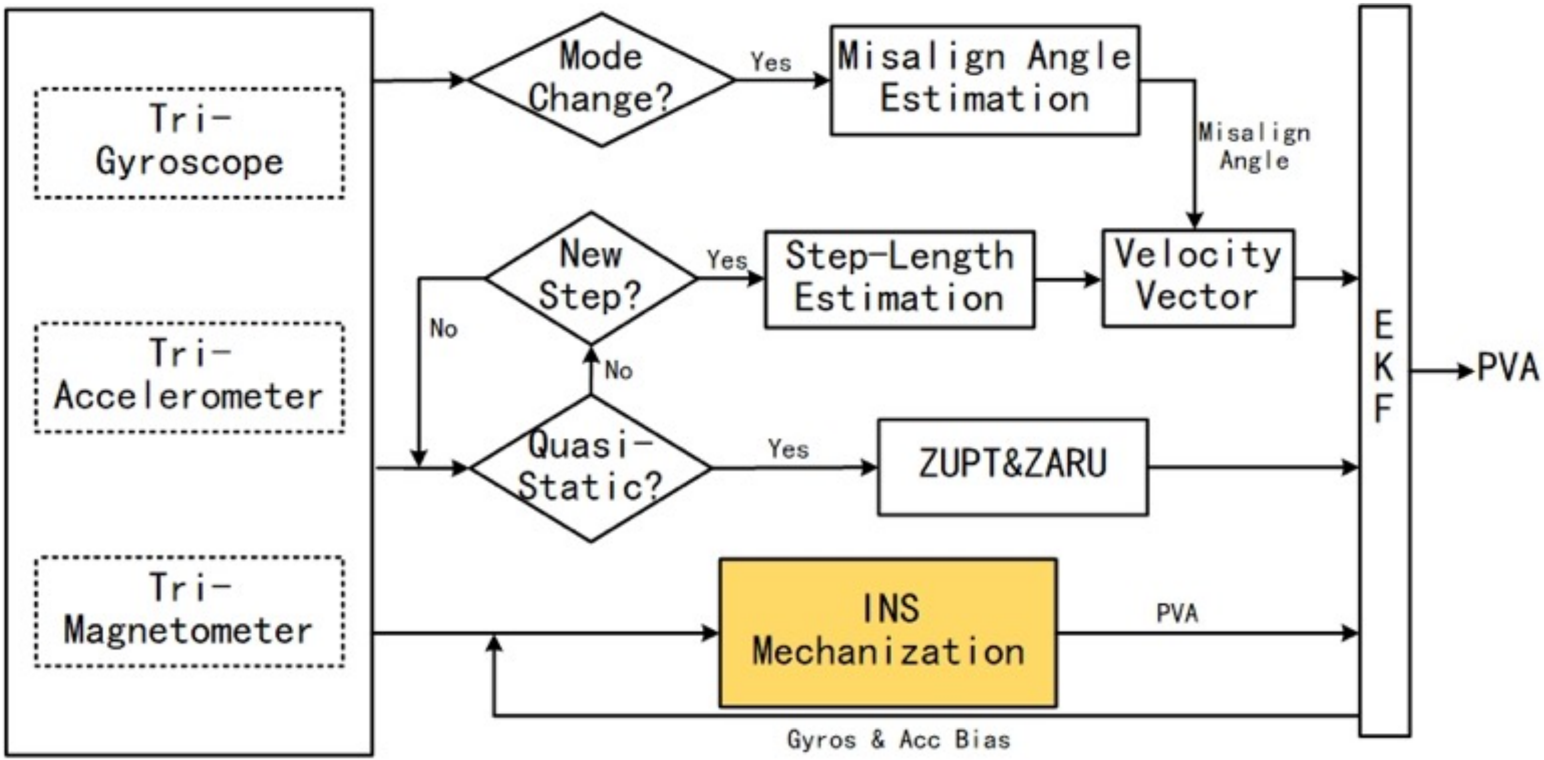


Test Dataset from Building 2 (Samsung)

Scenario	S01	S02	S03	S10	S12	S13	S14	S16
Number	25	22	8	21	22	17	21	14

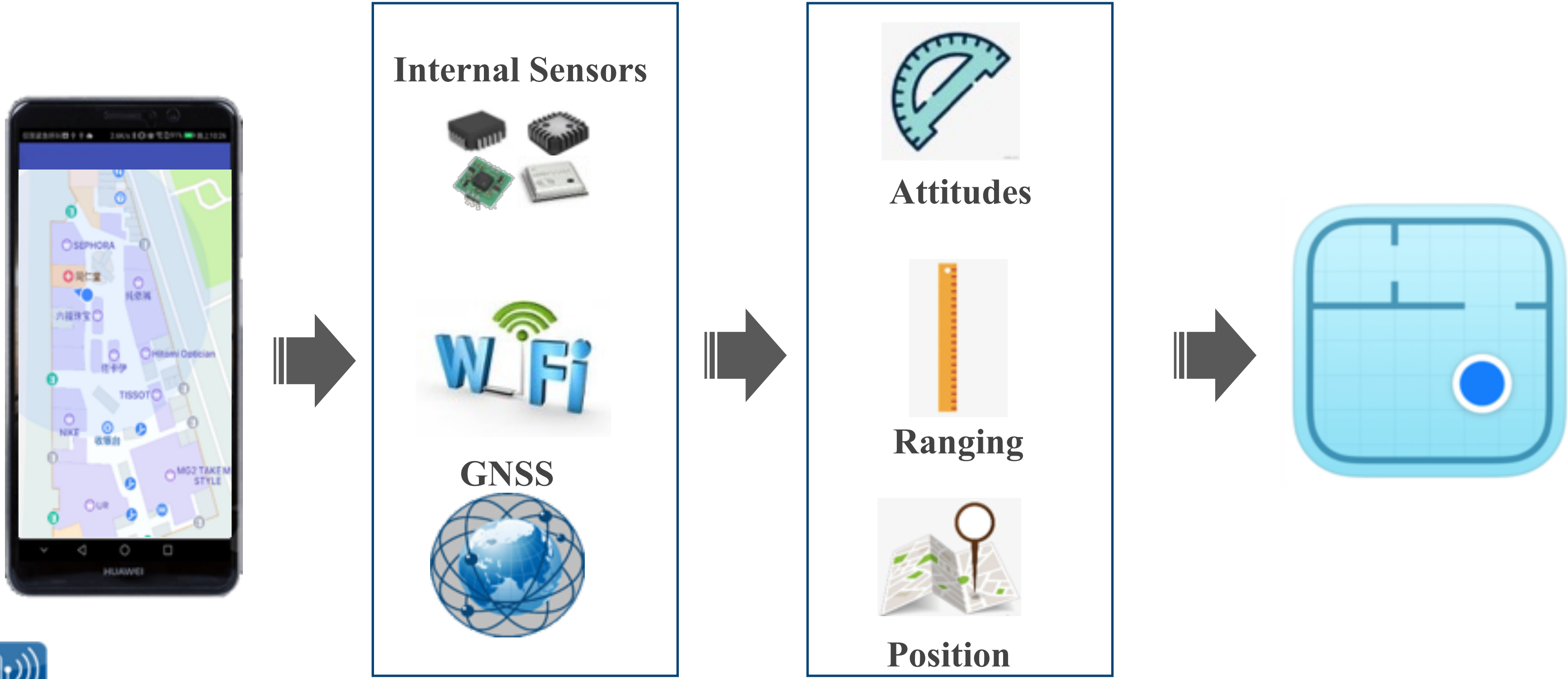
INS/PDR



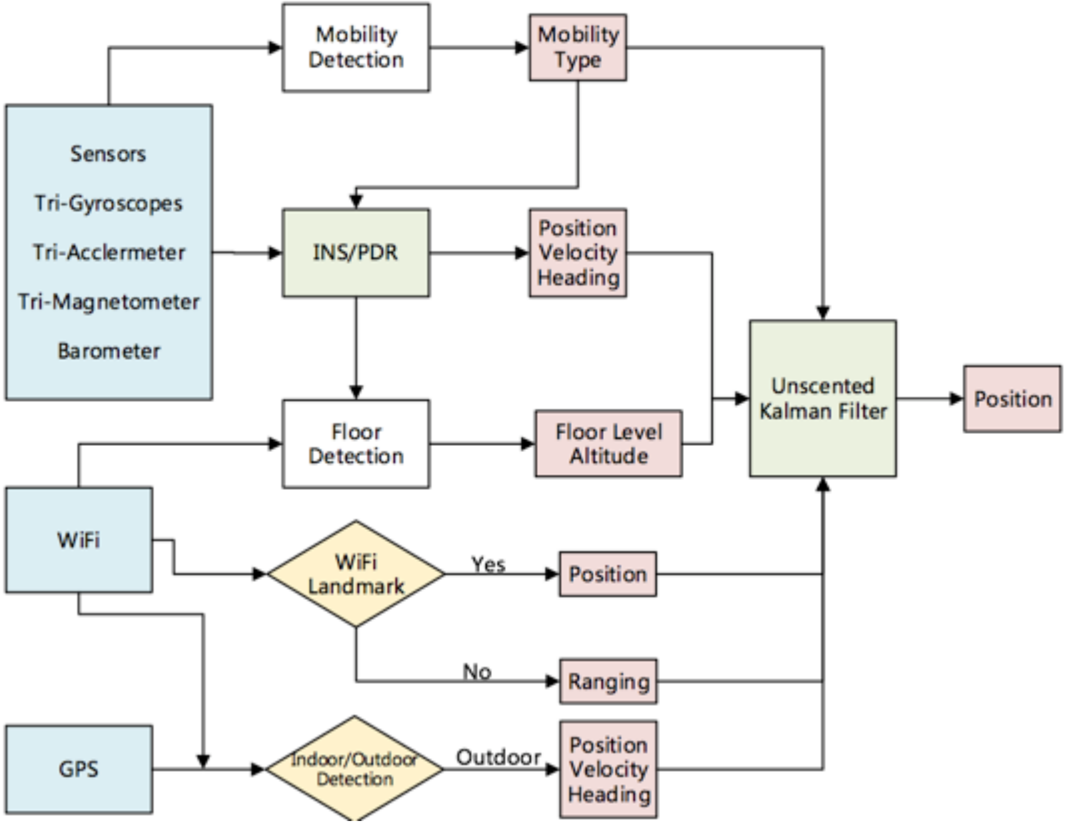
Tri-
Gyroscope
Tri-
Accelerometer
Tri-
Magnetometer
Mode
Change?
Yes
Misalign Angle
Estimation
Misalign
Angle
New
Step?
Yes
Step-Length
Estimation
Velocity
Vector
No
No
Quasi-
Static?
Yes
ZUPT&ZARU
INS
Mechanization
PVA
Gyros & Acc Bias
E
K
F
PVA

PSCR

UKF Integration



UKF Integration



Live Testing of the Winning PerfLoc App

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Live Testing

Test Setting:

- Total of 525 test points:
  - 395 for normal walking
  - 57 for cart
  - 33 for sidestepping
  - 31 for walking backwards
  - 9 for crawling
- No Training Data
- Real-time Location Estimation

Performance of Live Testing

	Overall	Normal Walking	Cart	Sidestepping	Walking Backwards	Crawling
Mean of the magnitude of horizontal error	17.66	10.76	49.67	27.79	38.07	10.31
Mean of the magnitude of vertical error	1.71	2.09	0.72	0.57	0.20	0.34
Mean of the magnitude of 3D error	18.16	11.43	49.68	27.81	38.07	10.32
Circular error 95%	72.84	24.86	78.92	79.17	83.10	18.56
Vertical error 95%	5.2	5.22	1.16	0.95	0.47	0.57
Spherical error 95%	72.84	24.86	78.92	79.17	83.10	18.56

Normal walking outperforms other mobility modes.
Horizontal error is dominant compared to vertical error.
Cart, sidestepping and walking backwards have poor performance.

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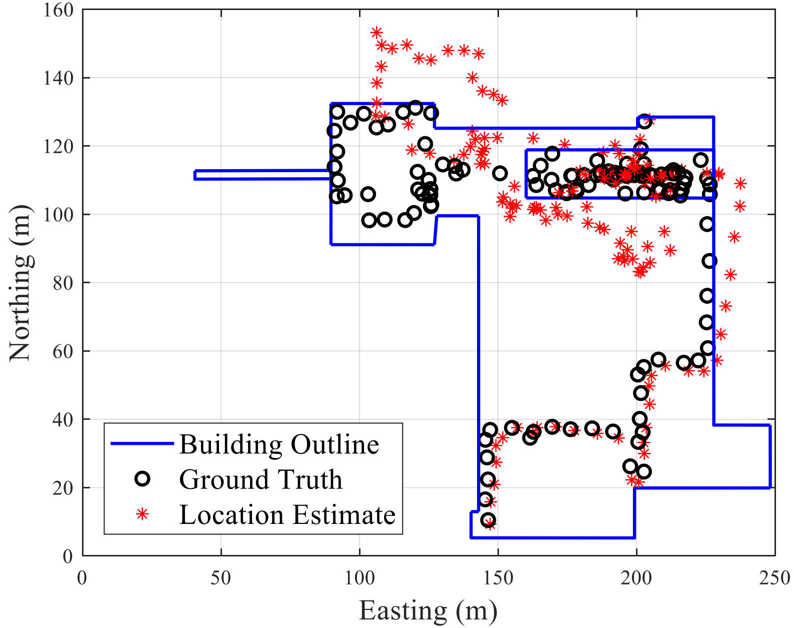
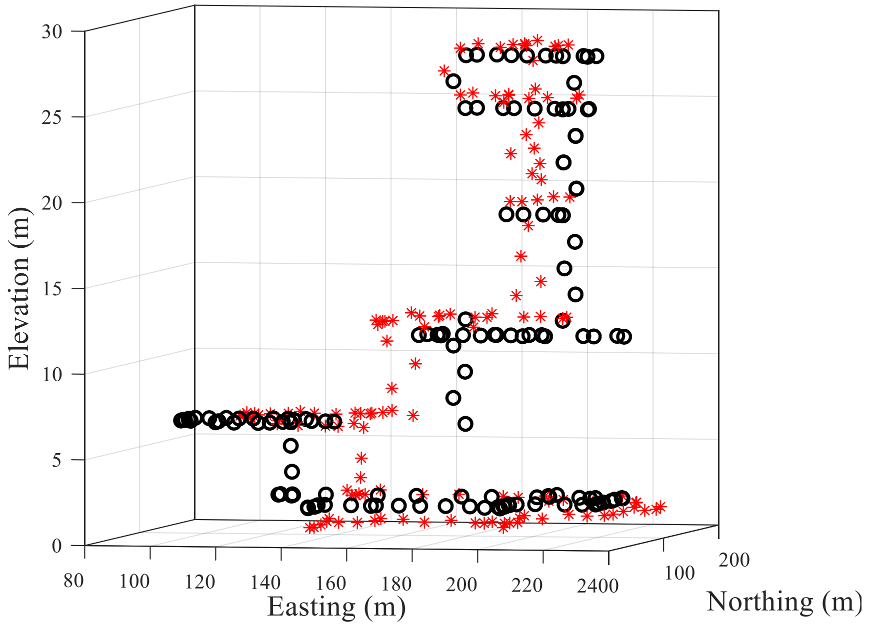
Performance of Live Testing: Walking w/o any Pause





Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
13.93 m	0.63 m	26.72 m	1.25 m

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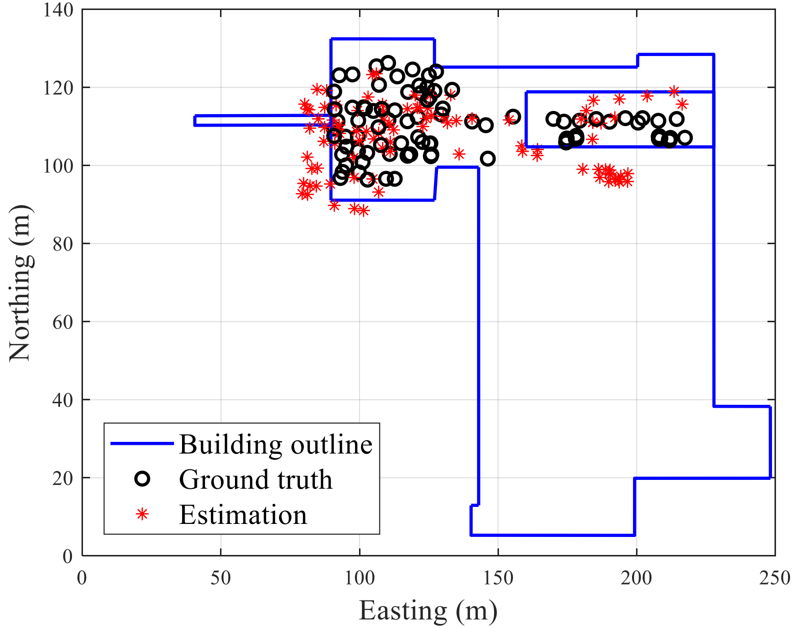
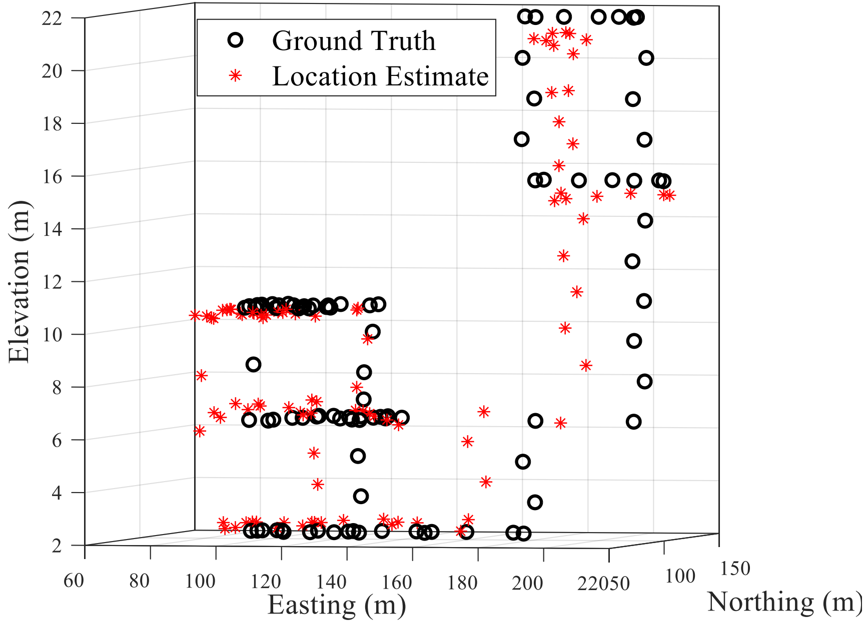
Performance of Live Testing: Walking with 3 s Stops at Dots





Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
12.72 m	0.37 m	21.20 m	0.90 m

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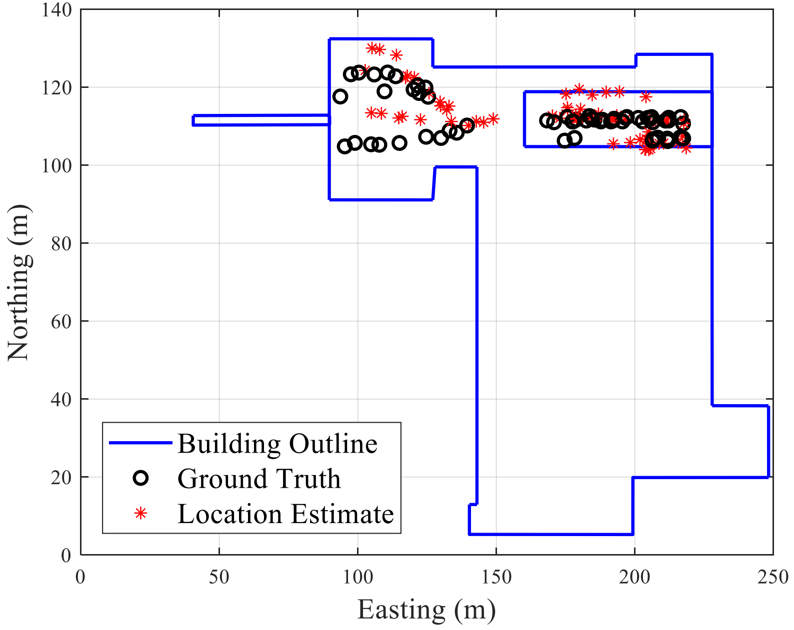
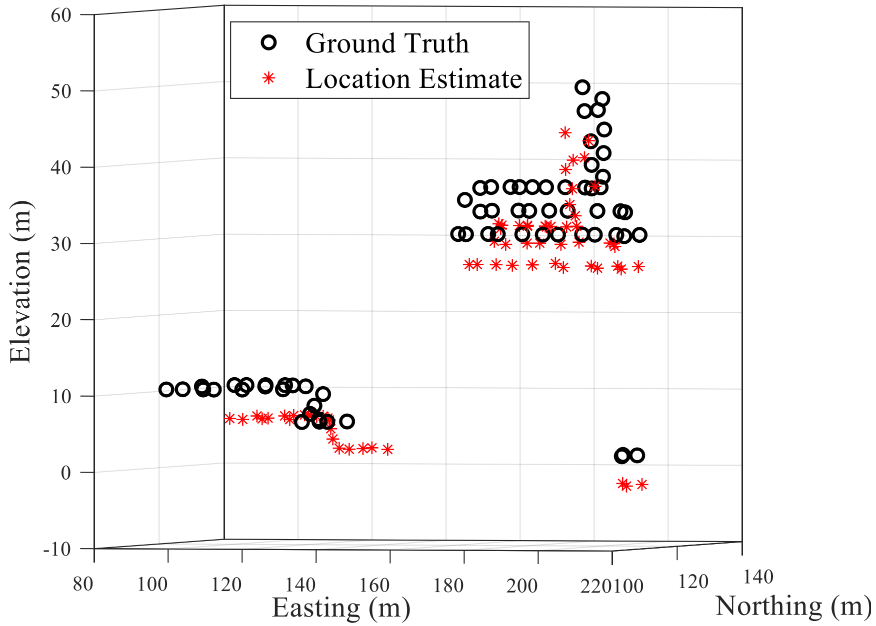
Performance of Live Testing: Walking and Using Elevators





Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
5.84 m	4.37 m	11.22 m	5.76 m

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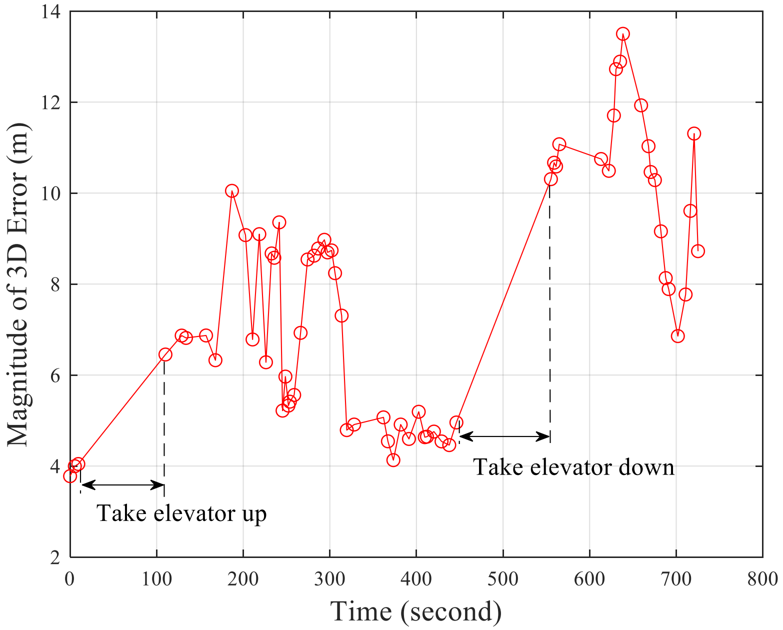
Performance of Live Testing: Walking and Using Elevators



Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
5.84 m	4.37 m	11.22 m	5.76 m

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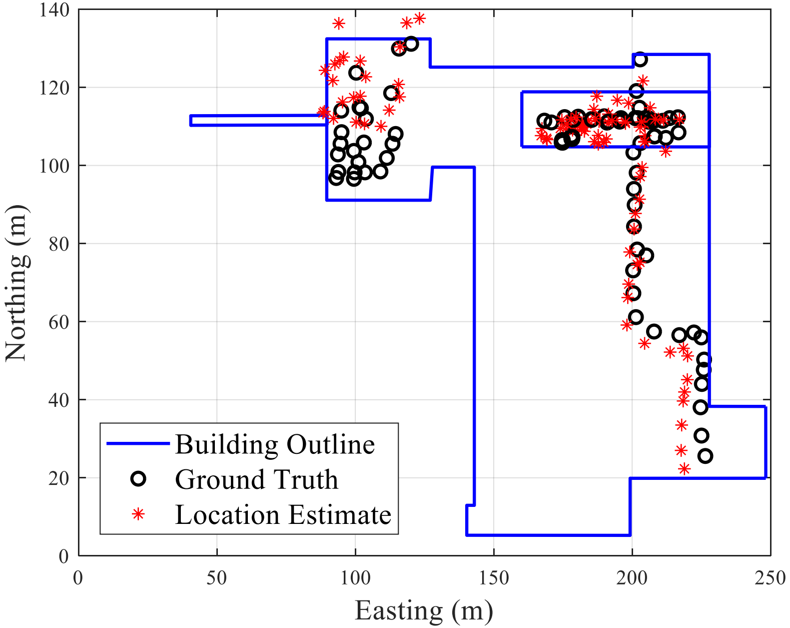
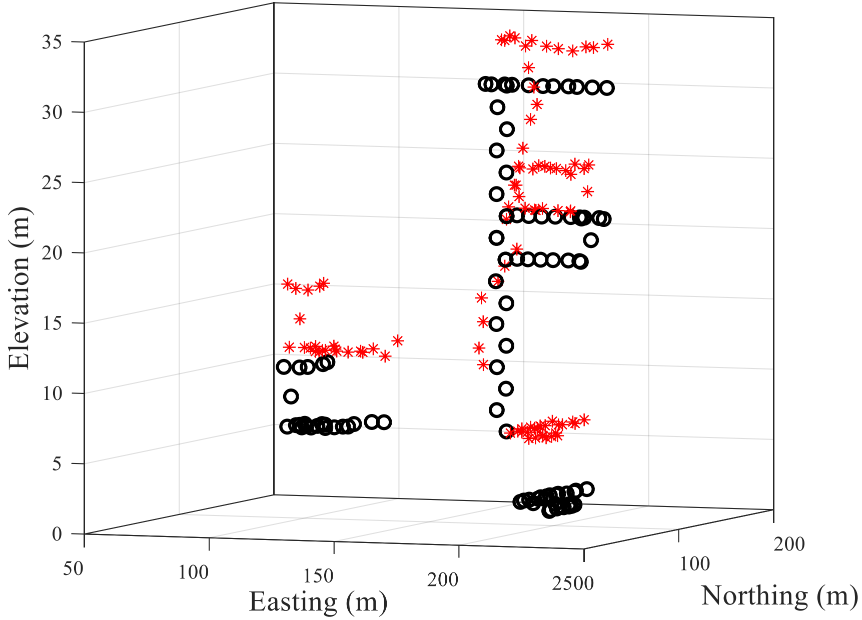
Performance of Live Testing: Walking in/out of Building





Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
7.63 m	4.33 m	16.42 m	5.40 m

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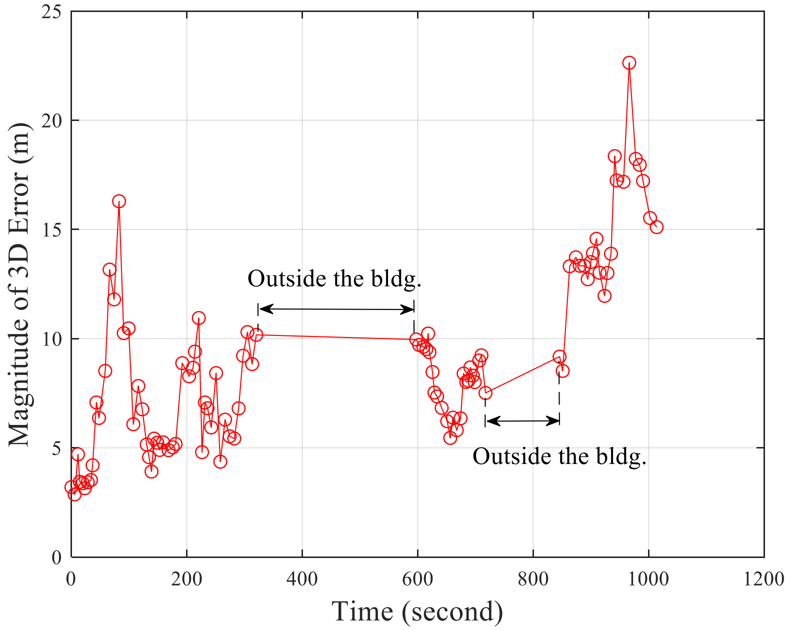
Performance of Live Testing: Walking in/out of Building



Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
7.63 m	4.33 m	16.42 m	5.40 m

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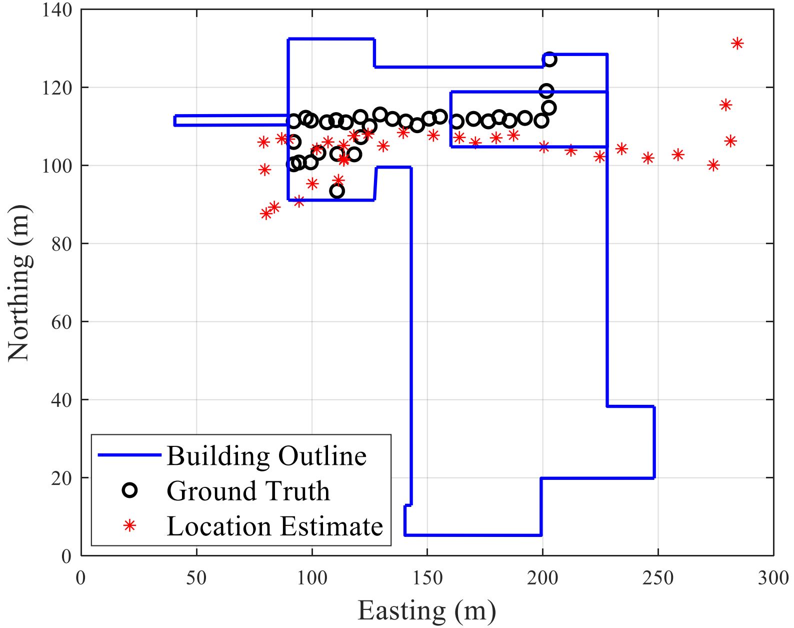
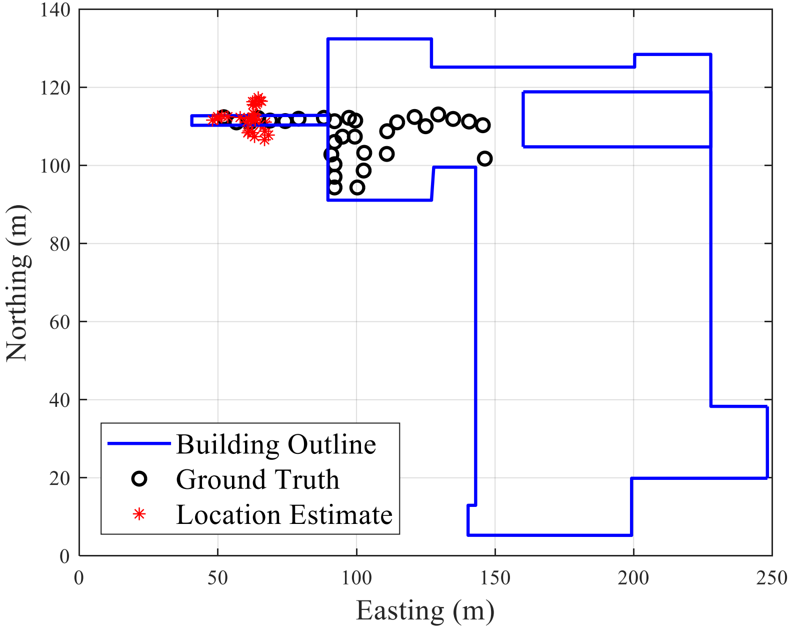
Performance of Live Testing: Sidestepping (L) and Walking Backwards (R)





	Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
Sidestepping	27.79 m	0.57 m	79.17 m	0.95 m
Walking Backwards	38.07 m	0.20 m	83.10 m	0.47 m

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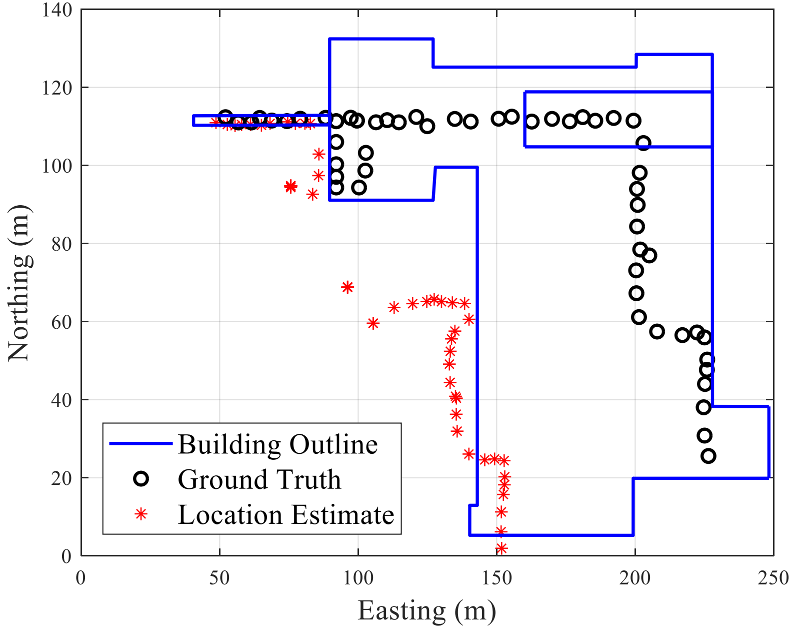
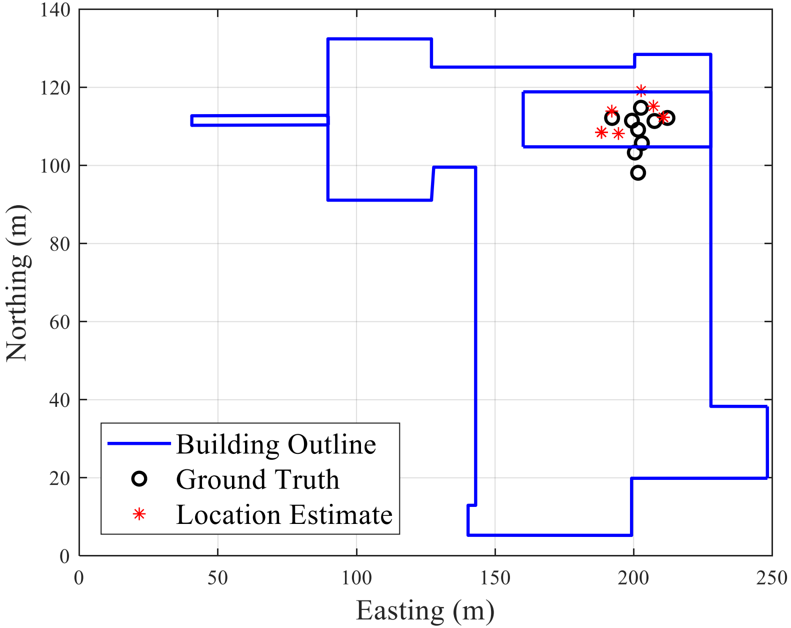
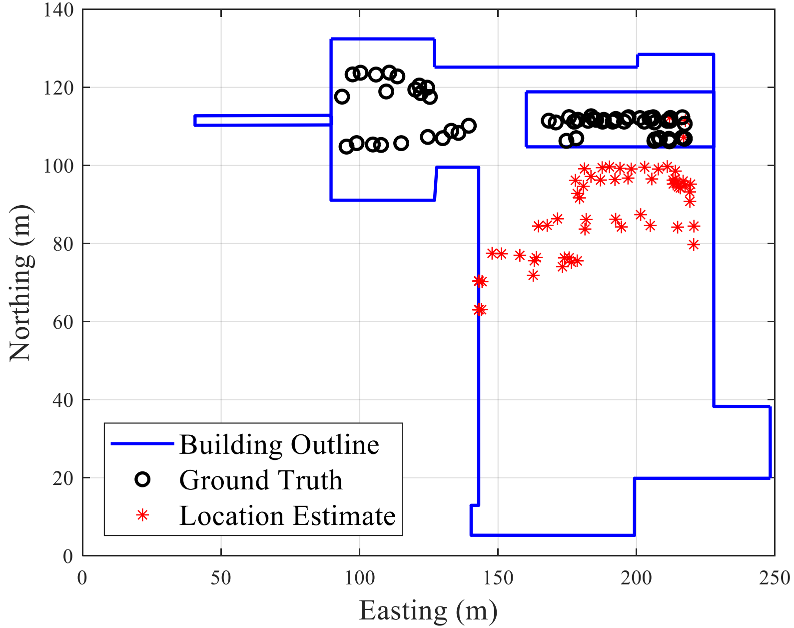
Performance of Live Testing: Cart (L) and Crawling (R)

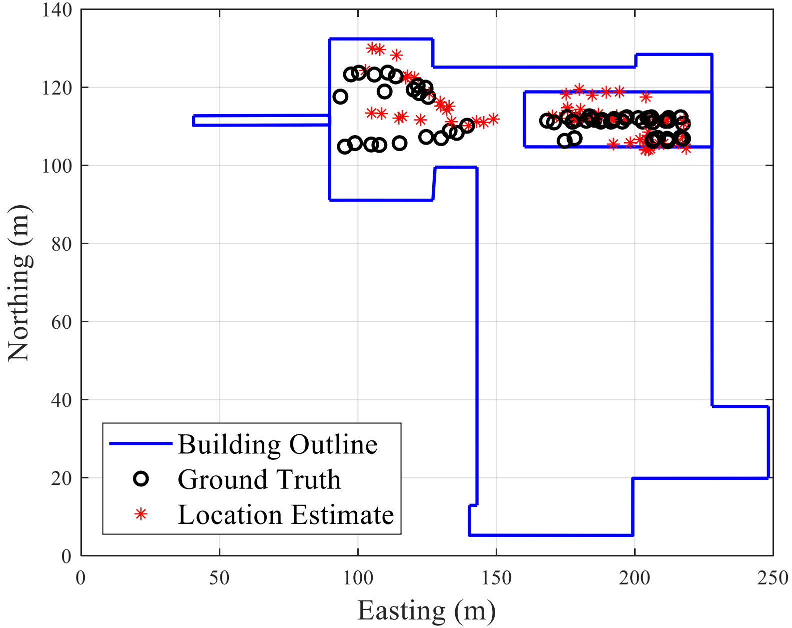




	Mean of Horizontal Error	Mean of Vertical Error	CE95	VE95
Cart	49.67 m	0.72 m	78.92 m	1.16 m
Crawling	10.31 m	0.34 m	18.56 m	0.57 m

Importance of Using Wi-Fi Info





	Mean of Horizontal Error	Mean of Vertical Error	Mean of 3D Error
Using Wi-Fi Info	17.66 m	1.71 m	18.16 m
w/o Wi-Fi Info	26.97 m	2.74 m	27.56 m

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Closing Remarks

- PerfLoc is the first worldwide indoor localization competition simulating real life scenarios.
- Offline test results
  - Abundant training data
  - Post-processing
- Live test results reflect localization accuracy with
  - Minimal information available
  - Testing in unknown environment
  - Achieved in real time
- Developing more effective indoor localization apps is still an open problem.
- PerfLoc data will continue to be available for use.

