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)
Traditional cellular network

D2D communications

D2D pair

Cellular UE

D2D pair

Cellular UE

D2D pair

Cellular UE

D2D pair

Cellular UE

D2D pair

Cellular UE
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

Sensor Nodes with unknown locations have different clock-offsets and drifts

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 $m$th sensor and received at the $i$th sensor:

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

$t_m$  Unknown transmission start time

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

$D t_i$  Unknown clock offset of the $i$th sensor

$t_i^m = t_m + d_{mi}/c + D t_i$  Delay at sensor $i$
The dTDOA Algorithm

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

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

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$t_i^m = t_m + d_{mi}/c + D t_i$ Delay at sensor $i$
The dTDOA Algorithm

- Two Tx and two Rx:

\[
t^A_C = t_A + \frac{d_{AC}}{c} + D t_C \\
t^A_D = t_A + \frac{d_{AD}}{c} + D t_D \\
t^B_C = t_B + \frac{d_{BC}}{c} + D t_C \\
t^B_D = t_B + \frac{d_{BD}}{c} + D t_D
\]

- Form the dTDOA (double difference):

\[
t^{AB}_{CD} = t^A_C - t^B_C = (t^{A}_C - t^{A}_D) - (t^{B}_C - t^{B}_D) \\
= (d_{AC} - d_{AD} - d_{BC} + d_{BD}) / c
\]

- These equations are in terms of sensor locations
The dTDOA Algorithm

\[ t^{AB}_{CD} = t^{A}_{CD} - t^{B}_{CD} = (t^{A}_{C} - t^{A}_{D}) - (t^{B}_{C} - t^{B}_{D}) = (d_{AC} - d_{AD} - d_{BC} + d_{BD})/c \]

• With \( N \) sensors, \( N(N-3)/2 \) independent equations

• In 2-D, 5 sensors \( \rightarrow \) 5 independent equations
  6 sensors \( \rightarrow \) 9 independent equations
  7 sensors \( \rightarrow \) 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

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

• 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
- Emergency-related data extraction algorithms
  - Geometric data
  - Semantic data
    - Simplified 3D model
    - Data Visualization and Scale
      - Interactive 3D model viewer
        - Location information integration and display

Location measurement and computation
Location information and coordinates
BIM Data Structure Investigation

- Distilled a clear sense of how building egress-related elements and information are set and defined.

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

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

Emergency-related data structure in BIM-compliance dataset
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

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.

**Example of building wall’s fire rating extraction**

**Extracted fire rating hour list**
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
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
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

- 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
Compartment Search Pattern
The direction and order of search is to be determined as part of the briefing.

Door Search Area
Entry Point

Compartment 1
Compartment 2
Compartment 3
Compartment 4
Compartment 5
Compartment 6

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

• ORB-SLAM
• Semi Direct Visual Odometry (SVO)
• Direct Sparse Odometry (DSO)
ORB SLAM
It loses tracking when the camera faces featureless scenes, e.g. white walls.
ORB SLAM

• ORB-SLAM failed to track successfully as the firefighter did a U-turn at the end of the corridor

• It covered half of the trajectory and then failed
Semi-Direct Visual Odometry
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 firefighter did a U-turn at the end of the corridor
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
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
Rx at 10m
Rx at 20m
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
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
Architecture

Noisy signal → Encoder Network (conv) → mean vector → sampled latent vector → Decoder Network (deconv) → Clean signal

standard deviation vector
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
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
PerfLoc Prize Competition for Development of Smartphone Indoor Localization Apps

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

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

2018 IPIN Competition
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”.
About the Data
About the Data
Data Collection Campaign

- Over 900 surveyed dots
- Total space more than 30,000 m²
- 34 Test & Evaluation scenarios
- Supplemental data collection with additional 386 dots
- Training and test data sets
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.

