First Responder Indoor Location Using LTE Direct Mode Operations

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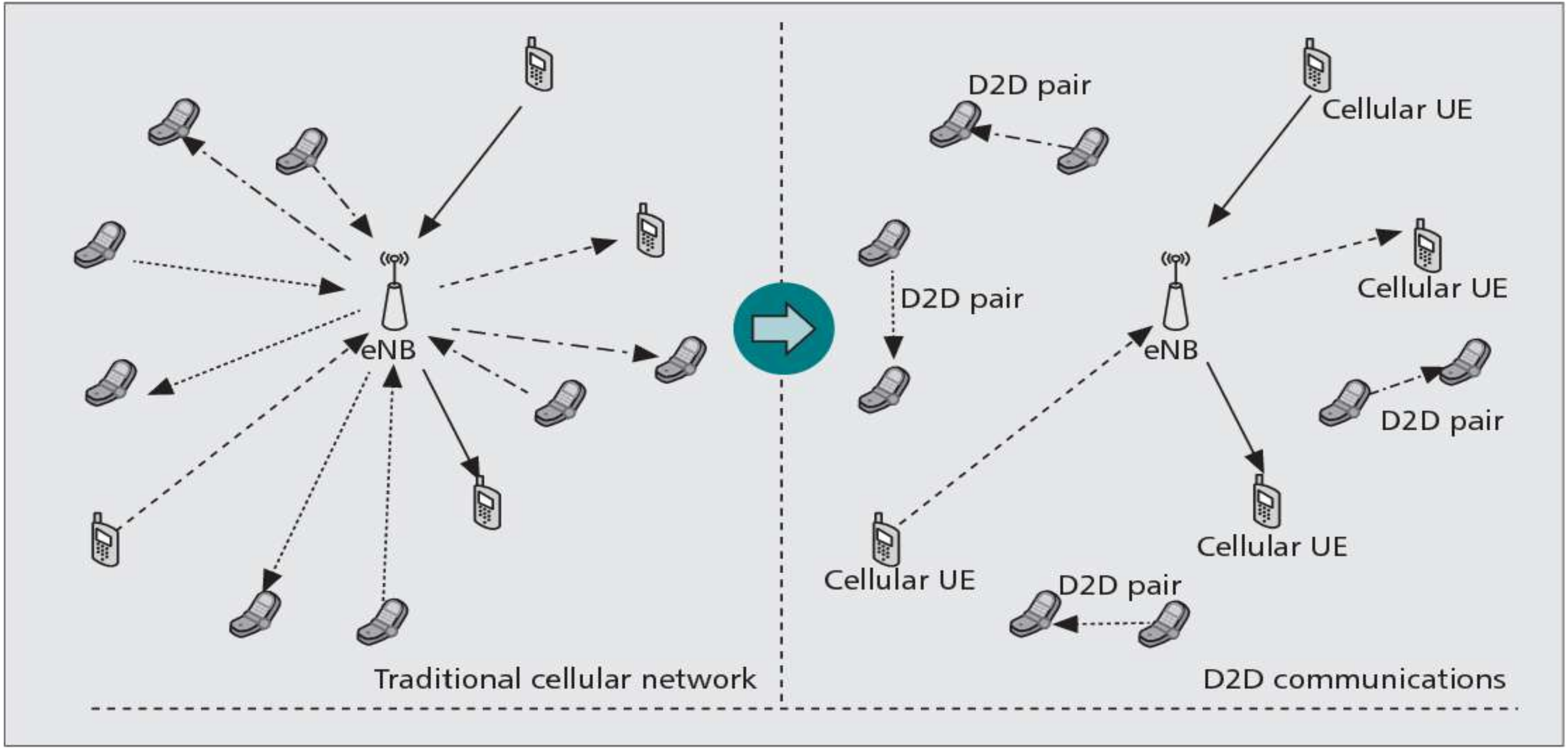
OVERVIEW

- 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
D2D pair
Cellular UE
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 w. comm. signals
- 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 & display with BIM-IL

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Form a D2D Wireless Network

- Need a protocol to establish D2D communication
- No such existing protocol
- A simplified multiuser protocol for D2D (MUP-D2D)
  - Assume 6 UEs, each given an ID
  - All start manually at (approximately) the same time
  - A pre-assigned timing diagram is followed
  - During each stage, one UE Tx, all other UEs measure TOAs
  - The Tx signals include 1) synch signal for TOA measurement
    2) measured TOA to processing center

	Stage 1	Stage 2	Stage 3
UE1	Transmit Discovery Waveform (TDW)	Receive,measure TOA with UE2	Receive,measure TOA with UE2
UE2	Receive,measure TOA with UE1	TDW with TOA UE1-UE2	Receive,measure TOA with UE2
UE3	Receive,measure TOA with UE1	Receive,measure TOA with UE2	TDW with TOA UE1-UE3,UE2-UE3
UE4	Receive,measure TOA with UE1	Receive,measure TOA with UE2	Receive,measure TOA with UE3
UE5	Receive,measure TOA with UE1	Receive,measure TOA with UE2	Receive,measure TOA with UE3
UE6	Receive,measure TOA with UE1	Receive,measure TOA with UE2	Receive,measure TOA with UE3

Stage	UE1	UE2	UE3	UE4	UE5	UE6
Stage 1	Tx	UE1-UE2	UE1-UE3	UE1-UE4	UE1-UE5	UE1-UE6
Stage 2	x	Tx	UE2-UE3	UE2-UE4	UE2-UE5	UE2-UE6
Stage 3	x	UE3-UE2	Tx	UE3-UE4	UE3-UE5	UE3-UE6
Stage 4	x	UE4-UE2	x	Tx	UE4-UE5	UE4-UE6
Stage 5	x	UE5-UE2	x	x	Tx	UE5-UE6

- UE6 acts as a processing center

Stage	Transmitter	TOAs calculated at UE6	TOAs received by UE6 from other UEs
Stage 1	UE1	UE1-UE6	None
Stage 2	UE2	UE2-UE6	UE1-UE2
Stage 3	UE3	UE3-UE6	UE1-UE3, UE2-UE3
Stage 4	UE4	UE4-UE6	UE1-UE4, UE2-UE4, UE3-UE4
Stage 5	UE5	UE5-UE6	UE1-UE5, UE2-UE5, UE3-UE5, UE4-UE5
Stage 6	UE2		UE3-UE2, UE4-UE2, UE5-UE2

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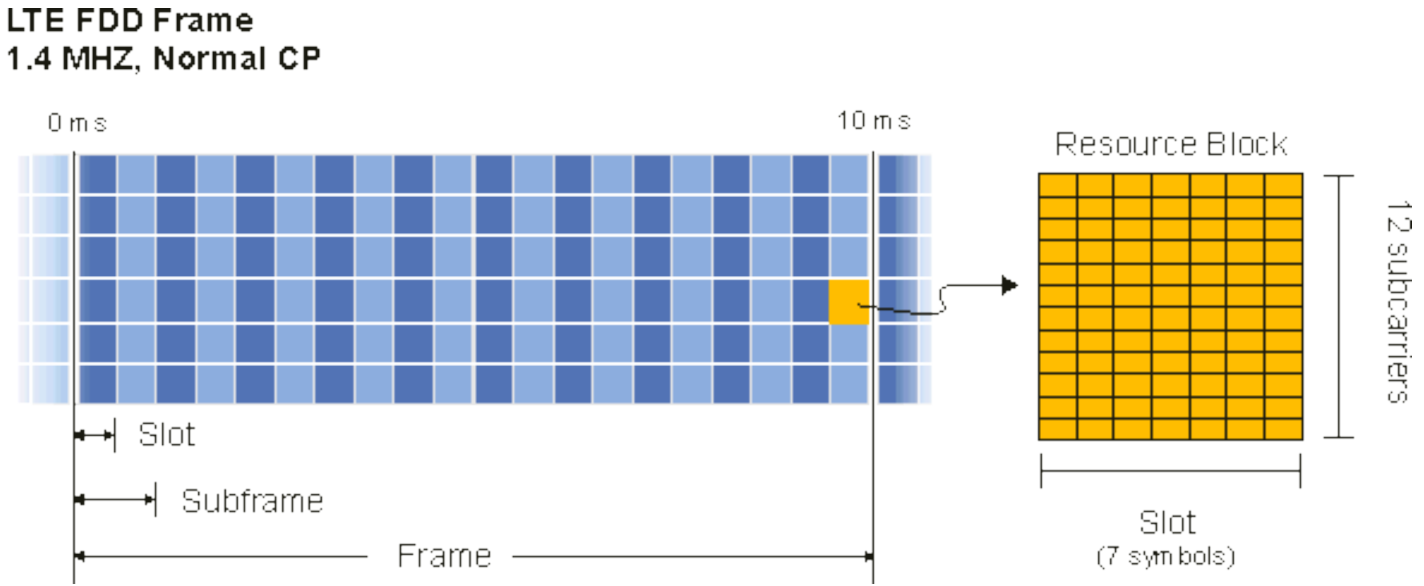
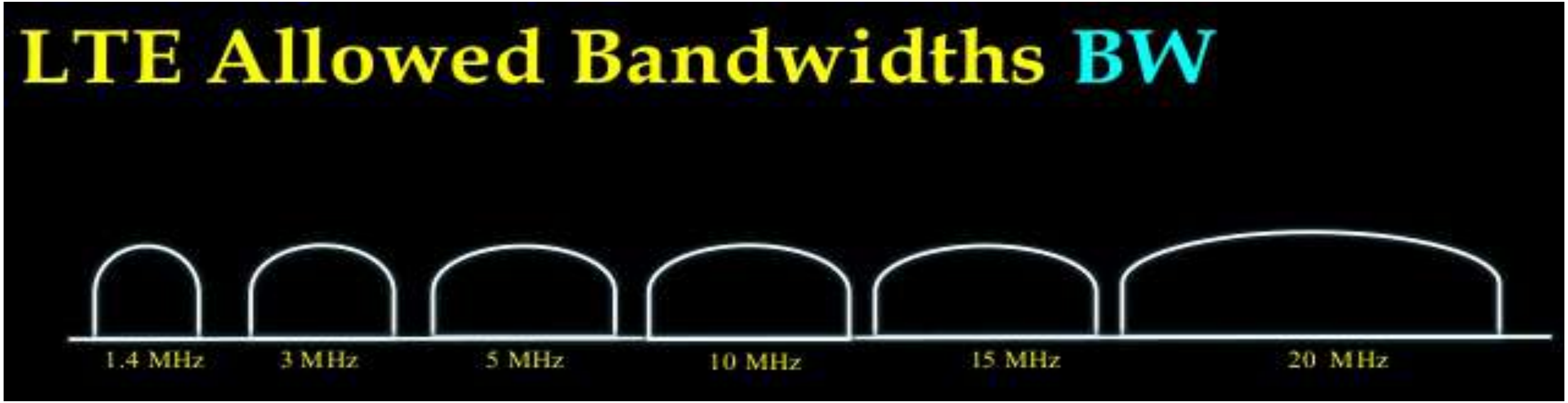
Measuring TOAs