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Jeb Benson
NIST LBS Program Manager

Heather Evans
NIST Challenge Coordinator

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PerfLoc Winners at NIST

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PerfLoc Winners

Texas A&M University Corpus Christi	Wuhan University	
Tianxing Chu *Official Team Representative*	Ruizhi Chen *Team Leader*	
	Xiaoji Niu	Jian Kuang
	Guangyi Guo	Haojun Ai
	Xiaoguang Niu	Xingyu Zheng
	Xuesheng Peng	Ge Zhu
	Liang Chen	Jingbin Liu
	Quan Zhang	

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Backup Slides

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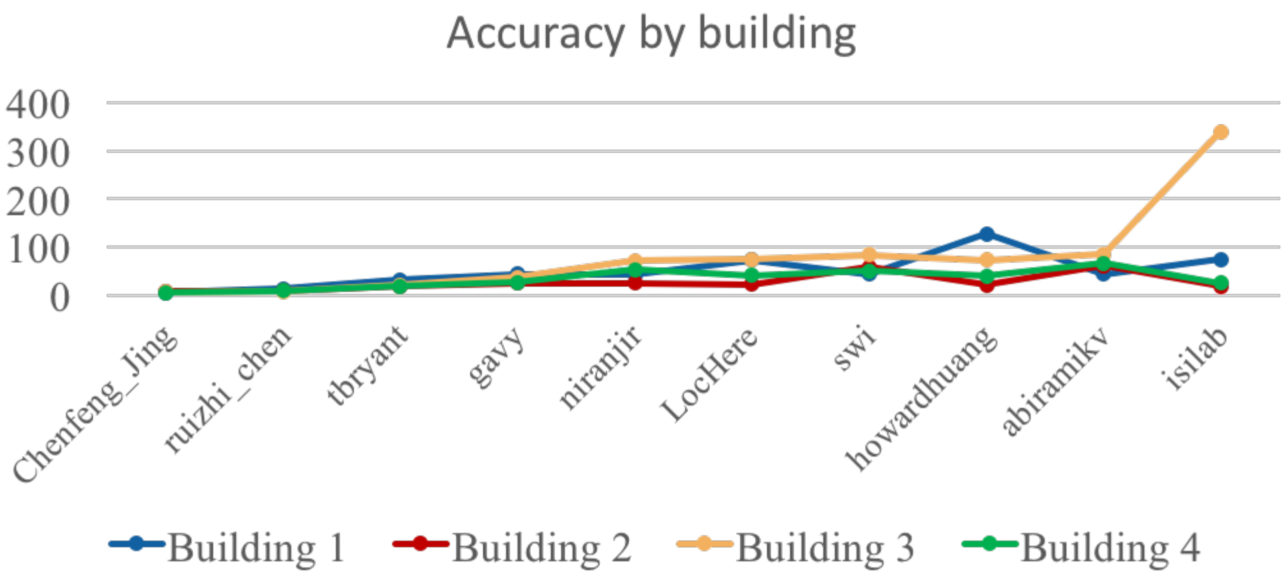
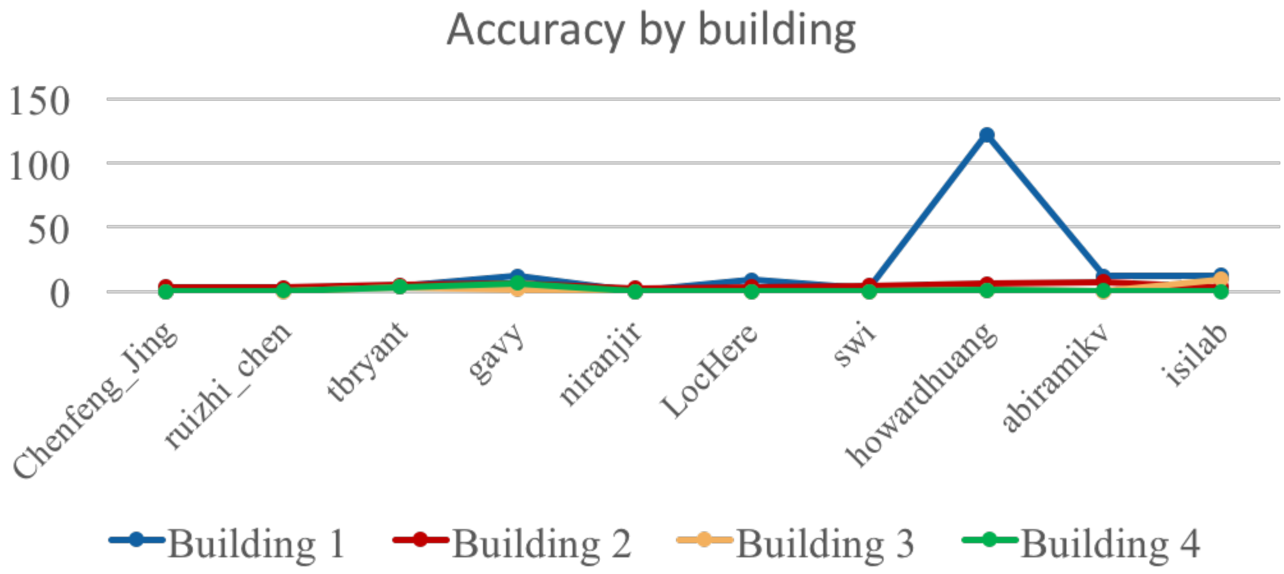
Performance of the Offline Evaluation

Rank	Participant	SE95 Performance (in meters)			
		Building 1	Building 2	Building 3	Building 4
1	Chenfeng_Jing	5.44	7.04	6.26	5.38
2	ruizhi_chen	12.74	8.6	7.34	8.99
3	tbryant	31.92	17.78	20.93	17.91
4	gavy	42.71	24.56	37.28	26.33
5	niranjir	41.88	24.81	71.25	52.27
6	LocHere	73.12	21.83	74.55	40.29
7	swi	42.79	57.68	82.99	49.62
8	howardhuang	126.9	20.2	72.77	39.83
9	abiramikv	42.71	60.14	84.95	65.39
10	isilab	73.59	17.98	339.3	25.03

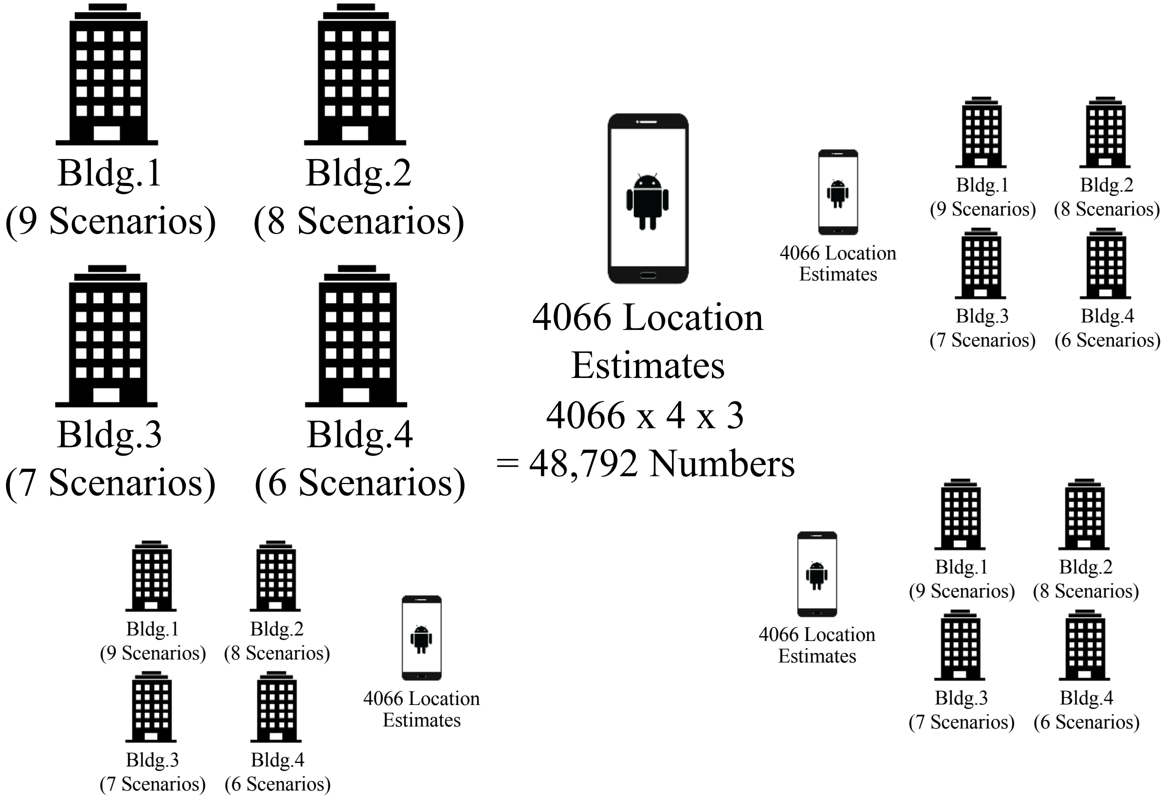
Performance of the Offline Evaluation



Performance of the Offline Evaluation



Offline Evaluation of Algorithms



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Closing Remarks

- Offline results are impressive reflecting
  - Availability of training data
  - Post-processing of location estimates
- Live test results reflect real-time operation with minimal building information.
- PerfLoc is over, but the problem of developing more effective smartphone indoor localization apps is still open.
- PerfLoc data will continue to be available for use. Take advantage of it!

Hyper-Reality Helmet for Mapping and Visualizing Public Safety Data

Carnegie Mellon University

Yang Cai (PI)

Mel Siegel
Pedro Pimentel
Lily Olson
Akshan Jain

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Web: cmu.edu/vis

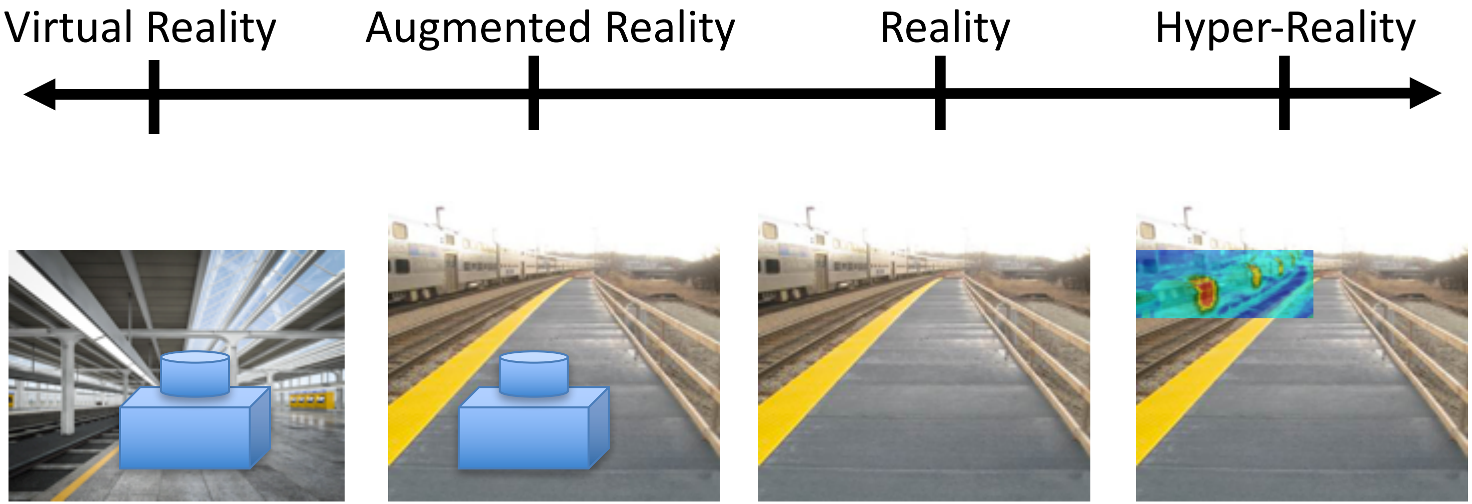
Research Problems

To be aware of the surrounding environment is critical to first responders.

It is challenging to work indoor where GPS signal is not available.

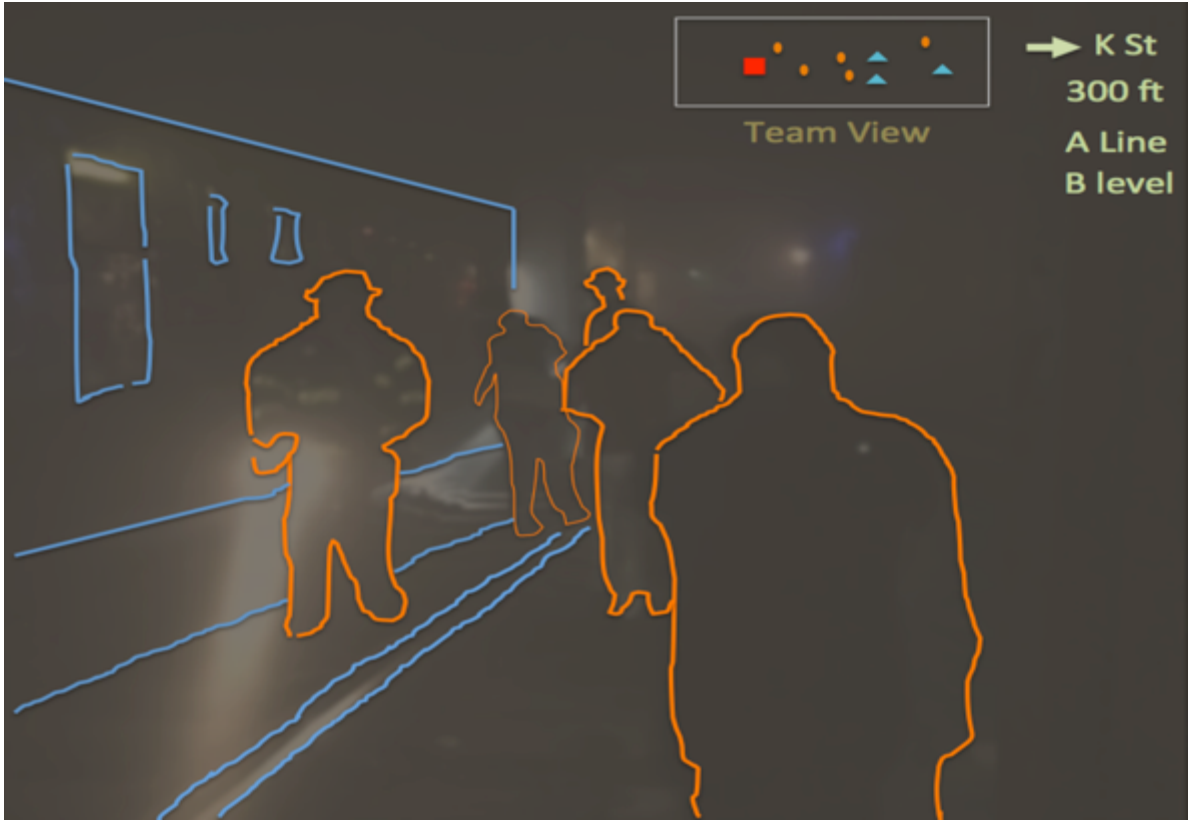
- Where am I heading?
- Which floor am I on?
- Where am I?
- What’s behind the smoke?

What is Hyper-Reality?



Hyper-Reality Display on a Plane Seatback

Subway Fire Scenario



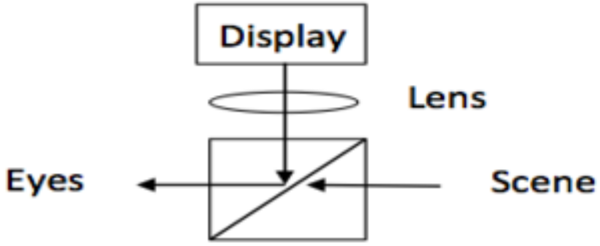
Specific Goals for Year One

1. Rapid prototyping the hyper-reality helmet

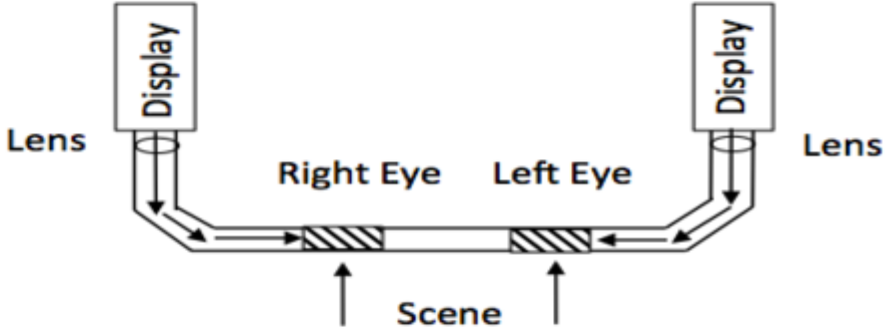
2. Landmark detection and tracking functions

Hyper-Reality Helmet Design

Optical Designs for Near Eye Displays (NED)

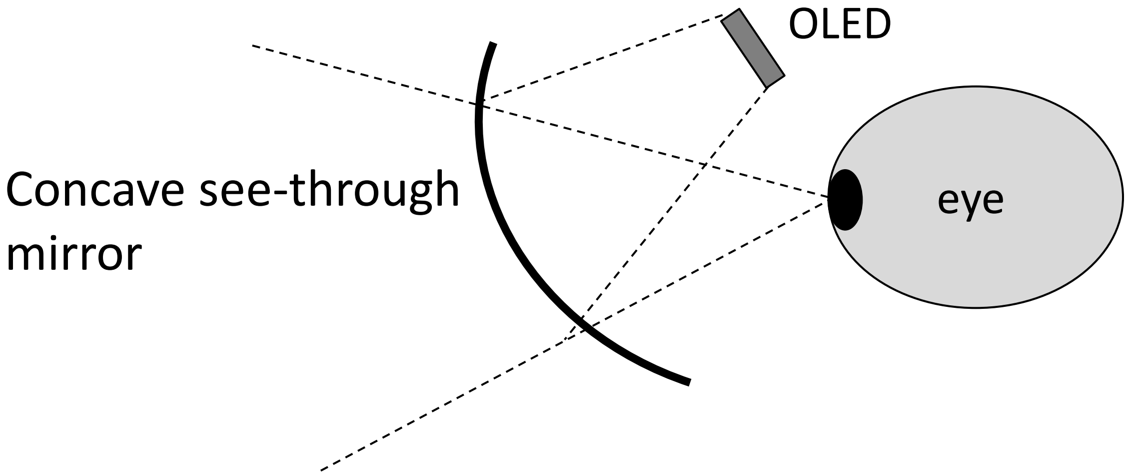


Projection



Waveguide

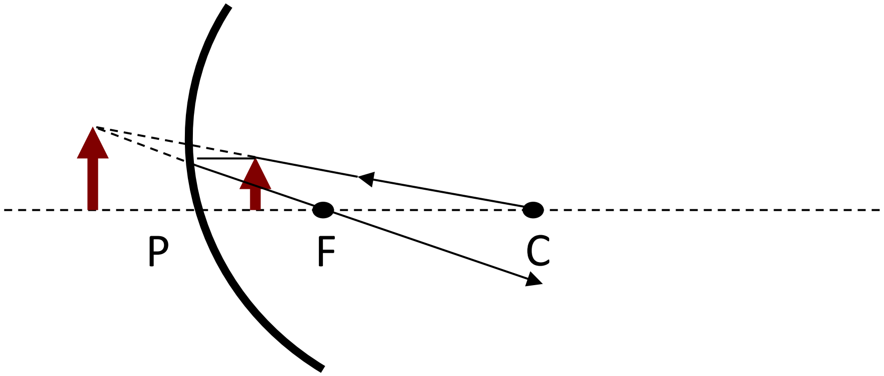
Near Eye Display (NED)



Properties of Holographic Image

When the object is placed between principal focus and pole of a concave mirror, an enlarged, virtual, upright, and mirrored image is formed behind the see-through mirror.

- Enlarged
- Virtual
- Upright
- Mirrored



Concave see-through mirror

Pros and Cons of Concave Visor Projection

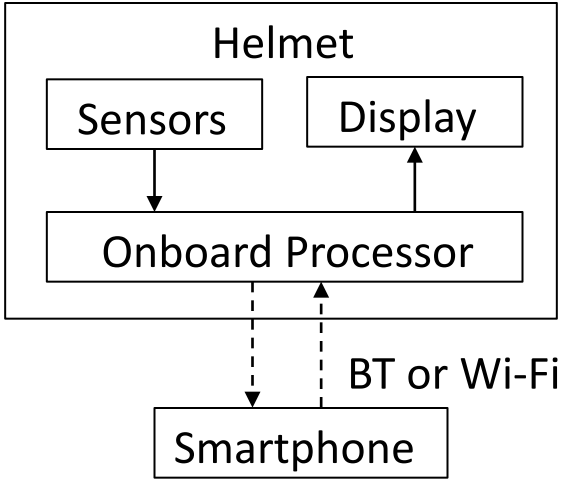
Pros:

- Wider view
- Simple optics
- Inexpensive to mass produce

Cons:

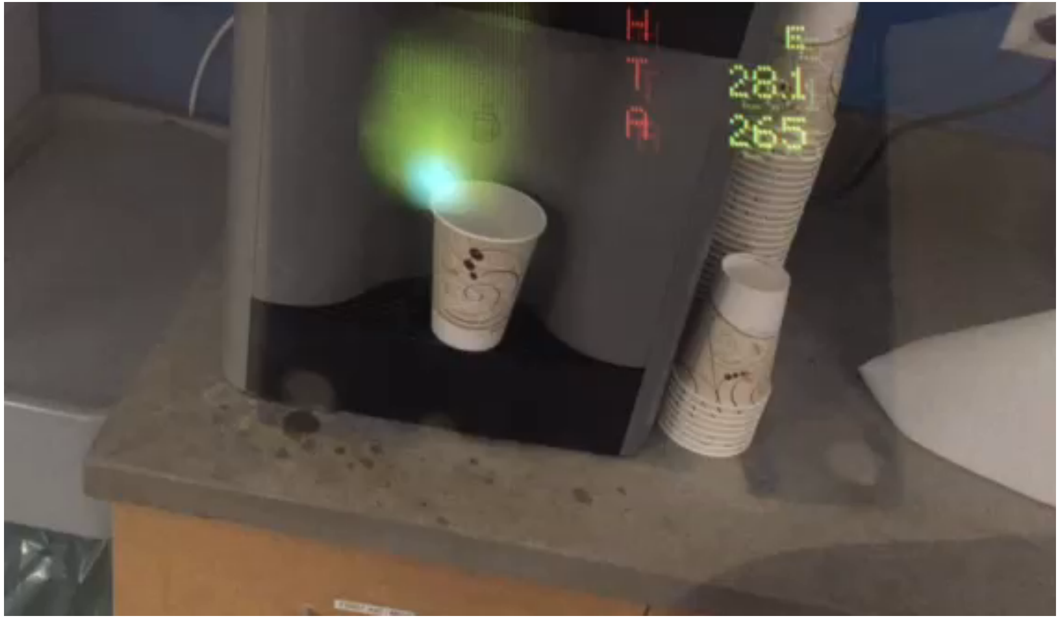
- Large visor
- Mirrored image
- Some Image distortion
- Complex molding

System Design



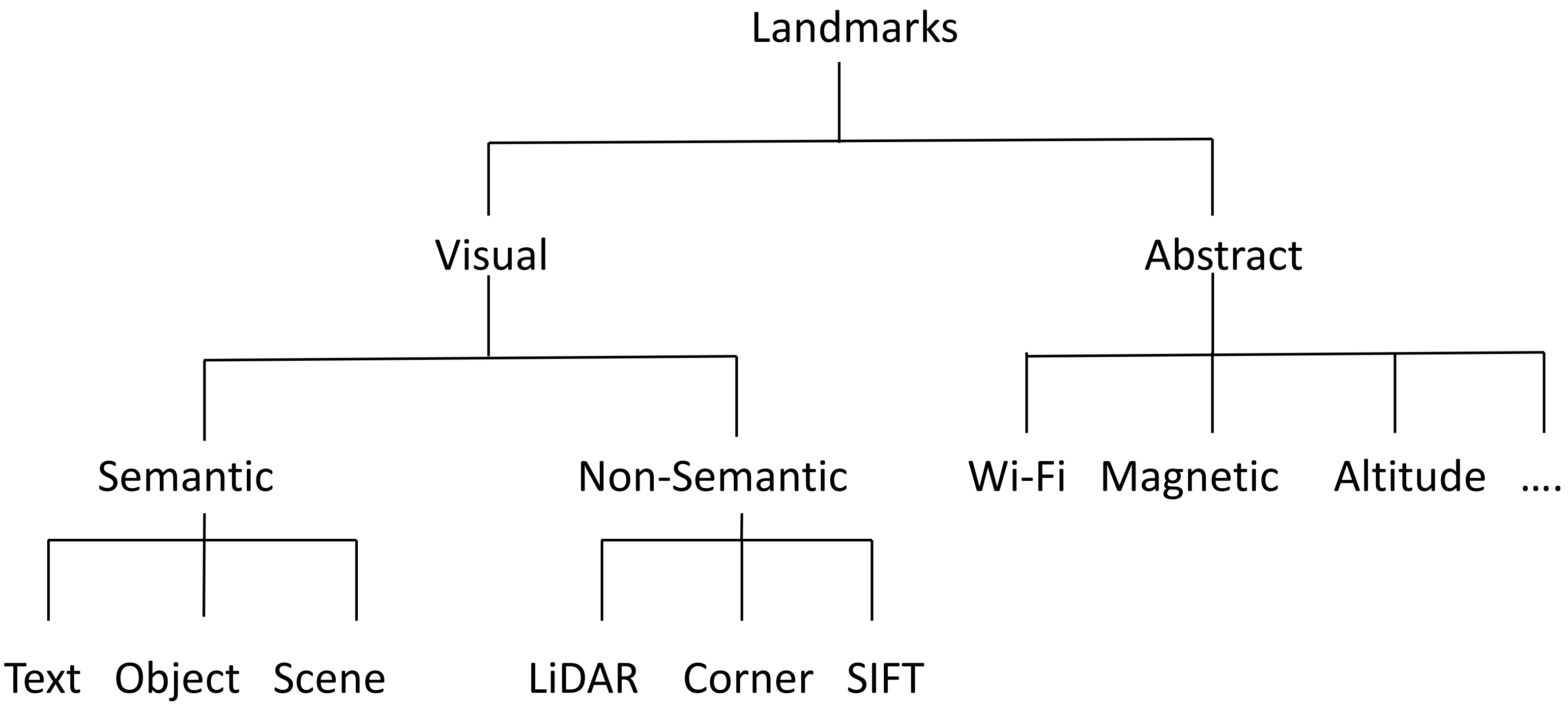
Prototype Demo

The HR helmet overlays the thermal image, heading (H), temperature (T), and altitude (A) on the visor.



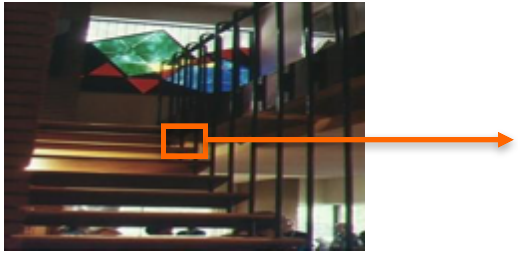
Landmark Detection and Tracking

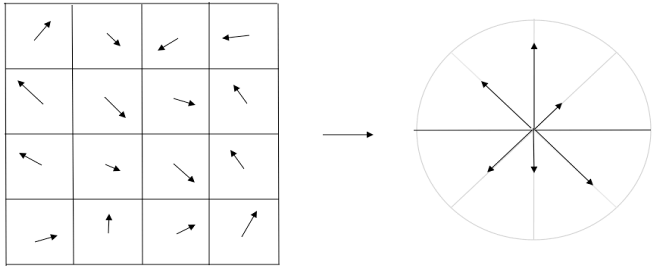
Landmarks and Tracking Algorithms



Detect Object or Scene with Histogram of Gradient (HOG)

1. Divide an image into a grid of cells
2. Calculate gradient for each cell
3. Produce histogram of gradients for each cell
4. Normalization for local contrast
5. Form feature vectors for train samples
6. Train a classifier with sample images (SVM, CNN, or RBF)



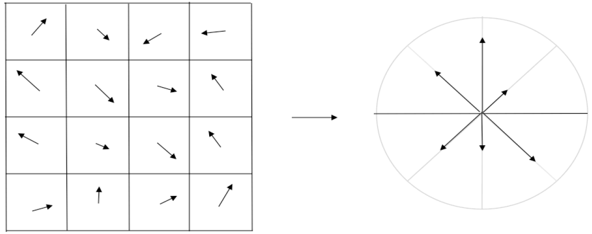


Staircase vs. Alley: 87.5%, Staircase vs. Jail Cell: 86%, Staircase vs. Ball Pit: 89%

Based on 2,000 training images per class from Places365 dataset, by Alan Cai

Detect and Track a Shape with SIFT Key Points

1. Calculate Difference of Gaussian (DoG)
2. Get key points by localizing maxima
3. Filter out edges and low contrast points
4. Assign the orientations for key points.

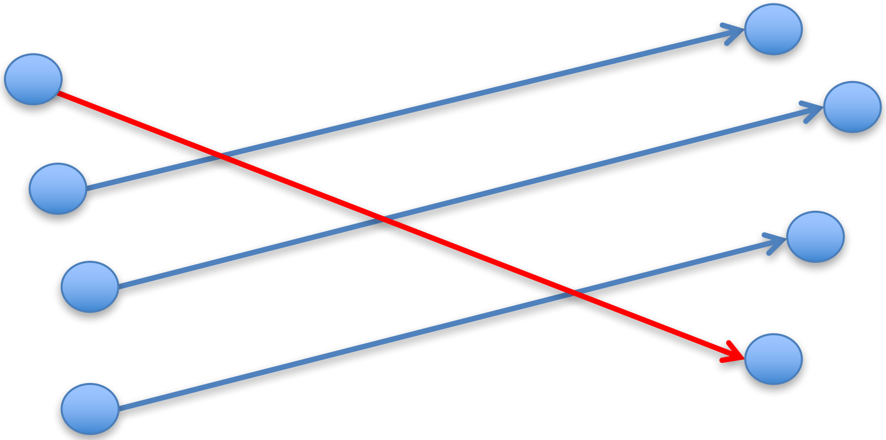


4 x 4 vectors x 8 directions = 128 dimensional feature vector

How to Find Matching Key-Points?

To spot the outliers that don't fit the model.

Inliers



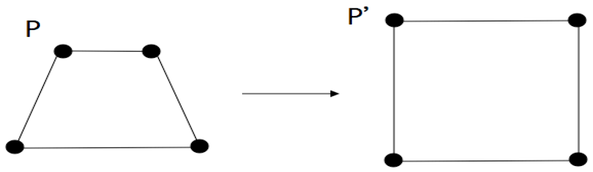
Outliers

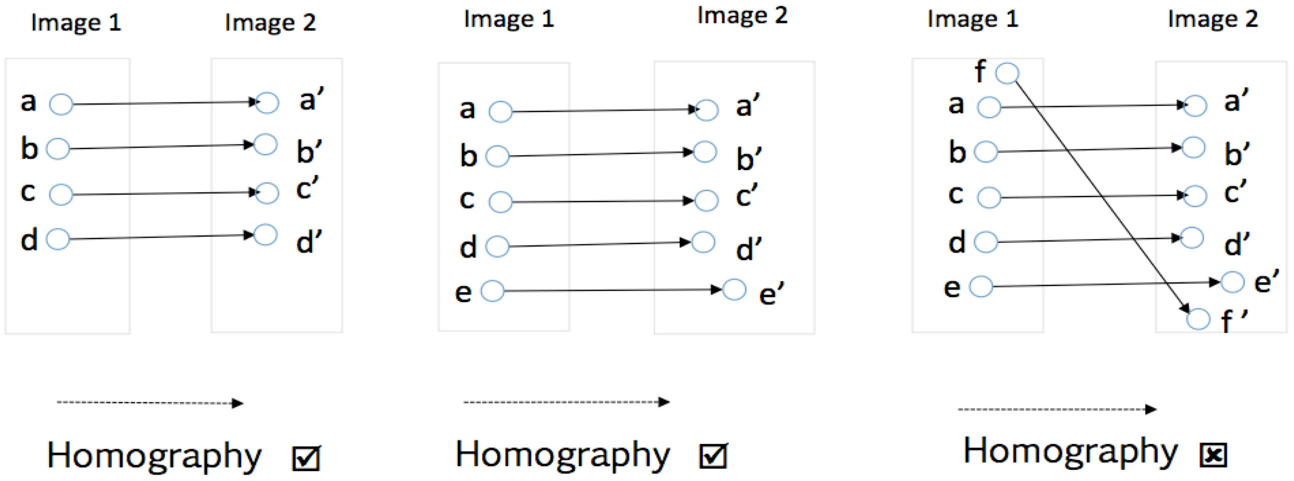
RANSAC (RAndom SAmple Consenus)

Fischler and Bolles in 1981

Example of Corresponding Points Validation

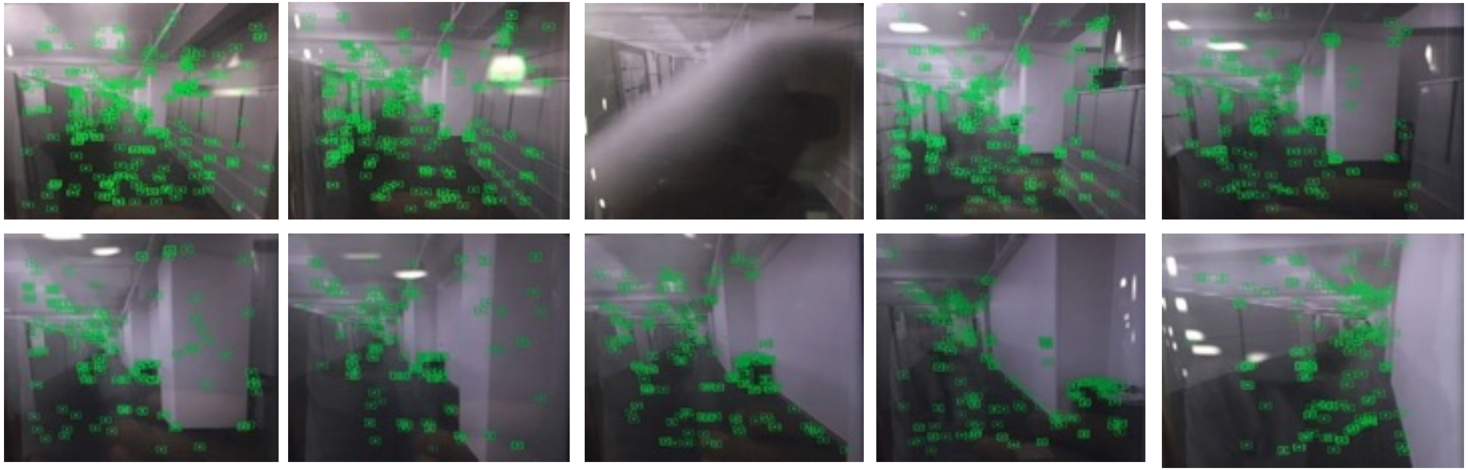
A homograph is a transform, including scaling, rotation and translation.





