INFORMATION ENGINEERING AND TECHNOLOGY FACULTY

GERMAN UNIVERSITY IN CAIRO

INTEGRATING WIRELESS SENSOR NETWORKS INTO INDUSTRY

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INTRODUCTION

Background and motivation

- Wireless sensor networks architecture
- Industrial environments
- UWB technology and its huge potential

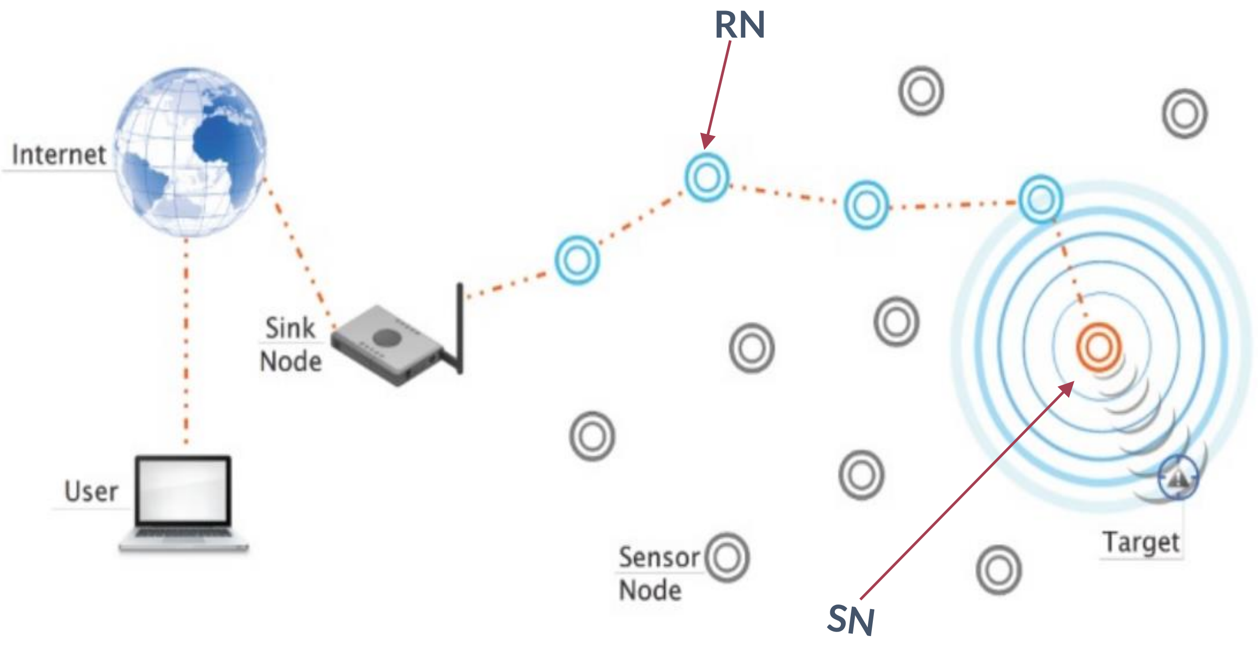
Wireless Sensor Networks

❖ Architecture

Any WSN consists of two main components:

1. Base station
2. Sensor nodes

A sensor node could behave both as a sensing node and/or a relay node.

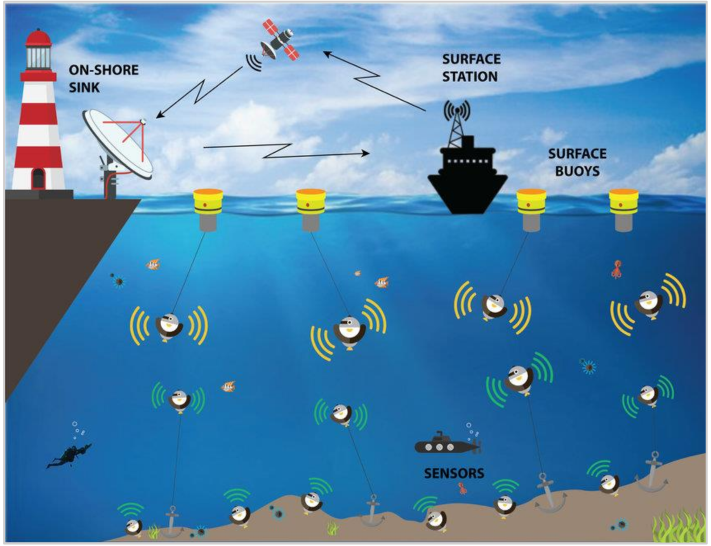


Typical WSN architecture

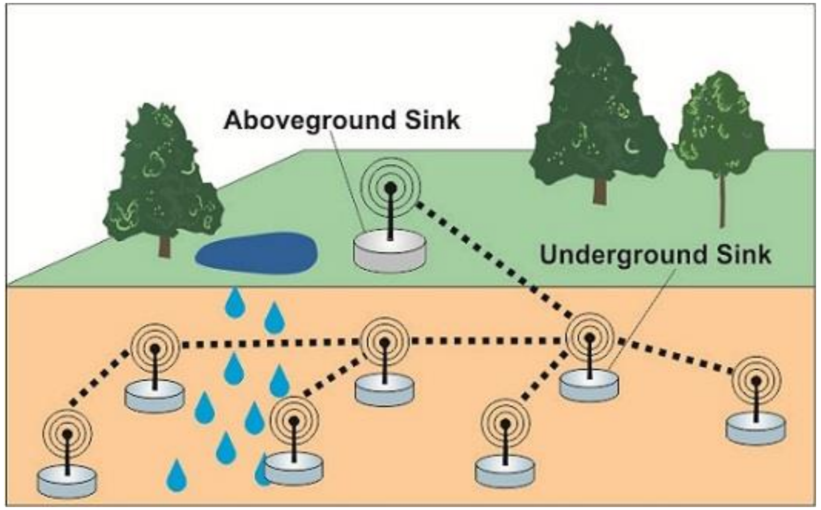
❖ Types

WSNs is categorized into different types according to the considered environment or function:

1. Wireless Multimedia Sensor Networks (WMSNs)
2. Underwater Wireless Sensor Networks (UWSNs)
3. Wireless Underground Sensor Networks (WUSNs)