- LTE has synch signals for comm. purpose (PSS/SSS)



LTE BW

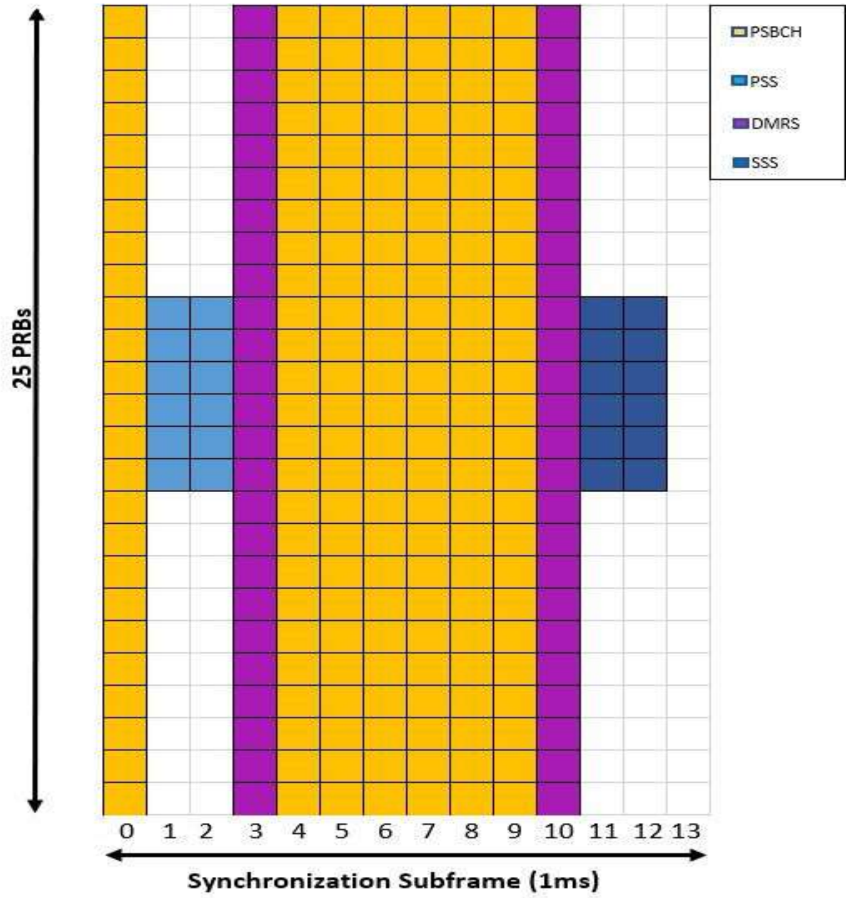


- Simulation performed in the baseband
- USRP test performed in the ISM band (900 MHz)

LTE BW

LTE BW Mode (MHz)	Effective Signal BW (MHz)	
	PSS/SSS	PSBCH
1.4	1.08	1.08
3	1.08	2.7
5	1.08	4.5
10	1.08	9
15	1.08	13.5
20	1.08	18

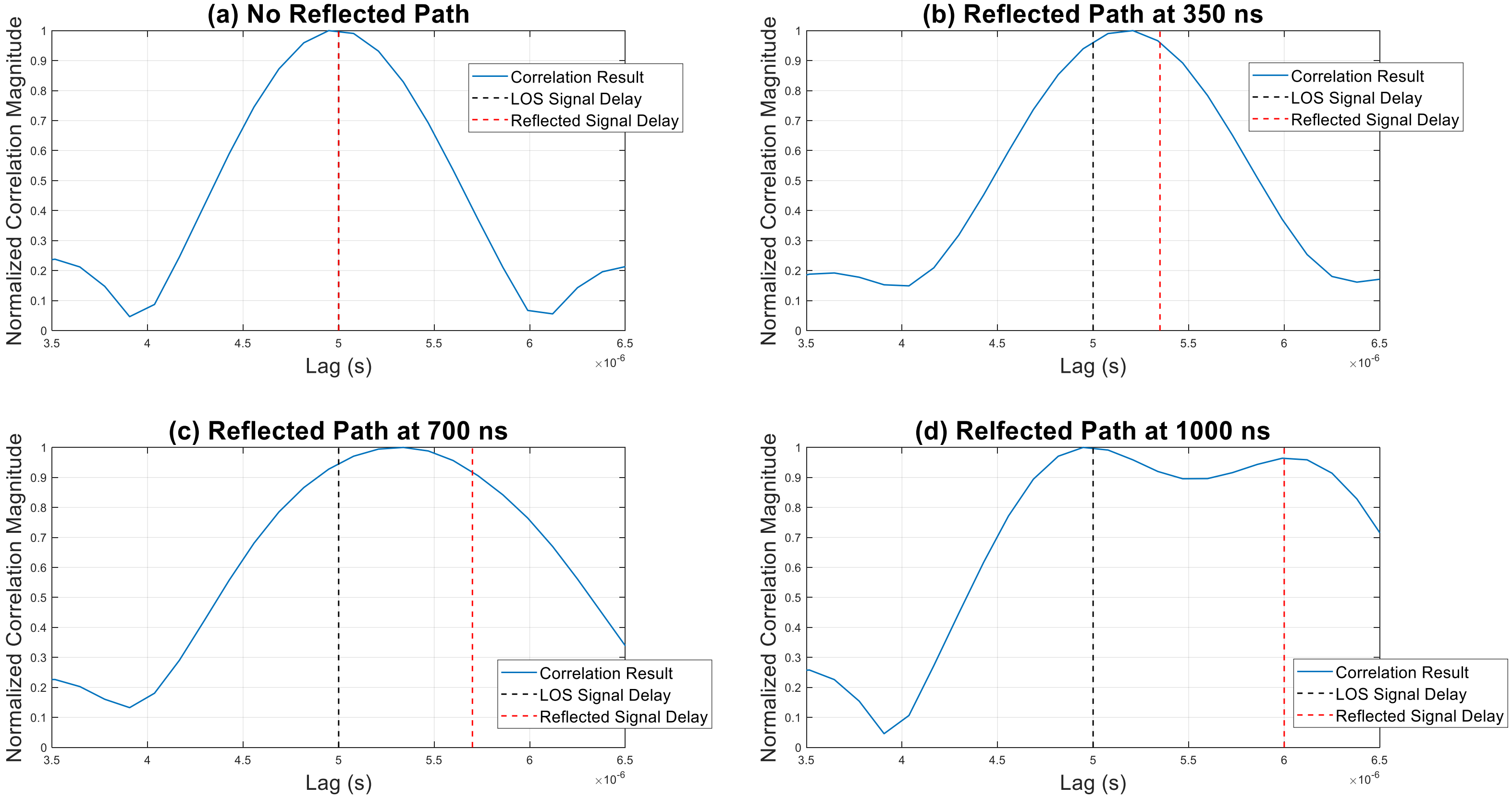
- PSBCH is used for demod. reference, is a known comm. overhead signal
- Use PSBCH for max BW and location accuracy



- This is 5 MHz BW case
- PSBCH is used for demodulation reference, and is a known comm overhead signal
- So can be used for our TOA by correlation
- No payload resource is used for TOA measurement

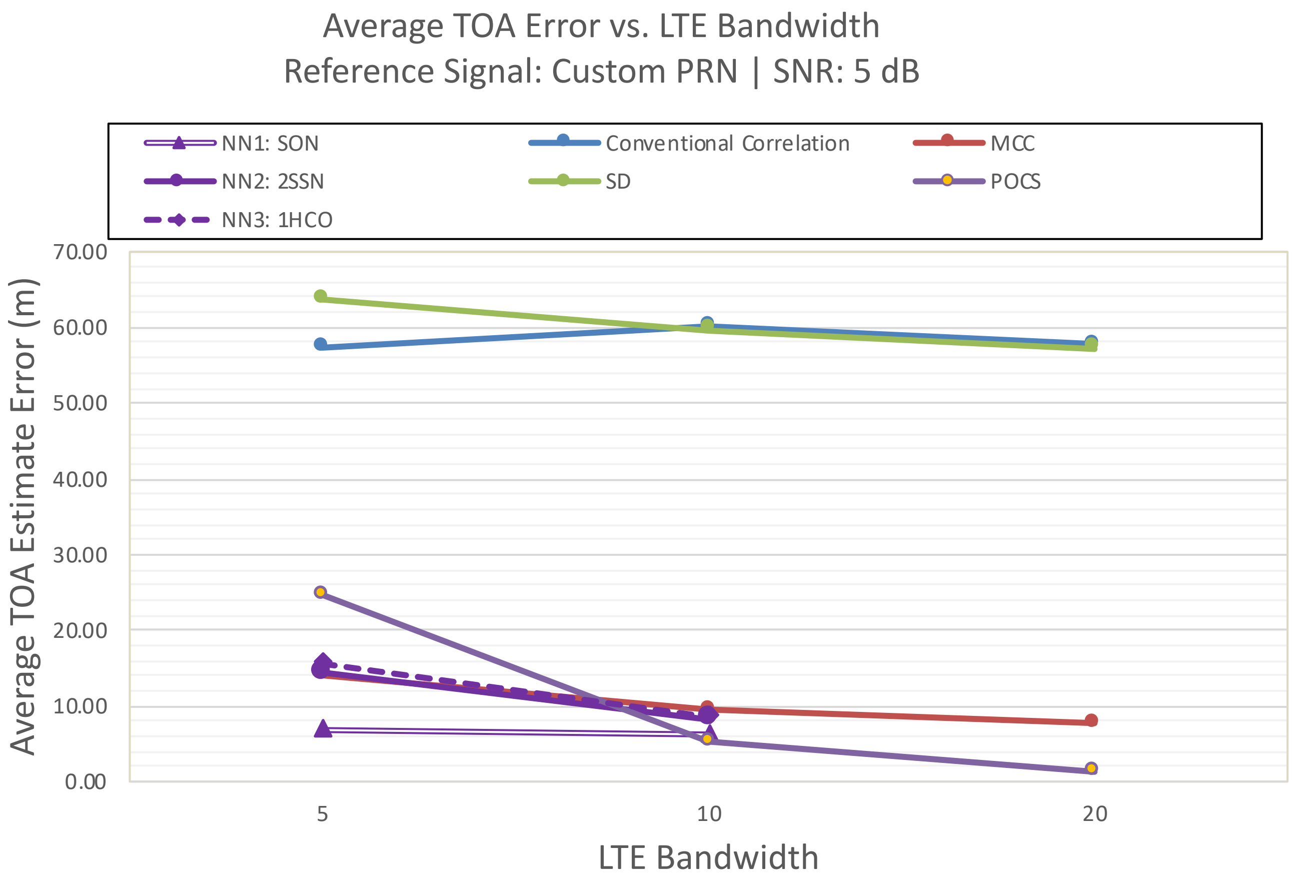
Multipath Mitigation

- Multipath is prevalent in indoor propagation
- LOS may also be blocked by walls etc.
- Receive multiple and delayed copies of signal
- Must find the first arrival time for location
- Correlation will give multiple peaks (large delay) or distorted peaks (small delay)