SIFT Feature Detection and Tracking

- Tracked well in smooth motion
- Recovered from interruption at the same area
- Failed to track in low feature areas or sharp turns

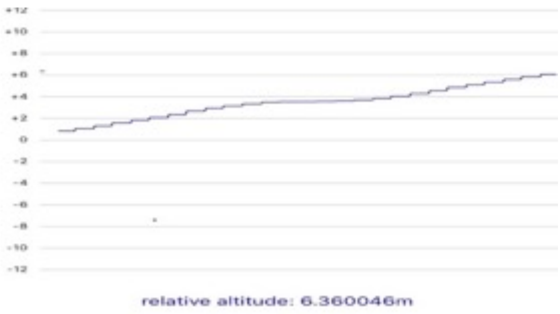


Breadcrumb Navigation

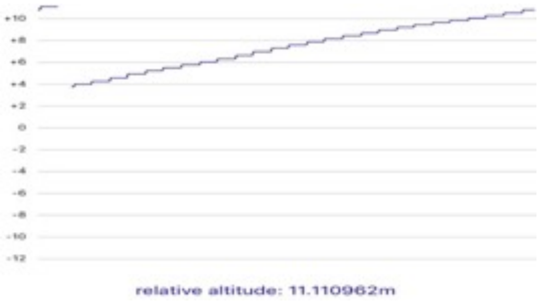
Hansel and Gretel left a trail of breadcrumbs to show their return path.

Motion and Location Signatures

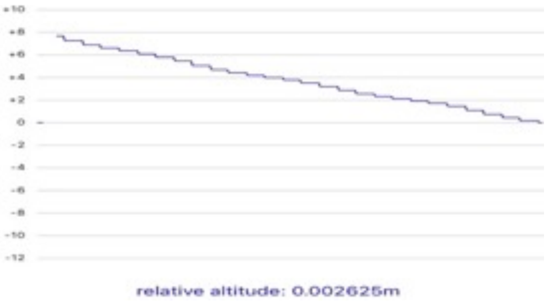
walking up stairs with turns



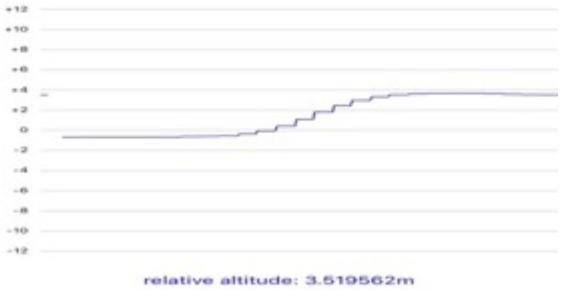
walking up stairs



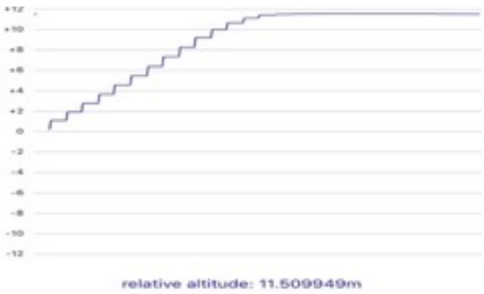
walking down stairs



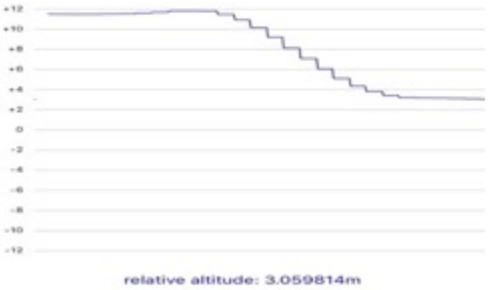
walking up stairs (short)



elevator moving up

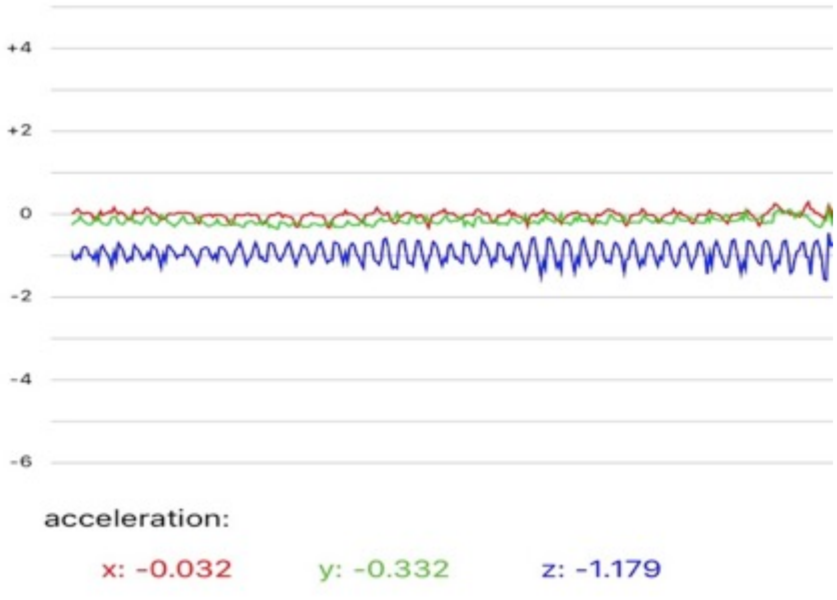


elevator going down

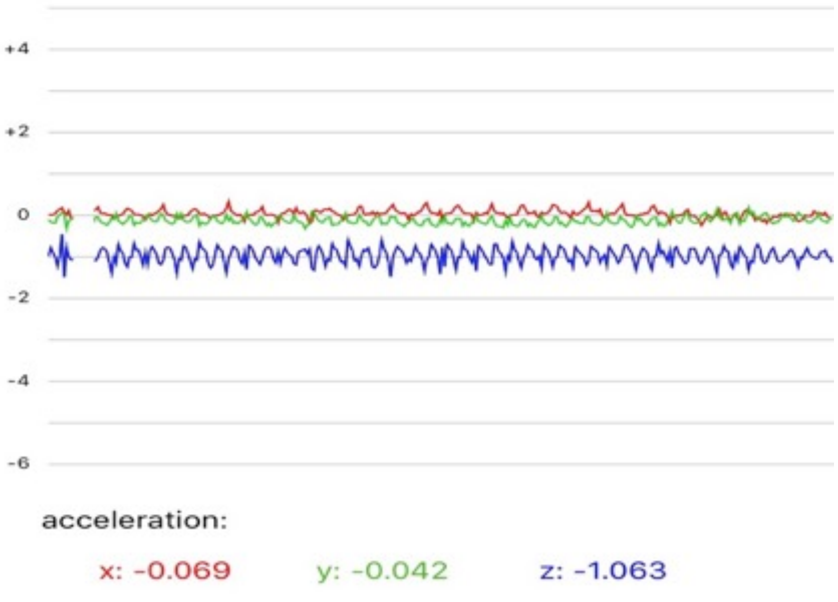


Accelerometer Signatures of Walking (Raw Data)

walking on carpet



walking on cement floor



Wi-Fi Signal Localization

91% CMU-SECURE
100% eduroam
73% wireless
93% CMU
93% CMU-GUEST
44% wireless
:

100% CMU-SECURE
100% eduroam
NA wireless
NA CMU
100% CMU-GUEST
100% wireless
48% HawxeyeNet5
:

73% CMU-SECURE
80% eduroam
86% wireless
NA CMU
100% CMU-GUEST
100% wireless
NA HawxeyeNet5
66% notours
73% DIRECT-6e-HPM477 LaserJet
:

Dynamics of Wi-Fi Signals

- Wall attenuation of signals
- Signal strength is dynamic
- Wi-Fi access points may change overtime
- Mobile phone IP addresses vs. land network IP addresses (e.g. 128.x.x.x for CMU)
- Some access point names indicate places (e.g. HP LaserJet)

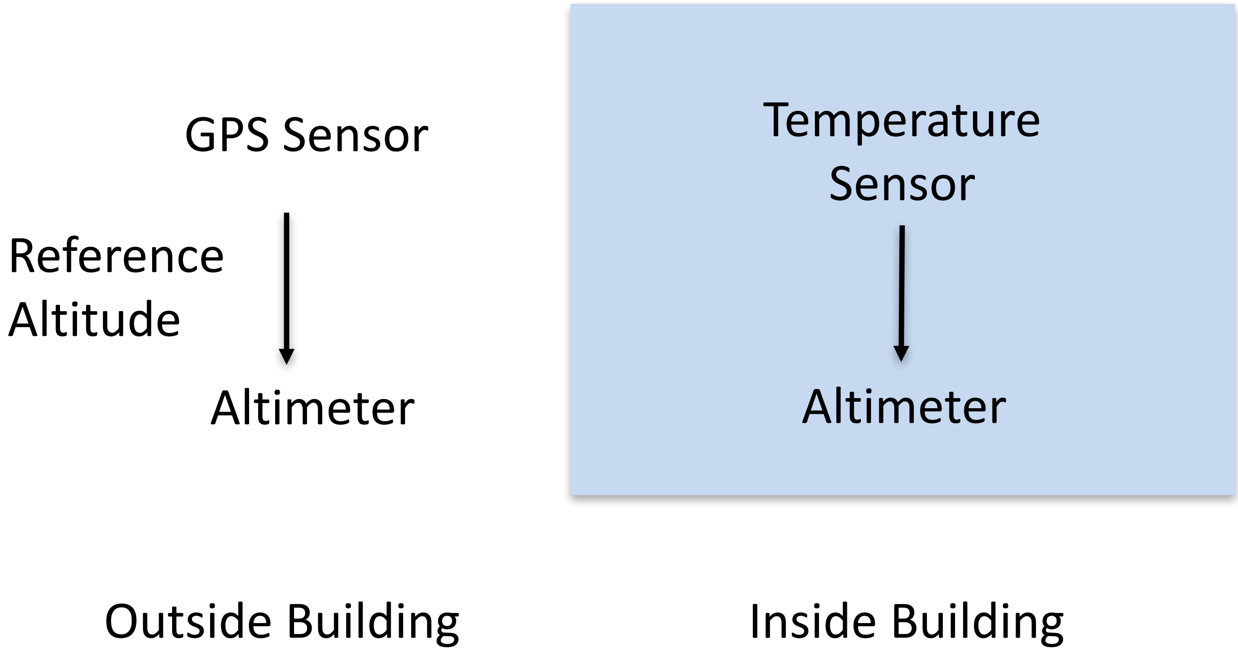
All Reality Is Interaction. – *Carlo Rovelli*

Sensor Calibration

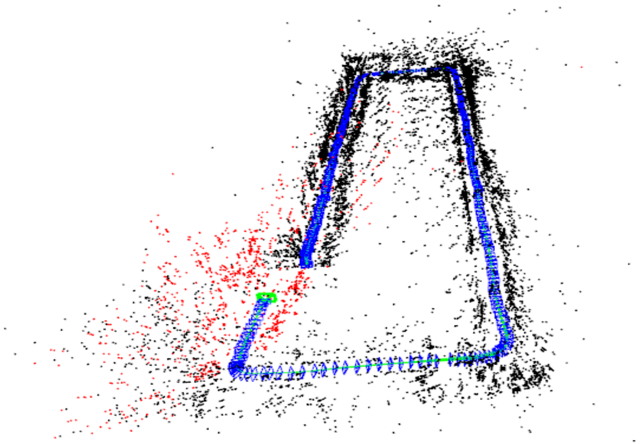
All sensors need calibration.

- Infrared camera: Flat Flash Calibration (FFC)
- Magnetic Field Sensor: Rotation
- Altimeter Sensor: Ground pressure
- Pedometer Sensor: Stride distance
- SLAM algorithms: Camera parameter calibration

Pervasive Sensory Fusion

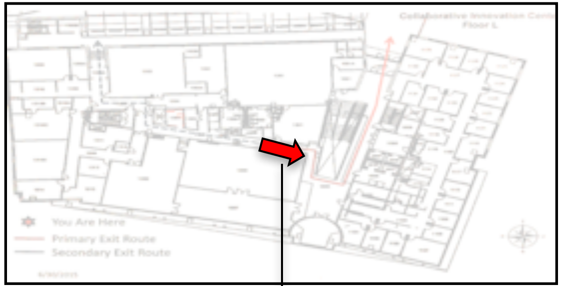


Moving from Path Reconstruction to Navigation Assistance



Reconstructed Path

Heading: SE
Ground Floor
10m to Lobby



My location and heading

Summary

1. We explored optical and electronic designs for the hyper-reality helmet for first responders.

2. We prototyped basic functions for heading, altitude and thermal imaging.

3. We explored methods for landmark detection and tracking.

4. Our challenge is how to interact with the real-world. We need to solve many Edge Computing problems, such as automatic sensor calibration and pervasive sensor fusion.

5. Our approach is “less-is-more” through situation-awareness and symbolic articulation.

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4. Ophir Tanz, et al.: Wireless Network Positioning. LNCS (LNAI), vol. 3345. Springer, Heidelberg (2005)

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Deployable Broadband Networks

Sam Ray
Hien Nguyen
Maxwell Maurice

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.

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Department of Homeland Security
Science & Technology Directorate
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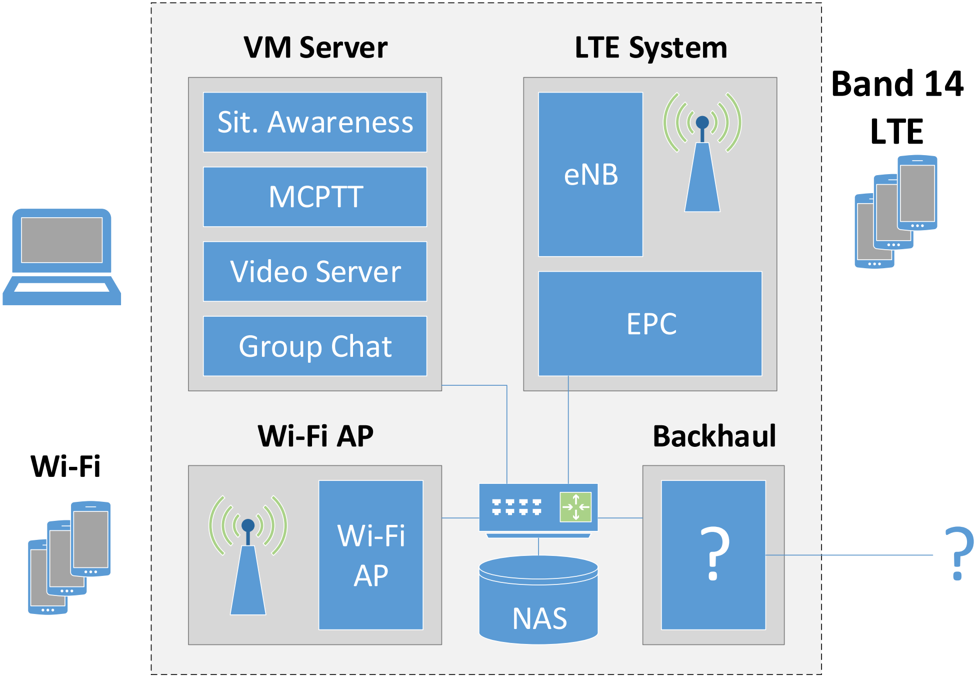
(DHS S&T OIC)

AGENDA

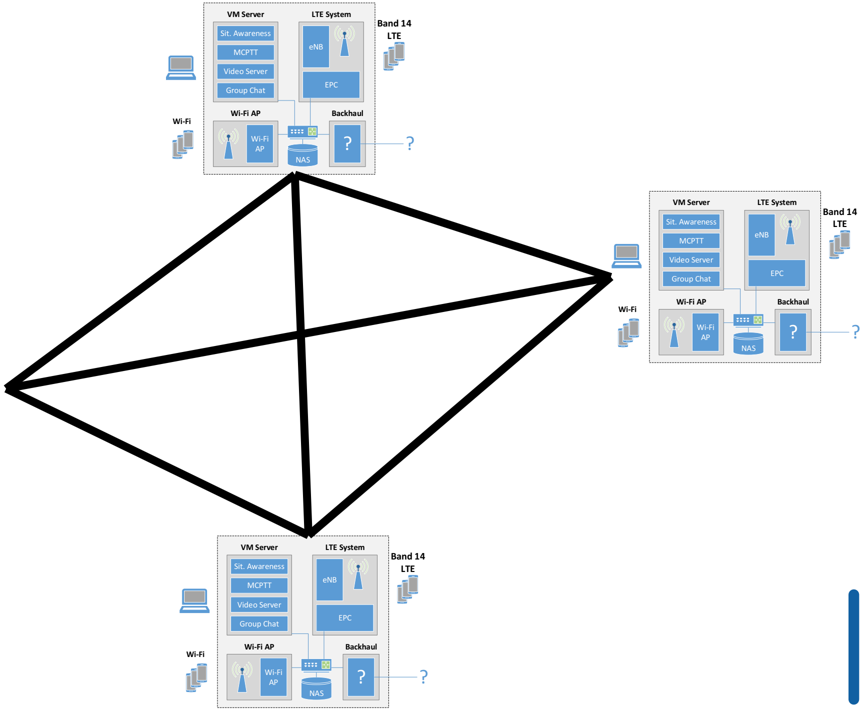
Deployable Systems

Hien Nguyen



Highly Mobile Deployed Networks (HMDN)

Max Maurice



AGENDA

Deployable Systems

Hien Nguyen

Current and Future Systems, Network Elements and Architecture

Identifying Essential Systems and Applications

Laboratory and Field Research Testing

Highly Mobile Deployed Networks (HMDN)

Max Maurice

DS interconnectivity

Completely isolated systems

Viability and performance of DS delivery platforms

Solutions to current problems in multiple and mobile systems

Deployable Systems (DS) Research Focus

- Exploring current and future systems, network elements and architecture
- Identifying essential systems and applications
- Laboratory and field research testing
- Engaging with first responders and public safety communities, academia and industries for feedback, adjustments and improvements

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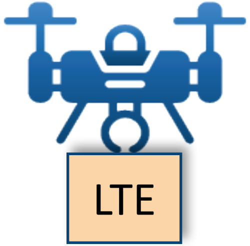
DS - Network Elements and Architecture

Cell On Wheels (COW)

System On Wheels (SOW)

Backpack



Airborne Platform

Range and Capacity

Transportability and Mobility

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DS – Typical Operational Parameters

DS Type	Operational	
	Coverage Radius	Number of Users
COW (40 watts)*	5 miles	> 100
SOW (5 watts)	2 miles	50
Backpack (3 watts)	1 mile	30
Airborne (250 milliwatts)	< 1 mile	< 20

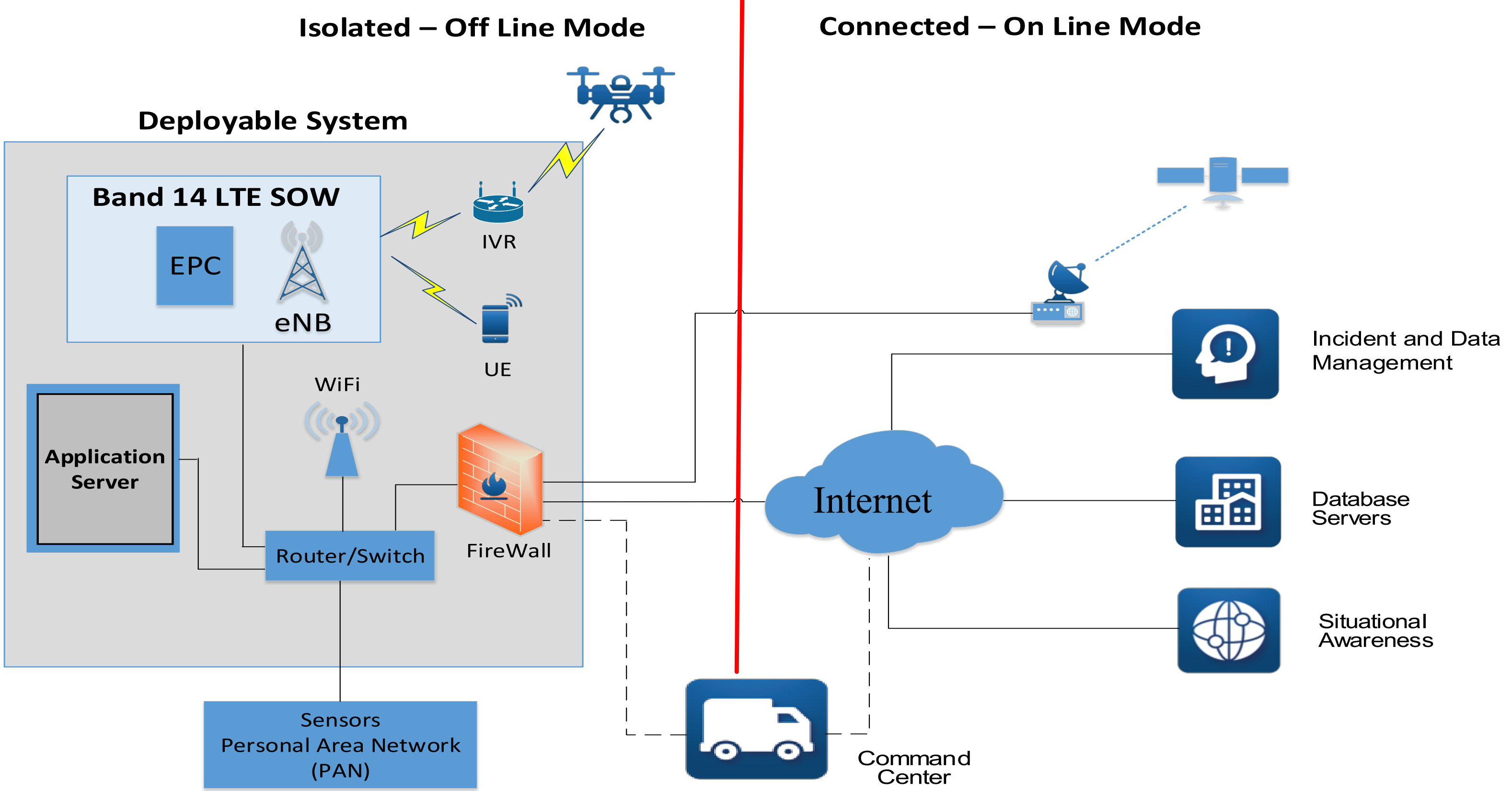
(*COW requires backhaul connection to EPC)

Note: All numbers are approximate depending on many factors, e.g., the system, environment and terrain, antenna gain and height

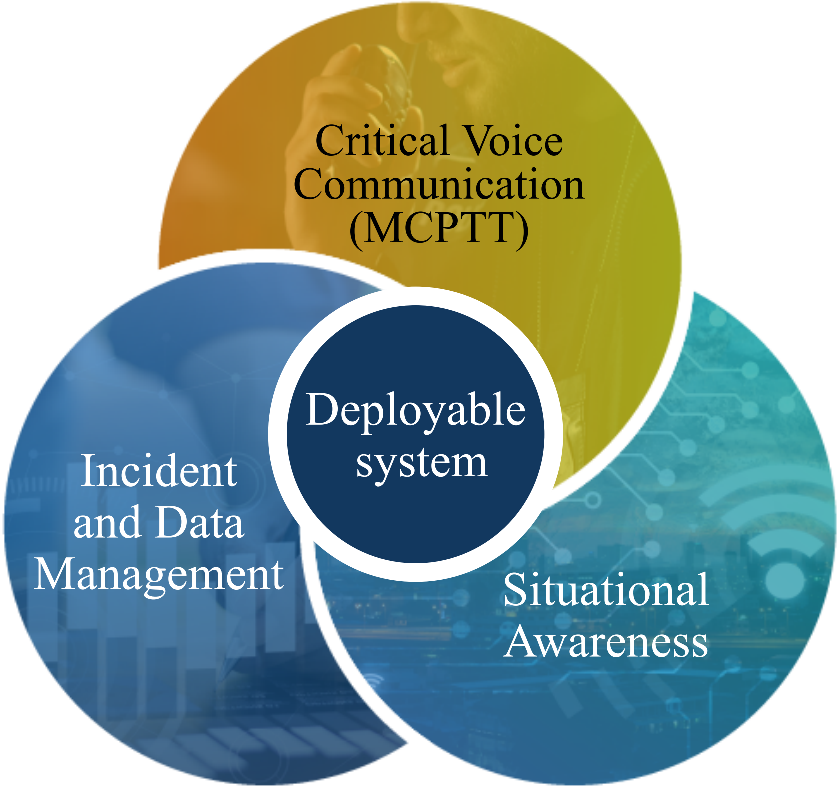
Finding from field testing:

"It is highly desirable for deployable systems to have a capability that can automatically recognize each other's presence and organize in such a way to enhance the overall coverage and performance"

DS - Network Elements and Architecture



DS - Essential and Integrated Systems and Applications



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DS - Critical Voice Communications

Features

- Priority Call(s)
- One to One Call
- Group Call
- LMR to LTE Interoperability

Future Activities

- MCPTT Features Testing
- Mission Critical Video

DS – Situational Awareness

Features

- Incident alert
- Intuitive and ease of use for users
- Personnel and resource location and management
- UAS flight path, telemetry data and video streaming
- IoT sensors inputs and displays
- Connected and isolated operation modes

Future Activities

- Transcoding H.263 video to H.264
- Adding FLIR thermal camera to drone
- Integrating sensor data and SA data to incident and data management system

Unexpected Findings

- Video stream from drone's camera coming into the control tablet is H.263 video format
- Most current video servers in the industry only accept H.264 video format

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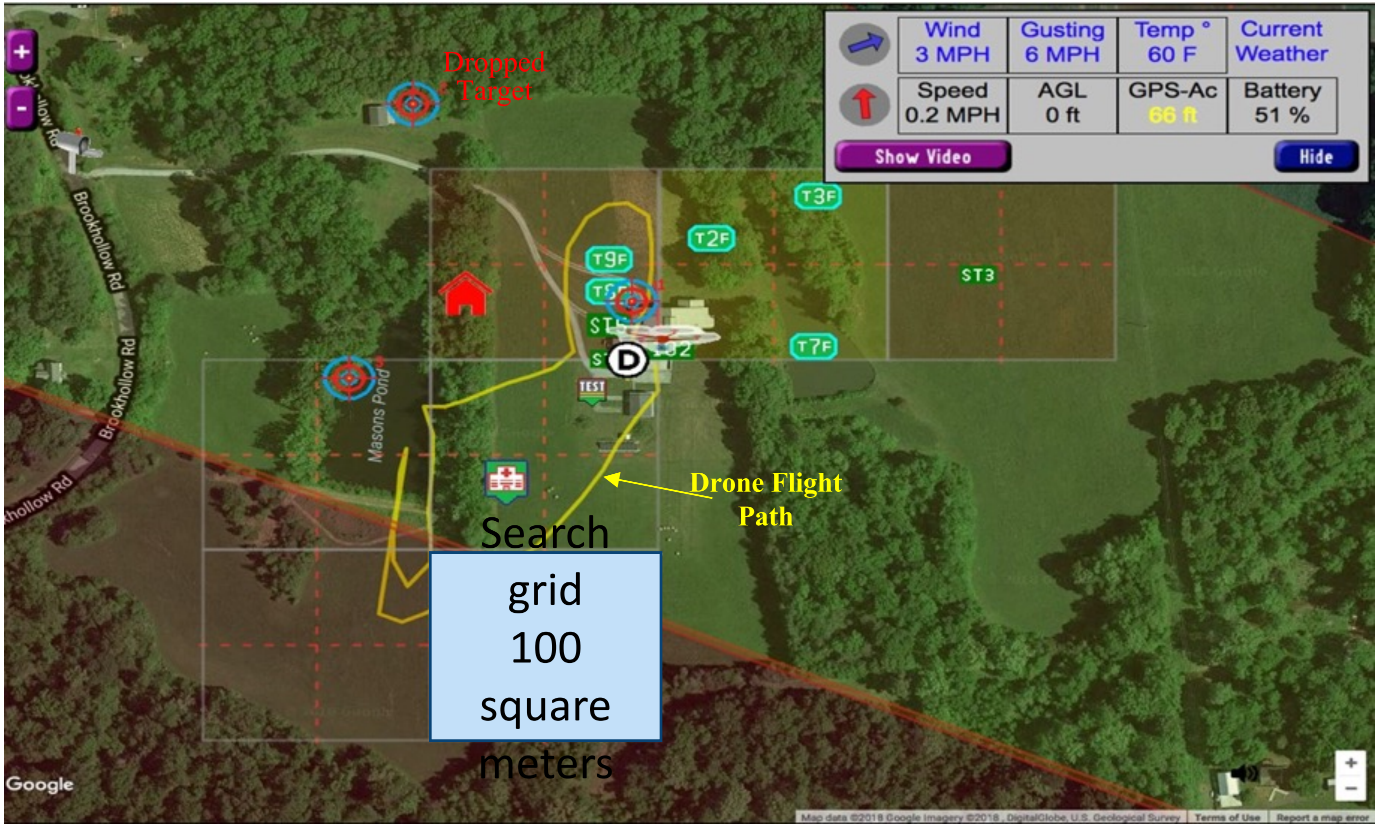
DS – Situational Awareness Incident Commander View



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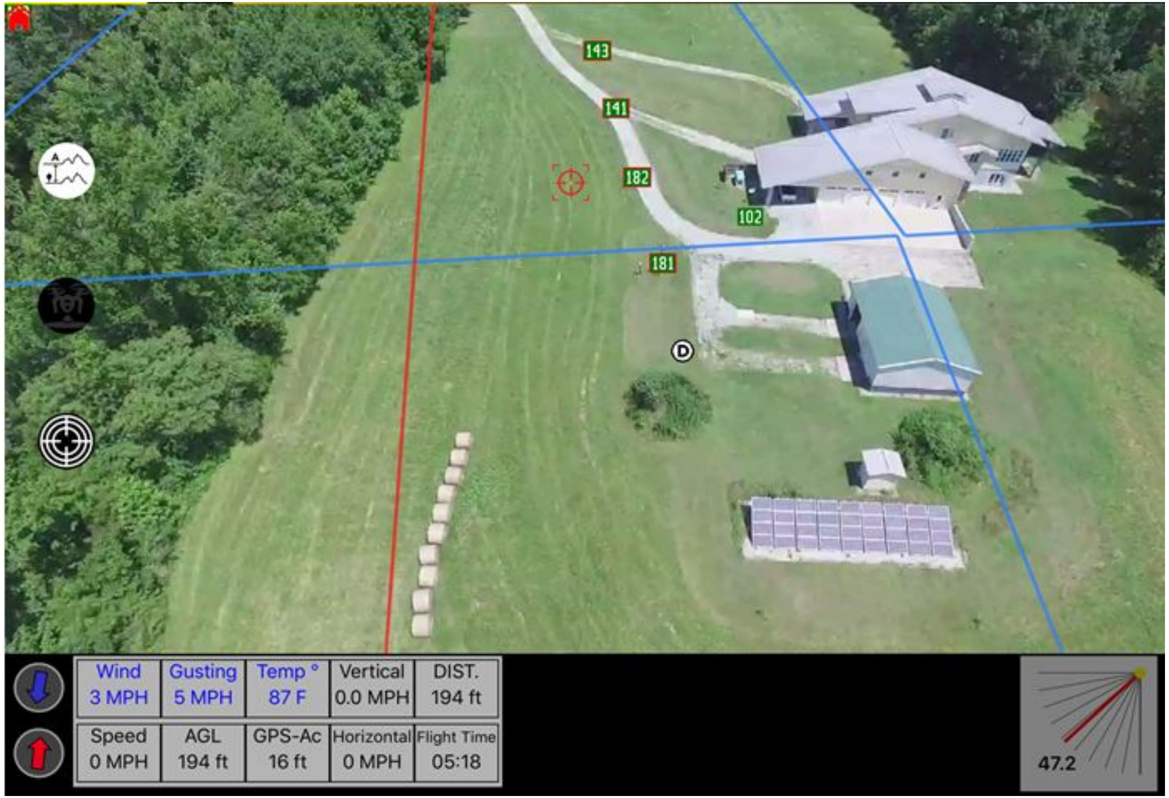
DS – Situational Awareness Drone Pilot View



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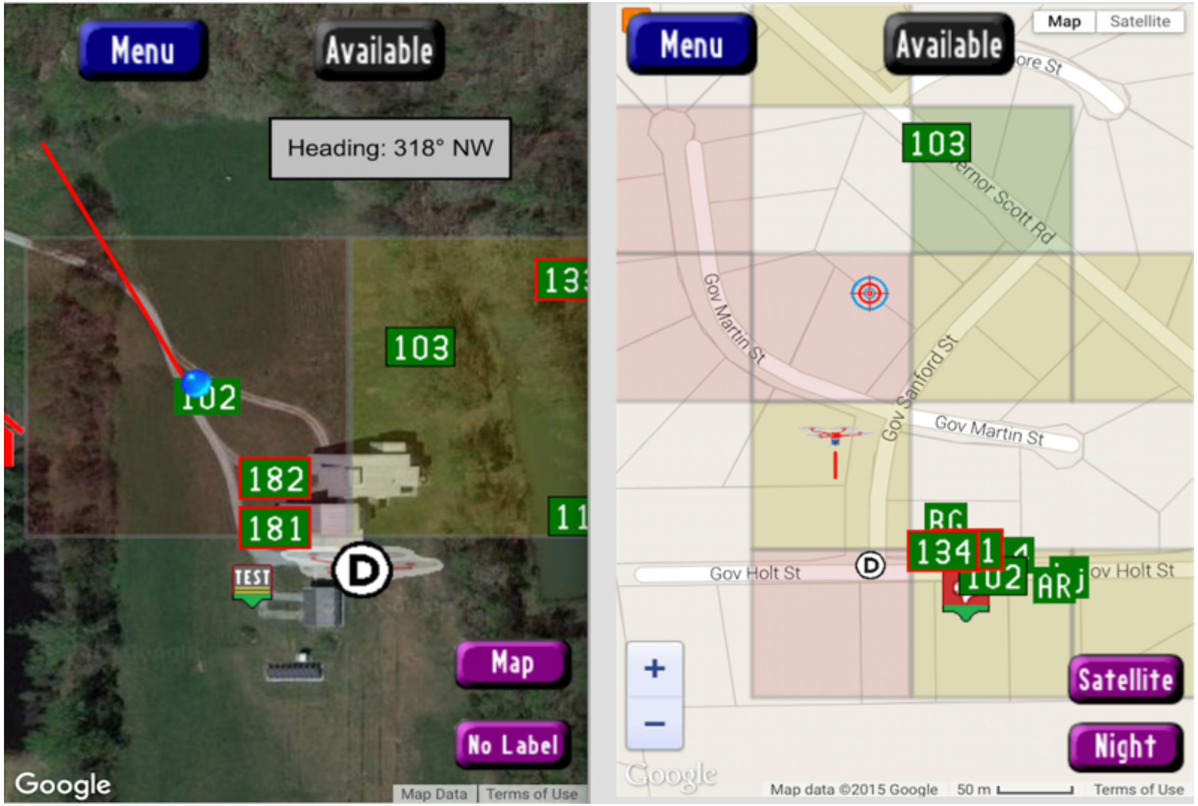
DS – Situational Awareness Responder View



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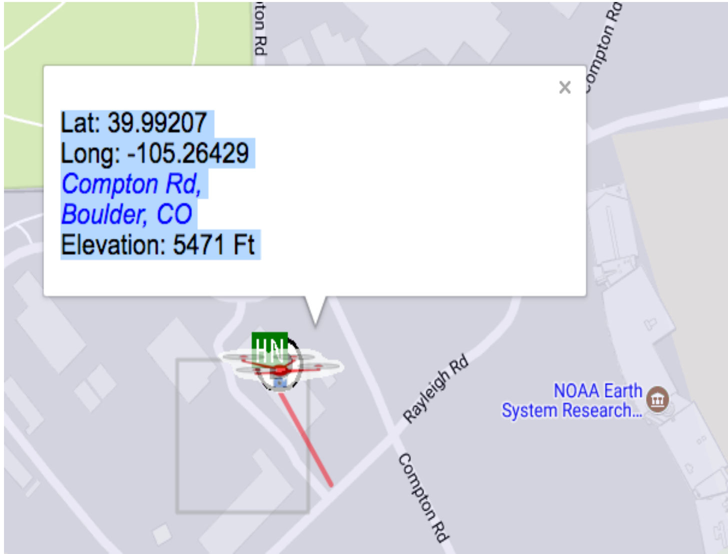
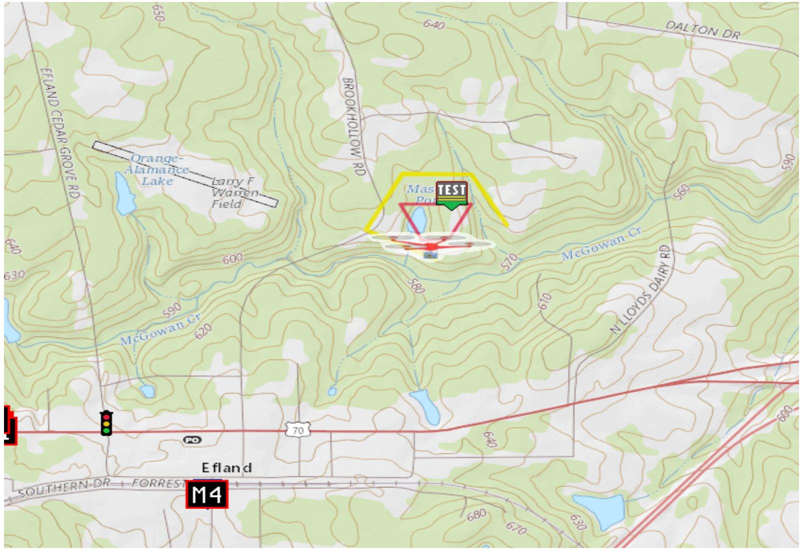
DS – Situational Awareness – On-Line and Off-Line Map Views