<table>
<thead>
<tr>
<th>SE95 / SE50 Performance (in meters)</th>
<th>Overall</th>
<th>Bldg. 1</th>
<th>Bldg. 2</th>
<th>Bldg. 3</th>
<th>Bldg. 4</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.29/2.04</td>
<td>5.44/1.64</td>
<td>7.04/2.84</td>
<td>6.26/2.24</td>
<td>5.38/1.90</td>
<td>61.70</td>
</tr>
</tbody>
</table>
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
Performance of the Offline Evaluation

Overall Performance for Top 10 Teams

CE95  VE95  SE95
Performance of the Offline Evaluation

Comparison of SE95 and Mean of 3D Error Magnitude

Mean of 3D Error Magnitude  SE95
Building 2 and 4 yield lower 3D error than Building 1 and 3.
Building 3 and 4 yield lower vertical error than Building 1 and 2.
Smartphone Indoor Localization App Developed by the PerfLoc Winners
Overview of the Real-Time Solution

Internal Sensors

- Mobility & Floor Detection
- INS/PDR
- Wi-Fi Landmark
- Wi-Fi Ranging
- Position

UKF

Fused Location
Mobility Detection

Walking Mode Recognition

Neural Network Classifier
Floor Detection

- Barometer
  - time-domain compensation

- Tri-Accelerometer
  - offset in Z-axis

- Scanned Wi-Fi AP
  - Scanned AP Coordinates

Floor change?

Floor Detection

Floor Level
## Wi-Fi Landmark

### Scenario S01, S02, S03, S10, S12, S13, S14, S16

<table>
<thead>
<tr>
<th>AP number</th>
<th>RSSI (dBm)</th>
<th>coordinates (AP) (m)</th>
<th>timestamp</th>
<th>coordinates (calculated by PDR) (m)</th>
<th>error (m)</th>
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<tr>
<td>1</td>
<td>-42</td>
<td>102534.2458 31139.9311</td>
<td>145496241</td>
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<tr>
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<td>162335.0595 38137.0147</td>
<td>3.9593</td>
</tr>
</tbody>
</table>

### Test Dataset from Building 2 (Samsung)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>S01</th>
<th>S02</th>
<th>S03</th>
<th>S10</th>
<th>S12</th>
<th>S13</th>
<th>S14</th>
<th>S16</th>
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</thead>
<tbody>
<tr>
<td>Number</td>
<td>25</td>
<td>22</td>
<td>8</td>
<td>21</td>
<td>22</td>
<td>17</td>
<td>21</td>
<td>14</td>
</tr>
</tbody>
</table>
INS/PDR
UKF Integration

Internal Sensors

Attitudes

Ranging

Position

GNSS

PSCR
UKF Integration
Live Testing of the Winning PerfLoc App
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

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

Normal walking outperforms other mobility modes.
Horizontal error is dominant compared to vertical error.
Cart, sidestepping and walking backwards have poor performance.
Performance of Live Testing: Walking w/o any Pause

<table>
<thead>
<tr>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.93 m</td>
<td>0.63 m</td>
<td>26.72 m</td>
<td>1.25 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Walking with 3 s Stops at Dots

<table>
<thead>
<tr>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.72 m</td>
<td>0.37 m</td>
<td>21.20 m</td>
<td>0.90 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Walking and Using Elevators

<table>
<thead>
<tr>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.84 m</td>
<td>4.37 m</td>
<td>11.22 m</td>
<td>5.76 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Walking and Using Elevators

<table>
<thead>
<tr>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.84 m</td>
<td>4.37 m</td>
<td>11.22 m</td>
<td>5.76 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Walking in/out of Building

<table>
<thead>
<tr>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.63 m</td>
<td>4.33 m</td>
<td>16.42 m</td>
<td>5.40 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Walking in/out of Building

<table>
<thead>
<tr>
<th></th>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.63 m</td>
<td>4.33 m</td>
<td>16.42 m</td>
<td>5.40 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Sidestepping (L) and Walking Backwards (R)

<table>
<thead>
<tr>
<th></th>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidestepping</td>
<td>27.79 m</td>
<td>0.57 m</td>
<td>79.17 m</td>
<td>0.95 m</td>
</tr>
<tr>
<td>Walking Backwards</td>
<td>38.07 m</td>
<td>0.20 m</td>
<td>83.10 m</td>
<td>0.47 m</td>
</tr>
</tbody>
</table>
Performance of Live Testing: Cart (L) and Crawling (R)

<table>
<thead>
<tr>
<th></th>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>CE95</th>
<th>VE95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cart</td>
<td>49.67 m</td>
<td>0.72 m</td>
<td>78.92 m</td>
<td>1.16 m</td>
</tr>
<tr>
<td>Crawling</td>
<td>10.31 m</td>
<td>0.34 m</td>
<td>18.56 m</td>
<td>0.57 m</td>
</tr>
</tbody>
</table>
Importance of Using Wi-Fi Info