(a) No Reflected Path
(b) Reflected Path at 350 ns
(c) Reflected Path at 700 ns
(d) Relfected Path at 1000 ns
Normalized Correlation Magnitude
Lag (s)
×10^-6
Correlation Result
LOS Signal Delay
Reflected Signal Delay
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
3.5
4
4.5
5
5.5
6
6.5

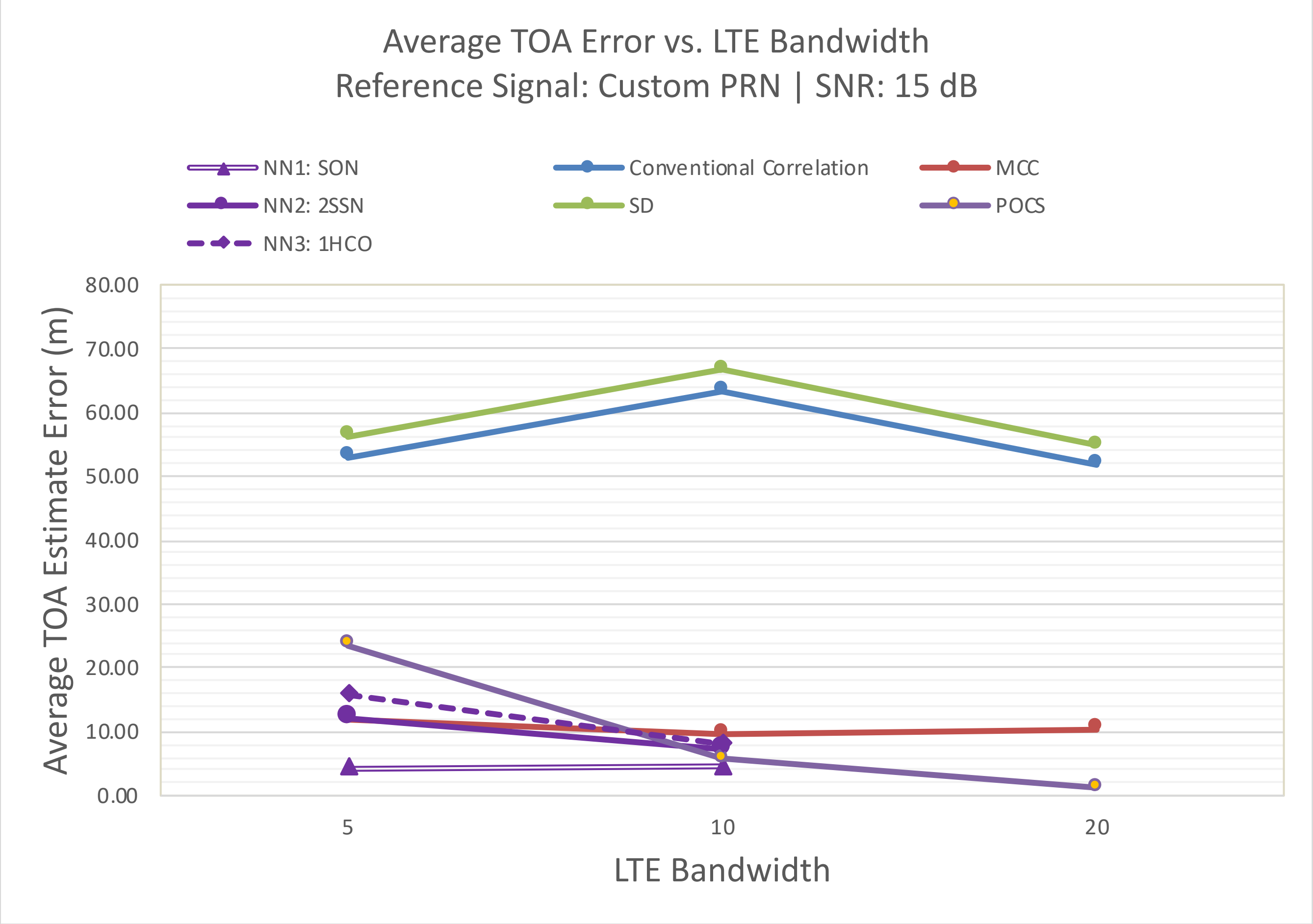
- We investigated many mitigation methods, distilled down to 5:

Method	Accuracy	Computation	Cons
POCS	Suboptimum solution	Light to medium	Costs about 50% more computation
MCC	Suboptimum solution	Light	Setting a threshold is a challenge
NN1: SON	Suboptimum solution	Light once trained	Needs training to cover all possible settings
NN2: 2SSN	Suboptimum solution	Light once trained	Needs training to cover all possible settings
NN3: 1HCO	Suboptimum solution	Light once trained	Needs training to cover all possible settings



Simulation with an indoor channel model

SNR = 5 dB



Simulation with an indoor channel model

SNR = 15 dB

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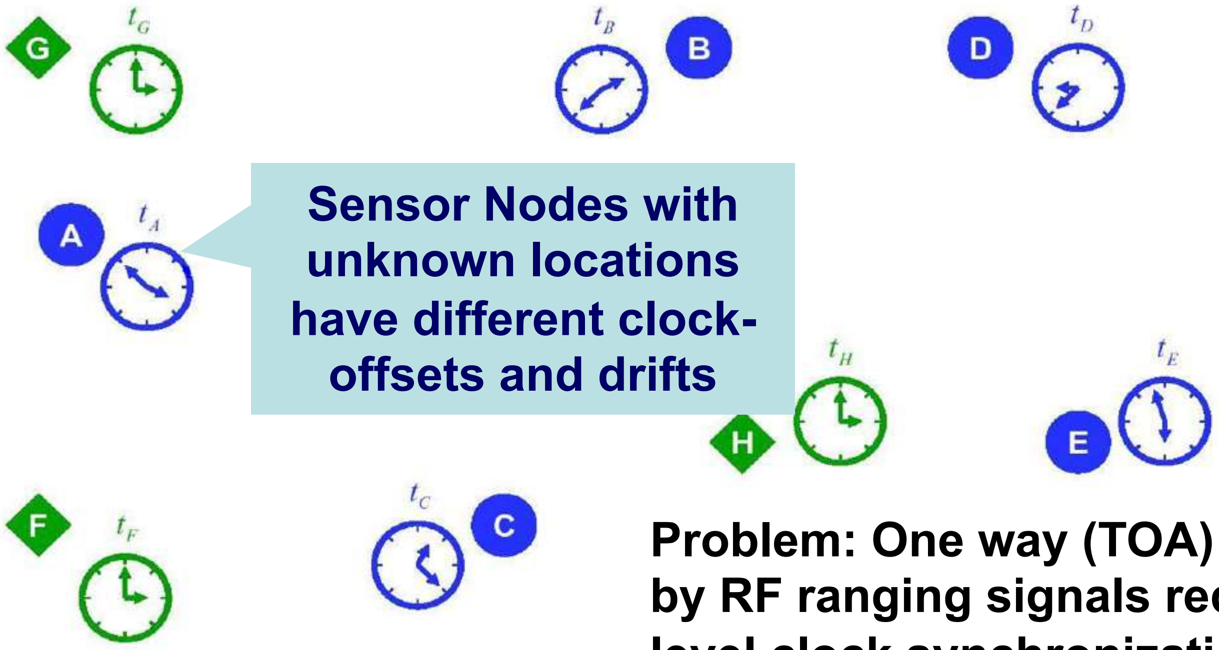
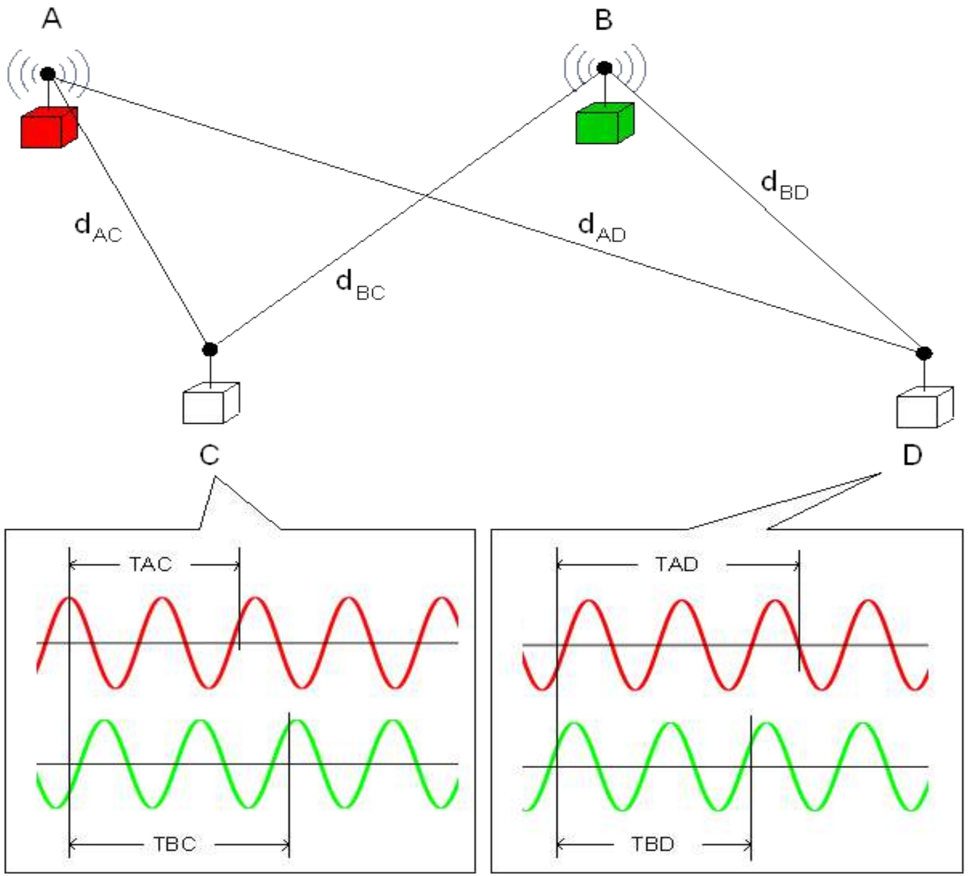
The dTDOA Algorithm