On-Line Mode with Google Maps



Off-Line Mode with US Topo Maps



DS – Incident and Data Management

Upcoming Research

- ➢ Delivering maximum relevant data and information to responders to minimize their interactions with technologies
- ➢ DHS and JPL Project - AUDREY (Assistant for Understanding Data through Reasoning, Extraction, & sYnthesis)
- ➢ AUDREY - Artificial Intelligent (AI) management system
  - ✓ Collect Data
  - ✓ Correlate and Analyze Relevant Data
  - ✓ Synthesize, Learn, Interpret and React
  - ✓ Deliver Insight to First Responder

  (Source: Dr. Ed Chow, JPL)

Future Goals

- ➢ Integration of AUDREY into DS for isolated incident operation
- ➢ Connection from DS to AUDREY for cloud based operation

DS - Laboratory and Field Research Testing

Laboratory Testing

Field Testing

DS - Public Engagement for Feedback and Improvements

First Responders and Public Safety Communities

- ✓ Fire Departments – Efland FD, NC
- ✓ Boulder Emergency Squad (BES)
- ✓ Colorado Center of Excellence for Advanced Technology Aerial Firefighting (CoE)

Industries

- ✓ LTE and Broadband Manufacturers and Suppliers
- ✓ UAS
- ✓ Situational Awareness
- ✓ Satellite

Academia and General Public

- ✓ Summits and Conferences
- ✓ Universities and National Labs
- ✓ Open Innovations - UAS Challenge
- ✓ Federal Agencies - USGS for mapping resources

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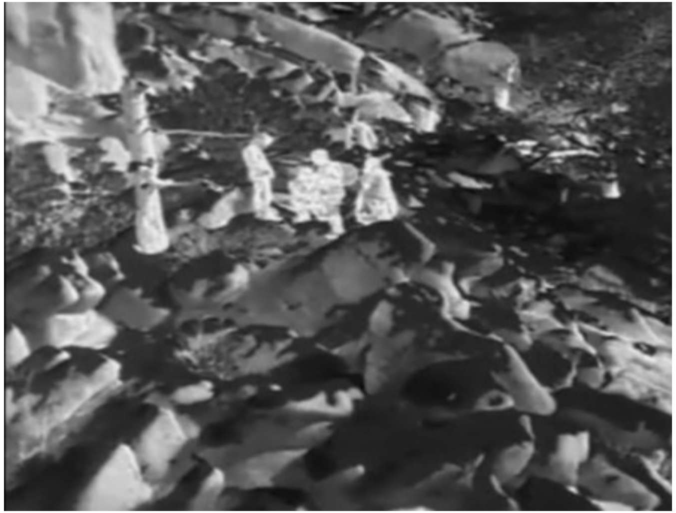
DS – Public Safety Comments and Feedback Samples



FD Live Fire Drill in Efland, NC

- ✓ Love SA app features. Wishing for FLIR thermal camera to distinguish heat sources
- ✓ Really like the target drop feature

Training Exercise With BES

- ✓ FLIR thermal camera is great in searching for people in snow
- ✓ Higher contrast on MCPTT app

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Highly Mobile Deployable Networks (HMDN) Research Focus

- Research into DS interconnectivity
- Research into completely isolated systems
- Identifying viability and performance of different DS delivery platforms
- In depth look at potential solutions to current problems in multiple and mobile systems
- Engagement with the First Responder community and the academics and industry members who support them

HIGHLY MOBILE DEPLOYED NETWORKS

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HMDN – July Round Table

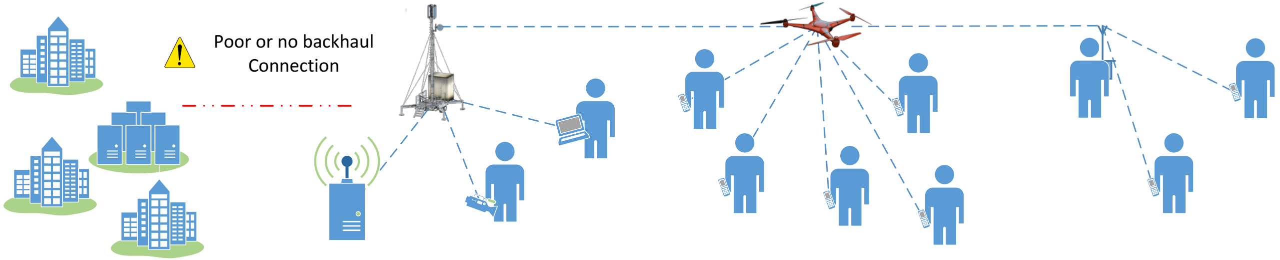
July 13th – 14th Roundtable

The July Roundtable meeting convened around 13 public safety stakeholder groups to discuss Deployable Systems. The meeting;

1. Fostered dialogue between PSCR, academia, industry and government to define what a broadband deployable system could look like in the coming years
2. Determined the key focus areas for broadband deployable networks research
3. Defined the use cases for a deployable system

We found that deployable systems fell under two general use case scenarios

Network 1 – National Public Safety Broadband Network	Network 2 – Incident Command Network	Network 3 – UAS Deployed Network	Network 4 – FRG local Netowork



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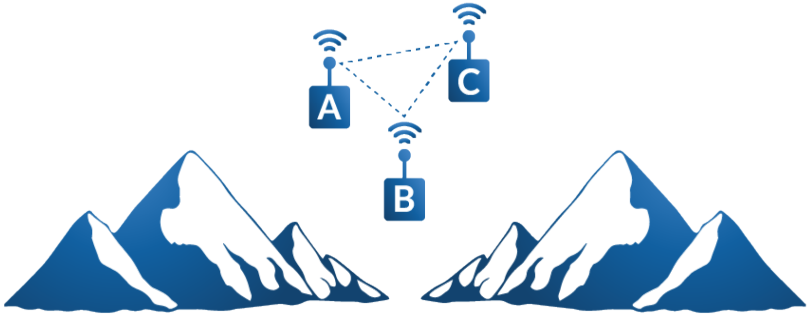
HMDN – July Round Table

Use Case 1: Dynamic Incident Area Network

Use case 1 is the completely isolated case where first responders must rely on what is brought in with them for their network and network services. There is no terrestrial LTE coverage.

This could be due to:

- Geographical factors such as remote locations.
- A disaster scenario where fixed infrastructure is compromised.
- A congested RF environment.



The other part to this use case is that these systems may be from different vendors, and operated by different agencies.

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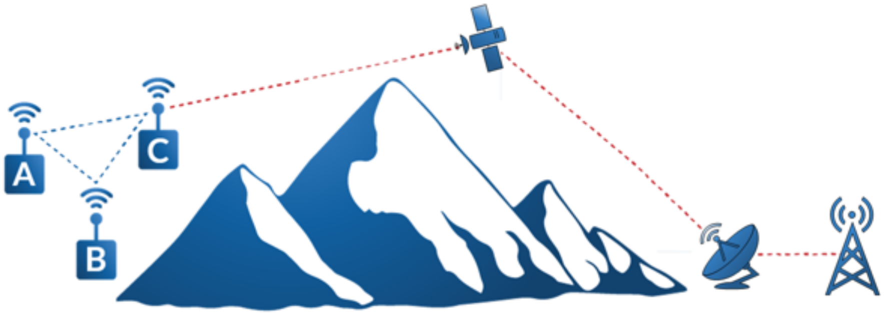
For a more comprehensive look, we put our detailed use case 1 definition below
https://www.nist.gov/sites/default/files/documents/2017/10/17/deployable_networks_use_case_1.pdf

Use Case 2: Dynamic Coverage of Existing Network

In use case 2, the deployable system is now moving in and out of connectivity with the macro network.

The system now has to evaluate
- Whether to move users' LTE connectivity to the macro network
- What processes should be moved to the macro network
- What application services can be brought in from the macro network



Having the option of being able to offload services to the macro network changes the way deployables operate entirely.

For a more comprehensive look, we put our detailed use case 2 definition below
https://www.nist.gov/sites/default/files/documents/2017/10/17/deployable_networks_use_case_2.pdf

HMDN – October Summit

October 18th - 19th Summit

The October Summit convened over 85 public safety stakeholders from industry, academia, and government. The primary outcomes of the summit were;

1. The perceived most important technology gaps in the current market of deployable systems for public safety.
2. High level solutions to advance LTE architecture, Application architecture, Network resiliency, and others to meet the technology gaps from part 1.
3. To come up with the ways PSCR can evaluate the technology gaps and solutions for future implementation.

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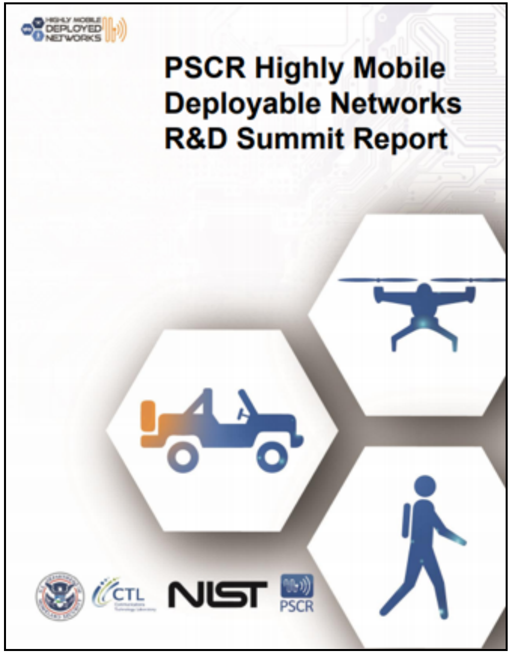
HMDN – October Summit R&D Report



The October Summit Report showed the next steps in the HMDN and Deployables projects. The major highlights from the report are in the technological gaps found by attendees; below are a couple examples:

Gap 1.1 -- The inability for automatic intelligent decision making for data routing, replication, storage, and processing

Gap 2.1 -- The inability for deployables made from different vendors to recognize and cooperate with each other

Gap 2.4 -- No decentralized core-to-core communication

Gap 3.2 -- No ad-hoc roaming agreement ability

Gap 4.2 -- No data or in depth description of the deployed network architecture is available

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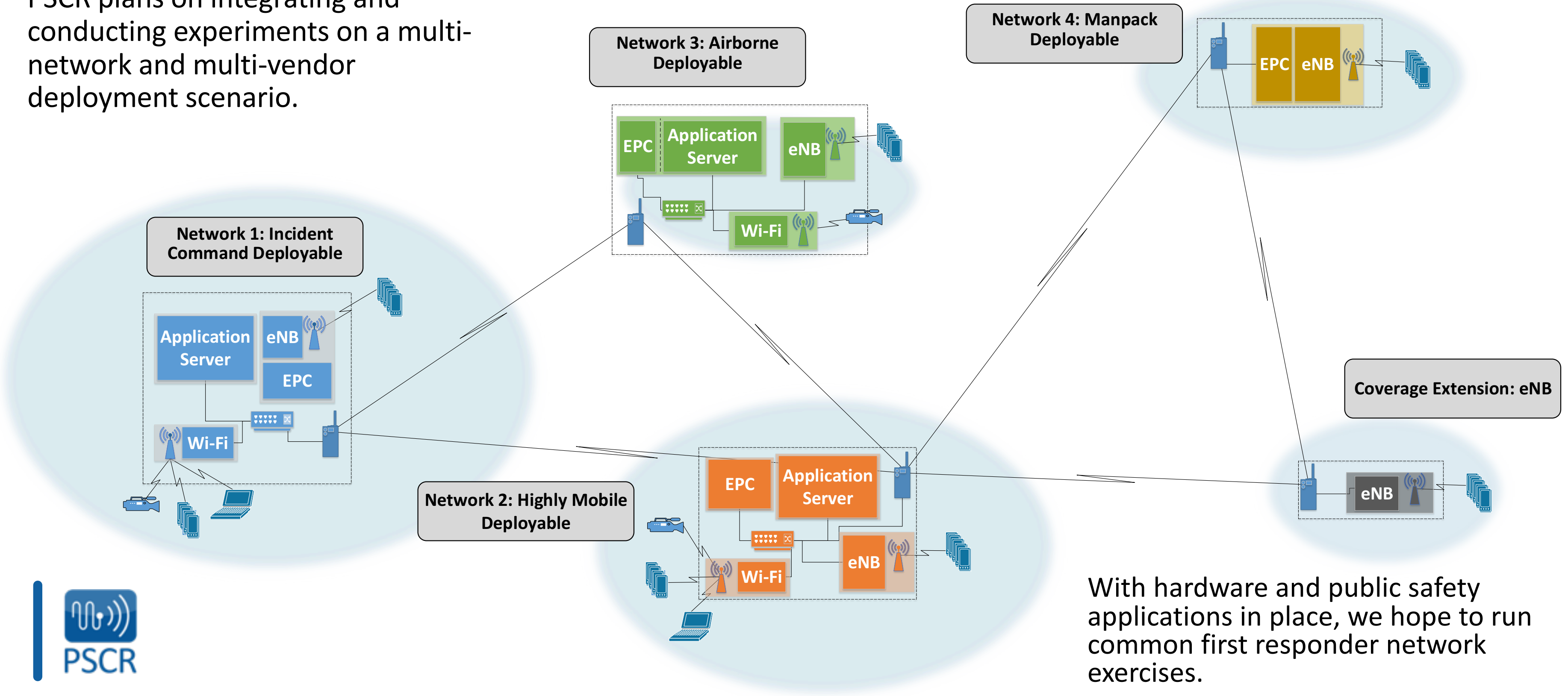
The report was published in February and can be accessed below
https://www.nist.gov/sites/default/files/documents/2018/02/27/hmdn_rd_summit_report.pdf

HMDN – Future Testing Architecture

PSCR plans on integrating and conducting experiments on a multi-network and multi-vendor deployment scenario.



With hardware and public safety applications in place, we hope to run common first responder network exercises.

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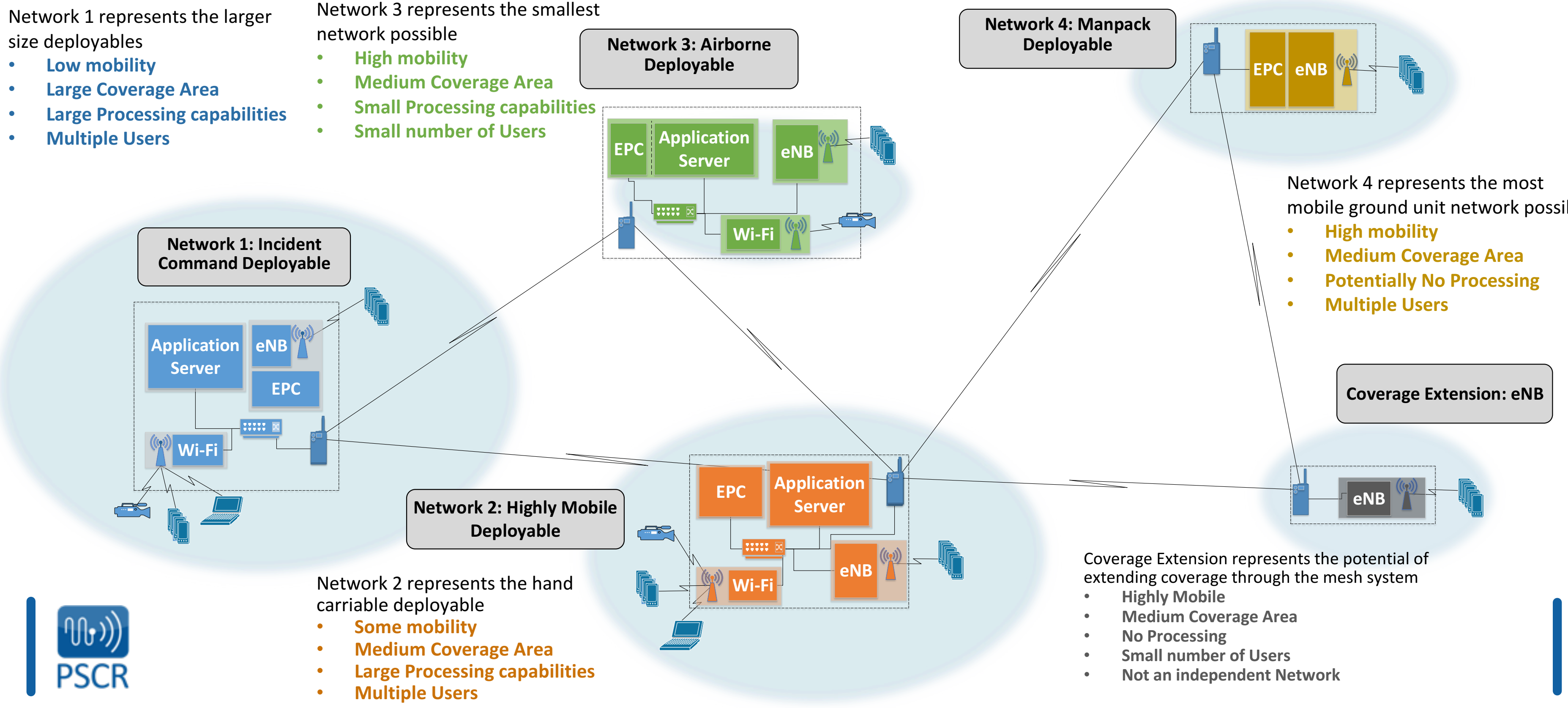
HMDN – Future Testing Architecture

Network 1 represents the larger size deployables
- Low mobility
- Large Coverage Area
- Large Processing capabilities
- Multiple Users

Network 3 represents the smallest network possible
- High mobility
- Medium Coverage Area
- Small Processing capabilities
- Small number of Users



Network 4 represents the most mobile ground unit network possible
- High mobility
- Medium Coverage Area
- Potentially No Processing
- Multiple Users

Network 2 represents the hand carriable deployable
- Some mobility
- Medium Coverage Area
- Large Processing capabilities
- Multiple Users

Coverage Extension represents the potential of extending coverage through the mesh system
- Highly Mobile
- Medium Coverage Area
- No Processing
- Small number of Users
- Not an independent Network

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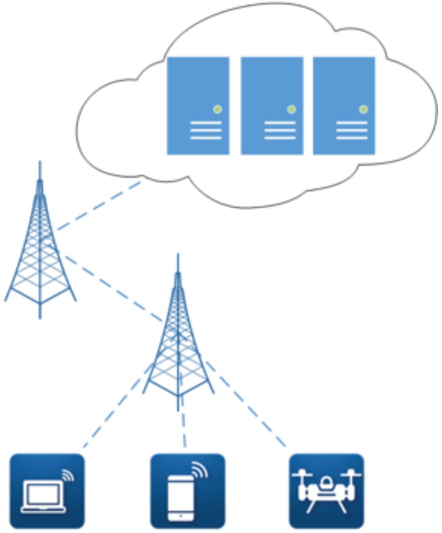
HMDN – Evaluation of an ICN for Deployable Systems

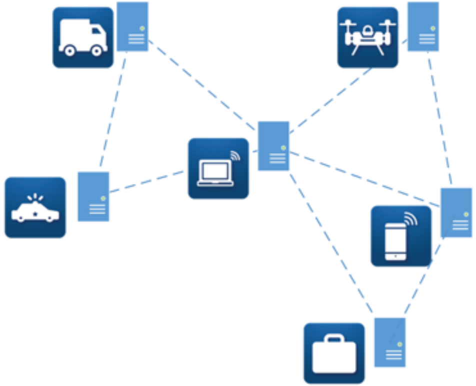
Most recently the HMDN project has taken a look at Information Centric Networking as a solution to solve the problem of routing and constant disconnectivity. An Information Centric Network can provide decentralized and constantly broken nodes natively through its networking architecture.

Large External Servers and Data Centers:

- Users must provide the connection back
- Method introduces multiple single points of failure
- All devices in the field must connect to the one link out somehow
- Higher latency



VS



Multiple Local Data Stores:

- Users must bring everything they need
- No single point of failure
- Low cost connections to each edge based data store
- Lower latency in this method

What this architecture could solve:

Gap 1.1 -- The inability for automatic intelligent decision making for data routing, replication, storage, and processing

With data now decentralized and on multiple nodes in the network, first responders can access critical information as the roam within the network.

A partnership between the Emerging Network Technologies group within NIST is work on establishing a demo NDN that would allow for lab testing and evaluation of what NDN can offer for the HMDN scenario.

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THANK YOU

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Maxwell Maurice | maxwell.maurice@nist.gov

Modeling and Development of Resilient Communication for First Responders in Disaster Management

Project Members

Prof. K. K. Ramakrishnan – University of California, Riverside

Prof. Murat Yuksel – University of Central Florida

Prof. Hulya Seferoglu – University of Illinois at Chicago

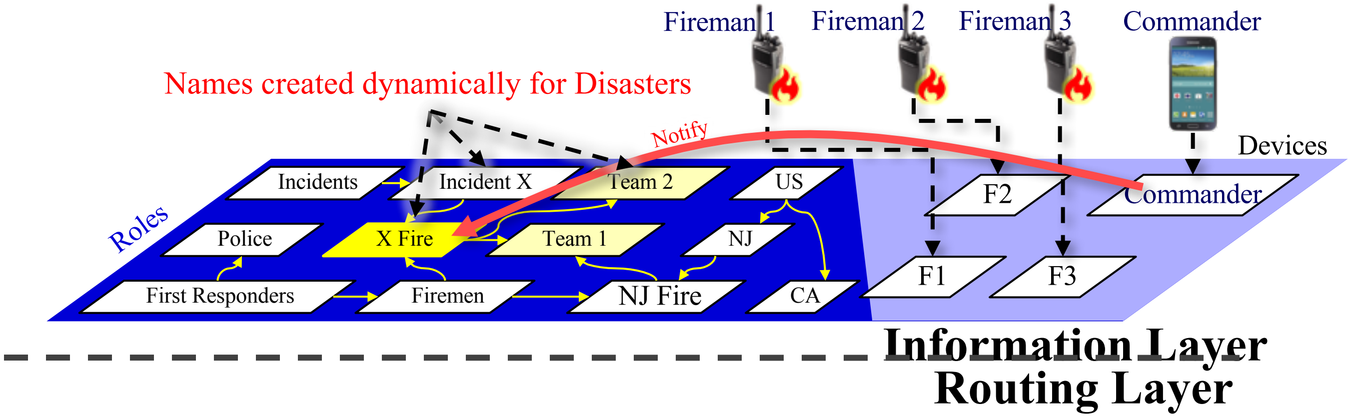
Dr. Jiachen Chen – WINLAB, Rutgers University

Importance of Communication for Disaster Management

- Communication is key to improving outcomes in the aftermath of a disaster
- However, it is in the aftermath of a disaster that we are likely to face communication challenges:
  - Infrastructure may be impacted
  - Communication channels may be congested
- Keys to an effective response to a catastrophic incident:
  - Effective communication within and among dynamically formed first responder teams
    - Public safety teams comprising: law enforcement, health, emergency, transport and other special services, depending on the nature and scale of the emergency
  - Communication with stranded individuals and the public at large
- **Project Objective: A network architecture for information and communication resilience in disaster management.**

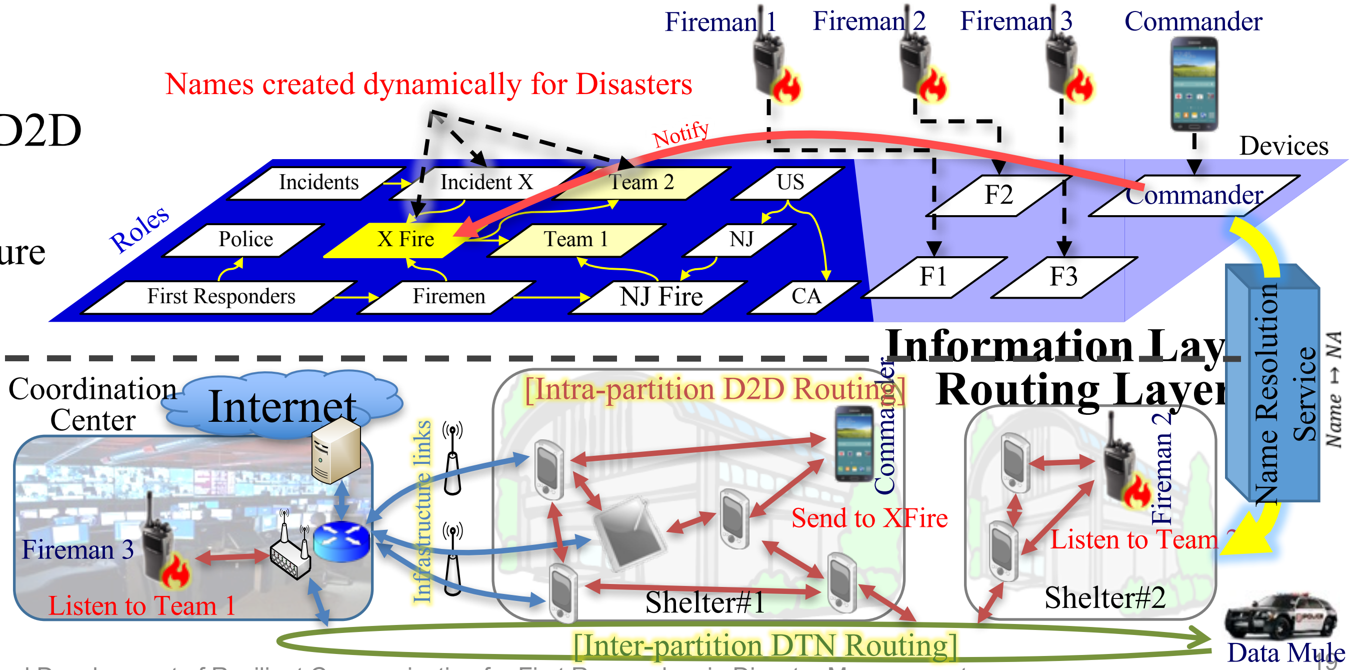
Proposed Architecture

- **Information Layer**
  - Facilitate communication among dynamically formed first-responder teams
  - Information-Centric (Role-Based) Communication
    - Communication based on dynamically created roles, rather than locations
- **Routing Layer**



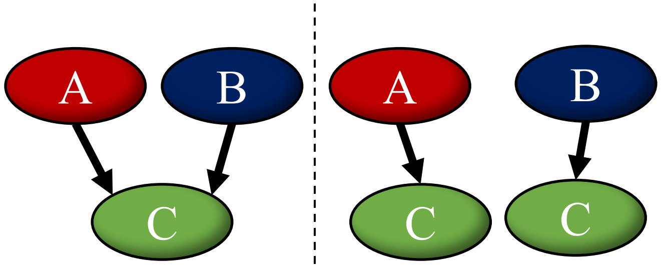
Proposed Architecture

- **Information Layer**
  - Facilitate communication among dynamically formed first-responder teams
  - Information-Centric (Role-Based) Communication
    - Communication based on dynamically created roles, rather than locations
- **Routing Layer**
  - Intra- & inter-partition D2D communication
    - Resilient to the infrastructure disruptions
    - Smart mode-switching
  - Coding for robustness and resiliency
    - D2D computation
  - Content-based security



Namespace Design

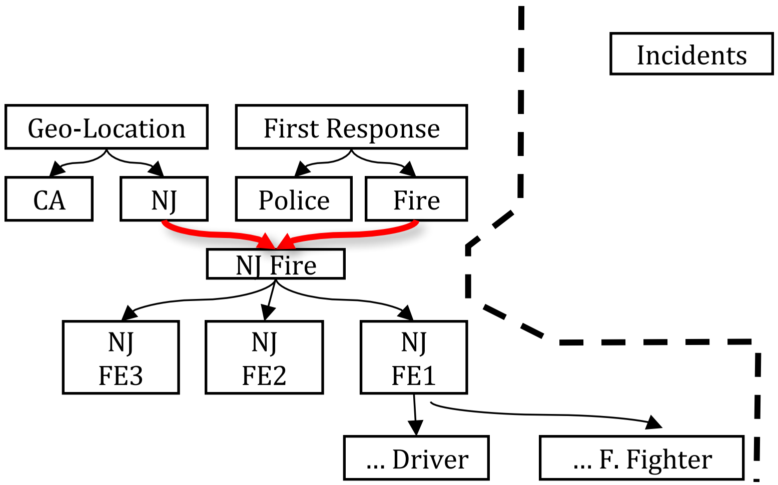
- **Multi-dimensional**
  - E.g. ‘FireEngine1’ has Time, Location and Department attributes (dimensions)
- **Graph structure**
  - More efficient than NDN-style strict hierarchy
- **Dynamic**
  - Edges (relations) pop in and out of existence
- **Publish/Subscribe**
  - Support a publish/subscribe capability for users to share information
  - Uses a shared multicast structure in network, using rendezvous points (RPs)



graph structure hierarchical

Improve Efficiency of Disaster Management by Graph-based Namespace

- Example namespace
  - Organizational structure: need information flow to members
    - Graph enables multiple dimensions (geo-location & functionality)
  - Incident place holder



Improve Efficiency of Disaster Management by Graph-based Namespace

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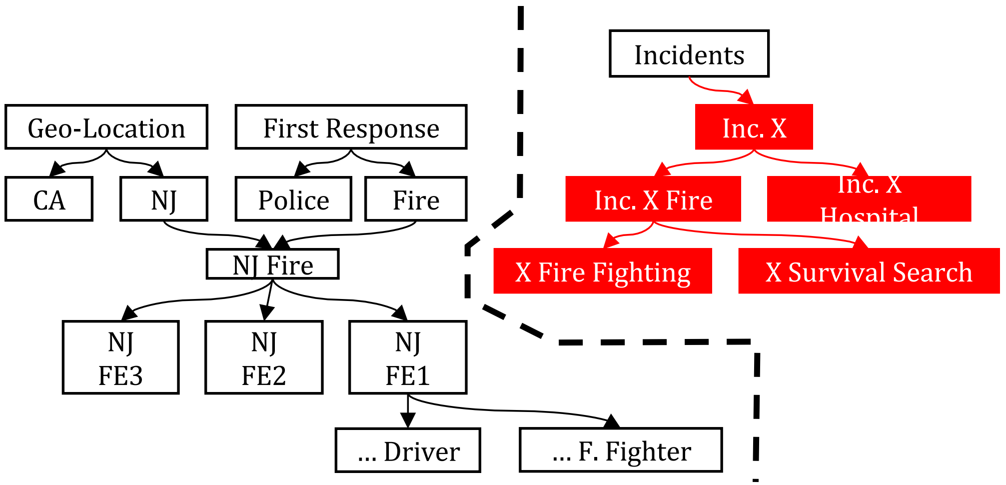
  - Incident place holder (on the right)
- Enable a disaster management template: preplanned namespaces



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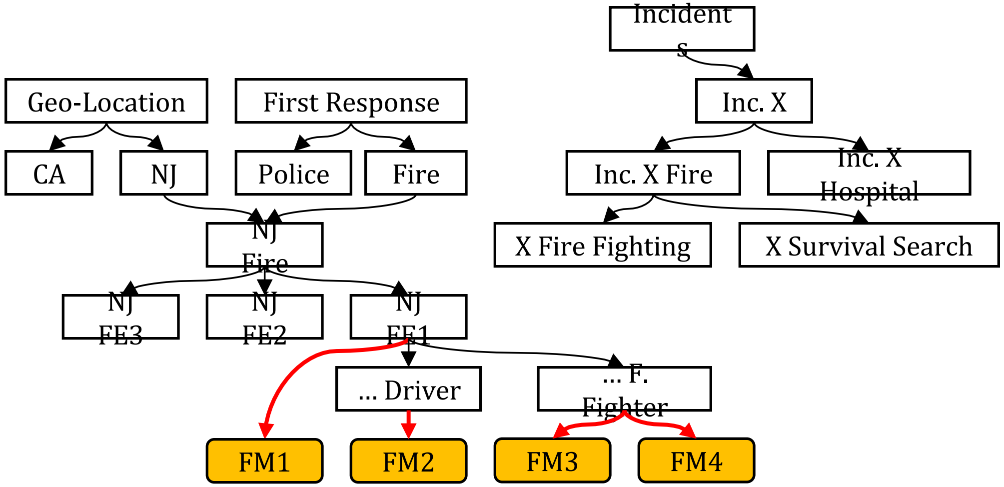

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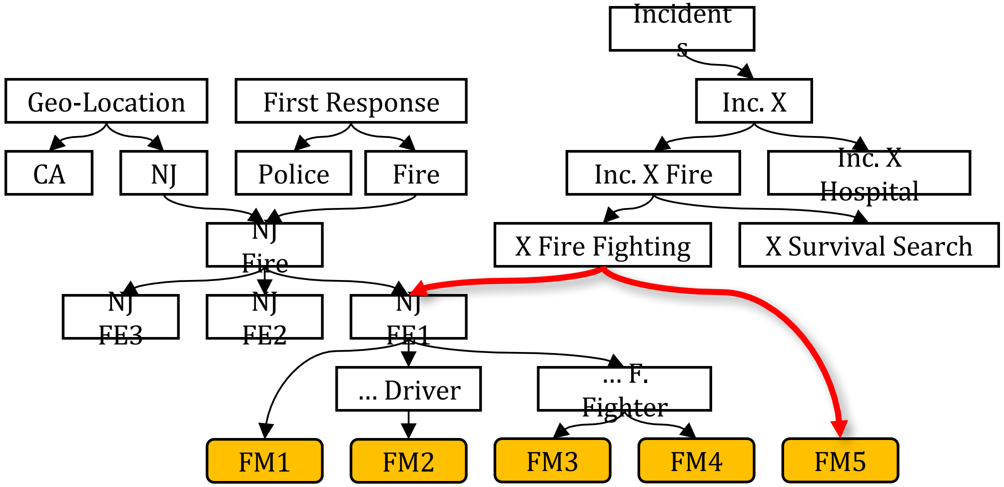

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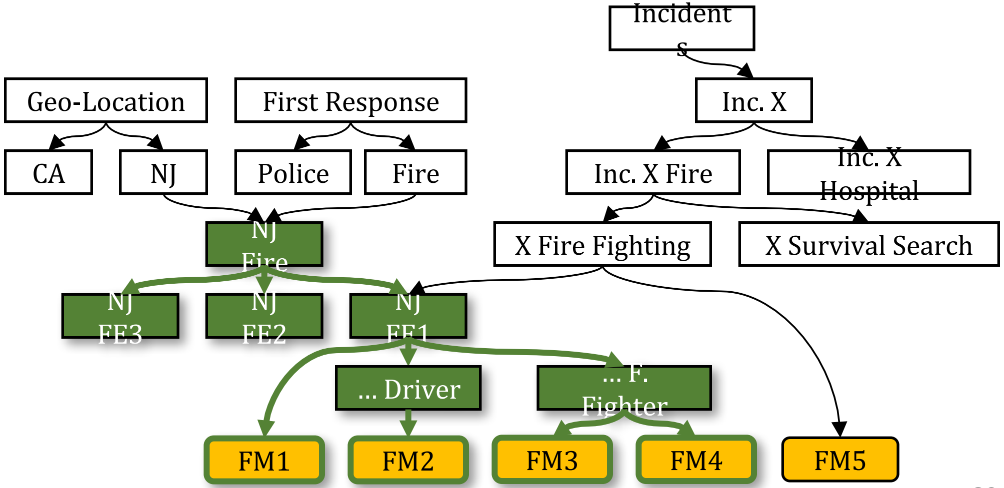
- Dispatch units to deal with functions in an incident
- Send messages to a role, e.g., "NJ Fire"



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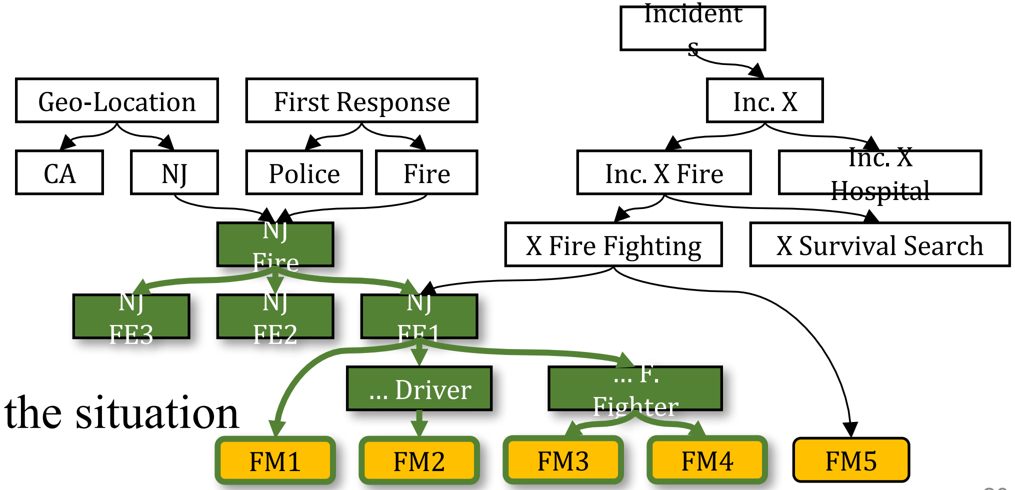
- First responders instantiate roles
- Dispatch units to deal with functions in an incident
- Send messages to a role, e.g., "NJ Fire"