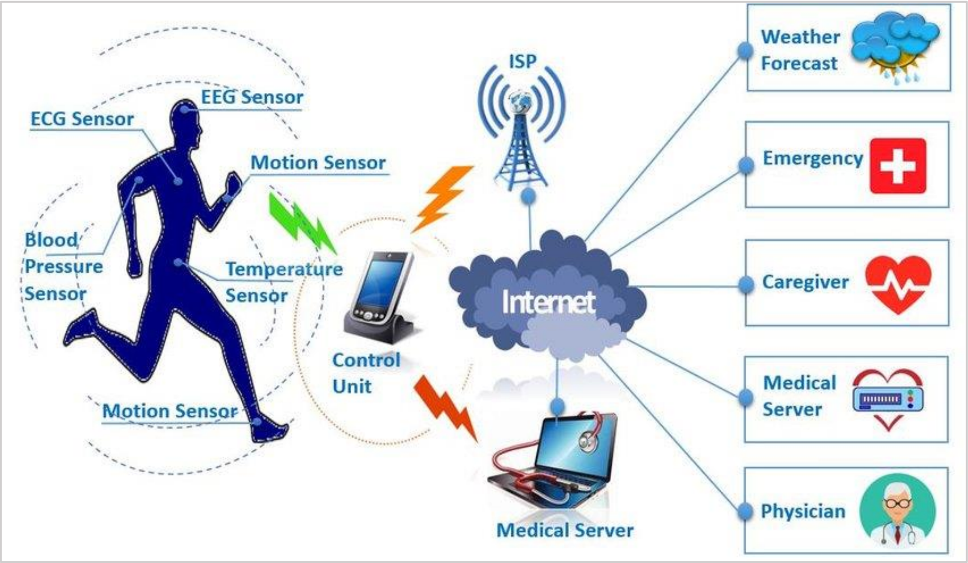
Underwater Wireless Sensor Networks



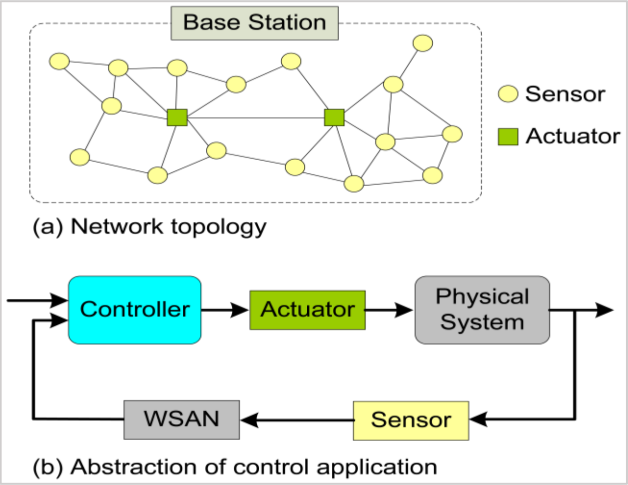
Wireless Underground Sensor Networks

❖ Types

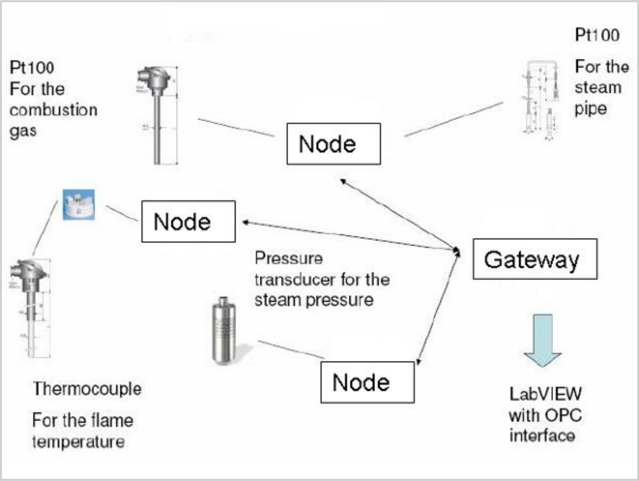
4. Wireless Body Sensor Networks (WBSNs)
5. Wireless Sensor Actor Networks (WSANs)
6. Industrial Wireless Sensor Networks (IWSNs)