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

$$s_m(t - t_m - t_{mi} - Dt_i)$$

t_m Unknown transmission start time

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

Dt_i Unknown clock offset of the *i*th sensor

$t_i^m = t_m + d_{mi}/c + Dt_i$ 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):

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

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

The dTDOA Algorithm

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

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

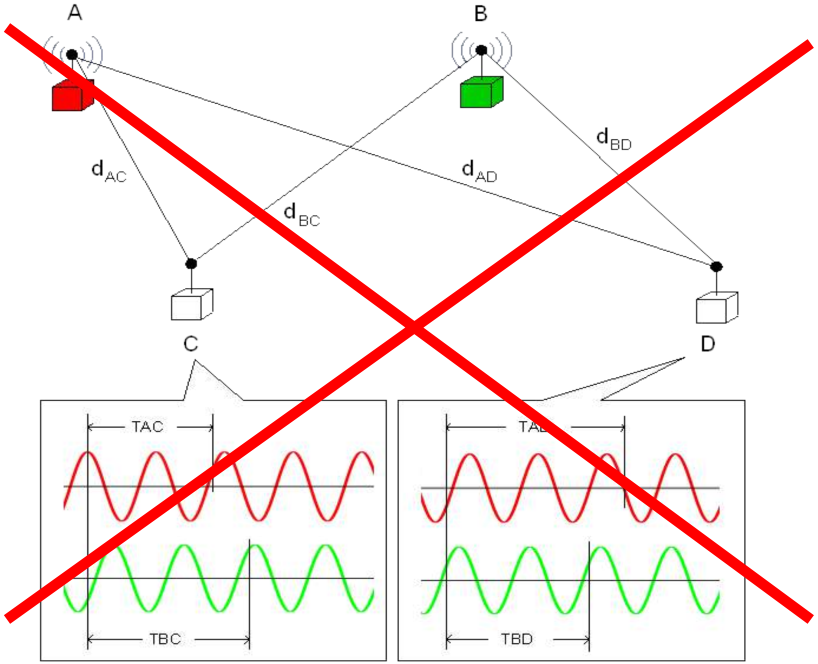
- With *N* sensors, *N*(*N*-3)/2 Independent equations
- In 2-D, 5 sensors → 5 independent equations

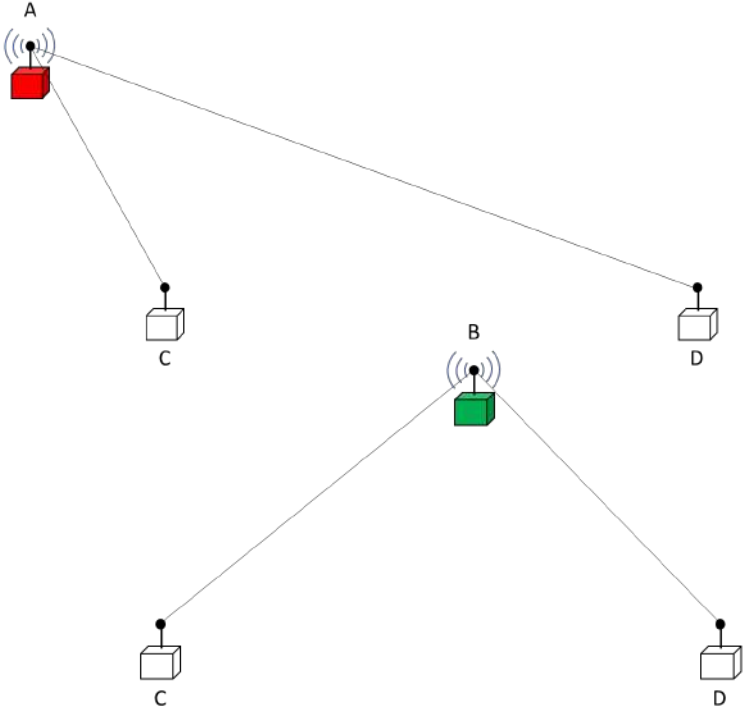
  6 sensors → 9 independent equations

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

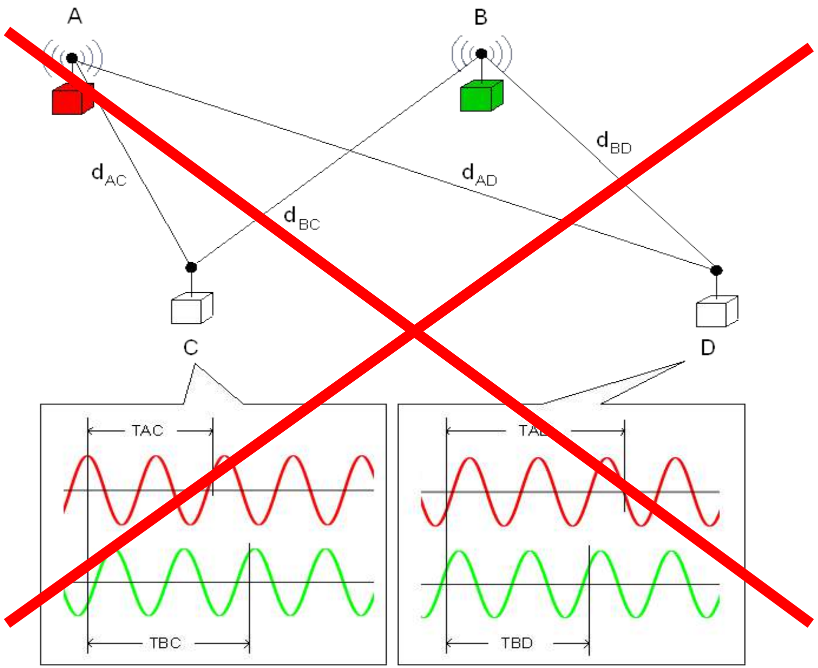
Implementation of dTDOA Using LTE ProSe

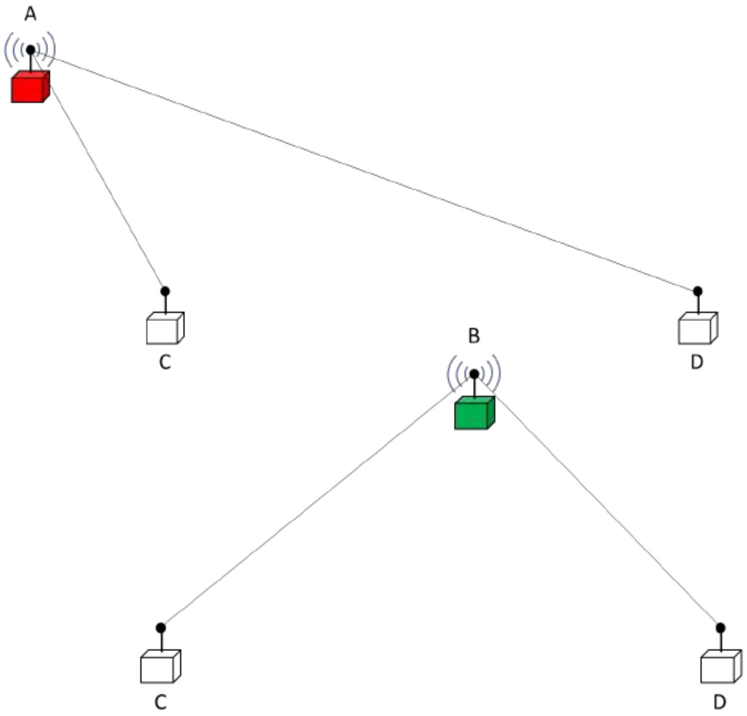
- Only one Tx can transmit at any given time to avoid collision

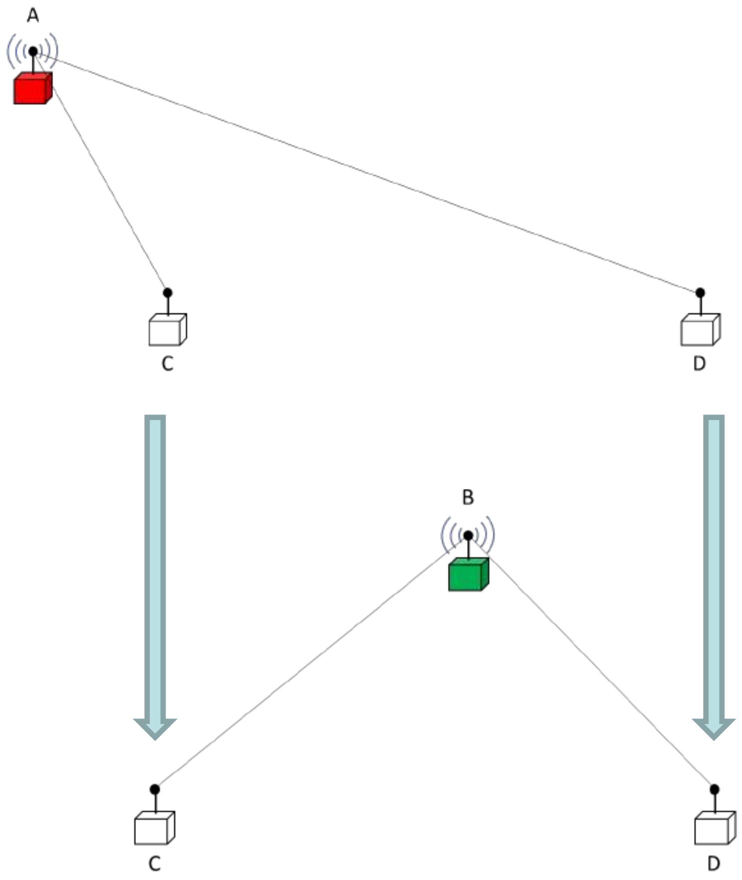




- This may cause a receiver to mix its clock offset with an unknown receive time from another Tx