Need: Support a graph-based namespace in the network

Dynamic Nature of Namespace

Dynamic installations of disaster namespaces

The namespace can evolve according to the situation



Supporting Graph-Pub/Sub in The Network

- Alternatives:
  - Perform BFS/DFS at each router
    - Benefit: fewer messages to be delivered
    - Issue: computation and storage cost at each router, infeasible, inefficient

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  - Network only deals with flat names/ids (e.g., IP multicast, MF multicast & COPSS with flat names)
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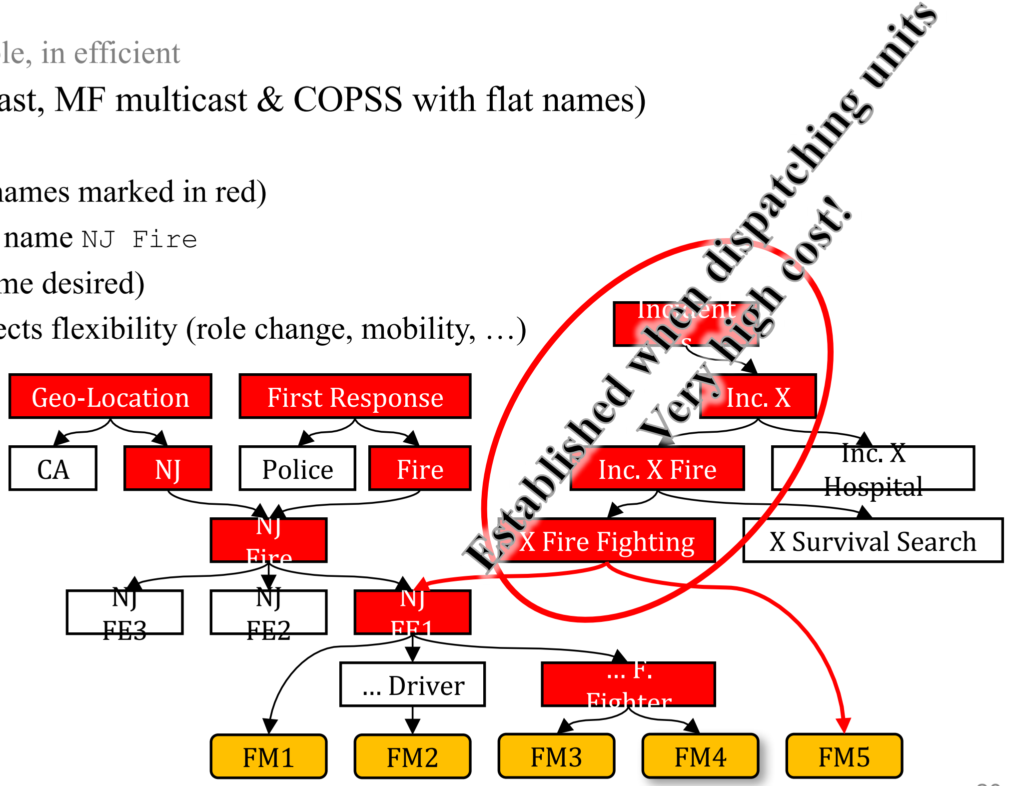
      - FM4 should subscribe to … `F. Fighter`, `NJ FE1`, … (names marked in red)
      - Messages/Commands to `NJ Fire` only needs to send to name `NJ Fire`
      - Benefit: easier publication procedure (publish to any name desired)
      - Issue: too many subscriptions (state) in the network, affects flexibility (role change, mobility, …)
    - Subscriber subscribe to one & publish to all names



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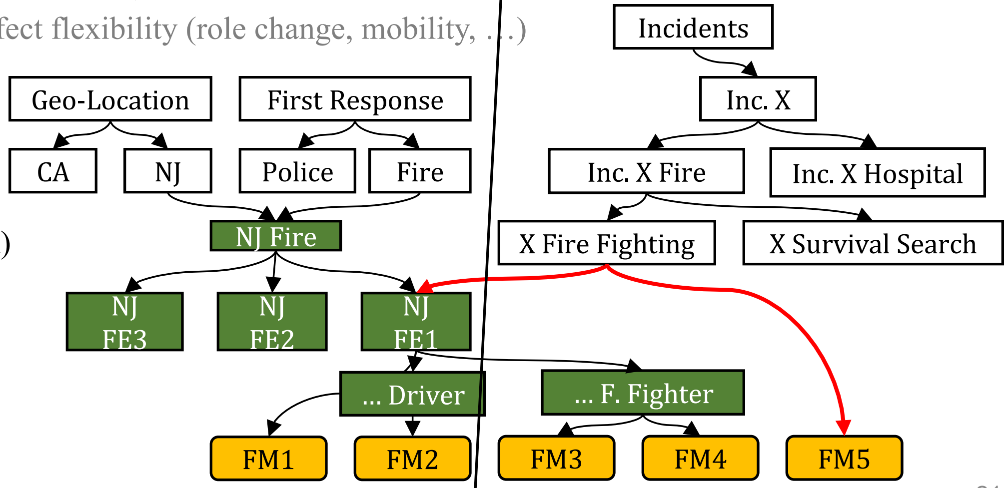
    - Subscriber subscribe to one & publish to all names
      - FM4 only subscribes to … `F. Fighter`
      - Messages/Commands to `NJ Fire` should be replicated and sent to `NJ FE1`, `NJ FE2`, … (names marked in green)
      - Benefit: better flexibility
      - Issue: overhead on publisher to publish to all names

Only 1 relationship added when dispatching units



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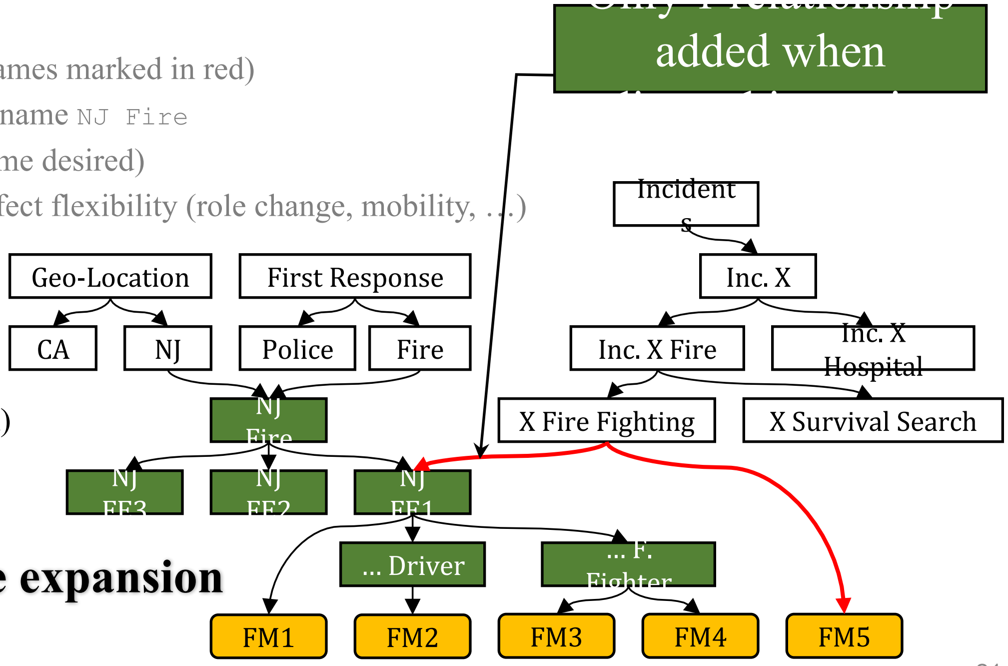
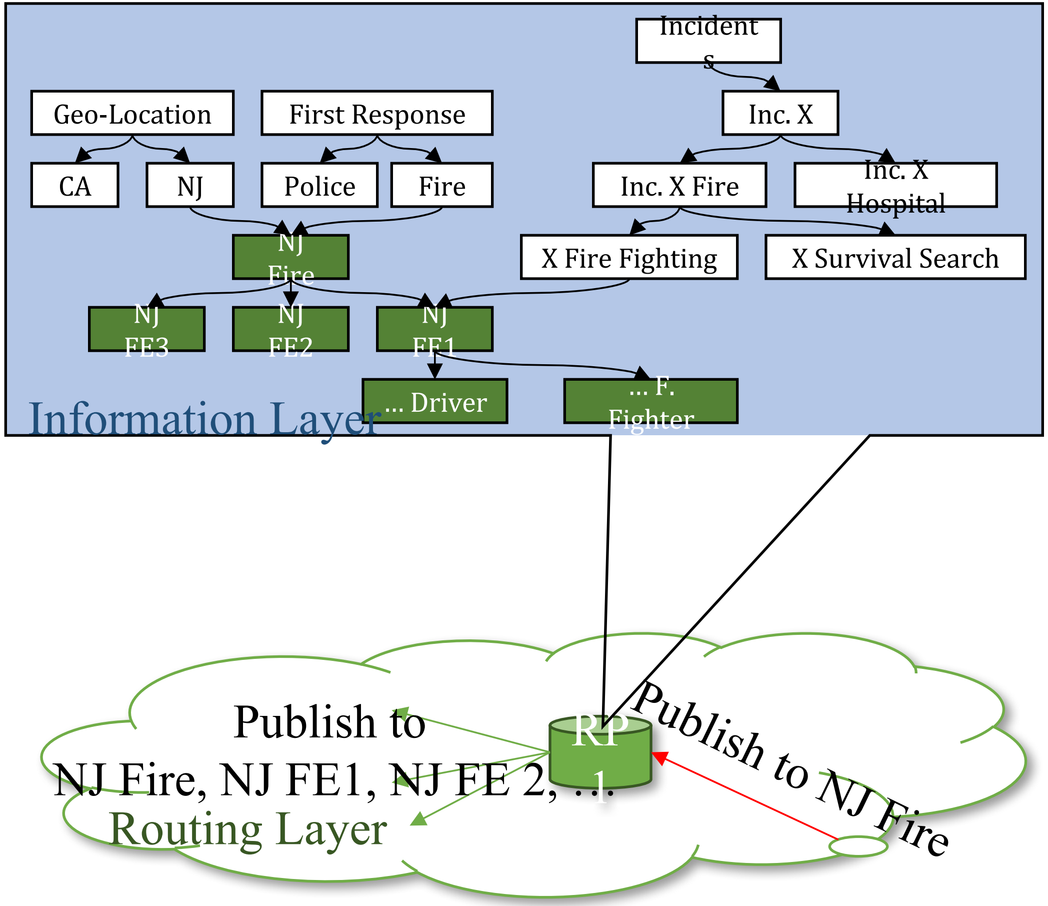
    - Subscriber subscribe to one & publish to all names
      - FM4 only subscribes to … `F. Fighter`
      - Messages/Commands to `NJ Fire` should be replicated and sent to `NJ FE1`, `NJ FE2`, … (names marked in green)
      - Benefit: better flexibility
      - Issue: overhead on publisher to publish to all names



Solution: information layer to do the name expansion

Solution Overview

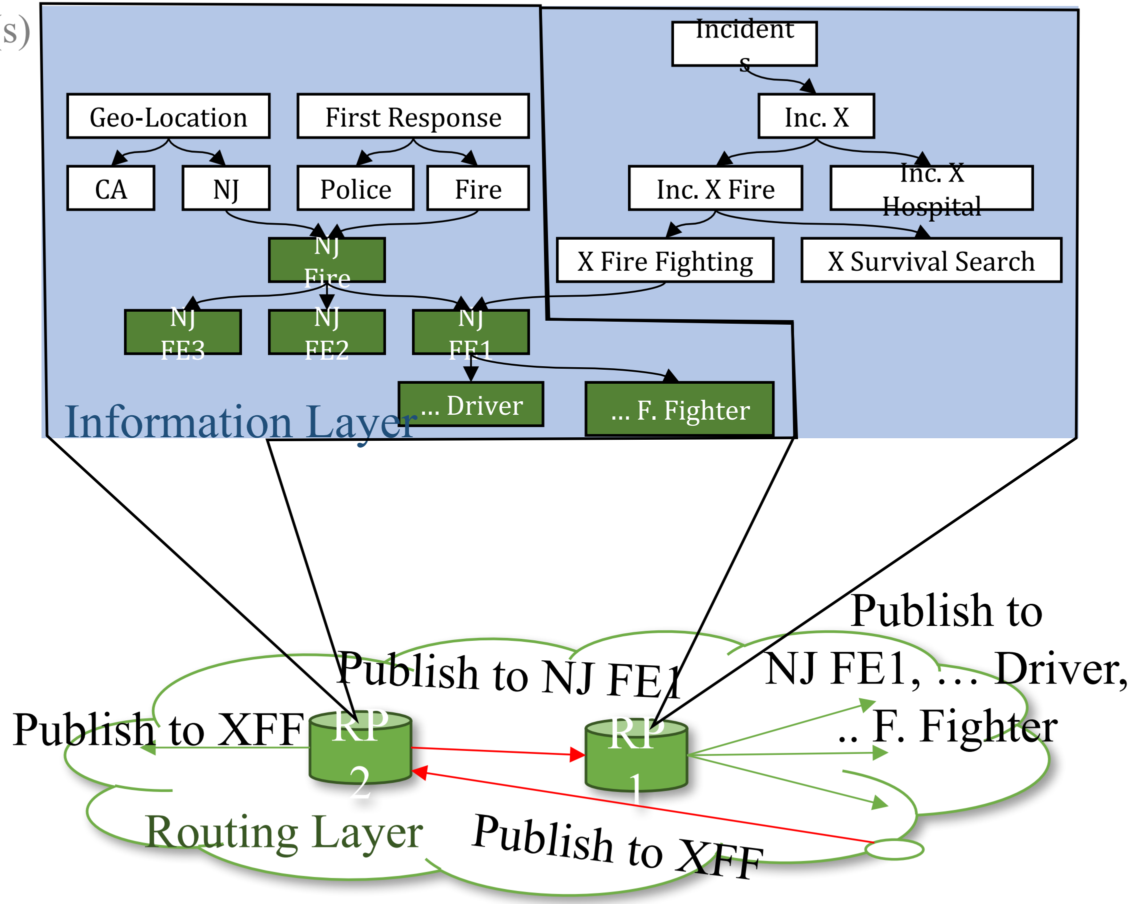
- Place the expansion functionality on the RP(s)
  - Multicast traffic will anyway go to RPs
  - Avoid triangular traffic
  - Can be implemented as middleboxes or VNFs physically residing on the same node as RP



Solution Overview

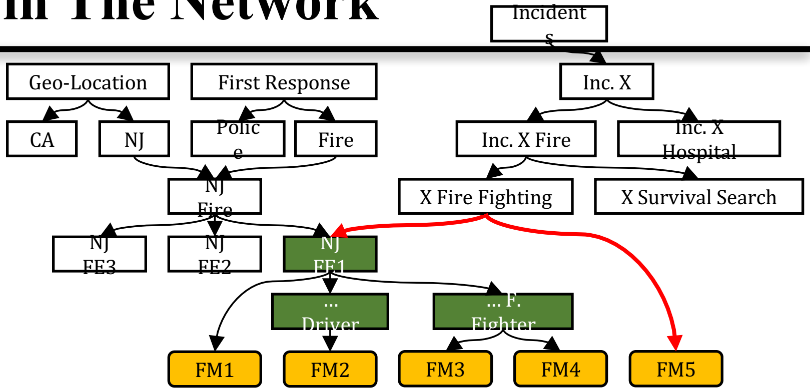
- Place the expansion functionality on the RP(s)
  - Multicast traffic will anyway go to RPs
  - Avoid triangular traffic
  - Can be implemented as middleboxes or VNFs physically residing on the same node as RP

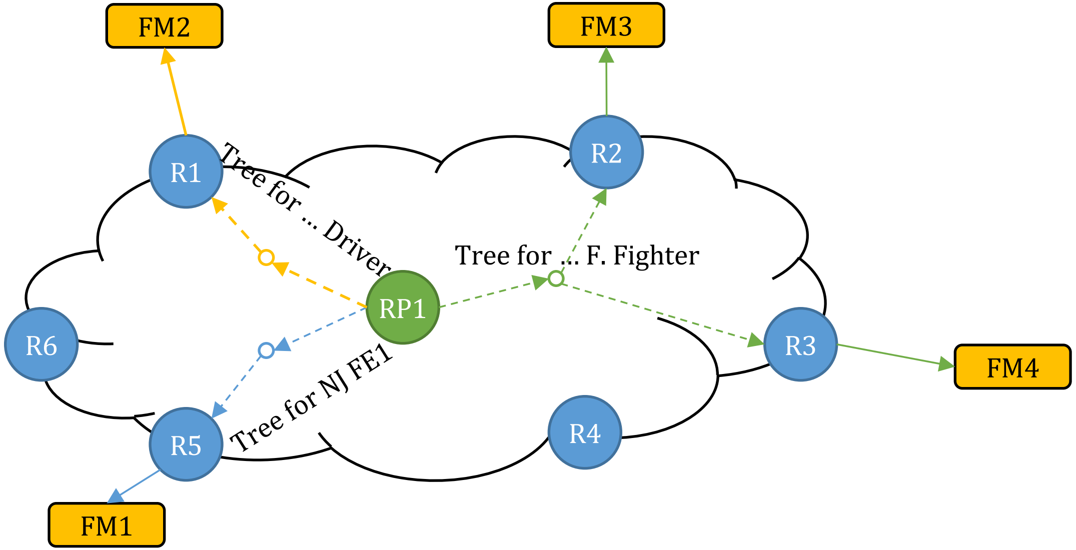
- Distribute the namespace on multiple RPs
  - Load-balancing
  - Minimize inter-RP traffic



Supporting Graph-Pub/Sub in The Network

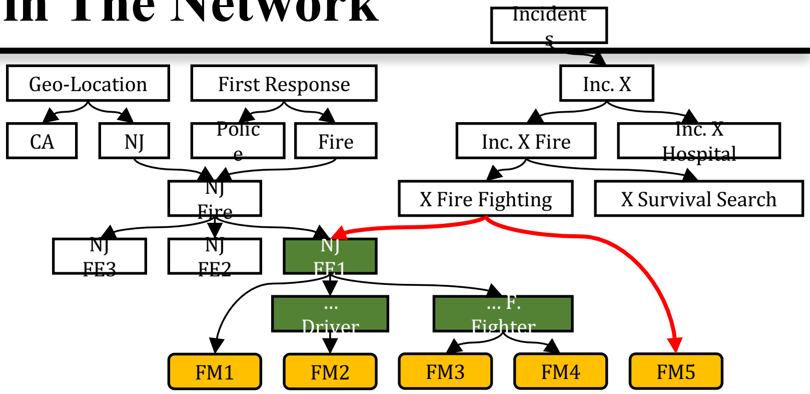
- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name

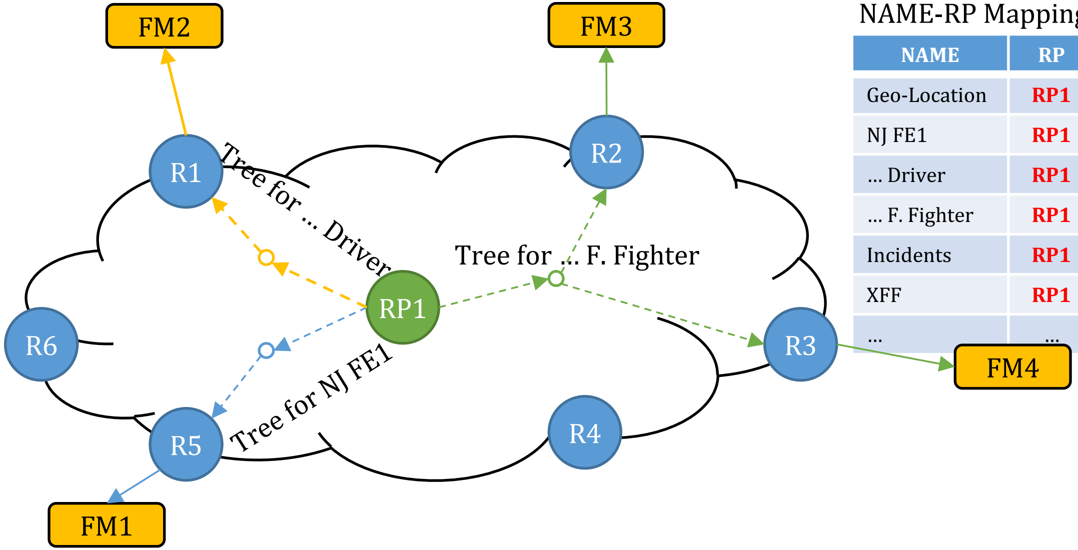




Supporting Graph-Pub/Sub in The Network

- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name

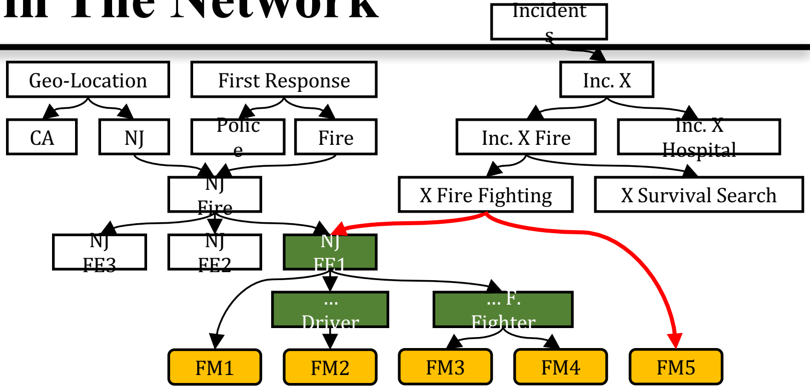




NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Supporting Graph-Pub/Sub in The Network

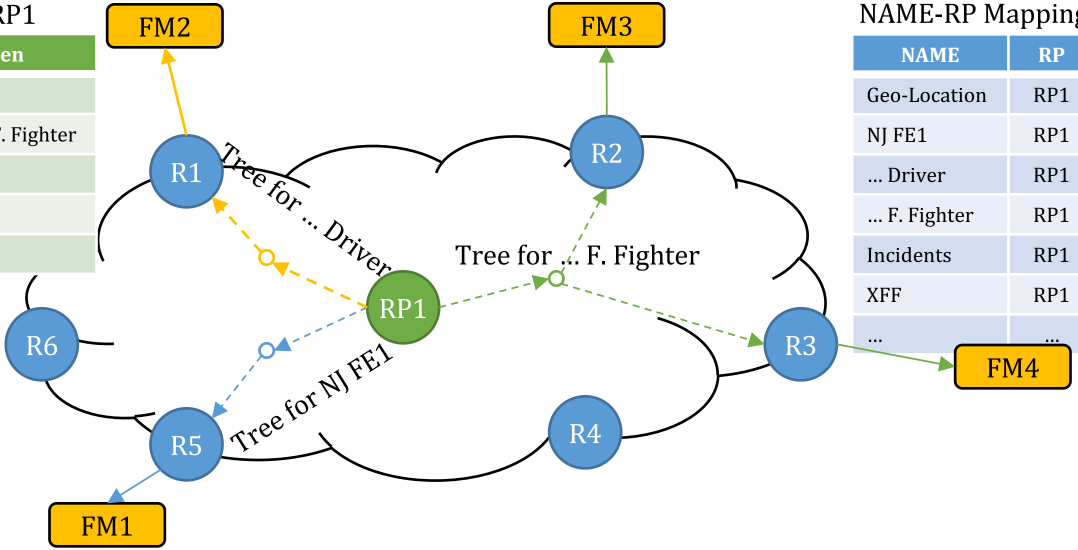


- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name

- The information layer (at RP) stores the name relationship
  - As an adjacency list

Name Storage on RP1

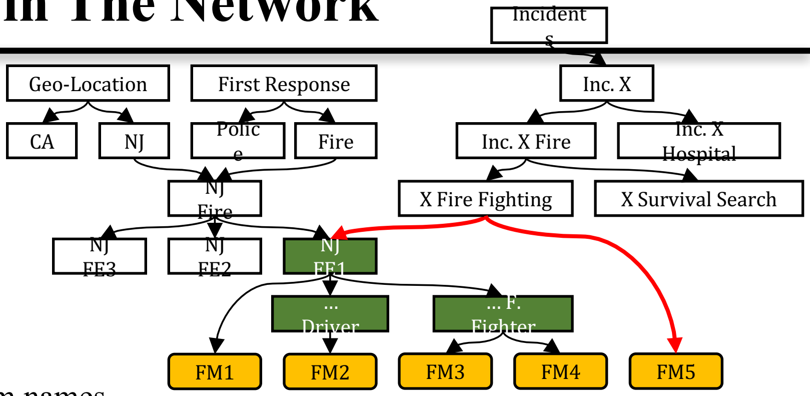
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

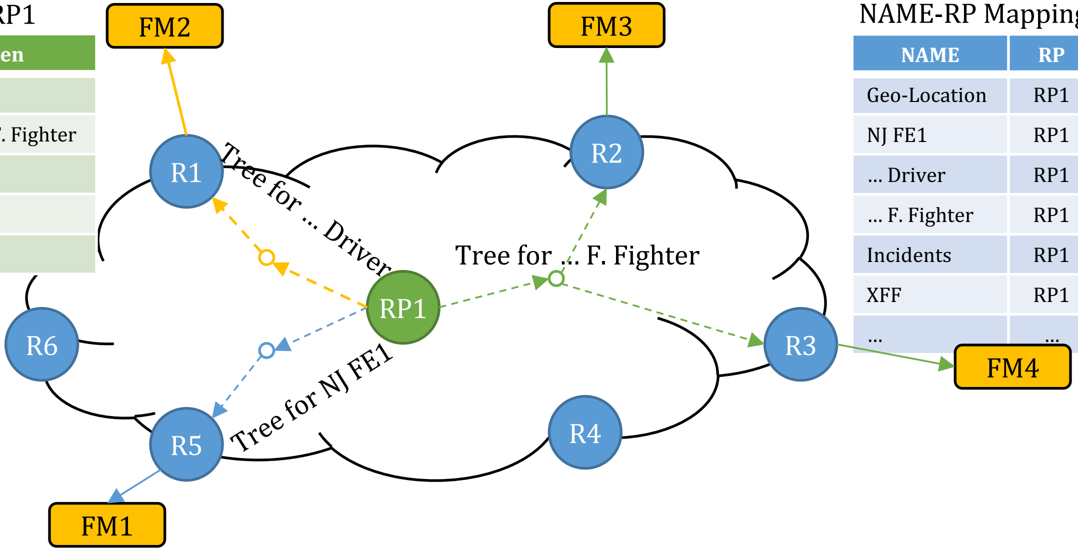
Supporting Graph-Pub/Sub in The Network



- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name
- The information layer (at RP) stores the name relationship
  - As an adjacency list
  - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)

Name Storage on RP1

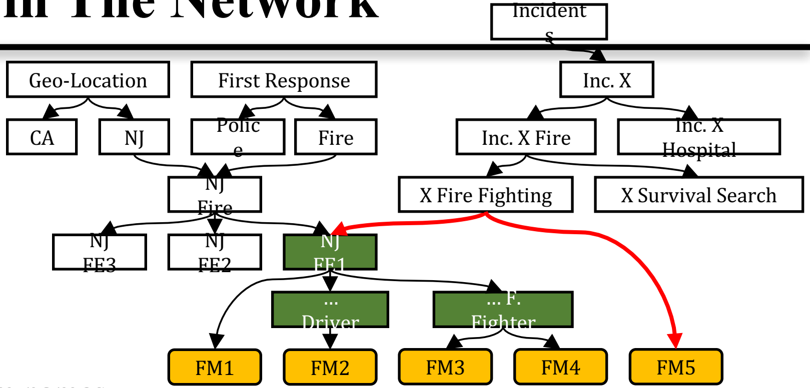
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	**[NULL]**
... F. Fighter	**[NULL]**
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

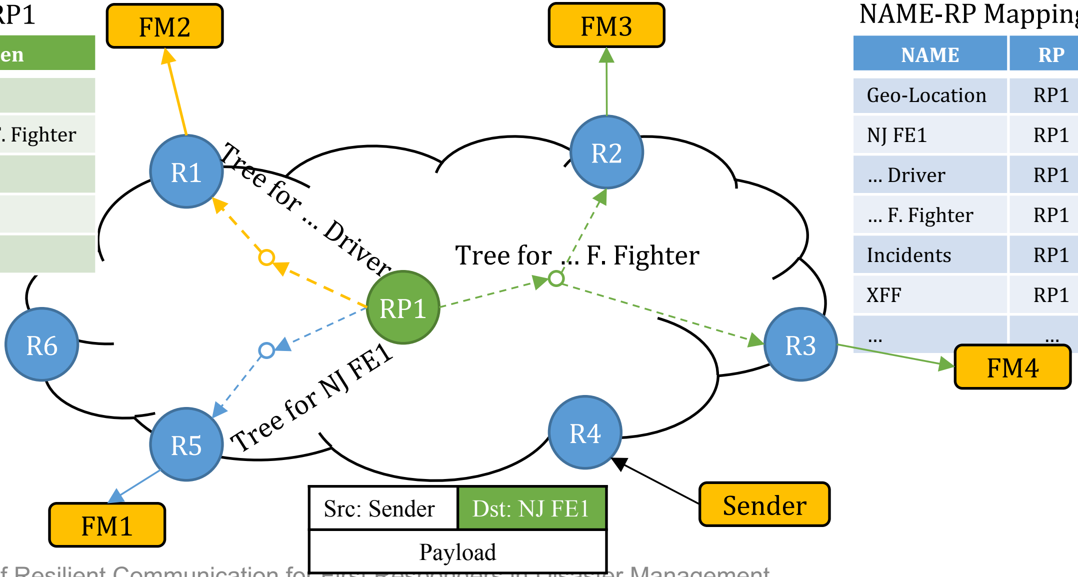
Supporting Graph-Pub/Sub in The Network



- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name
  - The information layer (at RP) stores the name relationship
    - As an adjacency list
    - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)
- Send a message to name NJ FE1

Name Storage on RP1

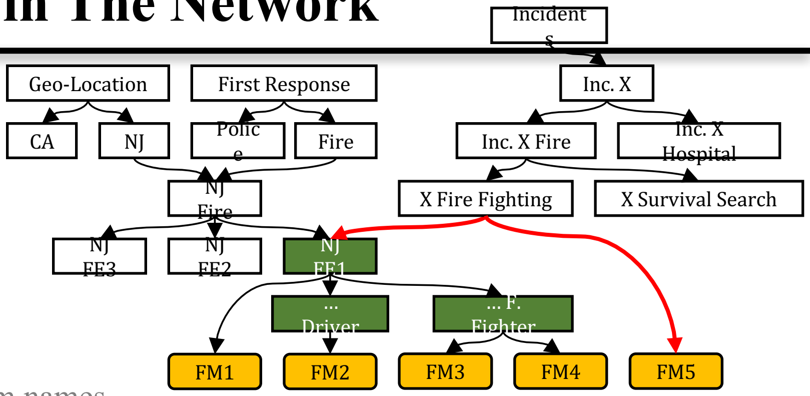
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Supporting Graph-Pub/Sub in The Network



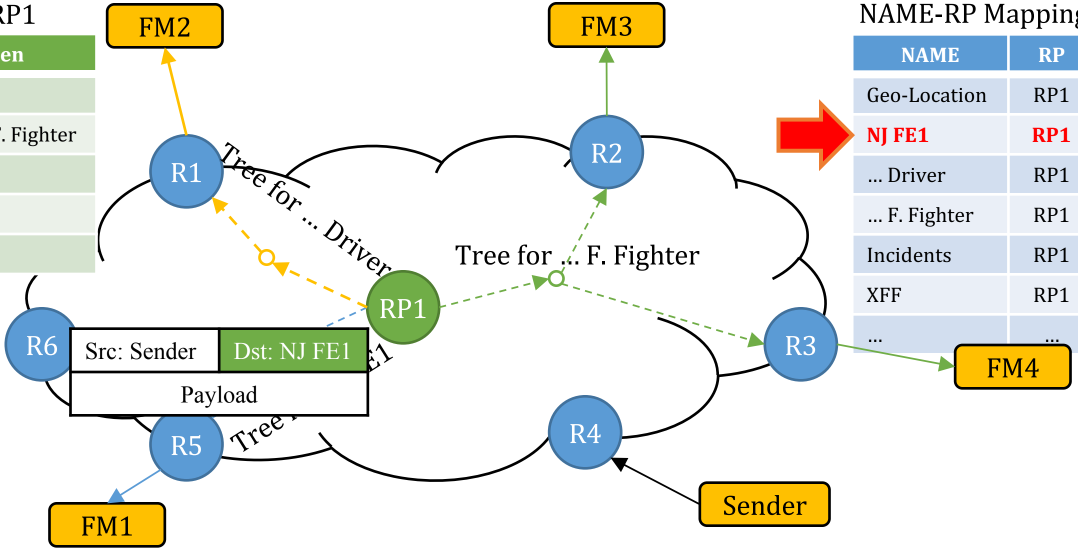
- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name

  - The information layer (at RP) stores the name relationship
    - As an adjacency list
    - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)

- Send a message to name `NJ FE1`
  - Msg reaches RP1

Name Storage on RP1

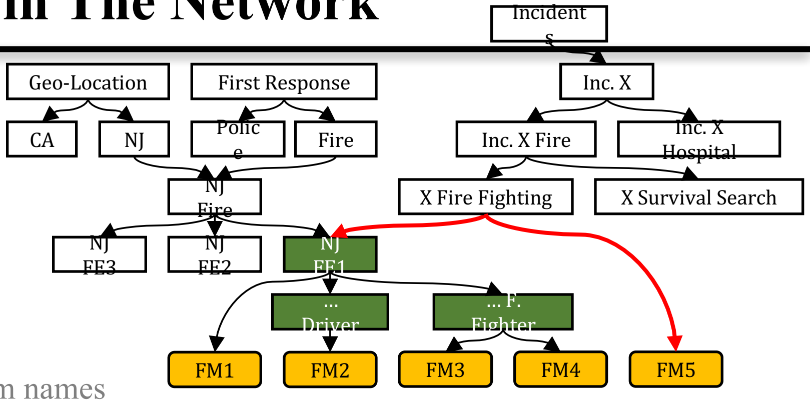
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	**RP1**
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Supporting Graph-Pub/Sub in The Network



- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
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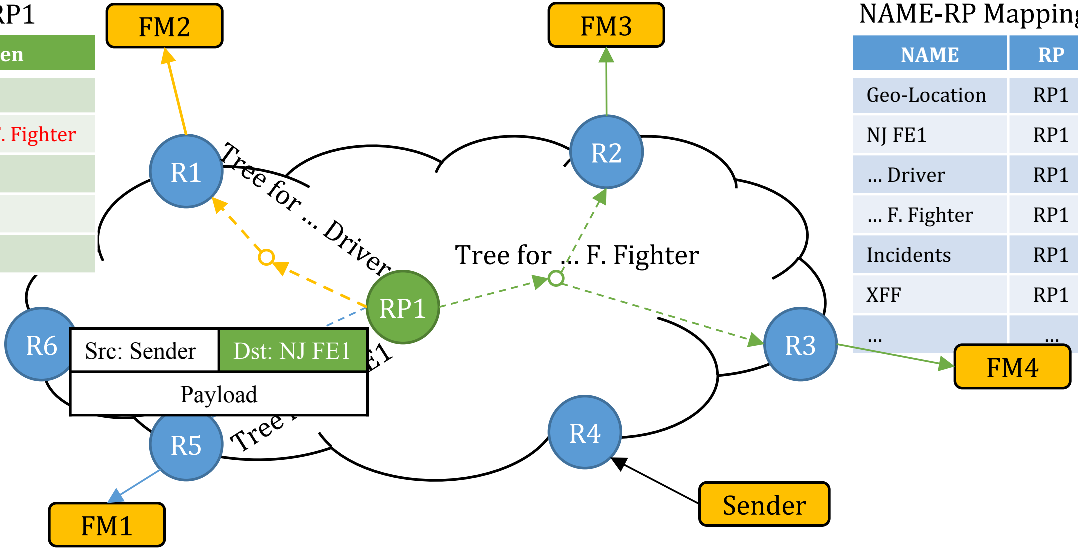
  - The information layer (at RP) stores the name relationship
    - As an adjacency list
    - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)

- Send a message to name `NJ FE1`
  - Msg reaches RP1
  - RP1 performs a BFS on `NJ FE1` and find the reachable names

Name Storage on RP1

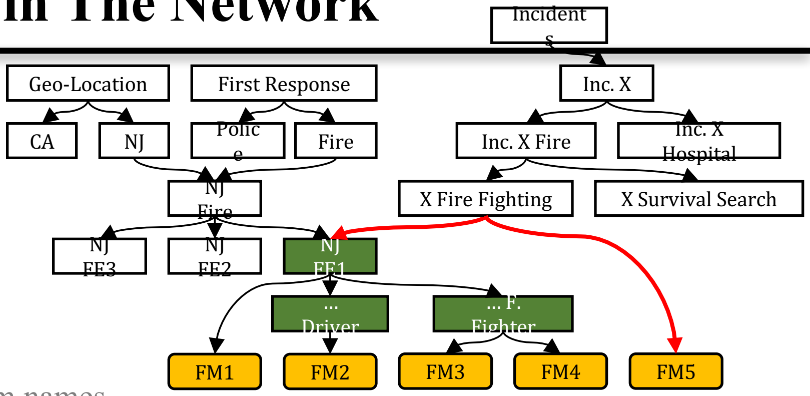
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Supporting Graph-Pub/Sub in The Network