<table>
<thead>
<tr>
<th></th>
<th>Mean of Horizontal Error</th>
<th>Mean of Vertical Error</th>
<th>Mean of 3D Error</th>
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</thead>
<tbody>
<tr>
<td>Using Wi-Fi Info</td>
<td>17.66 m</td>
<td>1.71 m</td>
<td>18.16 m</td>
</tr>
<tr>
<td>w/o Wi-Fi Info</td>
<td>26.97 m</td>
<td>2.74 m</td>
<td>27.56 m</td>
</tr>
</tbody>
</table>
• 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.
NIST Team Members

Nader Moayeri
NIST PerfLoc Manager

Chang Li
NIST Research Associate

Lu Shi
NIST Research Associate

Jeb Benson
NIST LBS Program Manager

Heather Evans
NIST Challenge Coordinator
PerfLoc Winners at NIST
<table>
<thead>
<tr>
<th>Texas A&amp;M University Corpus Christi</th>
<th>Wuhan University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tianxing Chu <strong>Official Team Representative</strong></td>
<td>Ruizhi Chen <strong>Team Leader</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Xiaojı Nıu</td>
<td>Jian Kuang</td>
</tr>
<tr>
<td>Guangyı Guo</td>
<td>Haojun Ai</td>
</tr>
<tr>
<td>Xiaoguango Nıu</td>
<td>Xingyu Zheng</td>
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<tr>
<td>Xuesheng Peng</td>
<td>Ge Zhu</td>
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<tr>
<td>Liang Chen</td>
<td>Jingbin Liu</td>
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<tr>
<td></td>
<td>Quan Zhang</td>
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</table>
THANK YOU
## Performance of the Offline Evaluation

<table>
<thead>
<tr>
<th>Rank</th>
<th>Participant</th>
<th>Building 1</th>
<th>Building 2</th>
<th>Building 3</th>
<th>Building 4</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Chenfeng_Jing</td>
<td>5.44</td>
<td>7.04</td>
<td>6.26</td>
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<td>2</td>
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<td>8.6</td>
<td>7.34</td>
<td>8.99</td>
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<tr>
<td>3</td>
<td>tbryant</td>
<td>31.92</td>
<td>17.78</td>
<td>20.93</td>
<td>17.91</td>
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<td>4</td>
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<td>24.56</td>
<td>37.28</td>
<td>26.33</td>
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<tr>
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<td>LocHere</td>
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<td>17.98</td>
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</table>
Performance of the Offline Evaluation

Accuracy by building

- Chenfeng_Jing
- ruizhi_chen
- tbyant
- gary
- niranjir
- LocHere
- swi
- howardhuang
- abramikv
- isilab

Building 1, Building 2, Building 3, Building 4
Performance of the Offline Evaluation
Offline Evaluation of Algorithms

Bldg. 1 (9 Scenarios)
Bldg. 2 (8 Scenarios)
Bldg. 3 (7 Scenarios)
Bldg. 4 (6 Scenarios)

4066 Location Estimates
4066 x 4 x 3 = 48,792 Numbers
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

Email: ycai@cmu.edu
Phone: 412-225-7885
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?

Virtual Reality  Augmented Reality  Reality  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)

Diagram showing the difference between projection and waveguide systems for near-eye displays.
Near Eye Display (NED)

Concave see-through mirror

OLED

eye
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

[Diagram showing a flowchart with boxes labeled: Helmet, Sensors, Display, Onboard Processor, Smartphone, and connections labeled: BT or Wi-Fi]
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

Landmarks

Visual

Semantic

Text Object Scene

Non-Semantic

LiDAR Corner SIFT

Abstract

Wi-Fi Magnetic Altitude ....
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.