Solution

- Each Rx must set an arbitrary time reference point (e.g. time the first sample is received)
- Each Rx clock keeps running without stop
- All TOAs are measured w.r.t. this time reference
- So that its unknown clock offset Δt_i is kept unchanged

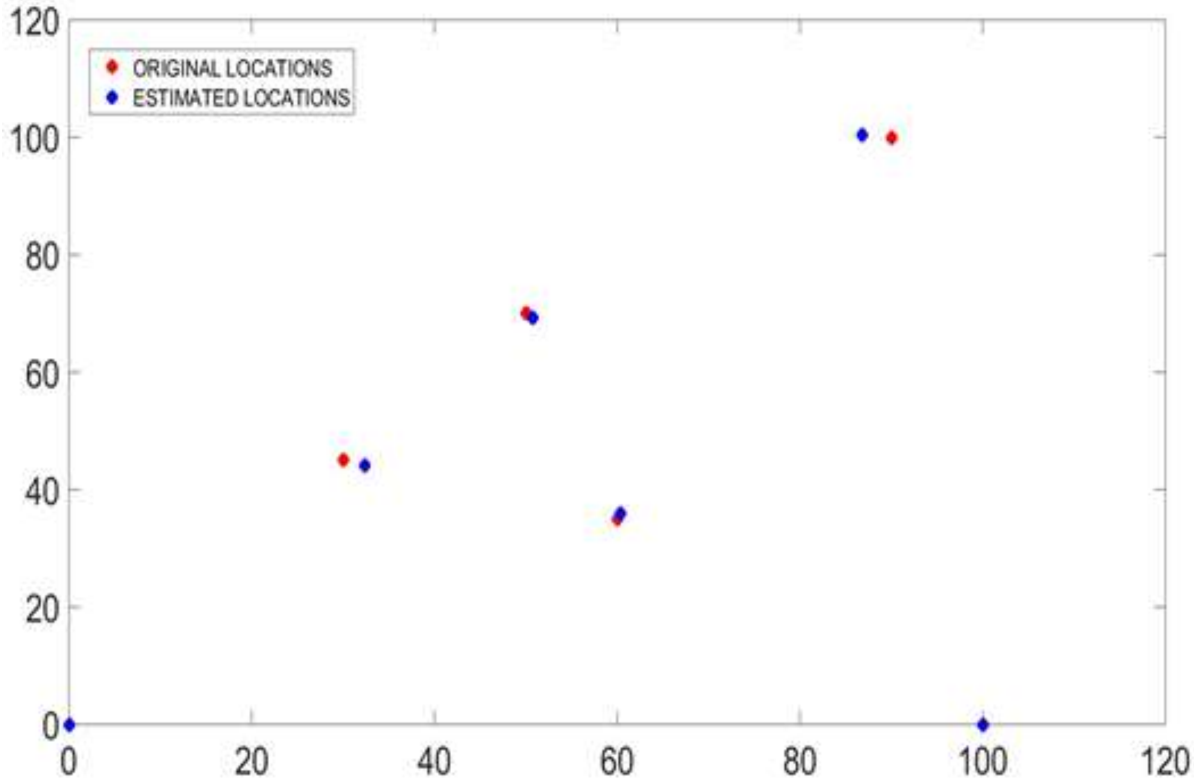
dTDOA Simulation

- Simulated 6 nodes in a 100mx100m 2D space
- Two nodes are fixed, with known locations
- Four nodes are at unknown locations
- Simulated noisy and multipath 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

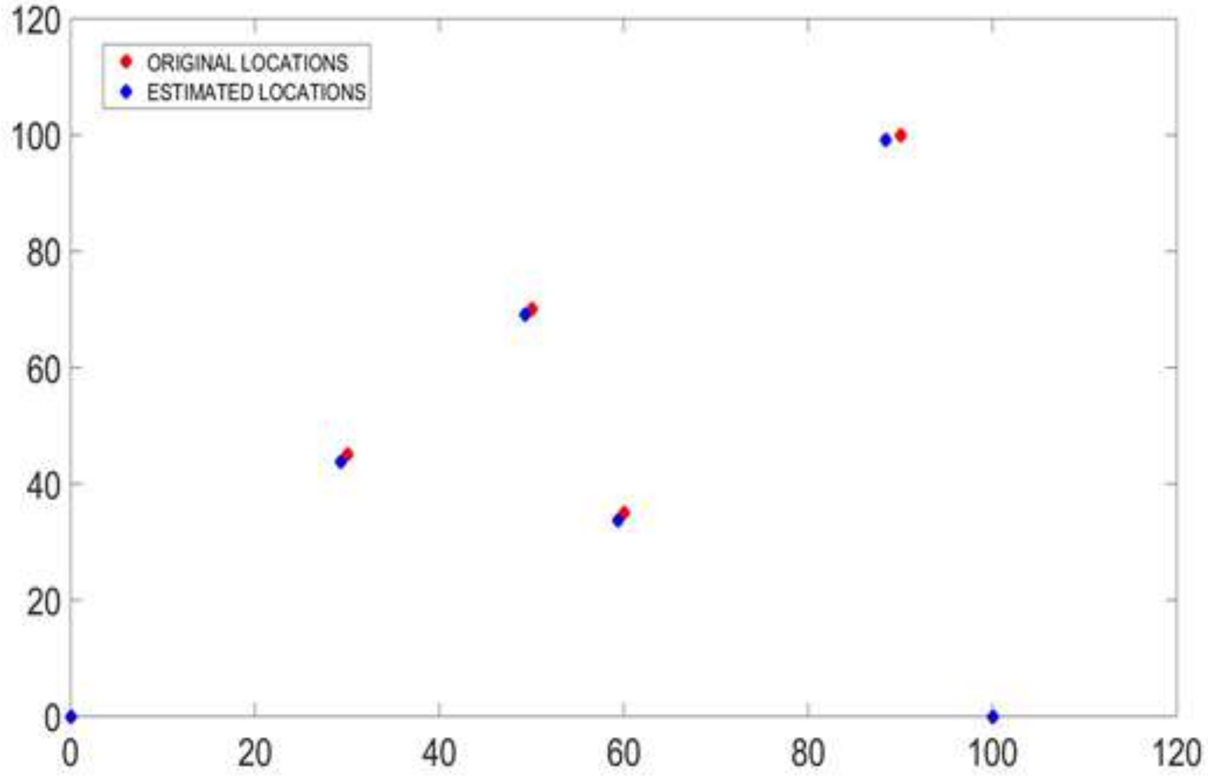


SNR = 10 ~ 25 dB varies among UEs

ITU indoor channel model

5 MHz BW

dTDOA Simulation



SNR = 10 ~ 25 dB varies among UEs

ITU indoor channel model

20 MHz BW

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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.