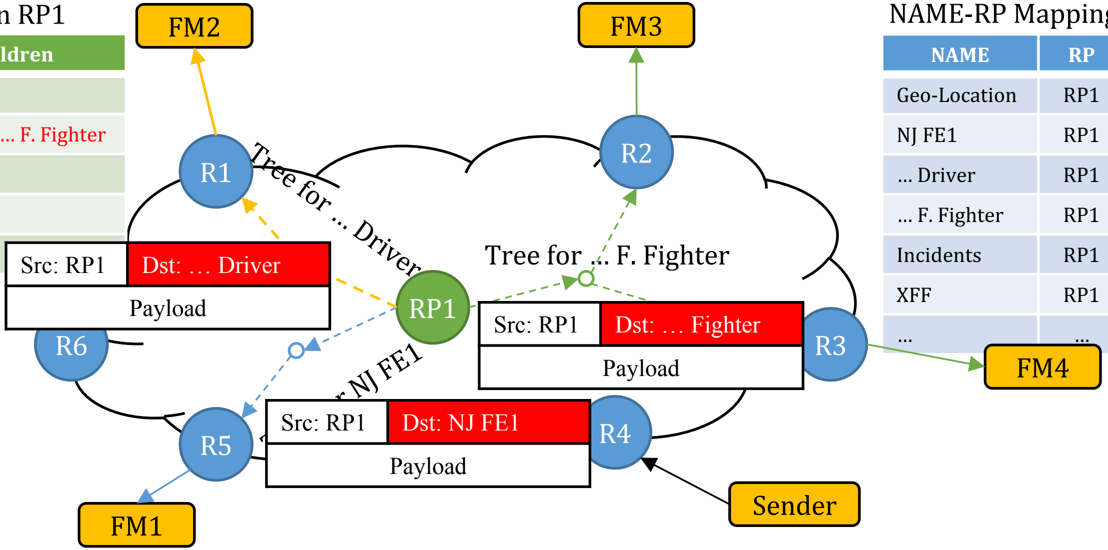


- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name
  - The information layer (at RP) stores the name relationship
    - As an adjacency list
    - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

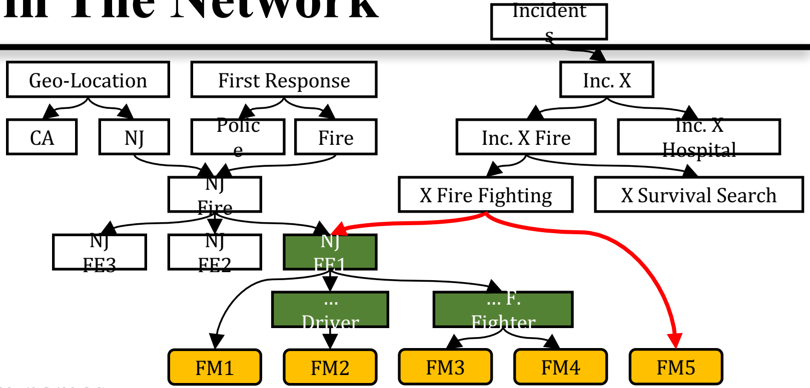
- Send a message to name `NJ FE1`
  - Msg reaches RP1
  - RP1 performs a BFS on `NJ FE1` and find the reachable names
  - RP1 sends one publication for each name



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Supporting Graph-Pub/Sub in The Network

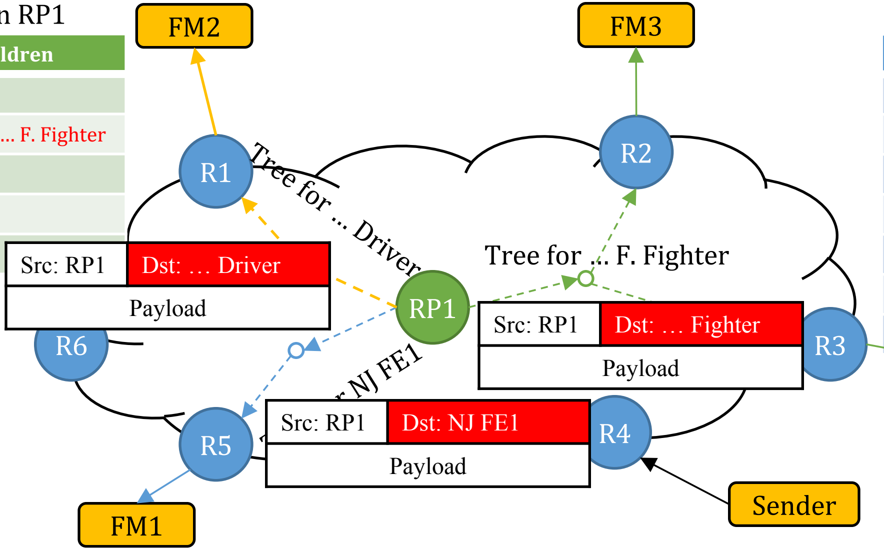


- To start with: Only 1 RP
  - Network would build subscription/multicast trees for each name
  - Network would know, how to reach RP for a given name
  - The information layer (at RP) stores the name relationship
    - As an adjacency list
    - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

- Send a message to name `NJ FE1`
  - Msg reaches RP1
  - RP1 performs a BFS on `NJ FE1` and find the reachable names
  - RP1 sends one publication for each name



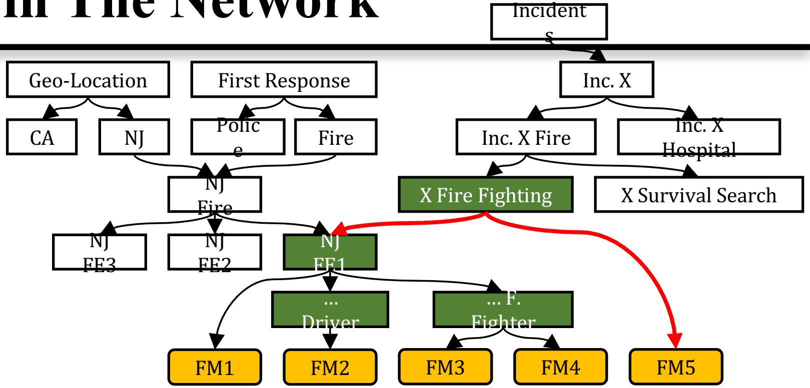
NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP1
XFF	RP1
...	...

Issue: traffic concentration

Supporting Graph-Pub/Sub in The Network

- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy

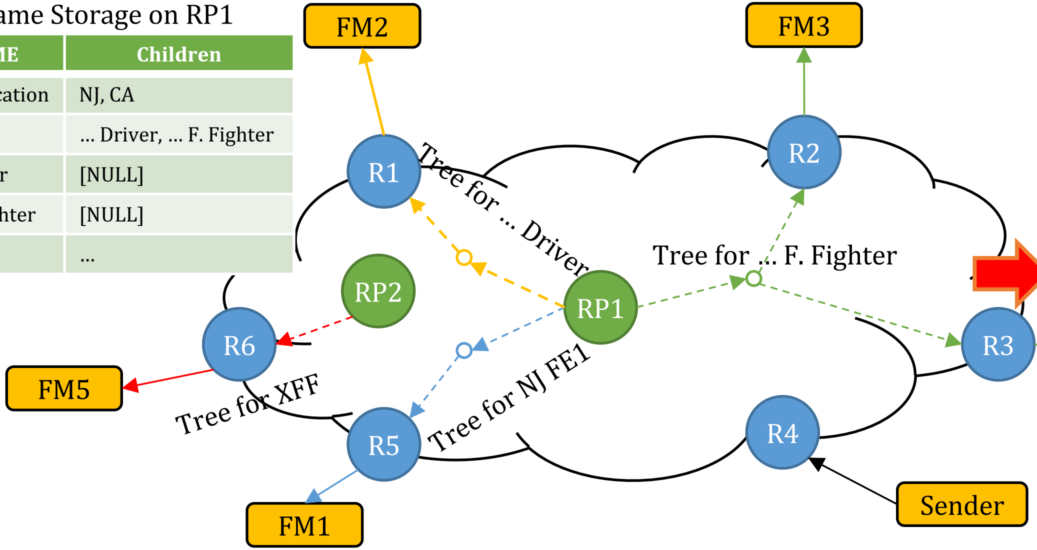


Name Storage on RP2

NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	NJ FE1
...	...

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



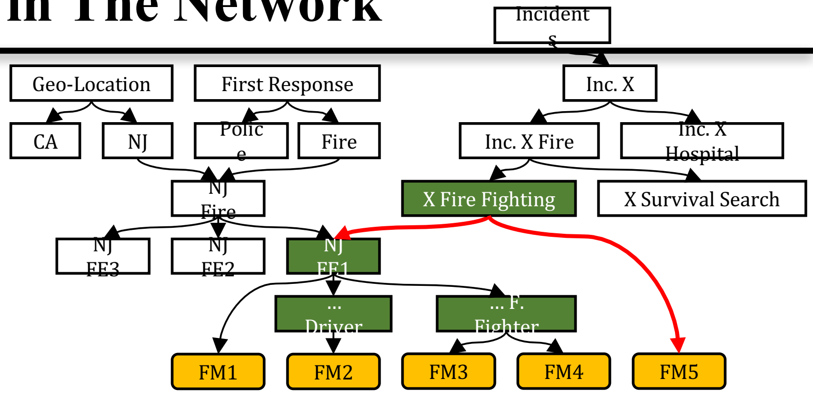
NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	**RP2**
XFF	**RP2**
...	...

FM4

Supporting Graph-Pub/Sub in The Network

- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy
  - Send a message to `X Fire Fighting` (`XFF`, served on RP2)



Name Storage on RP2

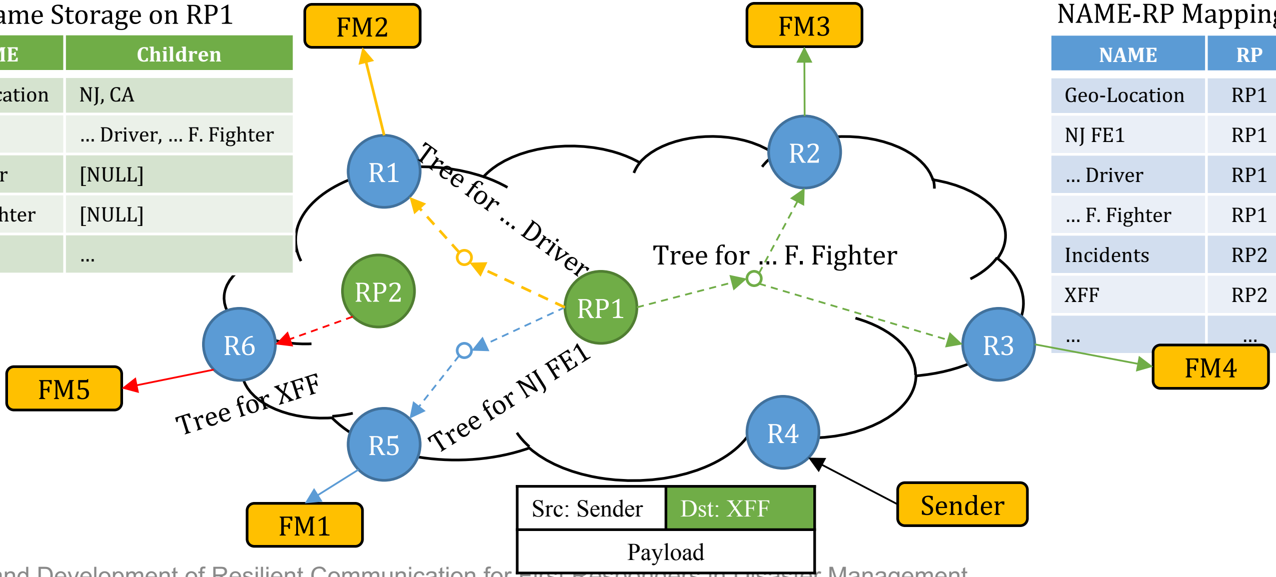
NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	NJ FE1
...	...

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

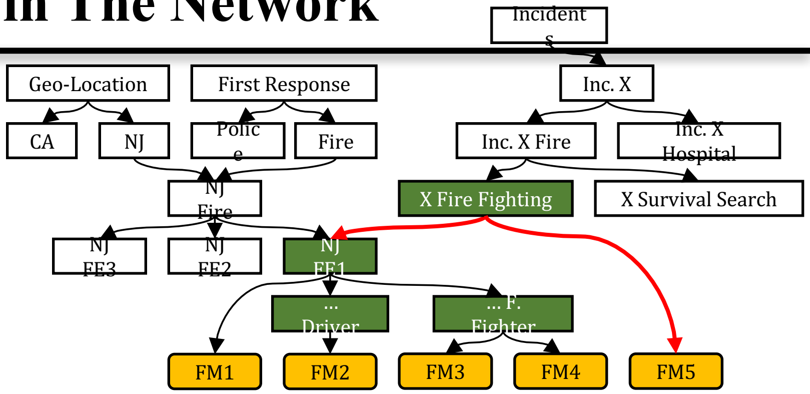
NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...



Supporting Graph-Pub/Sub in The Network

- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy
  - Send a message to `X Fire Fighting` (`XFF`, served on RP2)
    - Msg reaches RP2 according to NAME-RP Mapping



Name Storage on RP2

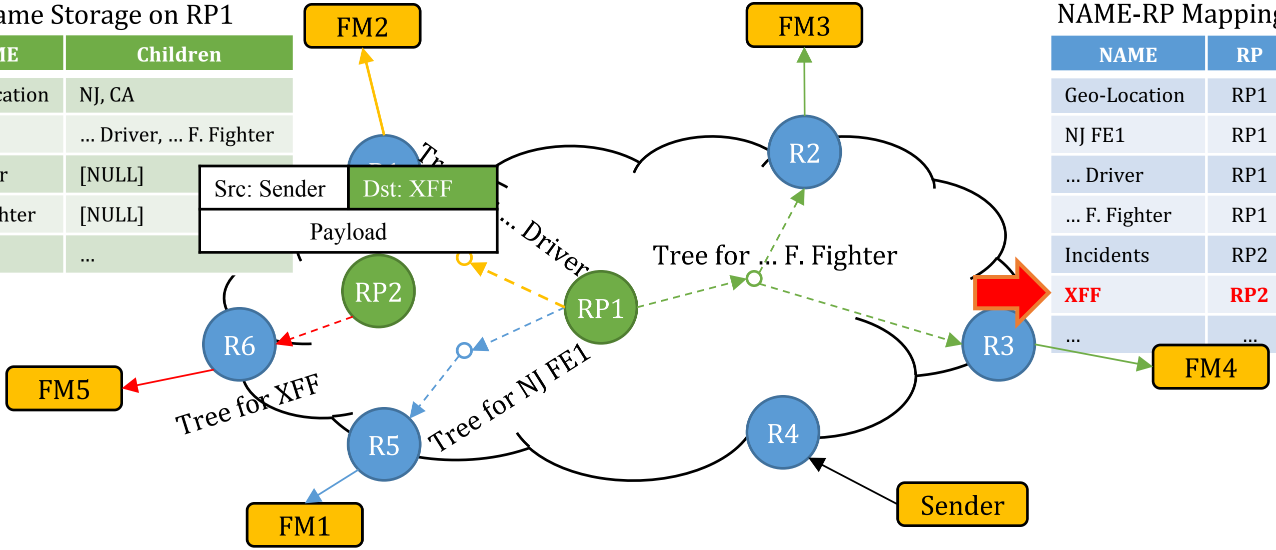
NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	NJ FE1
...	...

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

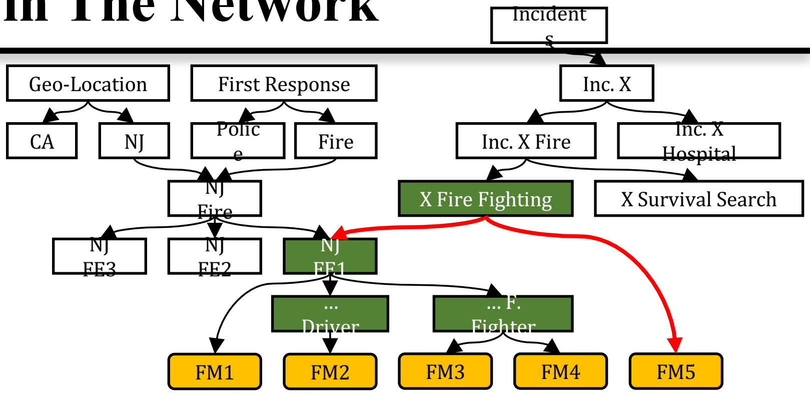
NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...



Supporting Graph-Pub/Sub in The Network

- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy
  - Send a message to `X Fire Fighting` (`XFF`, served on RP2)
    - Msg reaches RP2 according to NAME-RP Mapping
    - RP2 performs BFS on XFF and find out reachable names
      - `NJ FE1` does not have an entry in the name storage, not served by RP2

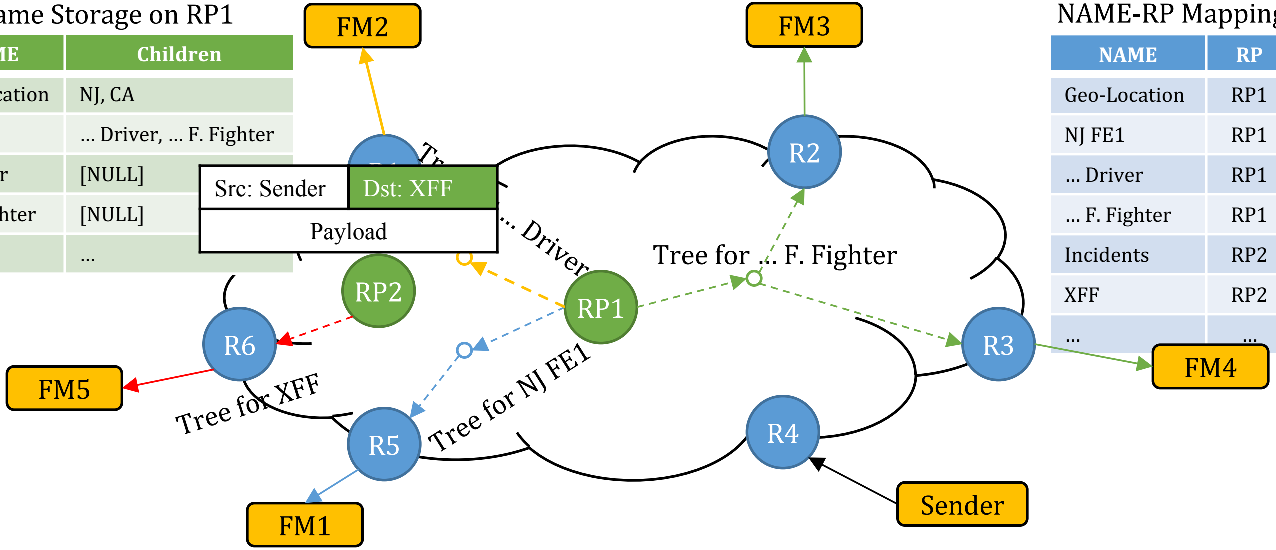


Name Storage on RP2

NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	**NJ FE1**
...	...

Name Storage on RP1

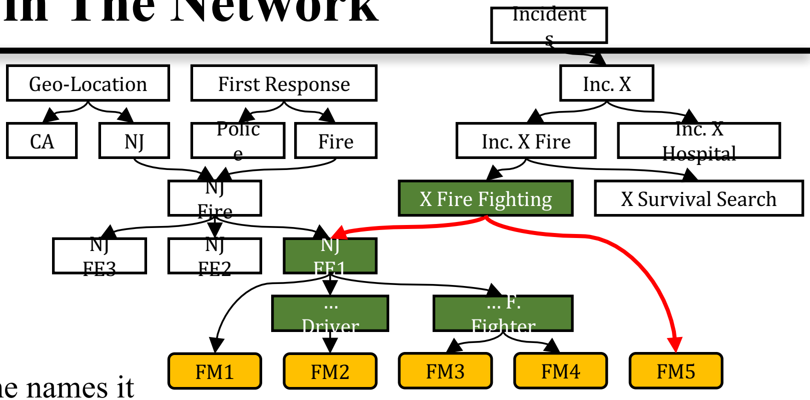
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...

Supporting Graph-Pub/Sub in The Network



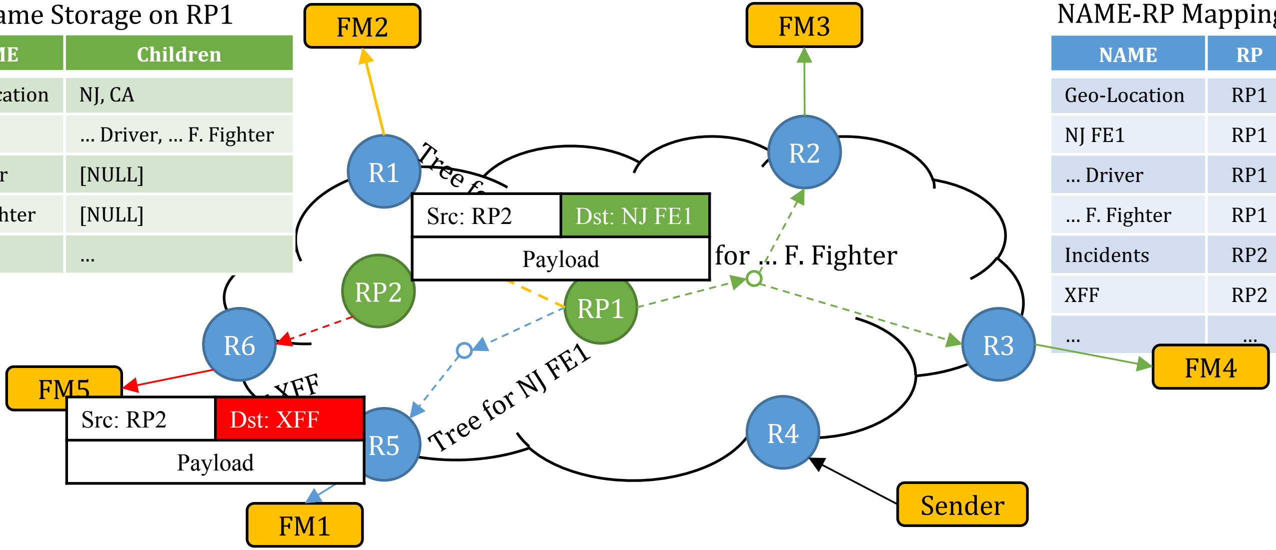
- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy
  - Send a message to `X Fire Fighting` (`XFF`, served on RP2)
    - Msg reaches RP2 according to NAME-RP Mapping
    - RP2 performs BFS on XFF and find out reachable names
      - `NJ FE1` does not have an entry in the name storage, not served by RP2
      - RP2 sends a publication for each name it serves, and a new unicast for the names it does not serve

Name Storage on RP2

NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	**NJ FE1**
...	...

Name Storage on RP1

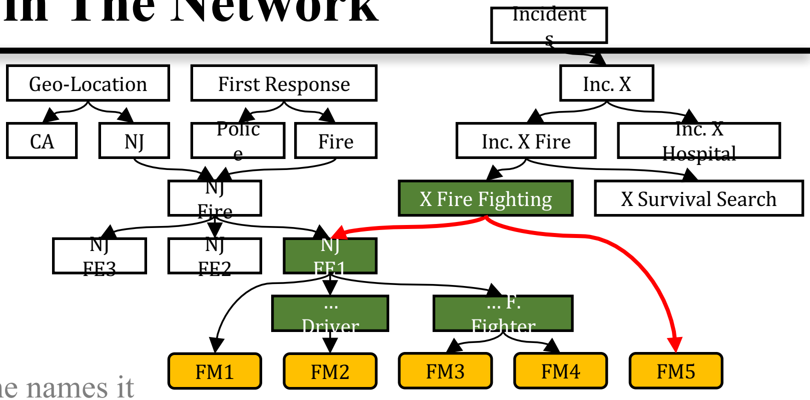
NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...

Supporting Graph-Pub/Sub in The Network



- Real protocol: graph pub/sub over multiple RPs
  - RP2 manages the incident hierarchy
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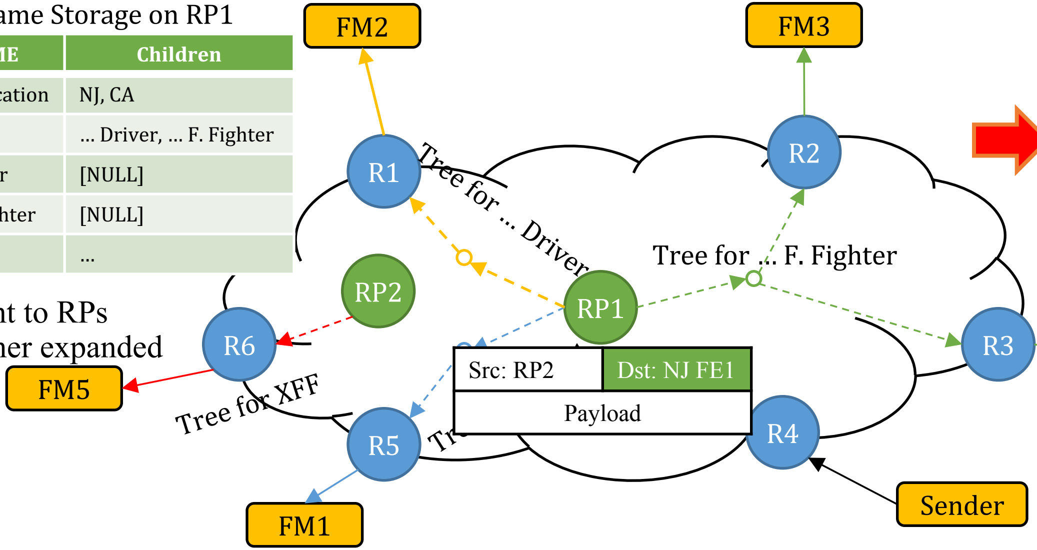
Name Storage on RP2

NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	**NJ FE1**
...	...

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

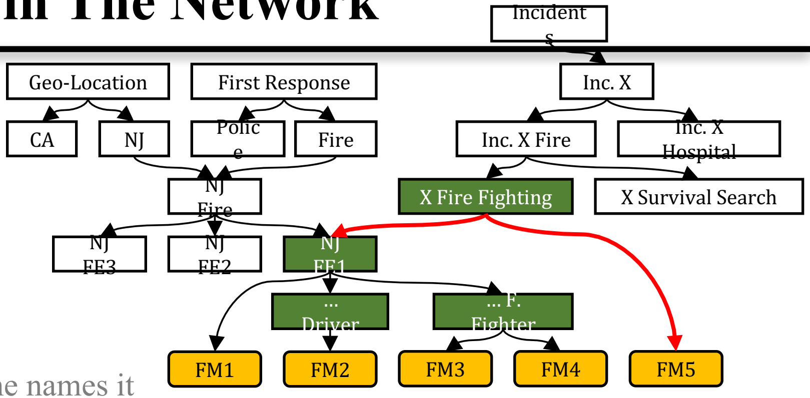
- The new unicast(s) will be sent to RPs serving the name and get further expanded



NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	**RP1**
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...

Supporting Graph-Pub/Sub in The Network



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Name Storage on RP2

NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	**NJ FE1**
...	...

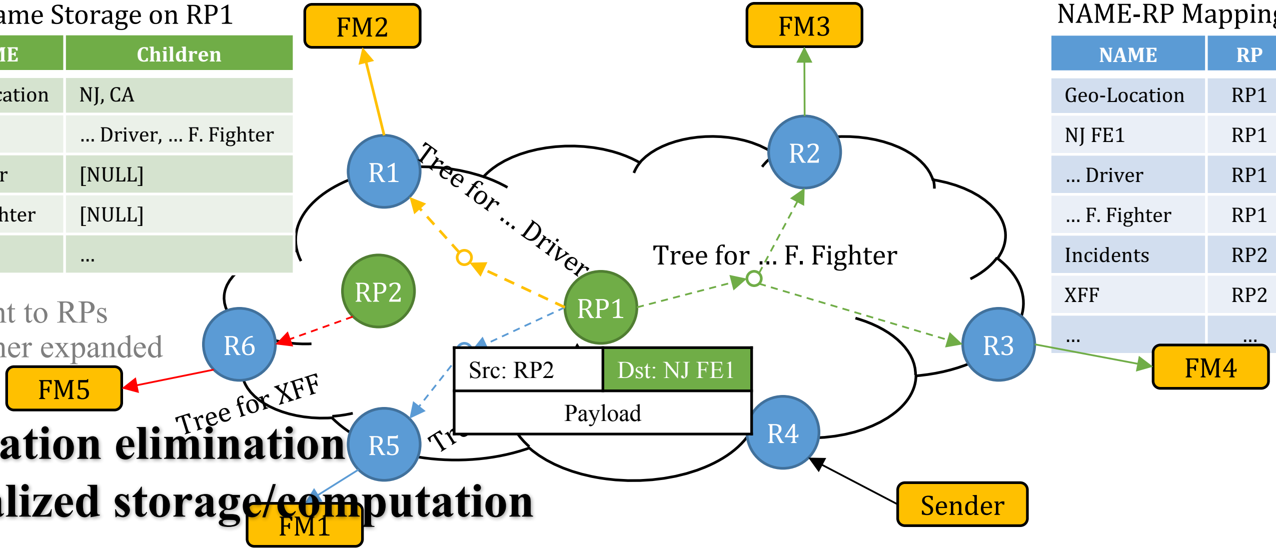
Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

NAME-RP Mapping

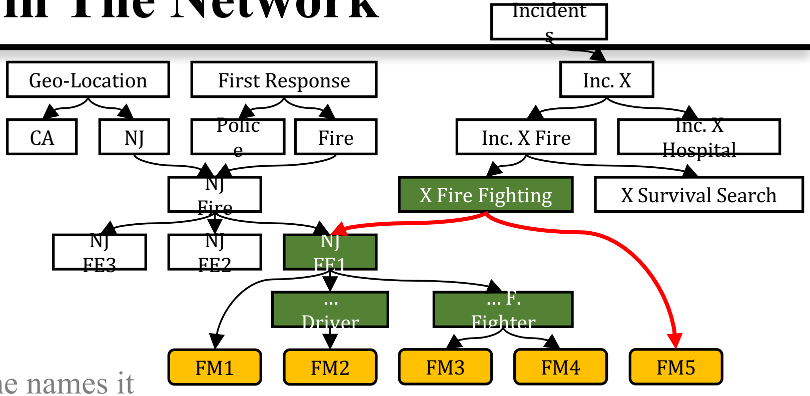
NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...

- The new unicast(s) will be sent to RPs serving the name and get further expanded



Benefits: traffic concentration elimination distributed & localized storage/computation

Supporting Graph-Pub/Sub in The Network



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    - RP2 performs BFS on XFF and find out reachable names
      - `NJ FE1` does not have an entry in the name storage, not served by RP2
      - RP2 sends a publication for each name it serves, and a new unicast for the names it does not serve

Name Storage on RP2

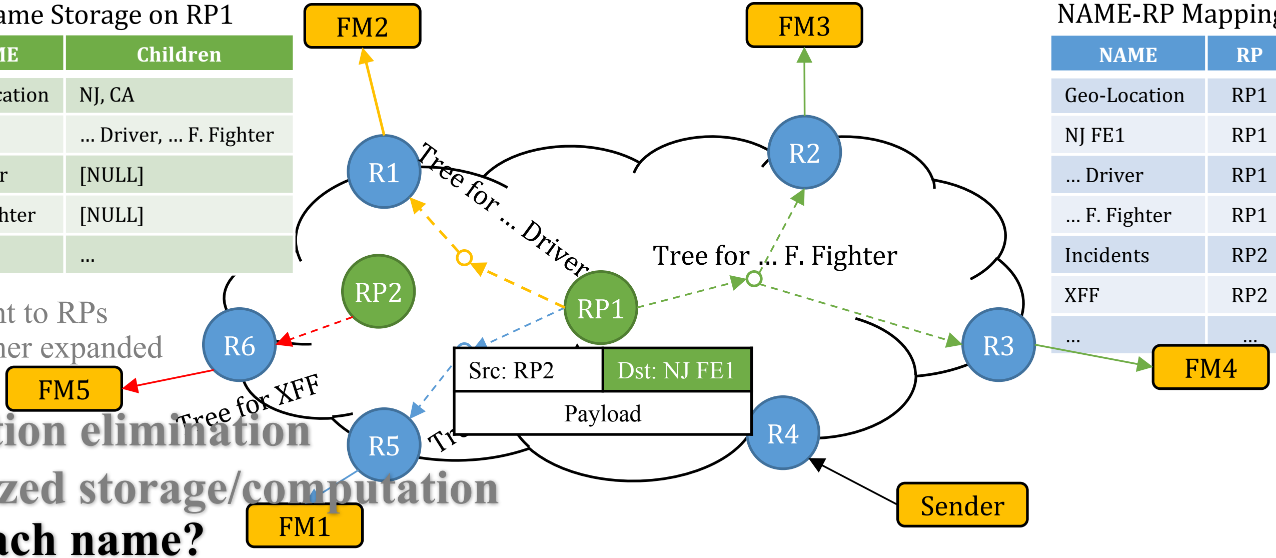
NAME	Children
Incident	Inc.X, ...
Inc.X	Inc.XFire, Inc.XH
Inc.XFire	XFF, XSS
XFF	NJ FE1
...	...

Name Storage on RP1

NAME	Children
Geo-Location	NJ, CA
NJ FE1	... Driver, ... F. Fighter
... Driver	[NULL]
... F. Fighter	[NULL]
...	...

NAME-RP Mapping

NAME	RP
Geo-Location	RP1
NJ FE1	RP1
... Driver	RP1
... F. Fighter	RP1
Incidents	RP2
XFF	RP2
...	...



- The new unicast(s) will be sent to RPs serving the name and get further expanded

Benefits: traffic concentration elimination distributed & localized storage/computation

Question: where to place each name?