Wireless Body Sensor Networks



Wireless Sensor Actor Networks

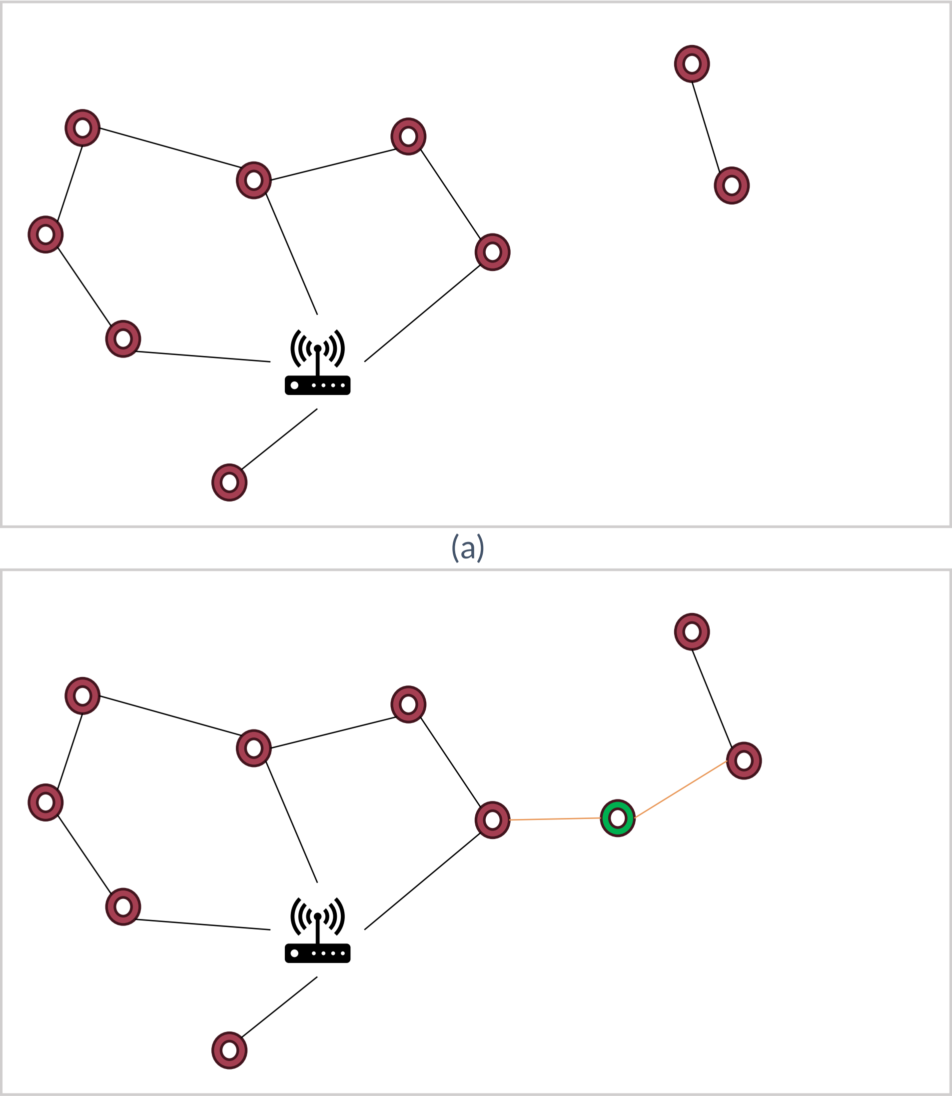


Industrial Wireless Sensor Networks

WSNs in Indoor Industrial Environments

❖ Requirements

1. Guaranteed coverage of monitoring points
2. Reliable data transmission
3. Guaranteed route to the Base Station
4. Immunity against interferences
5. Energy-efficiency



(a)

(b)

a) Disconnected WSN, b) Connected WSN

❖ Challenges

1. Large dimensions
2. Presence of multiple reflecting materials
3. Harsh environmental conditions
4. Presence of many sources of EMI

Table 2.1 Interferences sources in industrial environments [1]

Broadband interferences	Narrowband interferences
Motors	Cellular telephones
Inverters	Radio and TV transmitters
Computers	Signal generators
Ignition systems	Local oscillator, UPS system
Voltage regulators	Test equipment
Lightning electromagnetic pulses	Microwave & Ultrasonic equipment
Pulse generators	Medical equipment
Thermostats	Microprocessor systems
Welding apparatus	Pager transmitters
Frequency converters	High-frequency generators

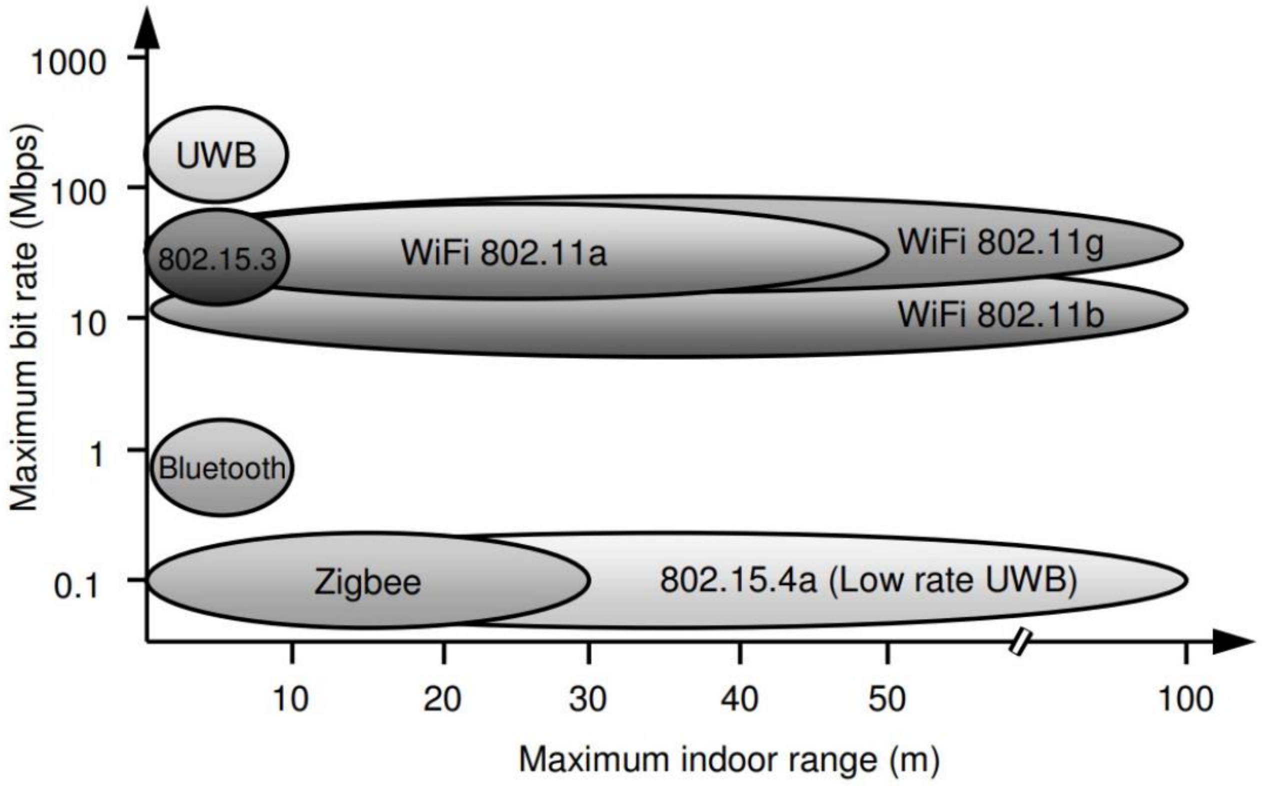
Ultra-Wide Band Technology

Definition

The typical bandwidth of UWB signals ranges from 500 MHz to several GHz.