RANSAC (RAndom SAmple Consensus)

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
Accelometer Signatures of Walking (Raw Data)

walking on carpet

walking on cement floor

acceleration:

- x: -0.032
- y: -0.332
- z: -1.179

acceleration:

- x: -0.069
- y: -0.042
- z: -1.063
## Wi-Fi Signal Localization

<table>
<thead>
<tr>
<th>Network Type</th>
<th>CMU-SECURE Accuracy</th>
<th>eduroam Accuracy</th>
<th>wireless Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>91%</td>
<td>100%</td>
<td>73%</td>
<td></td>
</tr>
<tr>
<td>100% eduroam</td>
<td>100%</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>73% wireless</td>
<td>NA</td>
<td>wireless</td>
<td></td>
</tr>
<tr>
<td>93% CMU</td>
<td>NA</td>
<td>CMU</td>
<td></td>
</tr>
<tr>
<td>93% CMU-GUEST</td>
<td>100%</td>
<td>wireless</td>
<td></td>
</tr>
<tr>
<td>44% wireless</td>
<td>100%</td>
<td>wireless</td>
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</tr>
<tr>
<td></td>
<td>48%</td>
<td>HawxeyeNet5</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Additional Networks
- **HawxeyeNet5**:
  - 73% CMU-SECURE
  - 80% eduroam
  - 86% wireless

- **DIRECT-6e-HPM477 LaserJet**:
  - 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

- GPS Sensor
  - Reference Altitude
  - Altimeter
  - Outside Building

- Temperature Sensor
  - Altimeter
  - Inside Building
Moving from Path Reconstruction to Navigation Assistance

Heading: SE
Ground Floor
10m to Lobby

Reconstructed Path

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.
References

1. Rolf R. Hainich, Freeform mirrors and displays for AR, preprint (v.0.6.5 of Sept. 15, 2015)


Acknowledgement

We would like to thank Jeb Benson, Thomas L. Nelson, Anthony Rowe, Thomas A. Ogden, Jr., and William Kutsuflakis for their support.

This project is sponsored by NIST, Public Safety Communications Research Division, PSIA Program, Award Number 70NAND17H173.
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.
Department of Homeland Security
Science & Technology Directorate
Office for Interoperability and Compatibility
(DHS S&T OIC)

This work is sponsored by:
AGENDA

Deployable Systems
Hien Nguyen

Highly Mobile Deployed Networks (HMDN)
Max Maurice

VM Server
- Sit. Awareness
- MCPTT
- Video Server
- Group Chat

LTE System
- eNB
- EPC

Wi-Fi AP
- Wi-Fi AP
- NAS

Backhaul
- Band 14 LTE

Sit. Awareness
MCPTT
Video Server
Group Chat
VM Server
eNB
EPC
Wi-Fi AP
Wi-Fi AP
NAS
Backhaul
Band 14 LTE

Wi-Fi

MCPTT
Video Server
Group Chat
VM Server
eNB
EPC
Wi-Fi AP
Wi-Fi AP
NAS
Backhaul
Band 14 LTE

Wi-Fi

MCPTT
Video Server
Group Chat
VM Server
eNB
EPC
Wi-Fi AP
Wi-Fi AP
NAS
Backhaul
Band 14 LTE

Wi-Fi

MCPTT
Video Server
Group Chat
VM Server
eNB
EPC
Wi-Fi AP
Wi-Fi AP
NAS
Backhaul
Band 14 LTE

Wi-Fi
AGENDA

Deployable Systems

Hien Nguyen

Highly Mobile Deployed Networks (HMDN)

Max Maurice

Current and Future Systems, Network Elements and Architecture
Identifying Essential Systems and Applications
Laboratory and Field Research Testing

DS interconnectivity
Completely isolated systems
Viability and performance of DS delivery platforms
Solutions to current problems in multiple and mobile systems

Engaging with First Responders and Public Safety Communities, Academia and Industries for Feedback, Adjustments and Improvements
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
DS - Network Elements and Architecture

Cell On Wheels (COW)

System On Wheels (SOW)

Backpack

Range and Capacity

Transportability and Mobility

Airborne Platform

LTE
DS – Typical Operational Parameters

(*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”

<table>
<thead>
<tr>
<th>DS Type</th>
<th>Operational</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Coverage Radius</td>
</tr>
<tr>
<td>COW (40 watts)*</td>
<td>5 miles</td>
</tr>
<tr>
<td>SOW (5 watts)</td>
<td>2 miles</td>
</tr>
<tr>
<td>Backpack (3 watts)</td>
<td>1 mile</td>
</tr>
<tr>
<td>Airborne (250 milliwatts)</td>
<td>&lt; 1 mile</td>
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</tbody>
</table>
DS - Network Elements and Architecture

Deployment System

Band 14 LTE SOW
- EPC
- eNB

Application Server

Router/Switch

FireWall

WiFi

Sensors
Personal Area Network (PAN)

Isolated – Off Line Mode

Connected – On Line Mode

Internet

Command Center

Incident and Data Management

Database Servers

Situational Awareness
Critical Voice Communication (MCPTT)

Deployable system

Incident and Data Management

Situational Awareness
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
DS – Situational Awareness Incident Commander View

Search grid
100 square meters

Drone Flight Path

Dropped Target
DS – Situational Awareness Drone Pilot View
DS – Situational Awareness Responder View
DS – Situational Awareness – On-Line and Off-Line Map Views

On-Line Mode with Google Maps

Off-Line Mode with US Topo Maps
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 - 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
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
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
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
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.