Supporting Graph-Pub/Sub in The Network

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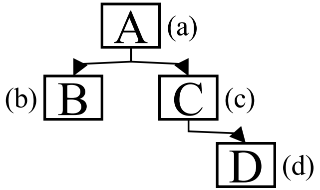

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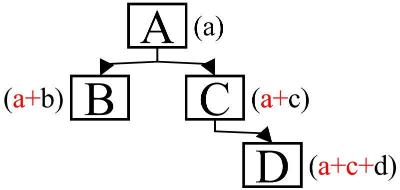

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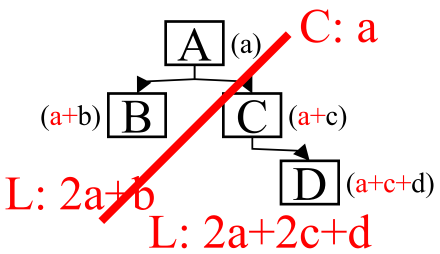

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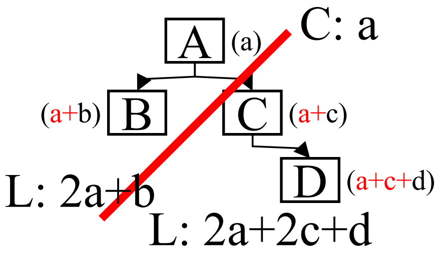

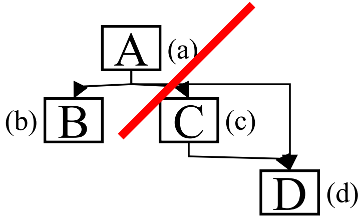

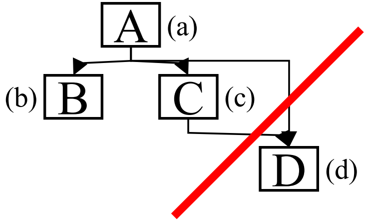

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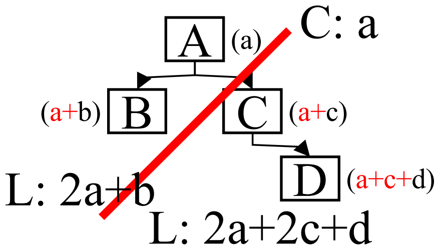

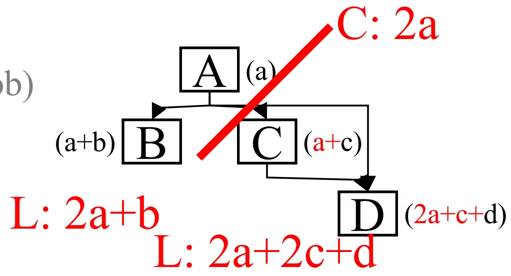

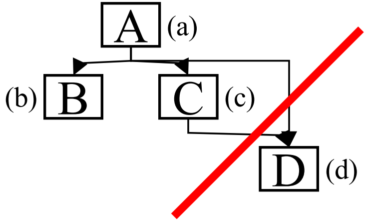

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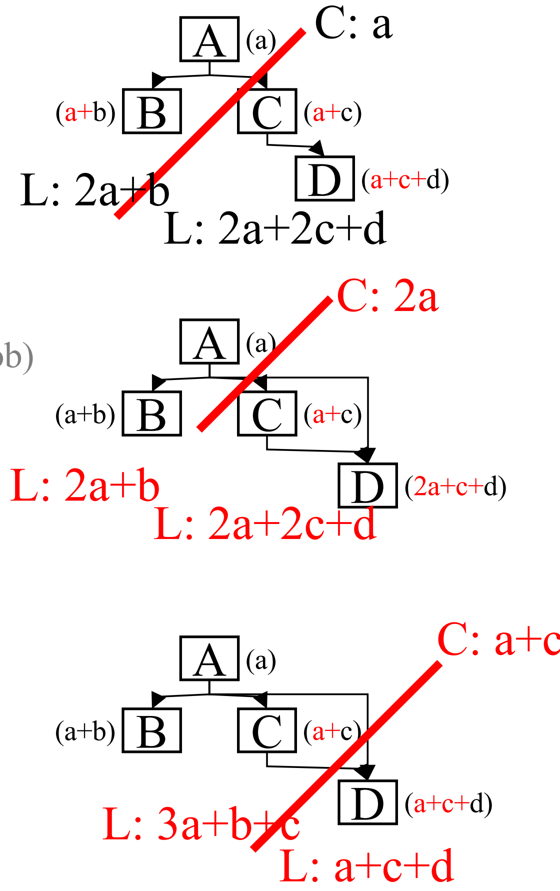

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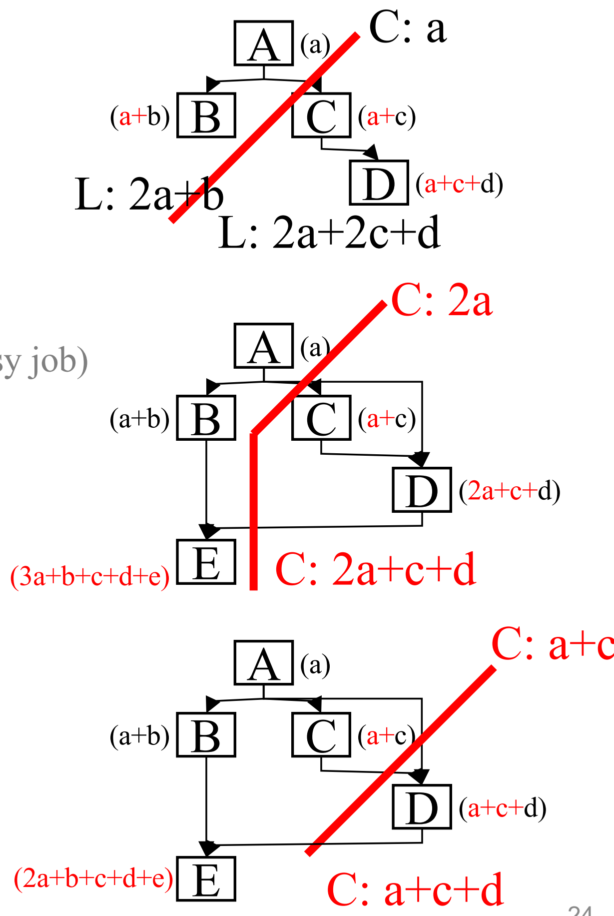

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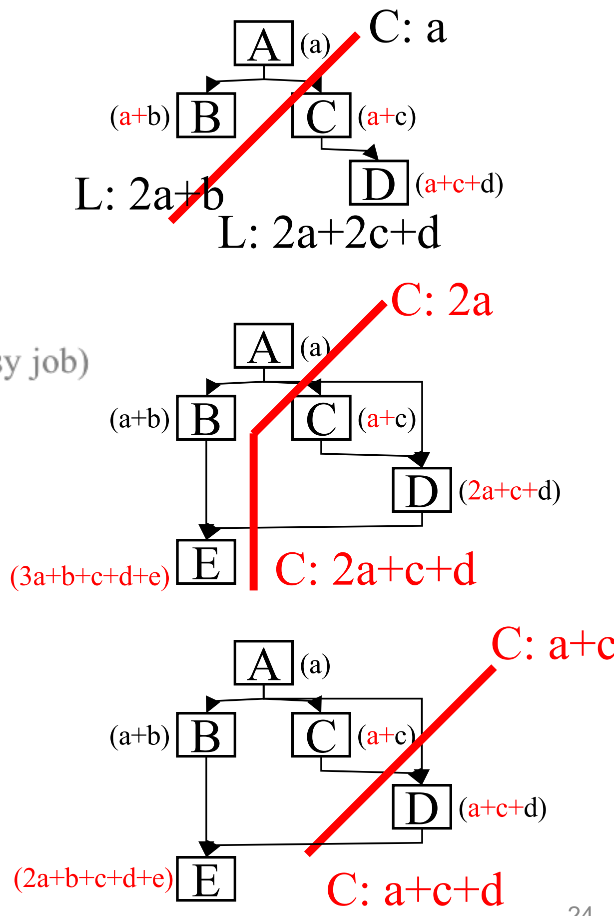
  - Our solution: TABU
    - Objective function: $\alpha \times |L_2 - L_1| + \beta \times C$



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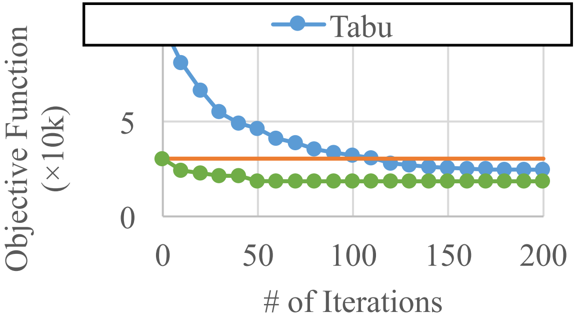

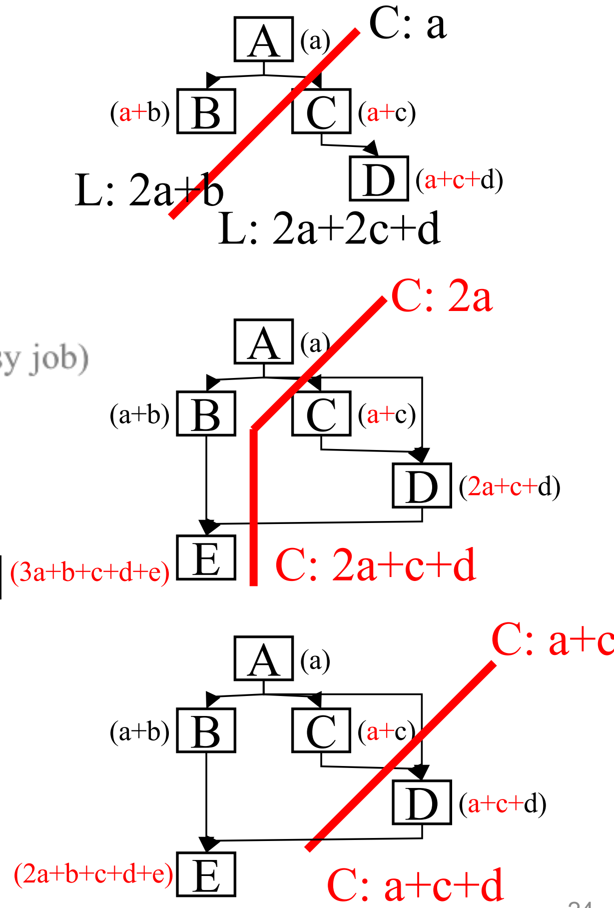

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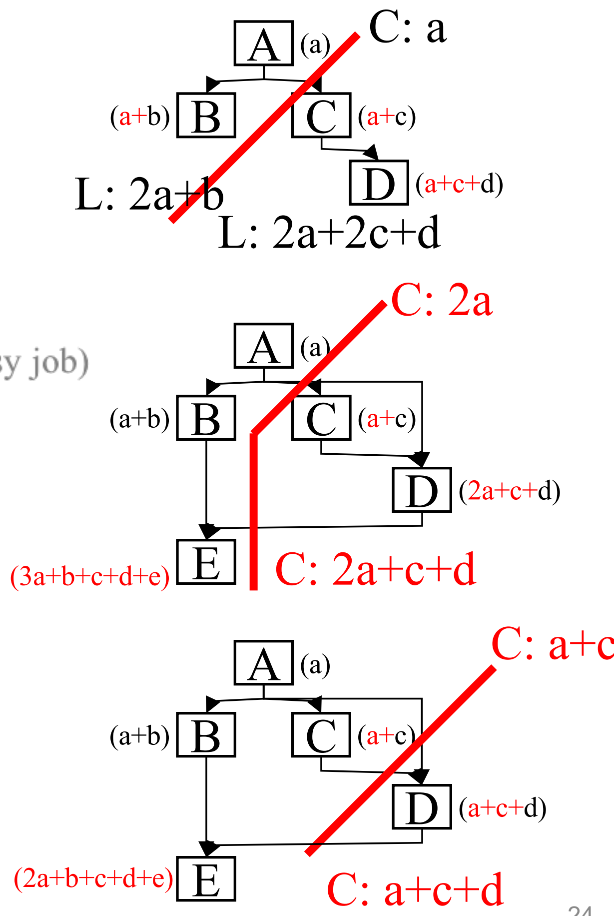
- Reliable RP splitting
  - Avoid packet loss during the migration (make before break)



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  - Trace:
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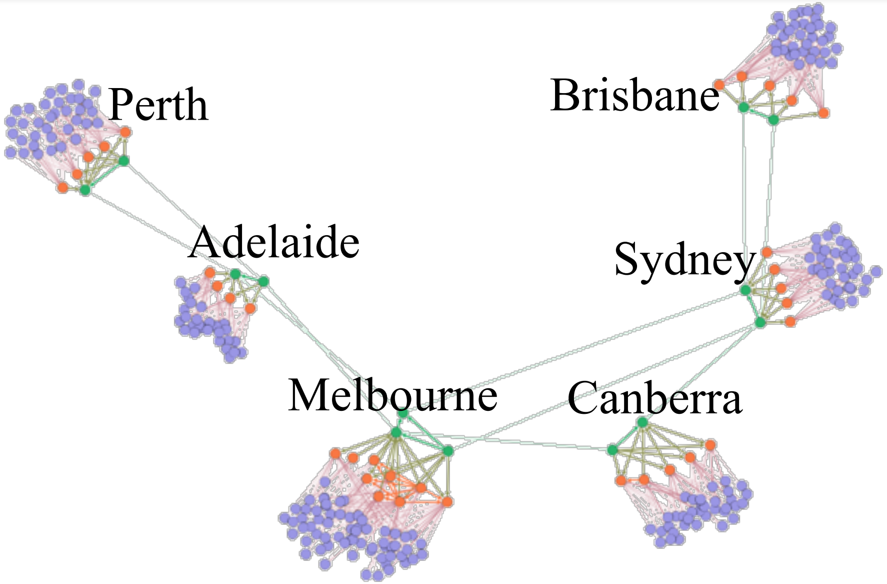

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- Evaluation
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    - Namespace: Wikipedia category data, 6 levels below "Disaster management"
      - Eg., Triage → Disaster medicine
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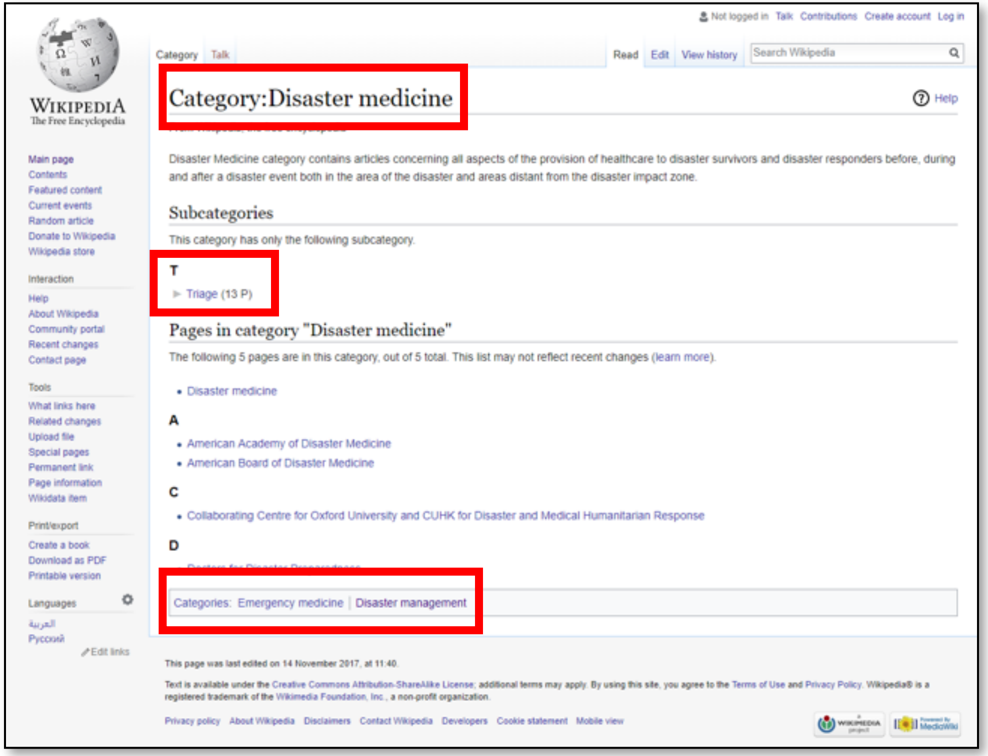
      - 489 cats, 732-1 relationships
      - 1,468 hierarchical names



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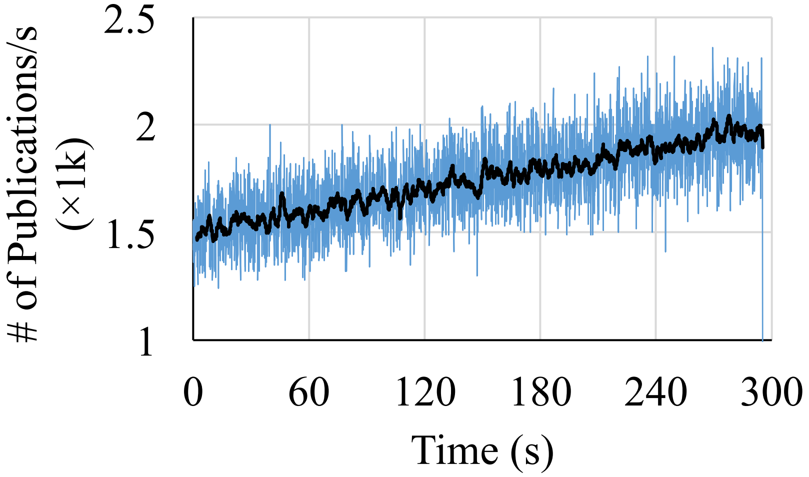

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  - Metrics:
    - Notification latency
    - Aggregate network load

- Comparison:
  - Network with hierarchical namespace
  - Graph namespace w/o RP splitting
  - Graph namespace w/ random RP splitting
  - Graph namespace w/ METIS+TABU RP splitting

Supporting Graph-Pub/Sub in The Network

- Evaluation result
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    - Hierarchical namespace sees huge latency due to more publications caused queueing on the RP
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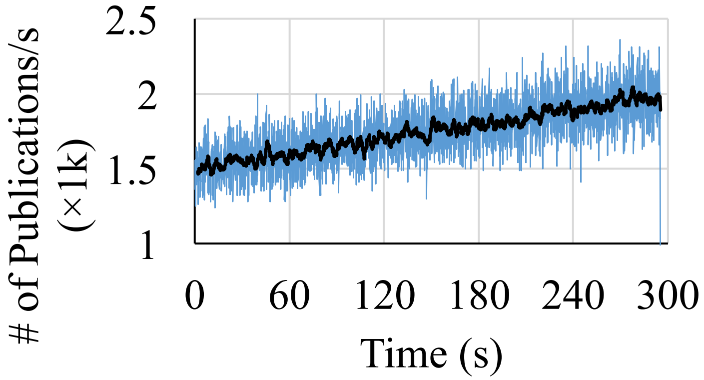

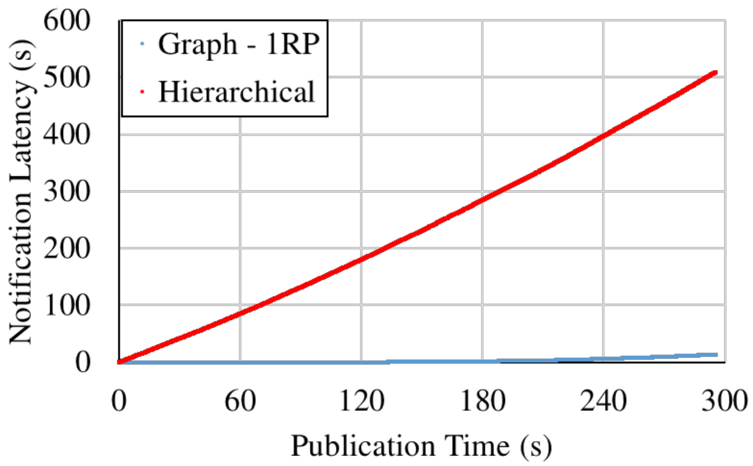

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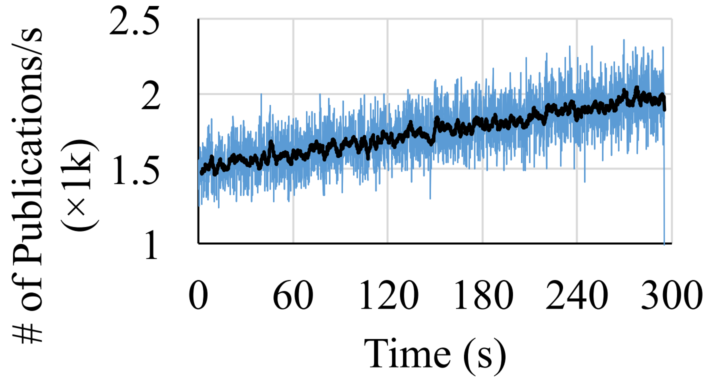
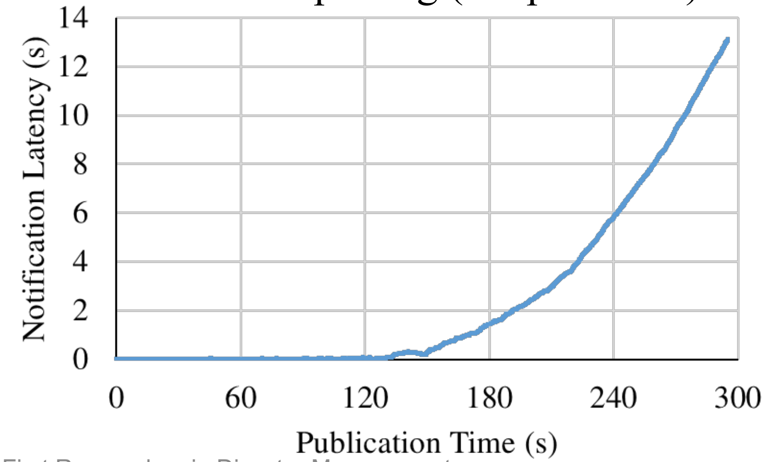


No RP Splitting (Graph – 1RP)



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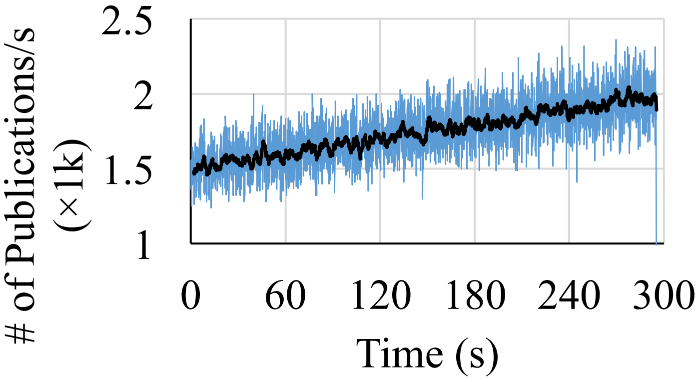
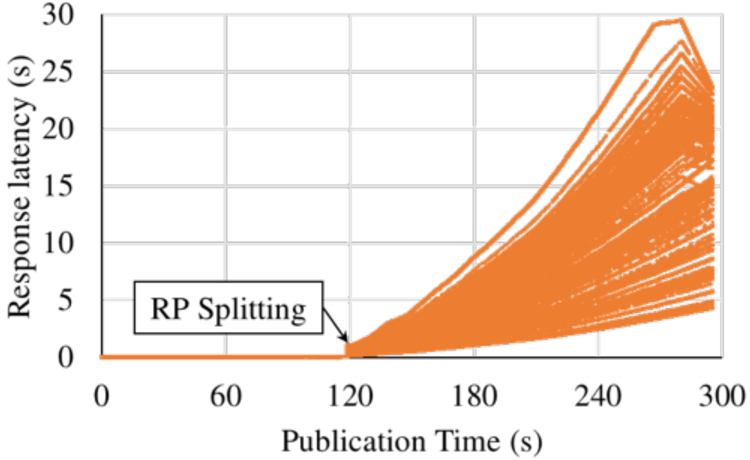


Random RP Splitting (Graph – Random)



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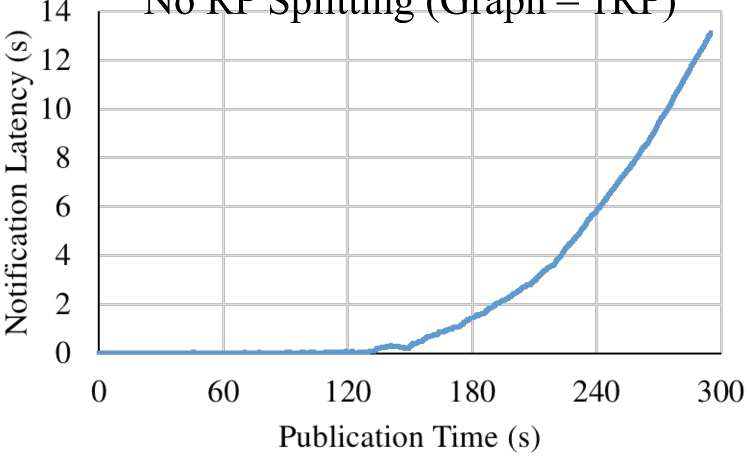

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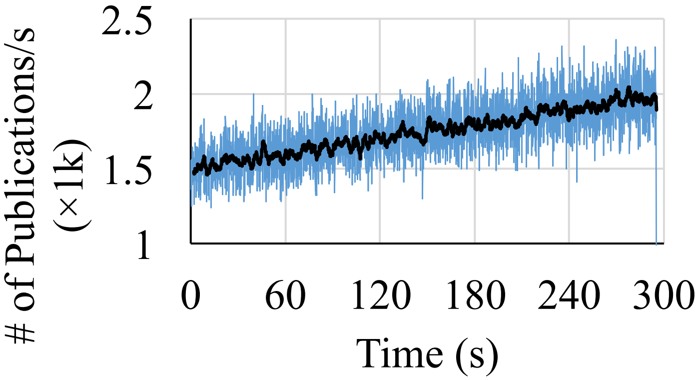

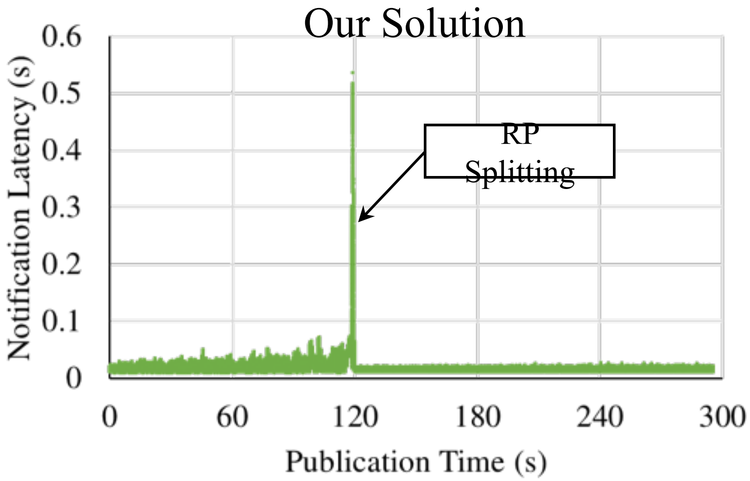

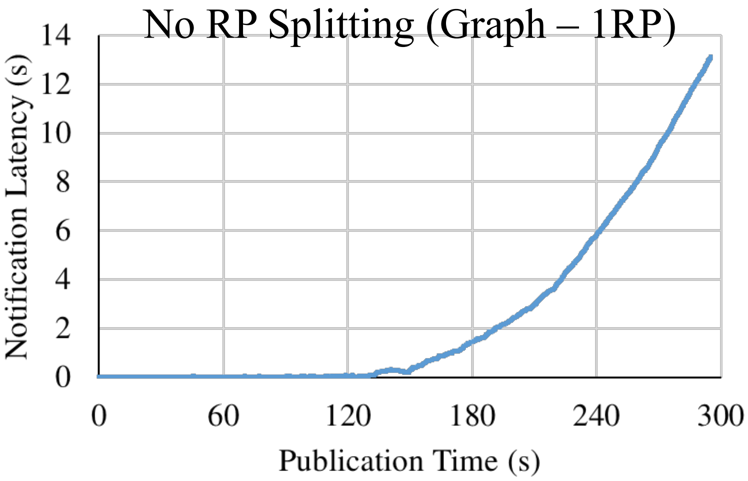

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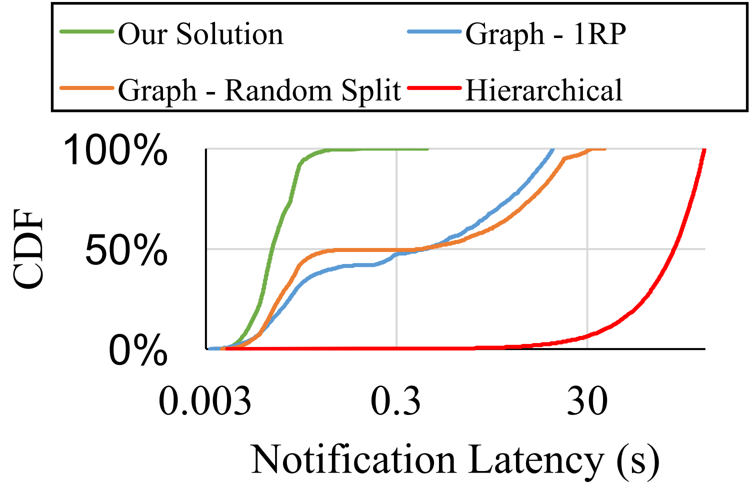
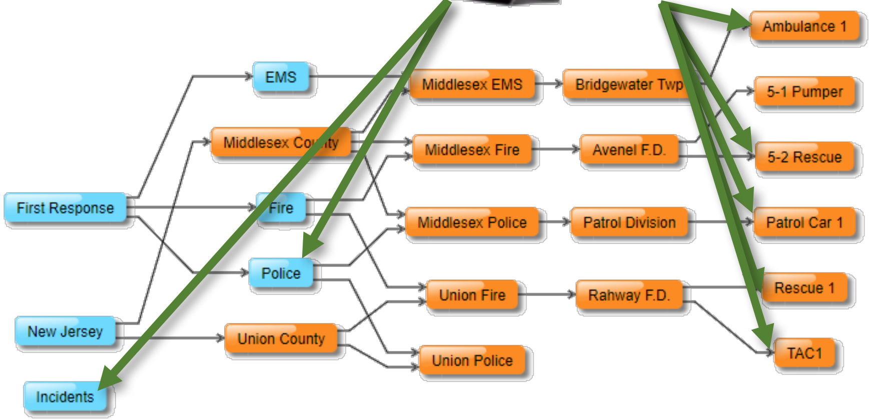


  - Aggregate network traffic
    - Our solution introduced a slightly higher traffic (<1%), to get the very low notification latency
    - Random splitting wastes a lot of traffic in sending the messages back and forth (> 30 times compared to our solution)
    - Graph namespace reduces network traffic (by 41.41%) compared to hierarchical names

Solution	Avg. Notification Latency (s)	Aggregate Network Traffic (Gb)
Our Solution	0.018	507.87
Graph – 1RP	2.741	503.61
Graph – Random	4.725	647.53
Hierarchical	247.742	866.85

Demo: Graph-based Communication in Disaster Management

- Purpose: demonstrate the benefits (flexibility) of using graph-based namespace in disaster management
- Namespace:
  - Administrative “hierarchy”
  - Incident space holder
  - Incident template
- Roles:
  - Unit dispatcher (laptop)
  - Incident commander (laptop)
  - First responders (phones)



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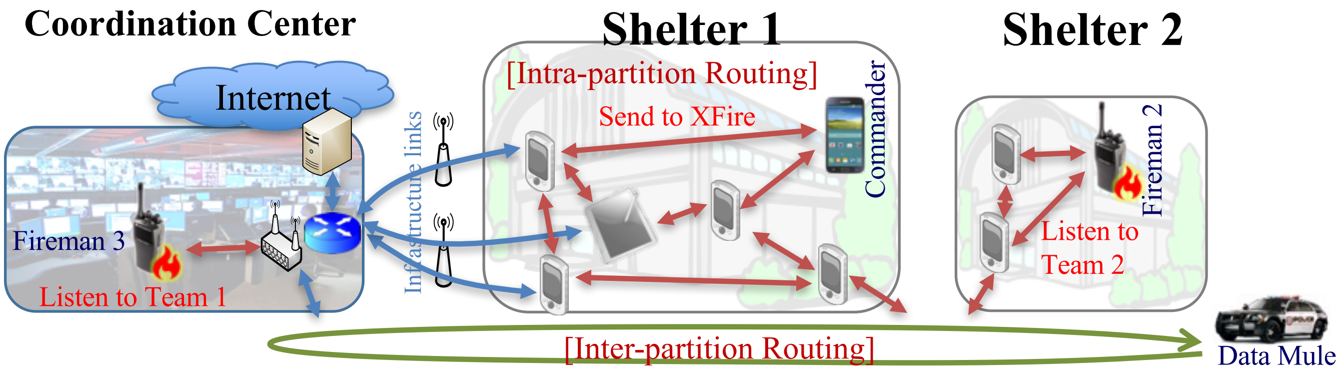
  - Unit dispatcher (laptop)
  - Incident commander (laptop)
  - First responders (phones)
- Scenarios:
  - Dynamically instantiate a template (several clicks)
  - Dynamically dispatch units (1 drag)
  - Exchange data (voice/text) based on roles

D2D Communication & Routing

- Routing in a disaster
  - Partitions created during the disaster due to the infrastructure failures, e.g., each shelter is a partition
  - First responders need to communicate within partitions and sometimes among partitions
  - Flooding is not efficient in terms of energy (battery-life) and storage
- D2D routing: Name-based, gossip-like protocol for resource/device discovery
  - <u>Intra-Partition</u> Routing
    - Control: Probabilistic, evenly distributed, weak state
    - Data follows the most probable path
  - <u>Inter-Partition</u> Routing
    - Control: Partition-summarizing floods: name-hash + MAC-hash
    - First responder vehicles as data mules
    - DTN-style opportunistic forwarding
- <u>Goal 3:</u> Efficient and resilient protocol set for reachability to roles and people scattered across partitions.

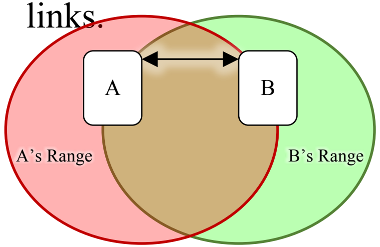


D2DMesh: D2D Mesh Network

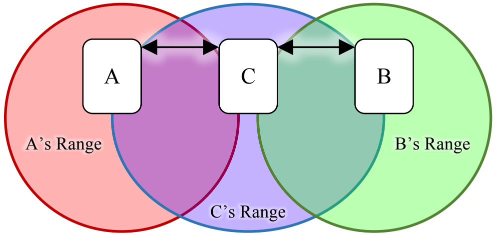
- A user-space D2D app that
  - Facilitates direct communication between mobile devices without using the infrastructure.
  - Utilize multi-hop heterogeneous wireless interfaces.
  - Enables sharing of services such as SMS, Internet, and camera.
- This application could
  - Help to maintain connectivity in infrastructure-less situations.
  - Be used by the first responders during disasters and for reaching to victims.
  - Help to crowdsource resources of individual devices.
  - Reduce traffic over the core network by offloading local traffic to D2D links.

Challenges:

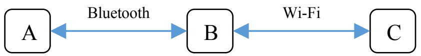
- Peer discovery
- Handling heterogeneous links from user space
- Quantifying D2D link quality
- D2D topology control
- Effective routing
- Vendor-specific issues (We use Android)



(a) Direct communication between A and B



(b) Communication between A and B via C



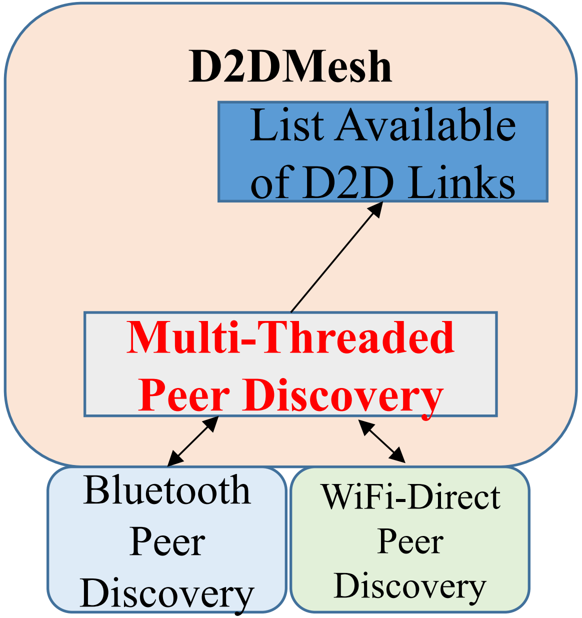
(c) Communication through Bluetooth and Wi-Fi

D2D Peer Discovery

- How to detect D2D links at the user space?
  - Both WiFi-Direct and Bluetooth use internal peer discovery
  - User apps can only start/stop these peer discovery processes.
  - Have to keep track of available heterogeneous links at a device
- Periodic peer discovery to handle dynamism in the D2D relationships
  - D2DMesh periodically discovers nearby devices (peers) using simultaneously both Bluetooth and WiFi-Direct

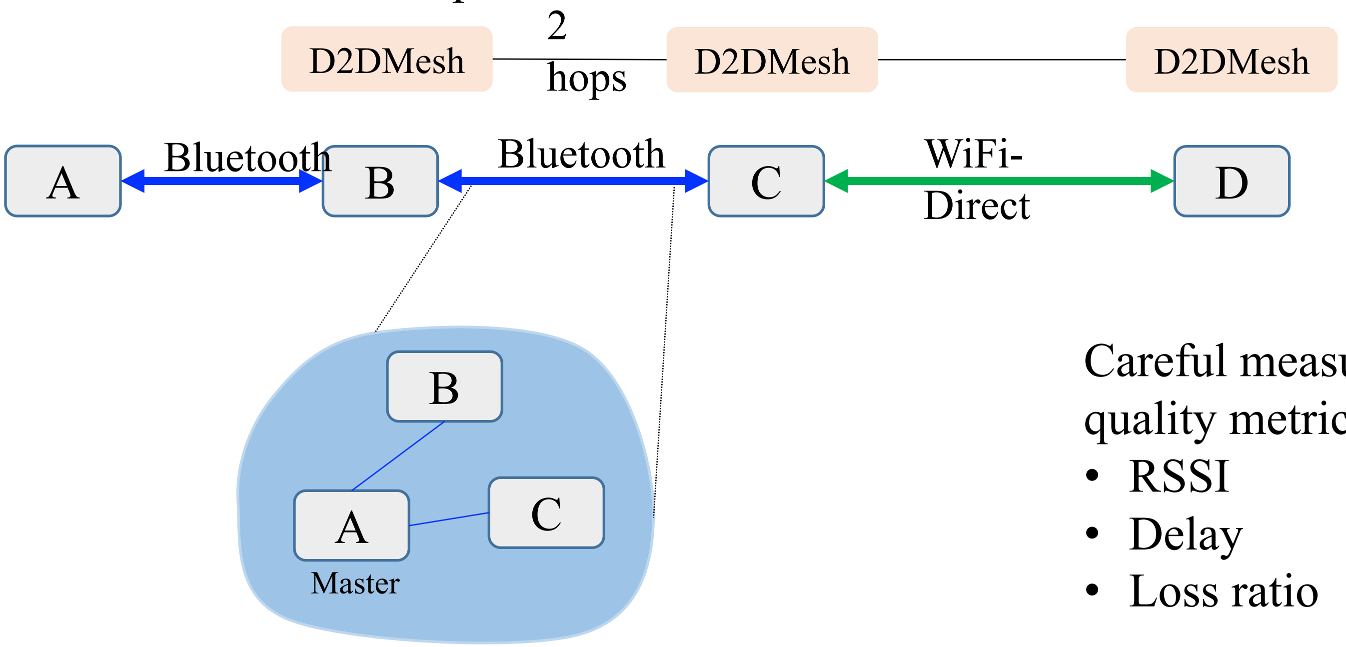
Time slot 1	Time slot 2	Time slot 3	Time slot 4	Time slot 5	…
Run discovery	Stop discovery	Run discovery	Stop discovery	Run discovery	…

- We had the following pitfalls:
  - To discover via WiFi-Direct, devices must be running the discovery process simultaneously.
  - Tradeoff: Discoverability vs. overhead of running continuous discovery.