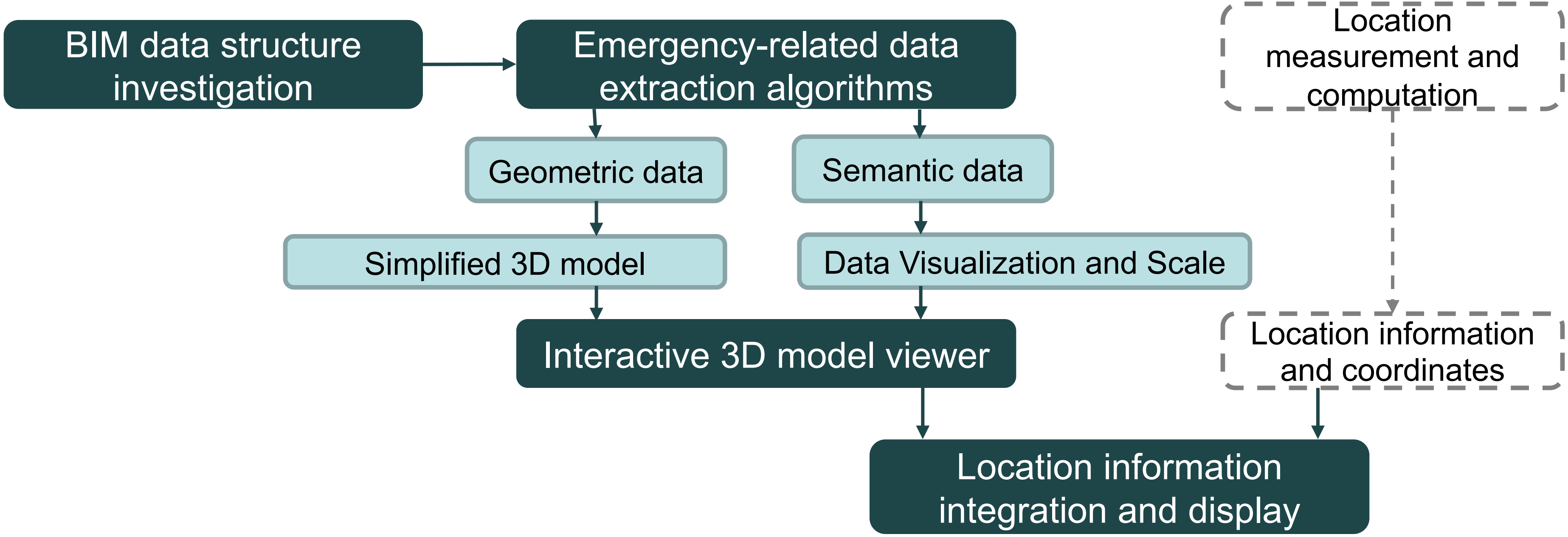
BIM-related Research Work

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

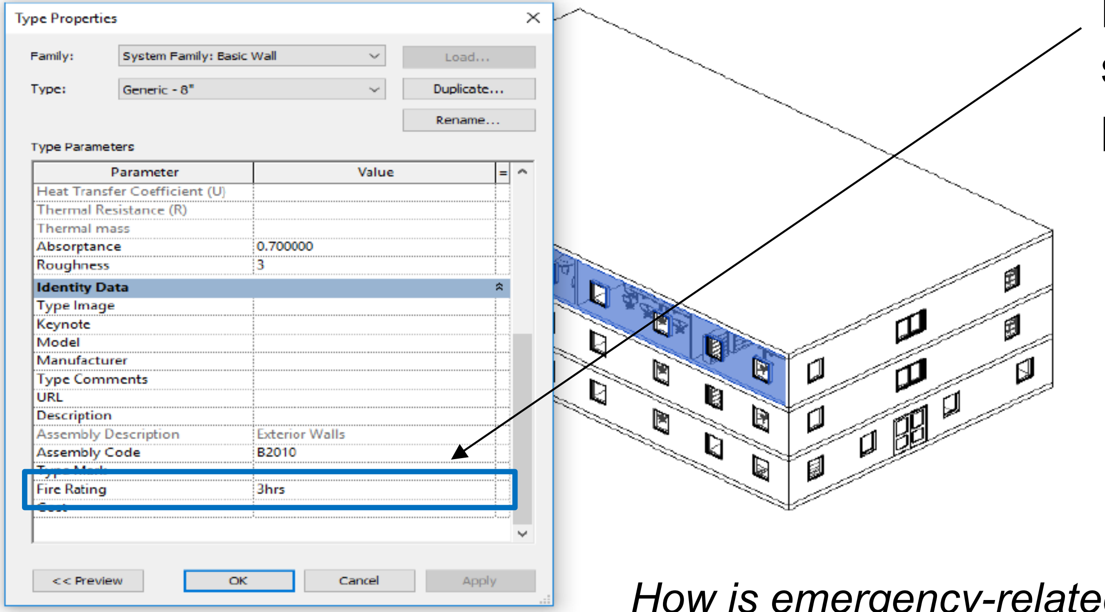


BIM Data Structure Investigation

- 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

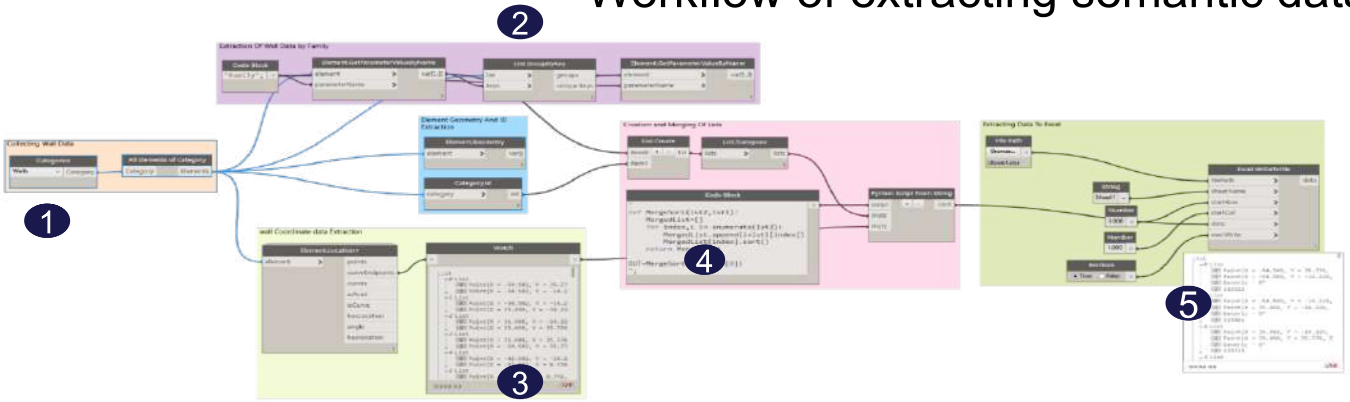


Fire rating hours is structured in wall-type-properties/identity data

How is emergency-related data structure in BIM-compliance dataset

Emergency-Related Data Extraction

Workflow of extracting semantic data



Example of building wall extraction

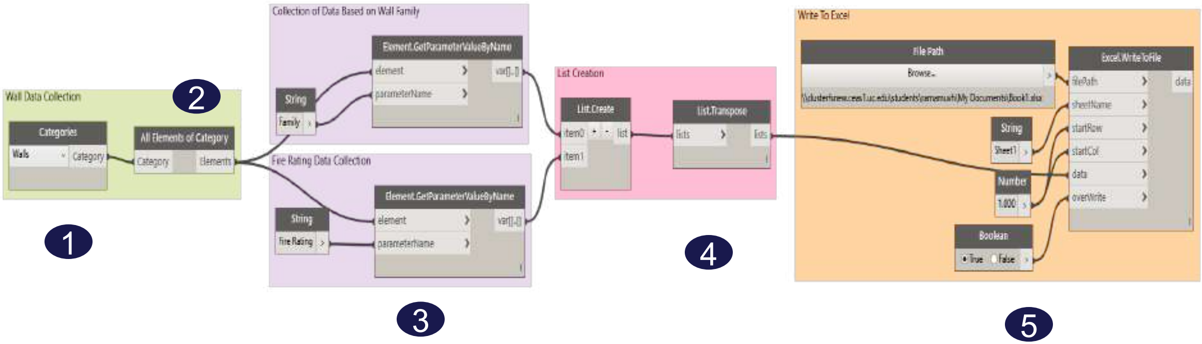
D	E
Wall Type:	Element ID:
Generic - 8"	325516
Generic - 8"	325661
Generic - 8"	325715
Generic - 8"	325767
Interior - 5 1/2" Partition (1-hr)	326034
Interior - 5 1/2" Partition (1-hr)	326066
Interior - 5 1/2" Partition (1-hr)	326306
Interior - 5 1/2" Partition (1-hr)	326663
Interior - 5 1/2" Partition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

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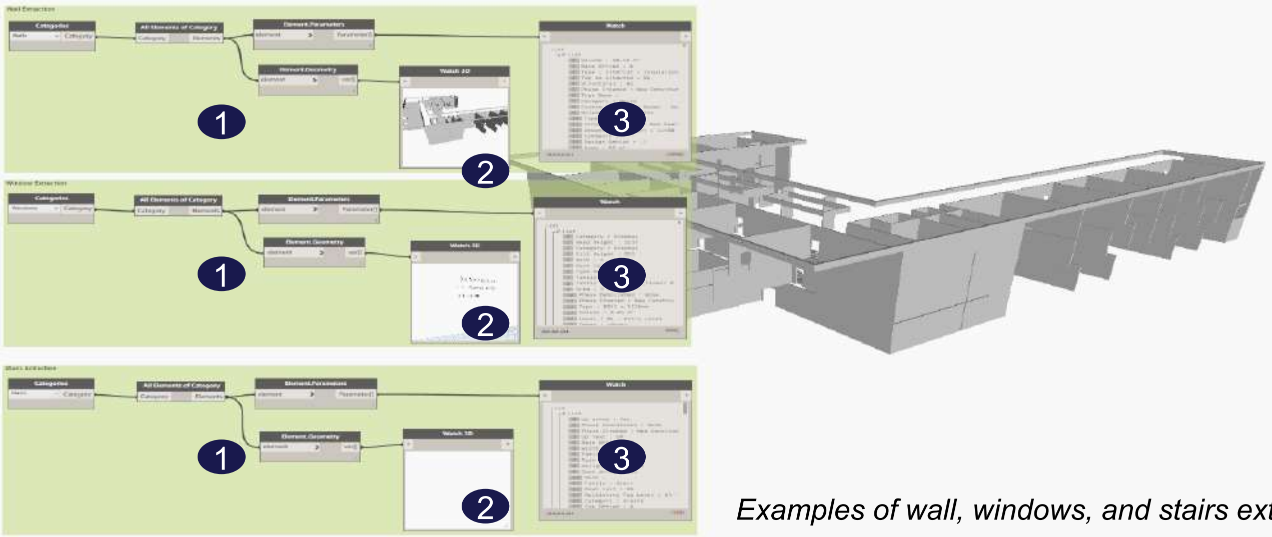
3. **Element Get parameter value by name** uses a string input (Fire Rating) and extracts all data corresponding to the selected element.
4. A list of all the elements' data is created using the **List Create** node.
5. **File Path** node is used for the data file type selection and output.

Emergency-Related Data Extraction

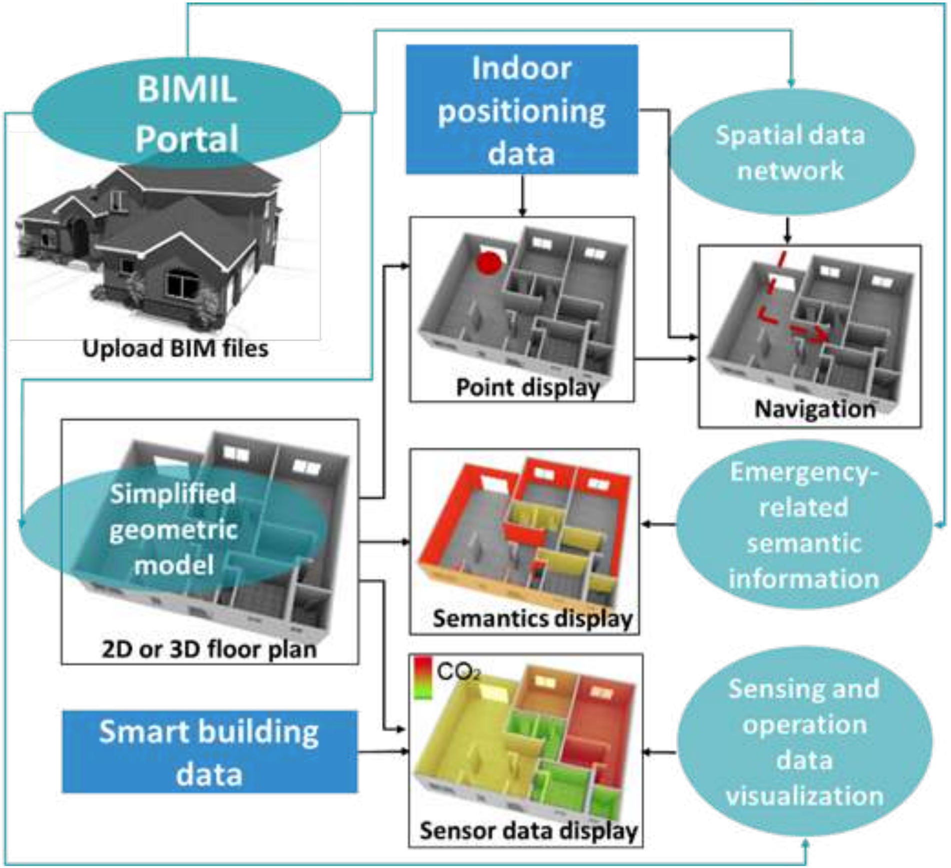
Workflow of extracting geometric data



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.