For a more comprehensive look, we put our detailed use case 1 definition below:
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:
October 18\textsuperscript{th} - 19\textsuperscript{th} 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.
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

The report was published in February and can be accessed below

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.
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
- Large Processing capabilities
- Multiple Users

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

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

**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.
THANK YOU

Sam Ray | samuel.ray@nist.gov
Hien Nguyen | hien.nguyen@nist.gov
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
• 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)
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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• Send messages to a role, e.g., “NJ Fire”
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- 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
Supporting Graph-Pub/Sub in The Network

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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, …)

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    - Messages/Commands to \text{NJ Fire} should be replicated and sent to \text{NJ FE1, NJ FE2, ...} (names marked in green)
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Solution: information layer to do the name expansion

Only 1 relationship added when
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
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  - Network would know, how to reach RP for a given name
Supporting Graph-Pub/Sub in The Network

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Name Storage on RP1

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NAME-RP Mapping

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  - Each name has an entry even when there are no children, to distinguish from names not served on this RP (next part)
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- Send a message to name NJ FE1
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• Send a message to name NJ FE1
  • Msg reaches RP1
  • RP1 performs a BFS on NJ FE1 and find the reachable names
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Issue: traffic concentration
Supporting Graph-Pub/Sub in The Network

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

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</tr>
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<td>Inc.X</td>
<td>Inc.XFire, Inc.XH</td>
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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)
Supporting Graph-Pub/Sub in The Network

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

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<tbody>
<tr>
<td>Geo-Location</td>
<td>NJ, CA</td>
</tr>
<tr>
<td>NJ FE1</td>
<td>... Driver, ... F. Fighter</td>
</tr>
<tr>
<td>... Driver</td>
<td>[NULL]</td>
</tr>
<tr>
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<td>[NULL]</td>
</tr>
<tr>
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</tr>
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NAME-RP Mapping

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<tr>
<th>NAME</th>
<th>RP</th>
</tr>
</thead>
<tbody>
<tr>
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<td>RP1</td>
</tr>
<tr>
<td>NJ FE1</td>
<td>RP1</td>
</tr>
<tr>
<td>... Driver</td>
<td>RP1</td>
</tr>
<tr>
<td>... F. Fighter</td>
<td>RP1</td>
</tr>
<tr>
<td>Incidents</td>
<td>RP2</td>
</tr>
<tr>
<td>XFF</td>
<td>RP2</td>
</tr>
</tbody>
</table>

8/8/18
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Name Storage on RP2

<table>
<thead>
<tr>
<th>NAME</th>
<th>Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident</td>
<td>Inc.X, ...</td>
</tr>
<tr>
<td>Inc.X</td>
<td>Inc.XFire, Inc.XH</td>
</tr>
<tr>
<td>Inc.XFire</td>
<td>XFF, XSS</td>
</tr>
<tr>
<td>XFF</td>
<td>NJ FE1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Name Storage on RP1

<table>
<thead>
<tr>
<th>NAME</th>
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</tr>
</thead>
<tbody>
<tr>
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</tr>
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**Benefits:** traffic concentration elimination

distributed & localized storage/computation

**Question:** where to place each name?
Supporting Graph-Pub/Sub in The Network

• Objective: balance the load on the RPs and minimize the internal traffic
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[Diagram with labeled nodes A, B, C, D, E and equations for L, C and Objective Function]
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- Reliable RP splitting
  - Avoid packet loss during the migration (make before break)
Supporting Graph-Pub/Sub in The Network

- Evaluation
- Trace:
  - Network topology (Rocketfuel 1221), modified
  - 46 core routers, 231 edge routers
Supporting Graph-Pub/Sub in The Network

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  - Eg., Triage → Disaster medicine
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    • Files/pages seen as publications ×60 times (514,620 pubs)
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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
- Notification latency
  - Hierarchical namespace sees huge latency due to more publications caused queueing on the RP
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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