UWB technology is characterized by:

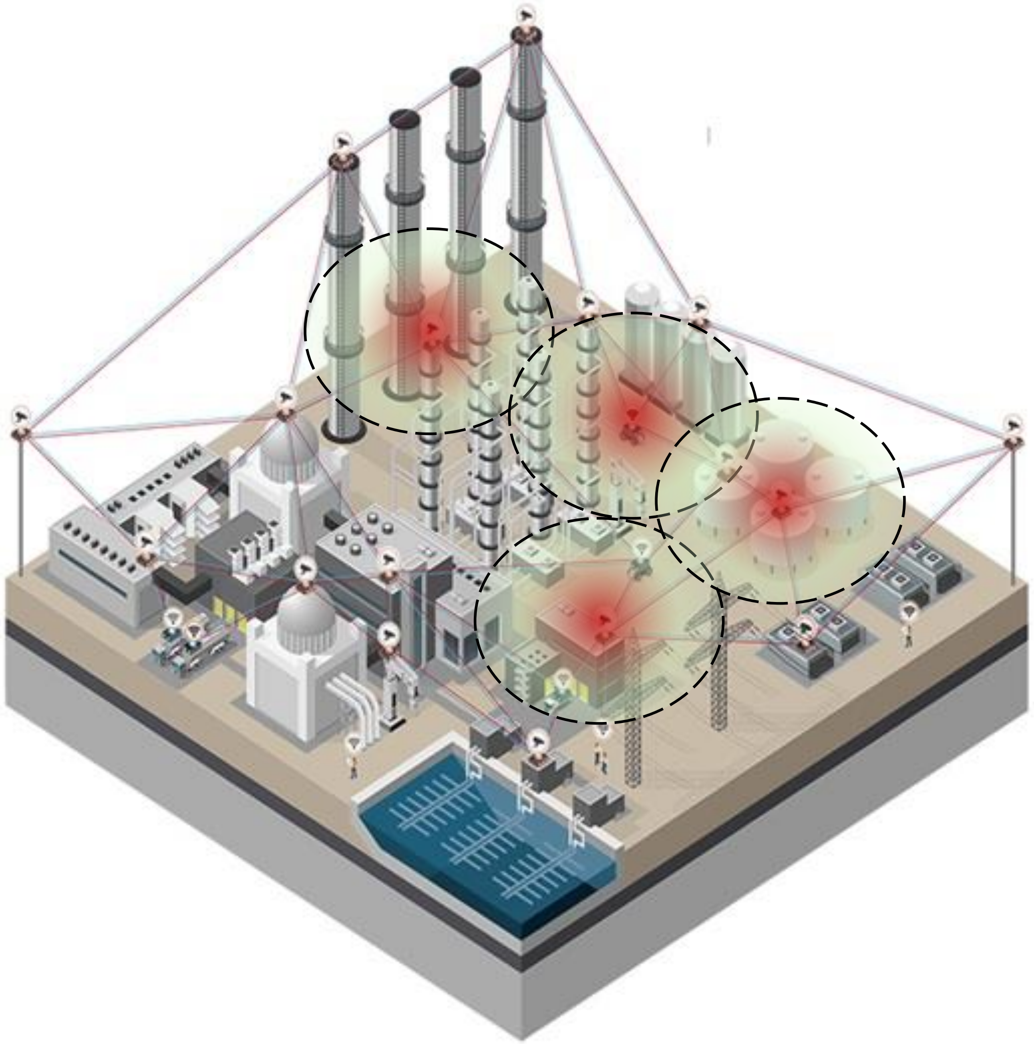
- High temporal resolution
- Robustness against multipath fading
- Low power spectral density
- Not susceptible to jamming
- Good obstacle penetration properties



WLAN and WPAN main standards: rate and maximum ranges

So, is Ultra-wide band is a good candidate for industrial WSNs ?

The answer is YES !



WIRELESS SENSOR NETWORKS DEPLOYMENT

Problem statement

- Characterization of WSNs
- Techniques of sensors deployment
- Sensor coverage model
- Sensor communication model