D2D Link Quality Measurement

- How to quantify a D2D link's quality – for later use in topology control and routing?
  - WiFi-Direct and Bluetooth maintain a star topology within their groups
  - Links can involve two hops

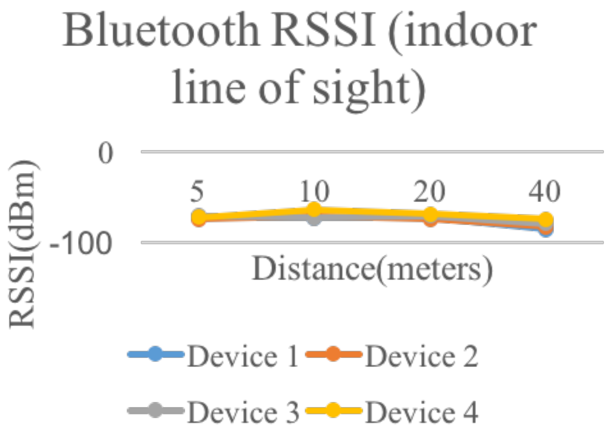


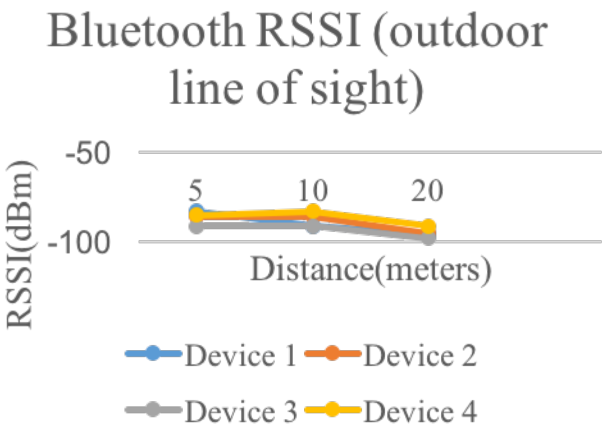
Careful measurement of link quality metrics is needed:

- RSSI
- Delay
- Loss ratio

D2D Link Quality Measurement – Ongoing Experiments

- Measuring RSSI

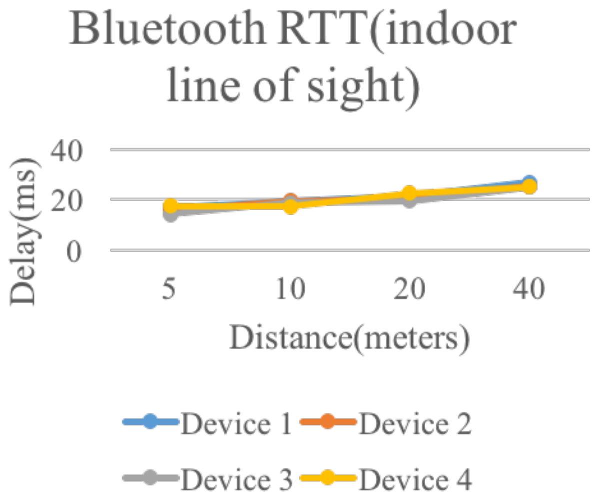


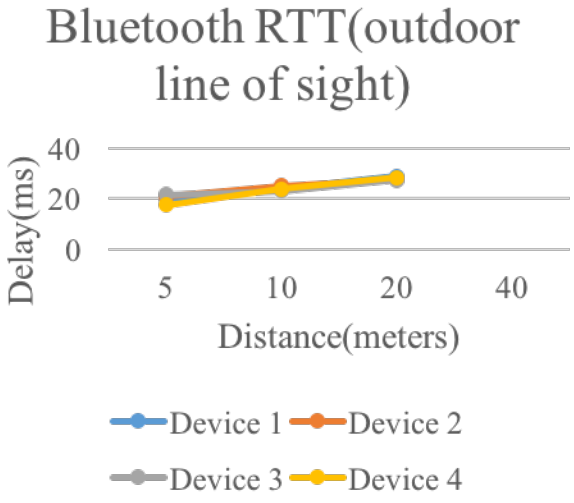


- For outdoor environment devices were mostly not seen at 40 meters distance
- For both indoor and outdoor environment signal strength gets weaker with increasing distance. For outdoor environment it shows sharp decrease at 20 meters distance
- We had the following pitfall
  - Measuring RSSI for WiFi-Direct links in the user space is not possible in Stock Android

D2D Link Quality Measurement – Ongoing Experiments

- Measuring Delay(Round Trip Time)

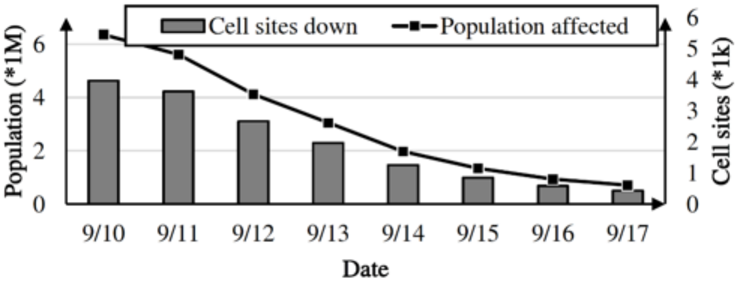




- Indoor and outdoor experiments both show increment in delay with increasing distance
- Delay time is slightly greater in outdoor environment than indoor environment

Cell Tower Failure Analysis

- Contacting 911 Emergency Response service becomes more challenging during natural disasters due to physically damaged or overloaded cell towers.



(D: down, U: up w/o ALI, R: reroute w/o ALI, A: reroute w/ ALI, Abnormal %: % of answer positions down or w/o ALI)

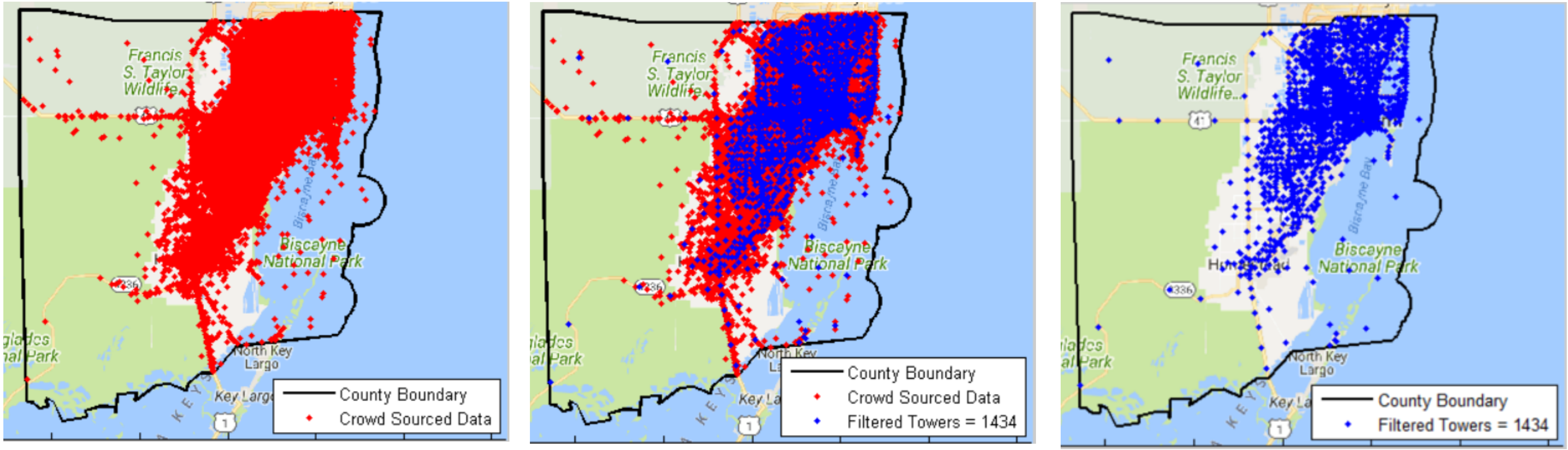
Date	County	PSAPs (Answer Positions)					Abnormal(%)	Cell sites down (%)
		Total	D	U	R	A		
9/10	Monroe	3 (11)	2 (7)				63.64	87 (80.56)
	Collier	2 (39)	2 (39)				100.00	160 (75.47)
	Hendry	4 (8)	2 (3)		1 (2)		62.50	31 (67.39)
	Lee	5 (41)	2 (15)	1 (14)	1 (2)		75.61	186 (54.23)
	Miami-Dade	7 (212)				1 (19)	0.00	739 (51.50)
	Broward	6 (126)					0.00	443 (47.94)
	Palm Beach	19 (142)				2 (13)	0.00	311 (42.84)
9/11	Monroe	3 (11)	2 (7)				63.64	89 (82.41)
	Collier	2 (39)		1 (33)	1 (6)		100.00	154 (72.64)
	Hendry	4 (8)		3 (5)			62.50	36 (78.26)
	Lee	5 (41)		4 (39)		1 (2)	95.12	170 (49.56)
	Miami-Dade	7 (212)				1 (19)	0.00	602 (41.95)
	Broward	6 (126)				1 (18)	0.00	353 (38.20)
	Palm Beach	19 (142)				2 (13)	0.00	244 (33.61)

- Questions:
  - How reliable is the cellular system?
  - How many D2D hops one would have to traverse to reach an active cell tower during a hurricane?

Predicting Cell Tower Reliability from Crowdsourced Data

- OpenCellid: A crowdsourced dataset https://opencellid.org/downloads
  - provides the location of the cells (base stations) within specific counties
- Miami Dade County:
  - FCC report states 1,435 towers while OpenCellid gives >64K cells.
- We used Closest Point Clustering to estimate the locations of the 1,435 towers.

Inter-tower distance: avg: 7.76 miles



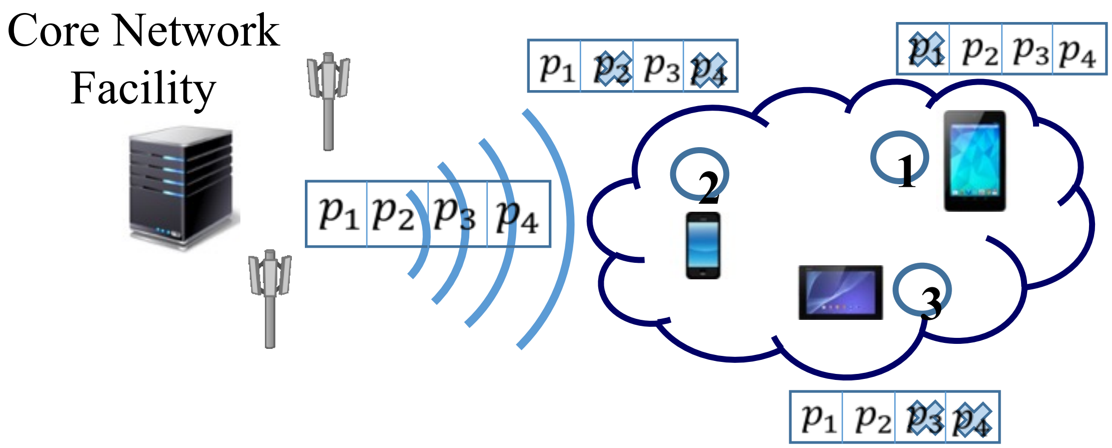
D2D Communications: Future Work

- Make further D2D link quality measurements:
  - Scheduling measurement periods considering device dynamism and energy
  - Inferring single vs. two hops
  - Ongoing source code: https://github.com/tausif-ah/D2DCommWithDynamicRouting/tree/Tausif-Working-Copy

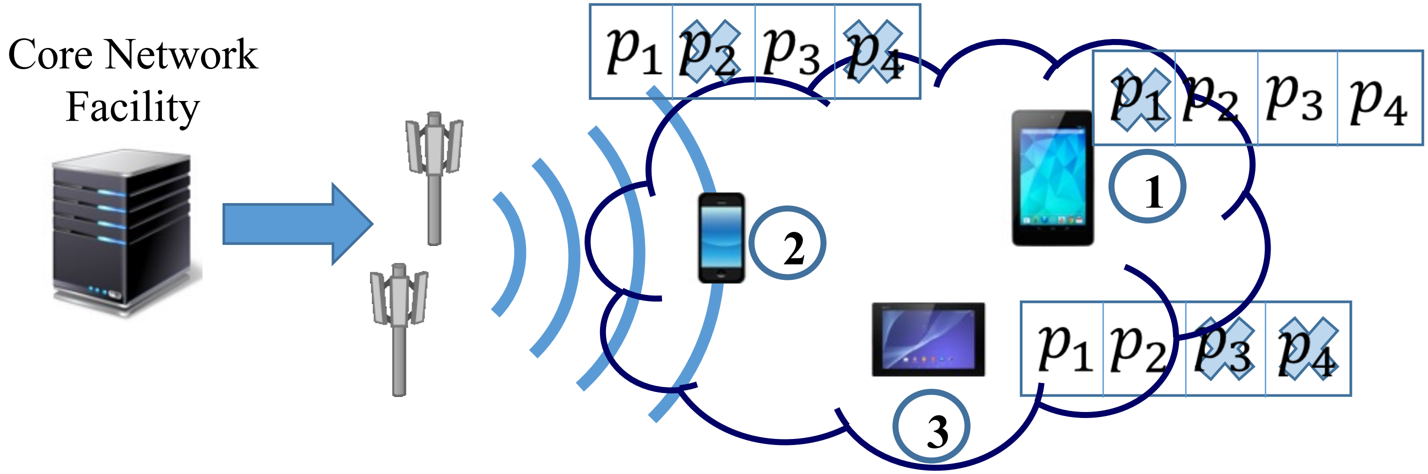
- Cell tower failures in hurricanes
  - Relate to population map
  - Infer worst, average and best case failure scenarios
  - Predict the need for D2D communications

Coding for reliable D2D communication

- A key component of our architecture is coding, where packets to/from first responders are coded together for throughput improvement and reliability.
- Consider an example scenario where a group of first responder devices is in the same transmission range (thus can hear one another).
  - A common content, *e.g.*, crucial voice instructions, can be broadcast over infrastructure-based links.
  - Simultaneous infrastructure-based and D2D links.



Data recovery - only infrastructure-based links



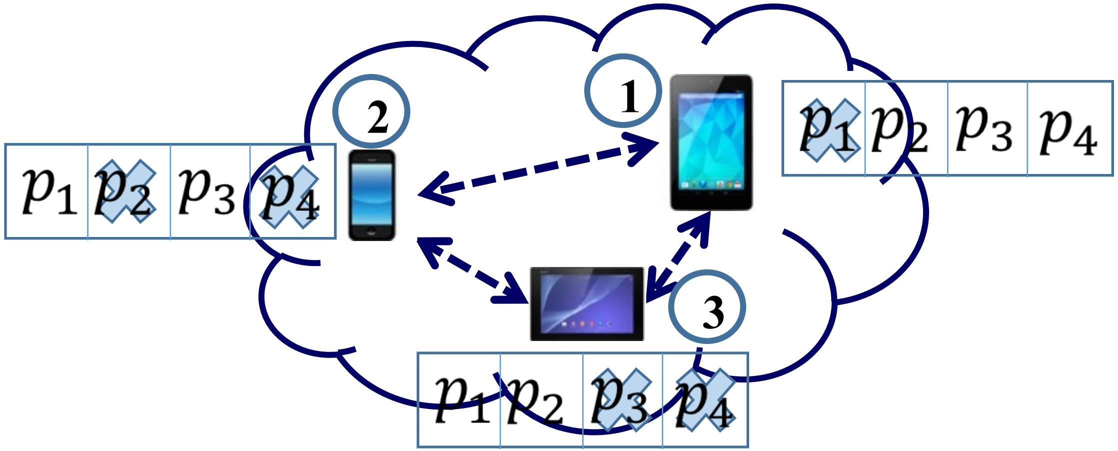
w/o Network Coding

- Four transmissions are required to recover all missing packets.
- p_1, p_2, p_3, p_4 should be transmitted.

Network Coding

- Two transmissions are required to recover all missing packets.
- $p_1 + p_2 + p_3$ and p_4 should be transmitted.

Data recovery - only D2D links



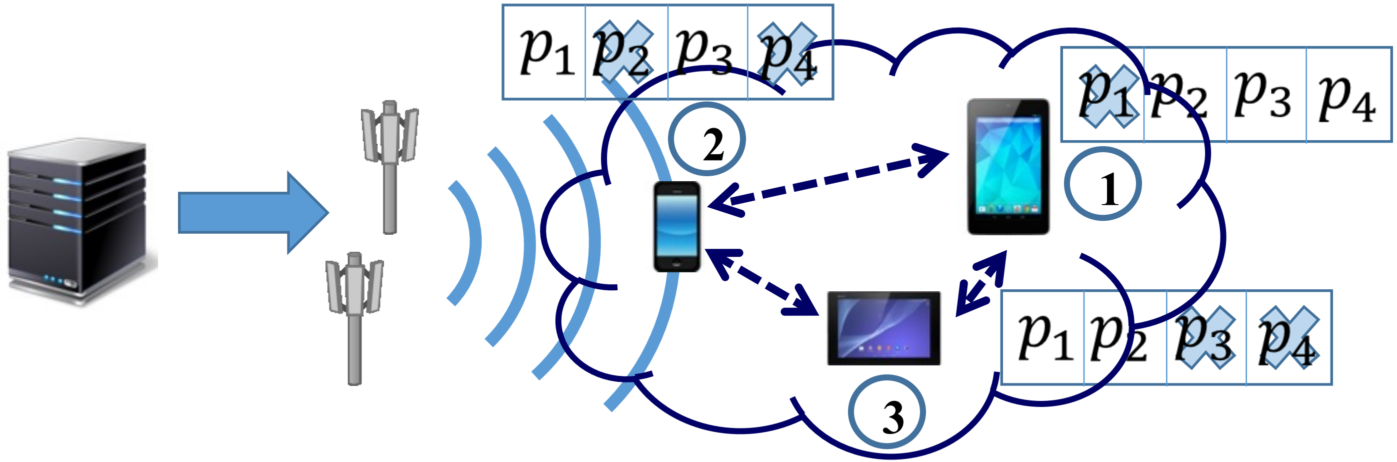
<u>w/o Network Coding</u>

- Four transmissions are required to recover all missing packets.
- p_1, p_2, p_3, p_4 should be transmitted.

<u>Network Coding</u>

- Three transmissions are required to recover all missing packets.
- $p_2 + p_3$, p_1, and p_4 should be transmitted via D2D links

Data recovery - joint infrastructure & D2D links



<u>Infrastructure or D2D only</u>

- Two (infrastructure) or three (D2D) transmission slots are required to recover all missing packets.

<u>Joint infrastructure & D2D links</u>

- One transmission slot is required to recover all missing packets.
- $p_1+p_2+p_3$ via infrastructure-based link and p_4 via D2D link should be transmitted.

How to determine $p_1+p_2+p_3$ and p_4?

Performance bounds?

Y. Keshtkarjahromi, H. Seferoglu, R. Ansari, and A. Khokhar, "Device-to-Device Networking Meets Cellular via Network Coding," in *IEEE/ACM Transactions on Networking*, vol. 26, no. 1, pp. 370-383, Feb. 2018.

Coding for reliable D2D computation

- Distributed computing can be crucial in first responder and PSC systems when there is little or no infrastructure support.
  - *E.g.*, creating a map showing the disaster area.

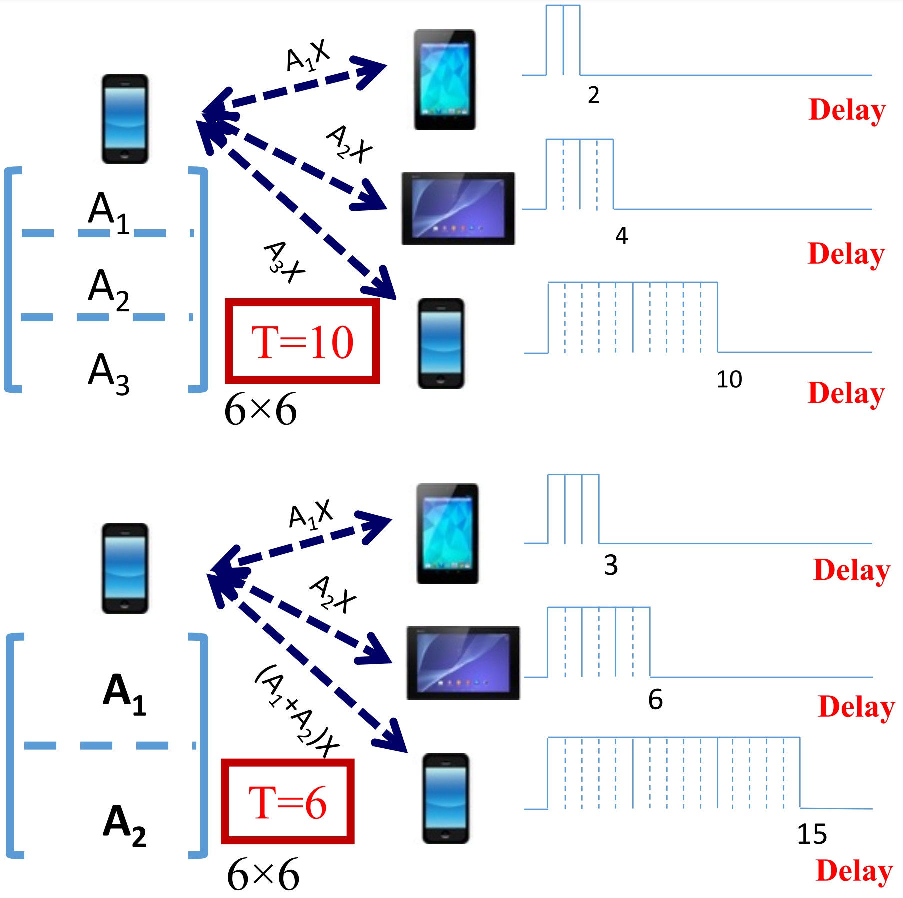
- Our approach:
  - Divide a computationally intensive task into small subtasks
  - Offload each subtask to multiple first responder/civilian devices after coding to improve resiliency of the system.

- Challenge: Heterogeneous nature of the first responder/civilian devices.
  - Different and time-varying computing power and energy resources
  - Mobility

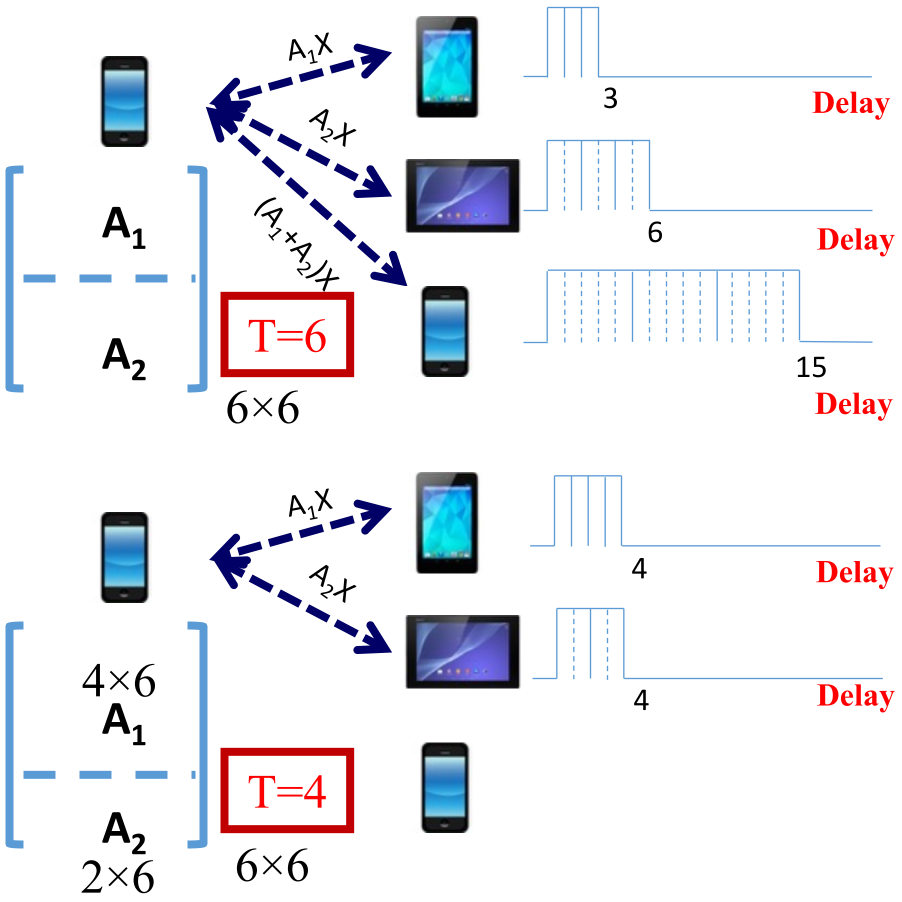
- Goal: Develop a dynamic and adaptive cooperative computation framework by taking into account the heterogeneity of resources in these devices.

How does coding help for computation?

- Calculation of matrix multiplication y = Ax
- Trivial Approach:
  - A is divided into 3 submatrices with equal size.
  - 3 tasks each consisting of one of the submatrices
- Coded Computation:
  - A is divided into 2 submatrices with equal size.
  - 3 coded tasks are generated from the 2 submatrices
- Advantage of coded computation:
  - Higher reliability
  - Smaller delay
  - Lower communication cost



Challenge: Heterogeneous and time-varying resources



Coded Cooperative Computation

- Goal: Develop dynamic and heterogeneity-aware coded computation algorithm.

- Master / worker (helper) setup. The master wishes to compute $y = Ax$, where A is an R by R matrix, x is an R by 1 vector.

- Coding: Packetize each row of A into a packet and create R packets; $\rho_1, \rho_2, \ldots \rho_R$. These packets are coded using Fountain codes to $p_1, p_2, \ldots p_{R+K}$, where K is the coding overhead.
  - Fountain codes suits well with the dynamic property of our work thanks to their rateless property, low encoding and decoding complexity, and low overhead.

- Inspired by the ARQ mechanism, the master transmits packets to workers gradually, estimates the runtime of each worker n based on the frequency of the received ACKs, and decides to send more/less coded packets to that worker.

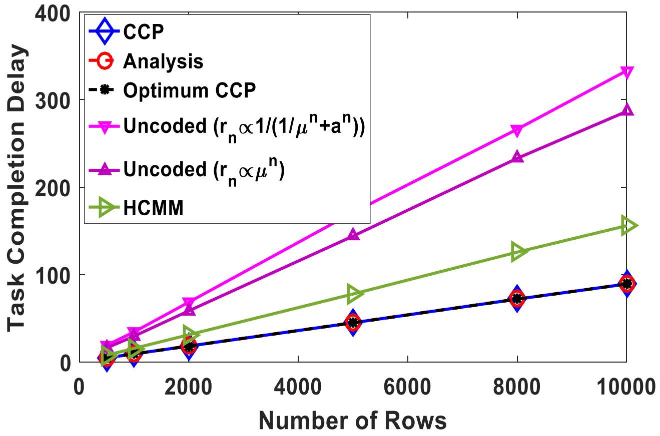
CCP: Coded Cooperative Computation - Performance

Theory:

- Efficiency and task completion delay analysis. Optimal task allocation guarantee on the average

Practice:

- Improves task completion delay significantly as compared to baselines
- Efficiency is higher than 99%
- Task completion delay is close to theory



- Uplink and downlink channel capacities follows a Poisson distribution with mean uniformly distributed within [10, 20] Mbps

- N=100 workers

- Fountain code overhead (K): 5%

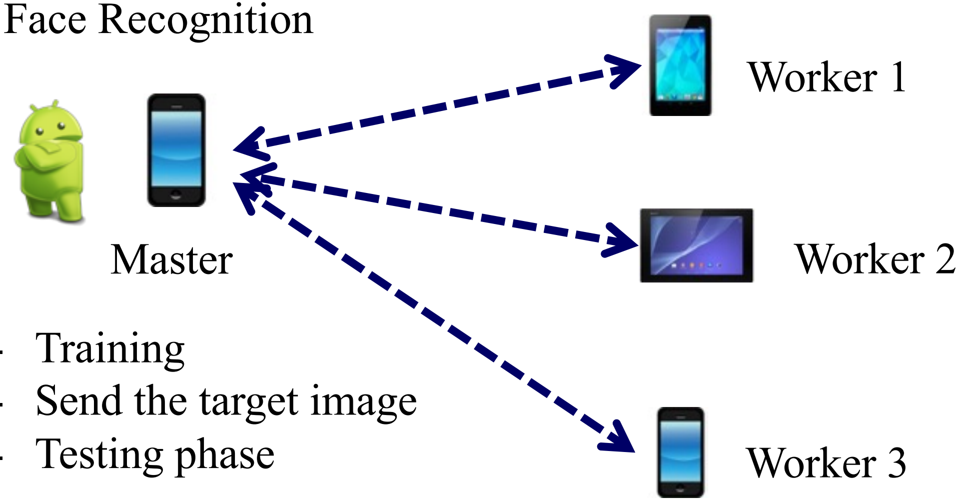
Y. Keshtkarjahromi, H. Seferoglu, "Coded Cooperative Computation for Internet of Things," under submission, 2018.

Y. Xing, H. Seferoglu, “Predictive Edge Computing with Hard Deadlines,” in *IEEE LANMAN*, Washington, DC, June 2018.

Demo: Reliable D2D Computation

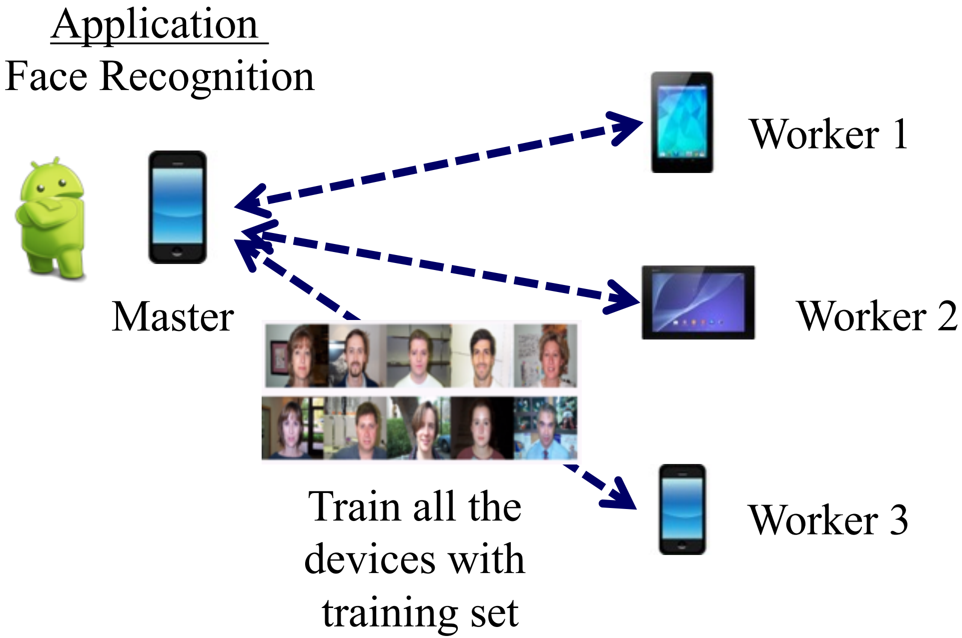
<u>Application</u>

Face Recognition



- Training
- Send the target image
- Testing phase

Demo: Reliable D2D Computation

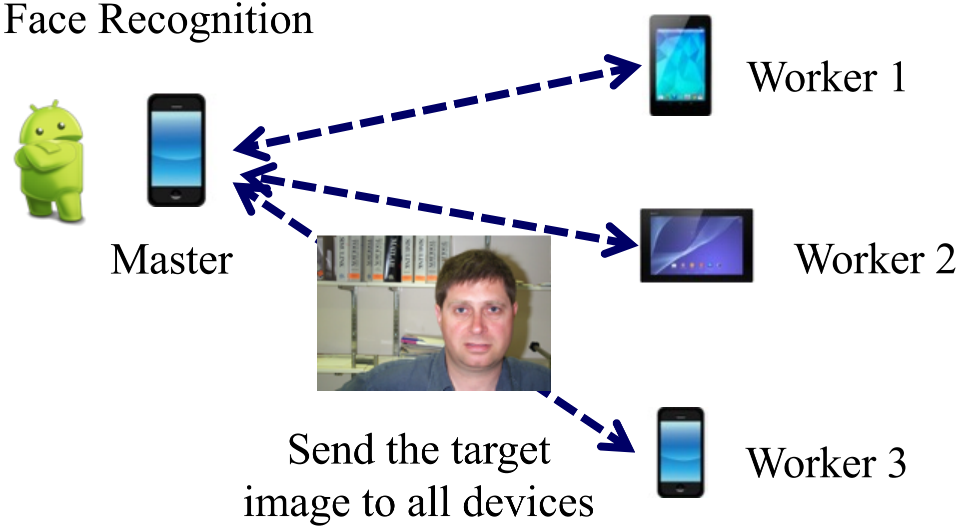


Dataset: Caltech 1999 front face dataset - http://www.vision.caltech.edu/html-files/archive.html

Demo: Reliable D2D Computation

Application

Face Recognition



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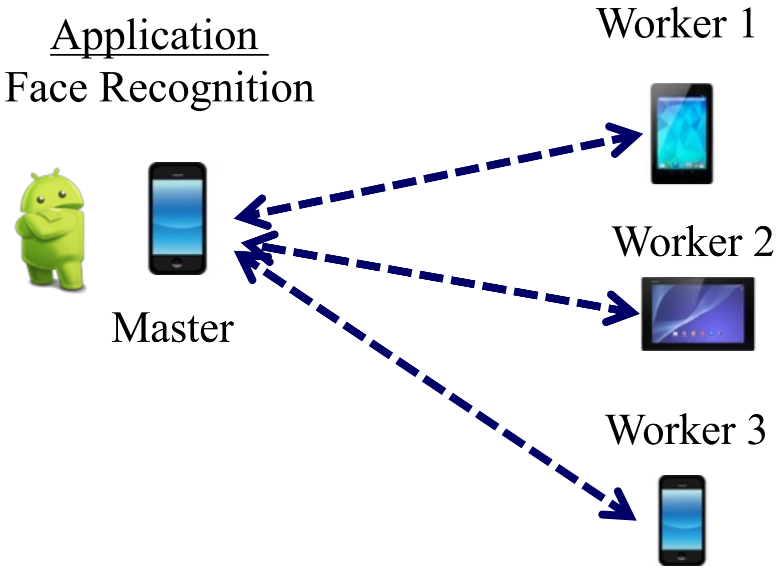
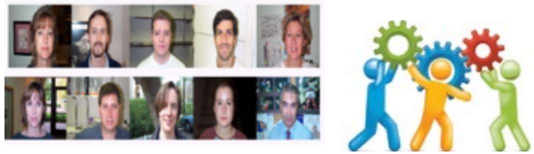
Demo: Reliable D2D Computation

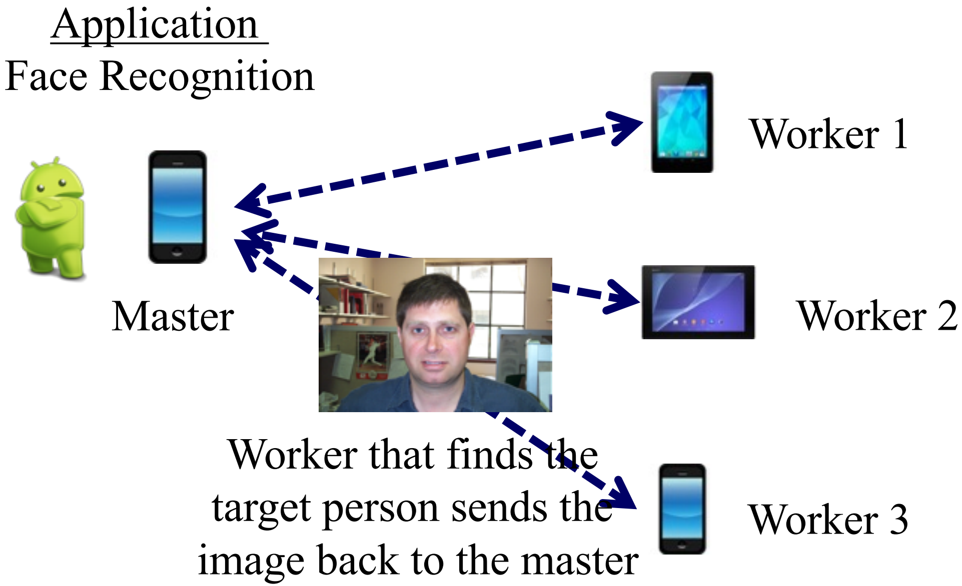




Devices cooperatively process test images

Dataset: Caltech 1999 front face dataset - http://www.vision.caltech.edu/html-files/archive.html

Demo: Reliable D2D Computation



Dataset: Caltech 1999 front face dataset - http://www.vision.caltech.edu/html-files/archive.html

Wrap Up & Plans for Next Year

- "Communication saves lives": provide a much improved framework for developing a communication system for first responders: deliver relevant information in a timely manner, even with infrastructure failures
  - Information layer for organizing teams
  - Integrated dissemination service model: publish/subscribe as a first-class capability
  - Exploit Device-Device communication
  - Exploit coding to improve communication over impaired channels
  - Use peer devices to develop D2D computational capabilities for speed up, especially when infrastructure is down
- Develop a prototype of Information layer and get feed back from stakeholders and users
- Begin to develop a means of discovering names reachable in a partitioned network, because of failures
- Integrate information layer and D2D communication and computation capabilities