<table>
<thead>
<tr>
<th>Solution</th>
<th>Avg. Notification Latency (s)</th>
<th>Aggregate Network Traffic (Gb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Solution</td>
<td>0.018</td>
<td>507.87</td>
</tr>
<tr>
<td>Graph – 1RP</td>
<td>2.741</td>
<td>503.61</td>
</tr>
<tr>
<td>Graph – Random</td>
<td>4.725</td>
<td>647.53</td>
</tr>
<tr>
<td>Hierarchical</td>
<td>247.742</td>
<td>866.85</td>
</tr>
</tbody>
</table>
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)
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- **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
  • Intra-Partition Routing
    • Control: Probabilistic, evenly distributed, weak state
    • Data follows the most probable path
  • Inter-Partition Routing
    • Control: Partition-summarizing floods: name-hash + MAC-hash
    • First responder vehicles as data mules
    • DTN-style opportunistic forwarding

• Goal 3: 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)

![Diagram](attachment:image.png)

(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

<table>
<thead>
<tr>
<th>Time slot 1</th>
<th>Time slot 2</th>
<th>Time slot 3</th>
<th>Time slot 4</th>
<th>Time slot 5</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>Stop</td>
<td>Run</td>
<td>Stop</td>
<td>Run</td>
<td>…</td>
</tr>
</tbody>
</table>
| discovery    | discovery    | discovery    | discovery    | 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

![Chart: Bluetooth RSSI (indoor line of sight)]

![Chart: Bluetooth RSSI (outdoor line of sight)]

• 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
• 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.

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?

<table>
<thead>
<tr>
<th>Date</th>
<th>County</th>
<th>PSAPs (Answer Positions)</th>
<th>Abnormal (%)</th>
<th>Cell sites down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>9/10</td>
<td>Monroe</td>
<td>3 (11)</td>
<td>2 (7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collier</td>
<td>2 (39)</td>
<td>2 (39)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hendry</td>
<td>4 (8)</td>
<td>2 (3)</td>
<td>1 (2)</td>
</tr>
<tr>
<td></td>
<td>Lee</td>
<td>5 (41)</td>
<td>2 (15)</td>
<td>1 (14)</td>
</tr>
<tr>
<td></td>
<td>Miami-Dade</td>
<td>7 (212)</td>
<td></td>
<td>1 (19)</td>
</tr>
<tr>
<td></td>
<td>Broward</td>
<td>6 (126)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Palm Beach</td>
<td>19 (142)</td>
<td></td>
<td>2 (13)</td>
</tr>
<tr>
<td>9/11</td>
<td>Monroe</td>
<td>3 (11)</td>
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<td></td>
<td>Palm Beach</td>
<td>19 (142)</td>
<td></td>
<td>2 (13)</td>
</tr>
</tbody>
</table>
Predicting Cell Tower Reliability from Crowdsourced Data

• OpenCellid: A crowdsourced dataset [https://opencellid.org/downloads](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

Core Network Facility

**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

**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**
- 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

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

**Joint infrastructure & D2D links**
- 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?

---

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

\[
\begin{align*}
A_1 & \quad 6 \times 6 \\
A_2 & \quad 6 \times 6 \\
A_1 & \quad 4 \times 6 \\
A_2 & \quad 2 \times 6
\end{align*}
\]
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 follow a Poisson distribution with mean uniformly distributed within [10, 20] Mbps
- N=100 workers
- Fountain code overhead (K): 5%

Demo: Reliable D2D Computation

Application
Face Recognition

Master
- Training
- Send the target image
- Testing phase

Worker 1

Worker 2

Worker 3

Face Recognition application involves training, sending the target image, and testing phases.
Demo: Reliable D2D Computation

Application
Face Recognition

Master
Train all the devices with training set

Worker 1
Worker 2
Worker 3

Demo: Reliable D2D Computation

Application
Face Recognition

Master
Send the target image to all devices

Worker 1
Worker 2
Worker 3

Demo: Reliable D2D Computation

Application
Face Recognition

Master

Worker 1

Worker 2

Worker 3

Devices cooperatively process test images

Demo: Reliable D2D Computation

Application
Face Recognition

Master

Worker 1

Worker 2

Worker 3

Worker that finds the target person sends the image back to the master

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 feedback 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