BIM-Indoor (BIMIL) Location User Interface Portal With user locations integrated



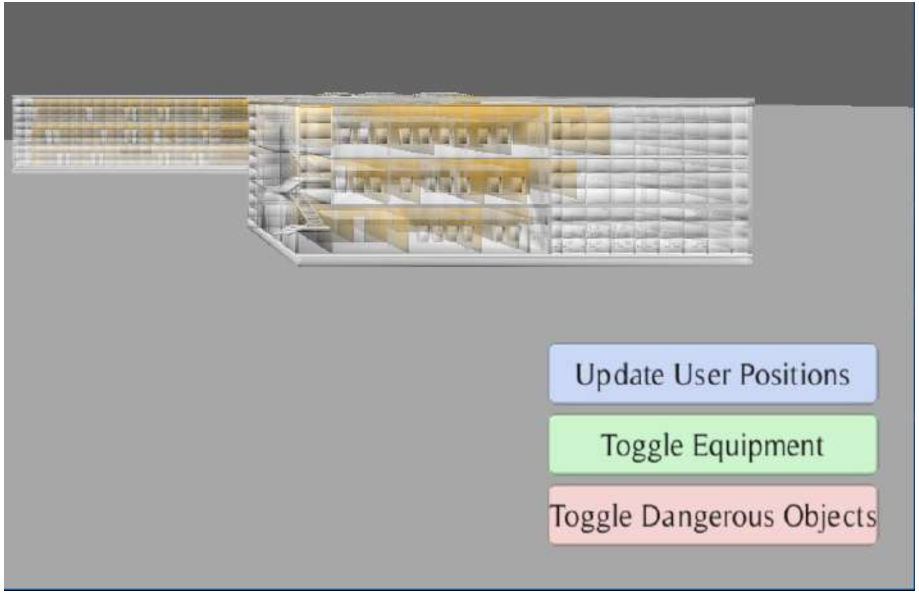
BIM-Indoor Location User Interface

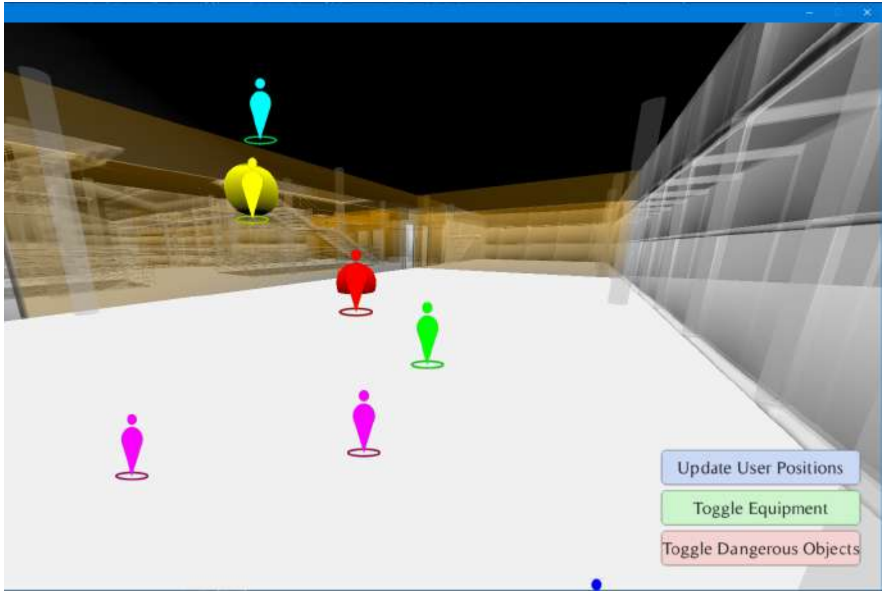
- To select a building BIM model to display, click the “Select Building Model” button.

- To select an emergency-related semantic data file, click the “Select Building Info File” button.

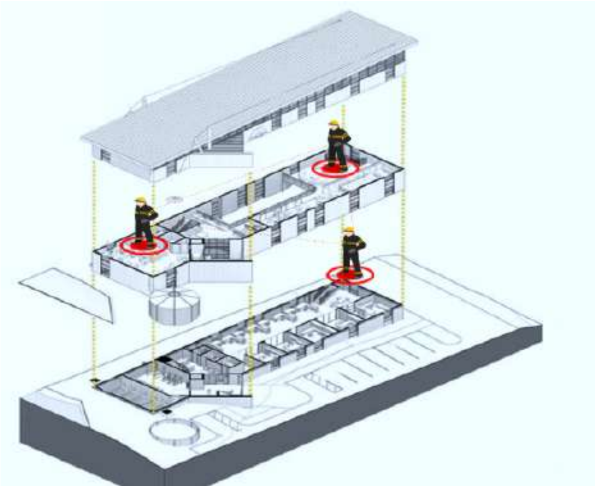
- When ready, press the “Start Simulation” button to start viewing the building file.