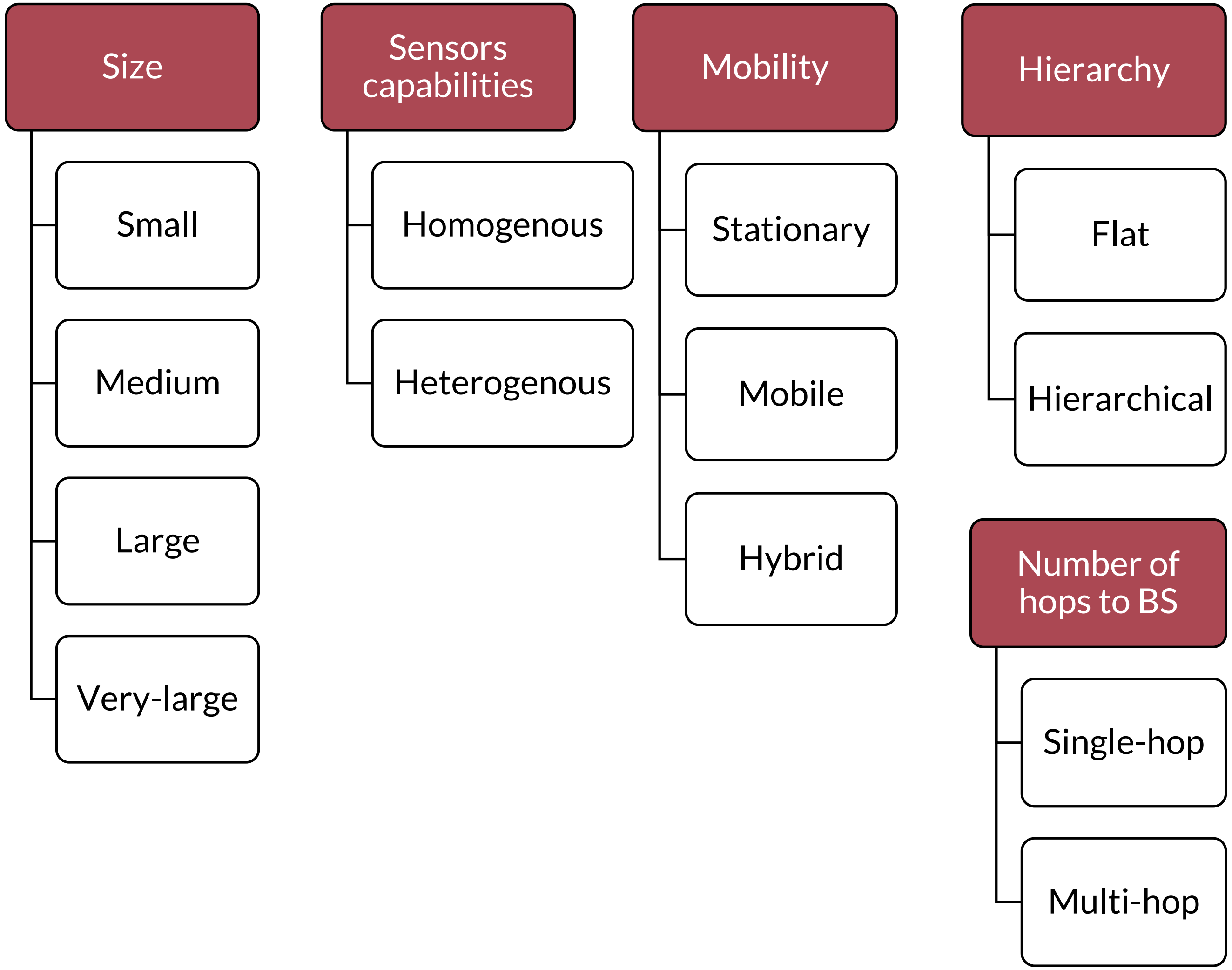
Characterization of WSNs

Common architectures

Different models and architectures can be utilized for sensor cooperation.

These are the main characteristics WSNs are grouped by:

- Size
- Sensors capabilities
- Mobility
- Hierarchy
- Number of hops to the Base Station



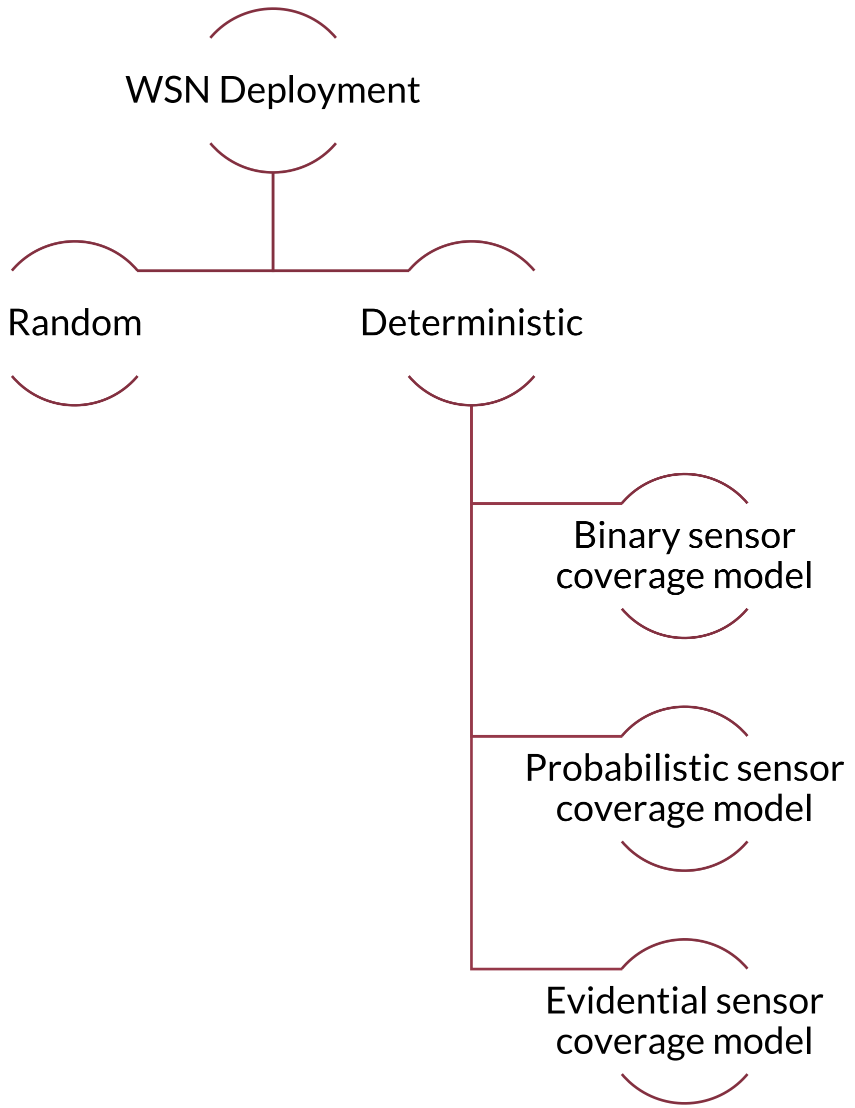
Sensor nodes deployment

Techniques

Efficient deployment plays a critical role in the operation of sensor networks.

There are two techniques for WSNs deployment:

1. Random deployment
2. Deterministic deployment



Sensor nodes

Coverage model

A sensor coverage model is a mathematical function that determines the coverage of a point in relation to the sensor node.

Three types of coverage models exist:

1. Binary
2. Probabilistic
3. Evidential

$$\boldsymbol{P}_{s/p} = \begin{Bmatrix} 1 & if \ \ ||sp|| \ \le R_s \\ 0 & otherwise \end{Bmatrix}$$