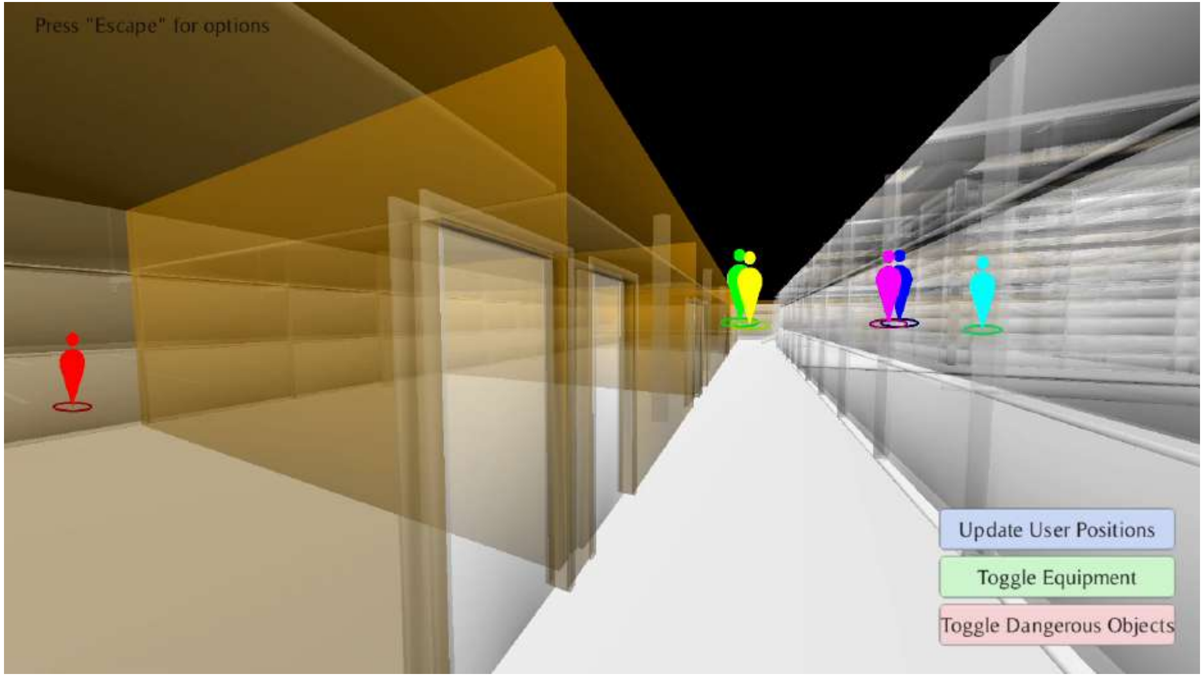
BIM-Indoor Location User Interface



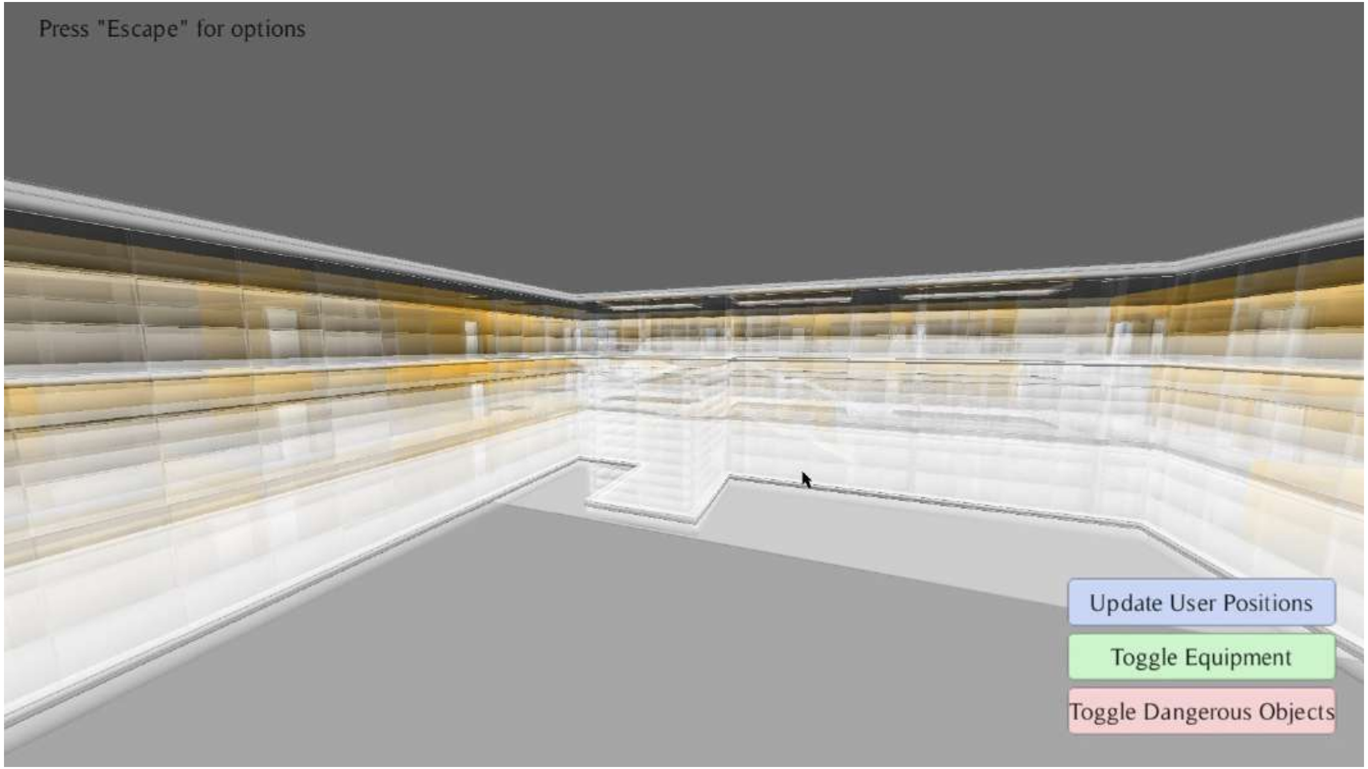


BIM-Indoor Location User Interface





BIM-Indoor Location User Interface



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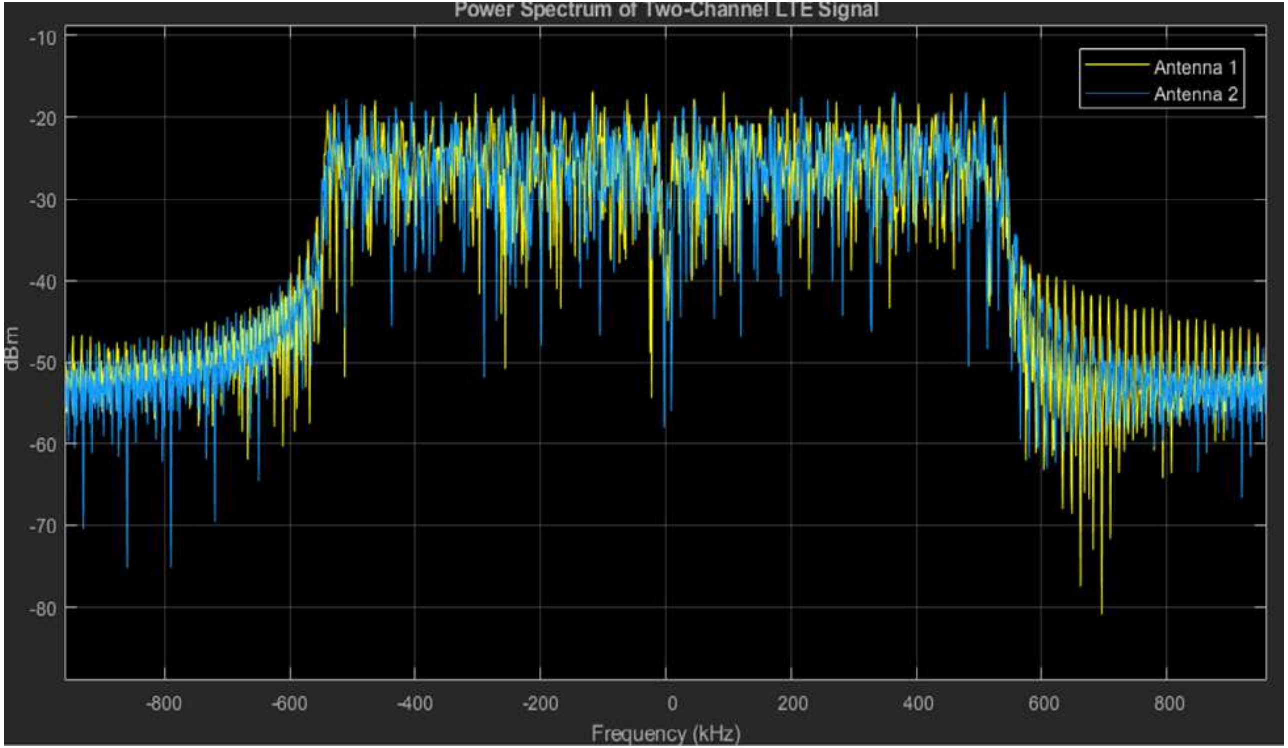
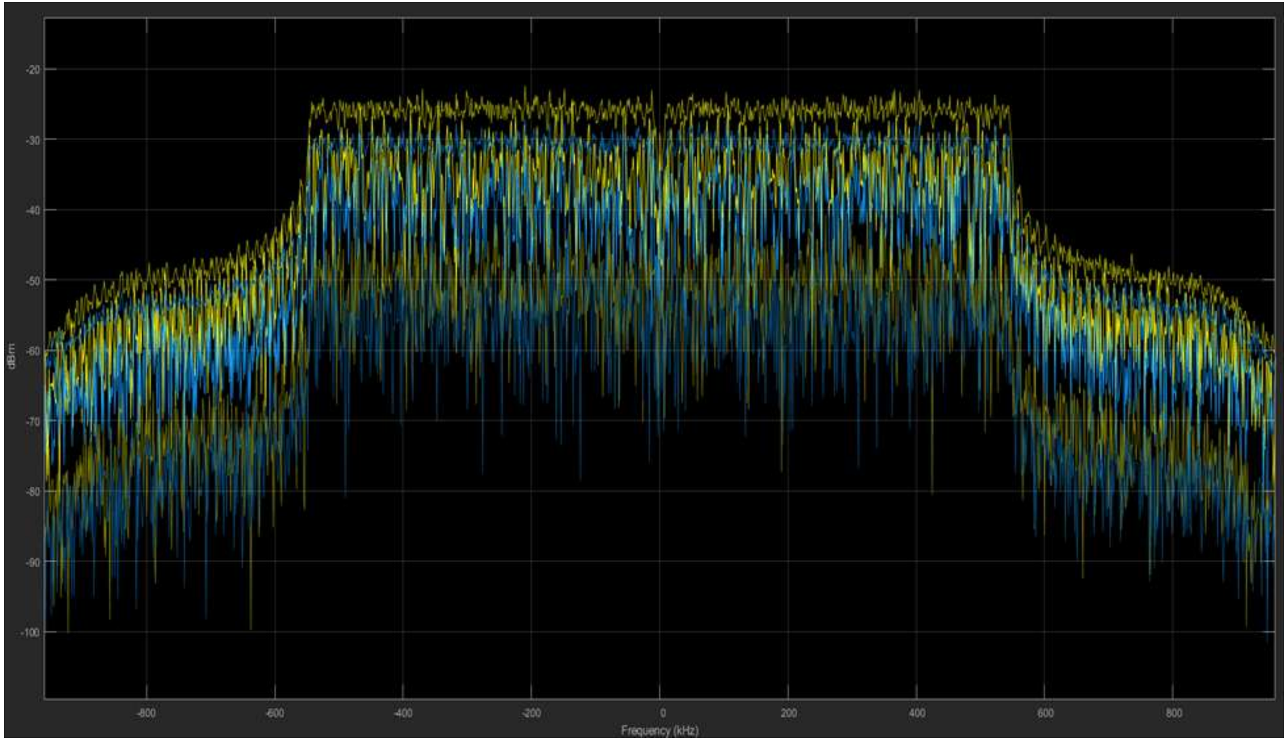
USRP Implementation

OTA Transmitted Signal



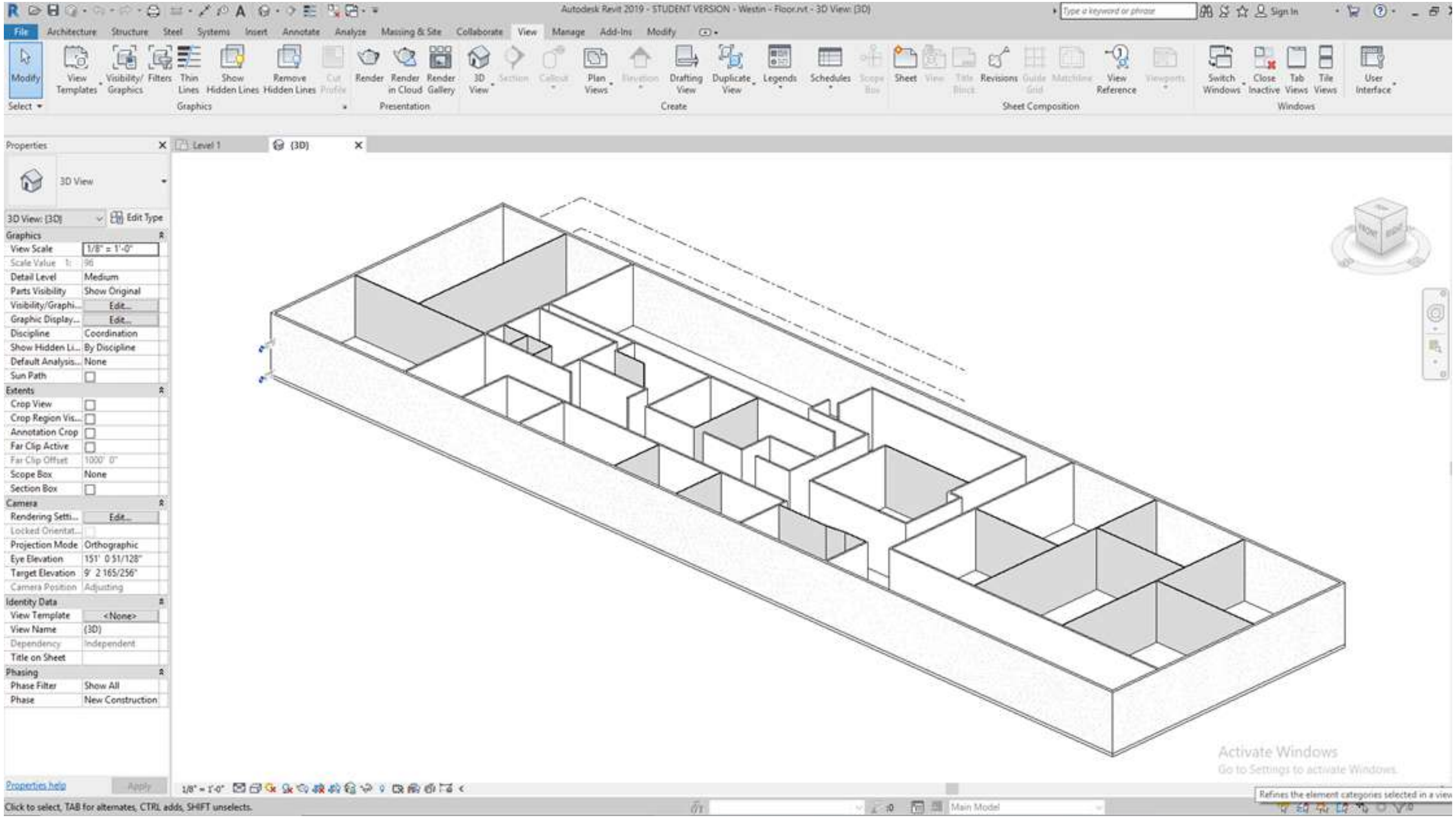
OTA Received Signal



Implementation Details

- 6 USRPs in 2D, 2 anchored
- Implemented in MATLAB for simplicity
- BW = 5 MHz
- Used the MCC alg. for multipath mitigation for simplicity
- Displayed on the conference demo site layout, no BIM data available for this building

Conf. Demo Site Layout



The team