Binary sensor coverage model

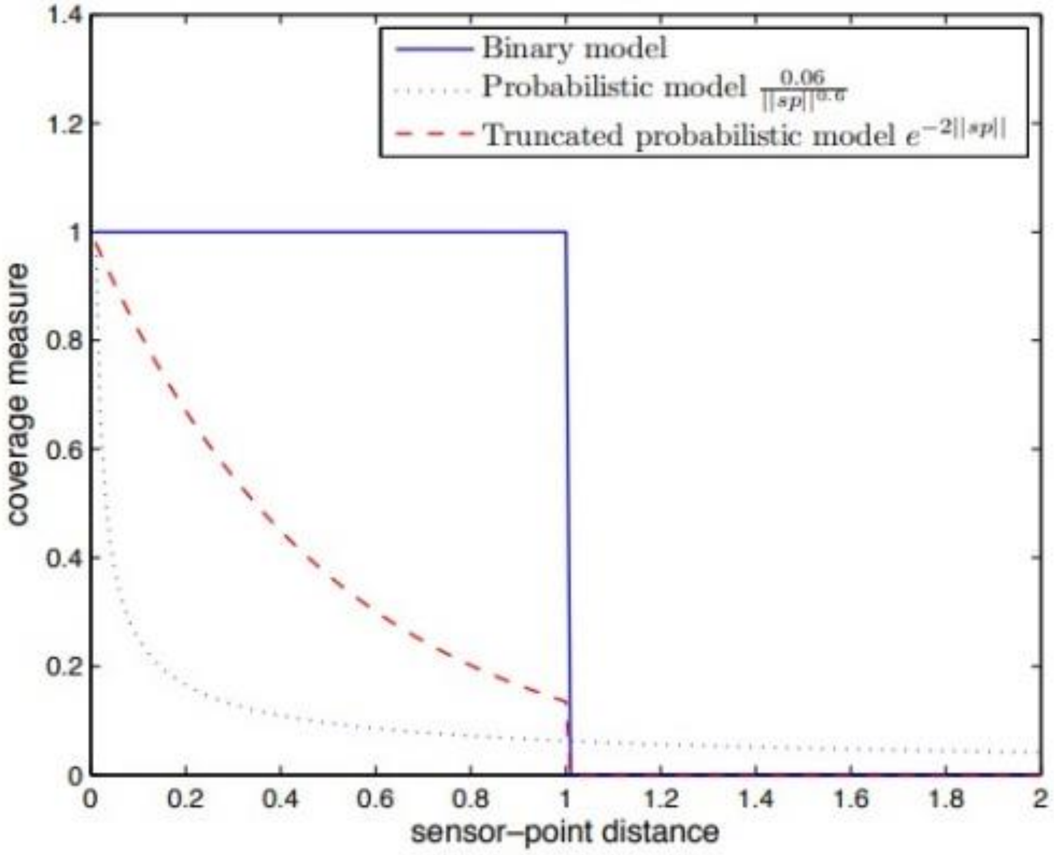
$$\boldsymbol{P}_{s/p} = \frac{C}{||sp||^{\gamma}}$$

Probabilistic sensor coverage model

$$\boldsymbol{P}_{s/p} = \begin{Bmatrix} Ce^{-\delta||sp||} & if \ \ ||sp|| \ \le R_s \\ 0 & otherwise \end{Bmatrix}$$

Truncated probabilistic sensor coverage model

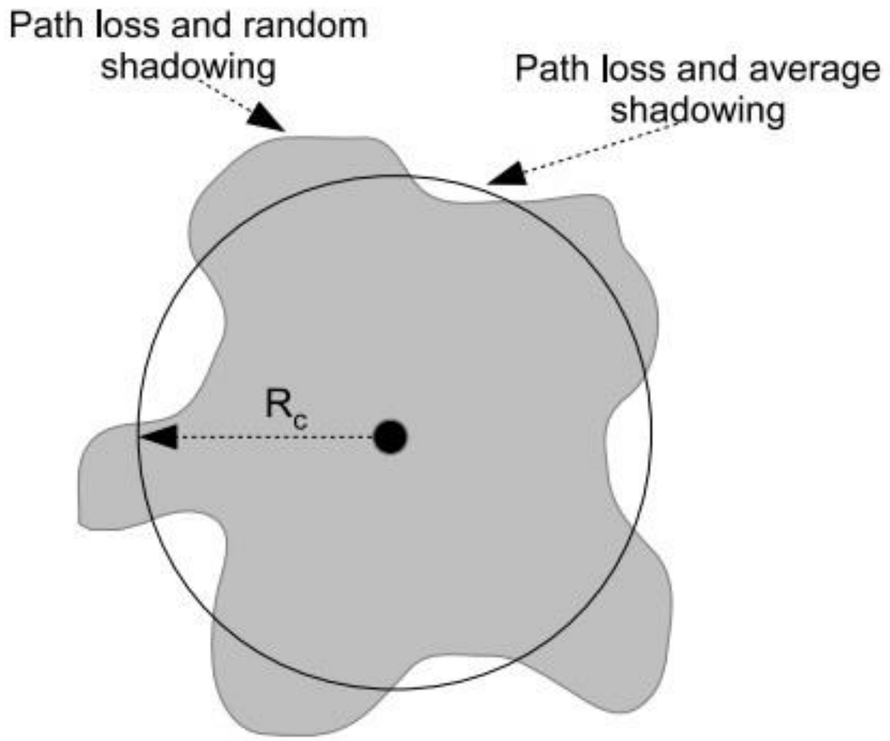
Coverage model



Coverage measure vs. the sensor-point distance for the binary model, probabilistic model, and truncated probabilistic model

Communication model

A sensor communication model, also known as a transmission model, is a mathematical representation that quantifies the direct connectivity between sensor nodes.



Connectivity model

METHODOLOGY

Problem formulation and optimization framework

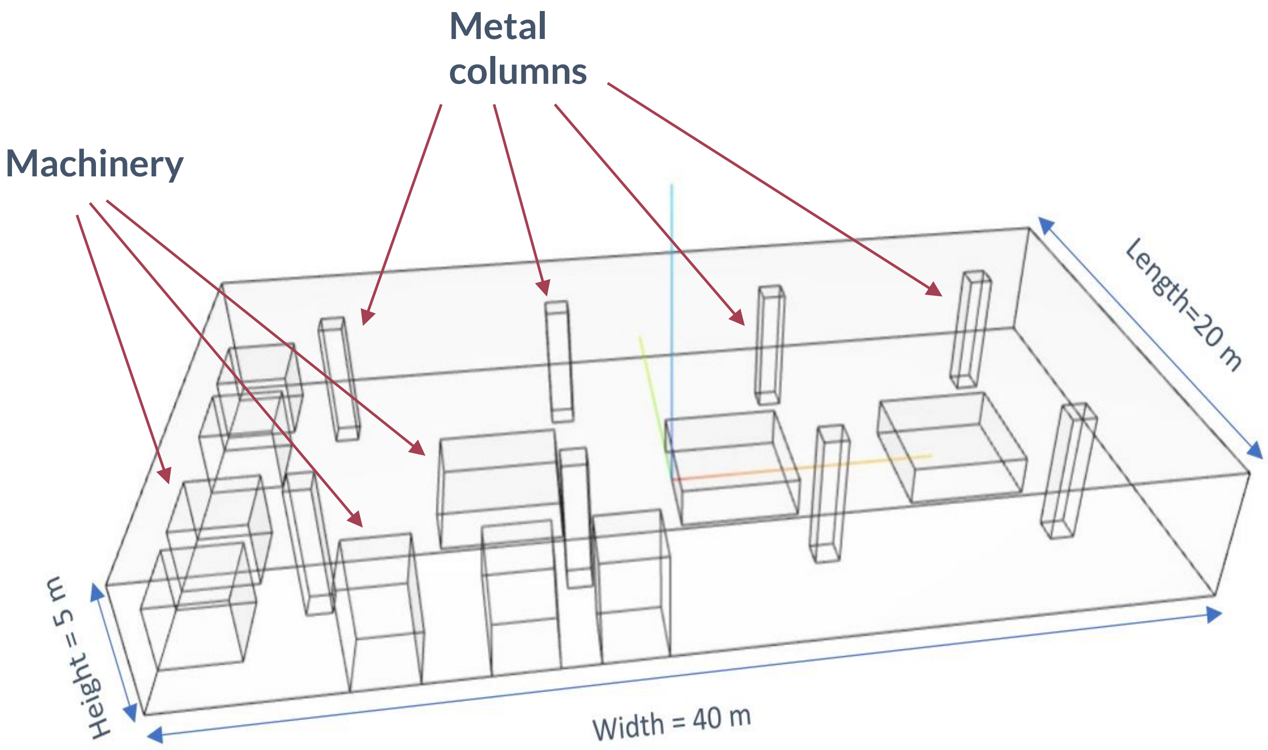
- 3D simulation of the region of interest
- UWB channel estimation
- Problem formulation
- Optimization framework

Region of Interest

3D Simulation

The 3D model was created using MATLAB.

Obstacles were included to model the presence of machinery and metal columns.



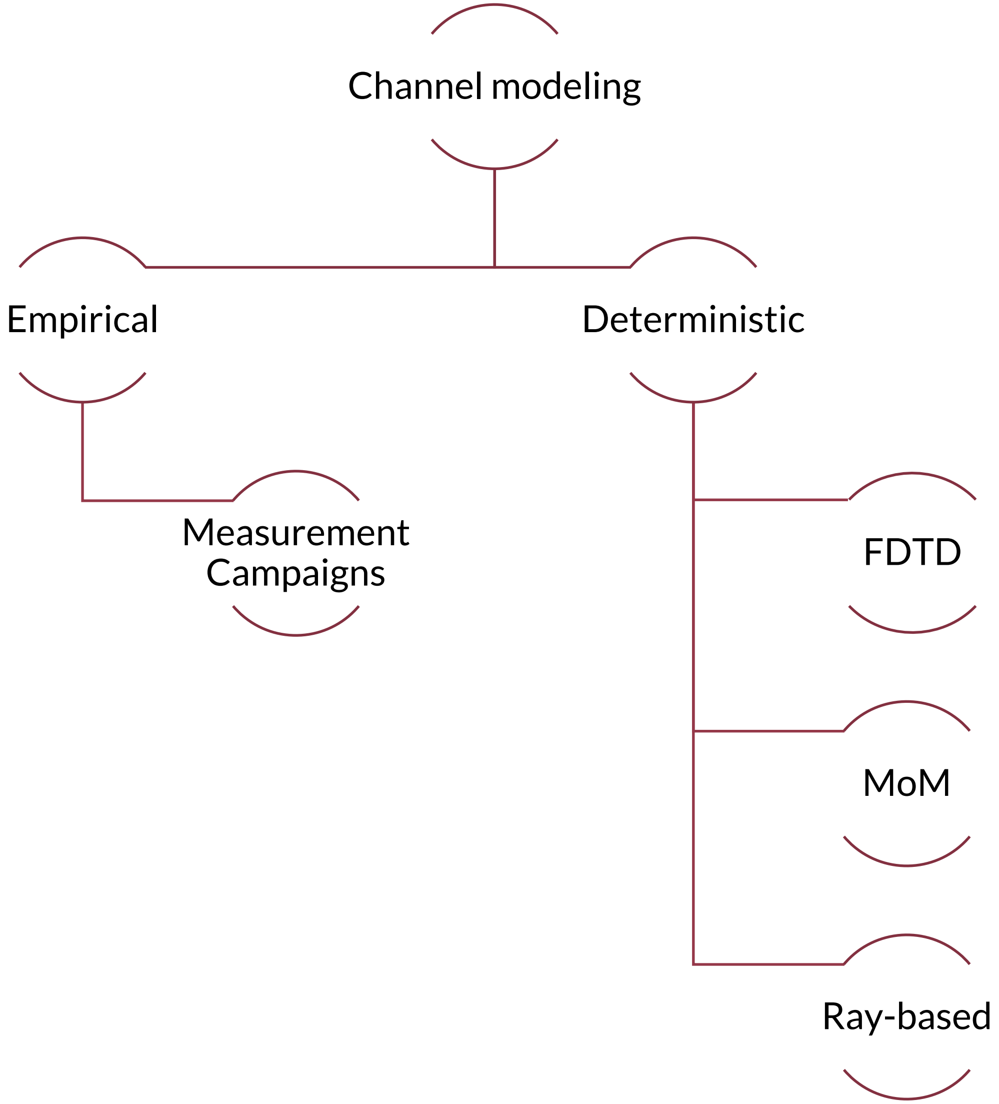
3D industrial environment model

UWB Channel Estimation

Channel model

The channel model is the impulse response of the channel medium in the time domain, or its Fourier transform in the frequency domain.

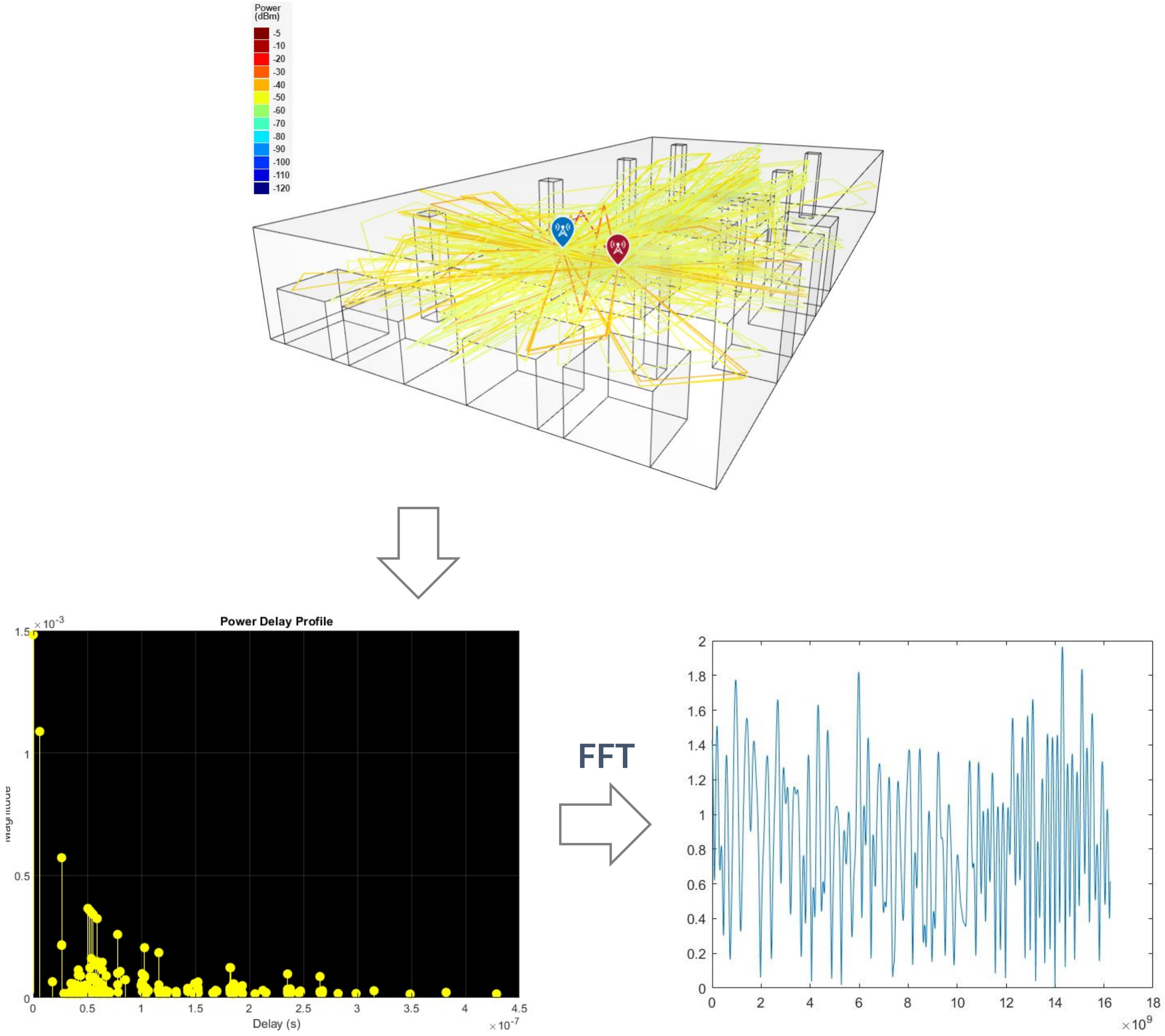
Channel models are derived either empirically or deterministically.



Band-divided ray tracing

To characterize the UWB propagation channel:

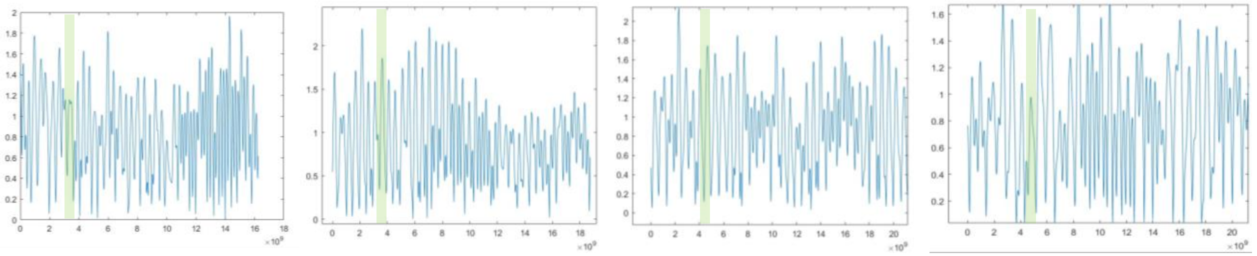
1. Divide the bandwidth into multiple sub-bands.
2. Employ ray tracing in the considered environment to obtain channel frequency response.



Ray tracing at f_c=3.25Ghz

Band-divided ray tracing

3. Extract the accurate portions from each frequency response and combine them to create a new frequency response.



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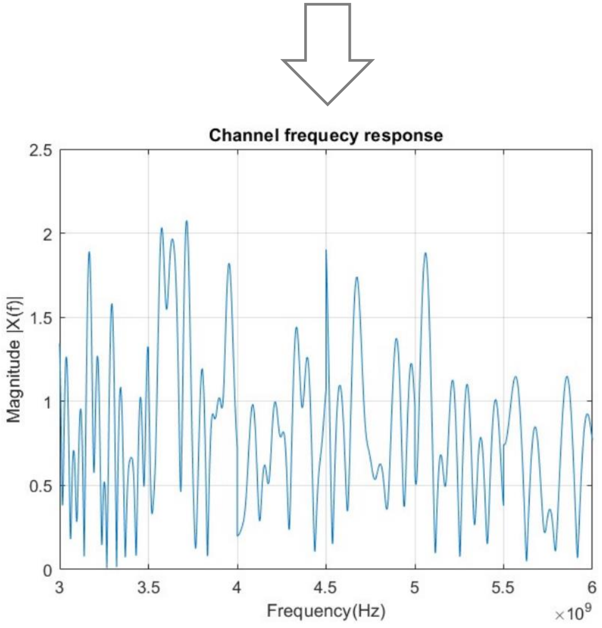


UWB channel estimated frequency response

Band-divided ray tracing

To capture the effect abundance of metallic surfaces in industrial environments, the propagation model was modified.

```
pm = propagationModel("raytracing", ...
    "CoordinateSystem","cartesian", ...
    "Method","sbr", ...
    "AngularSeparation","low", ...
    "MaxNumReflections",3, ...
    "MaxNumDiffractions",1,...
    "SurfaceMaterial","metal");
```

Ray tracing propagation model initialization in MATLAB

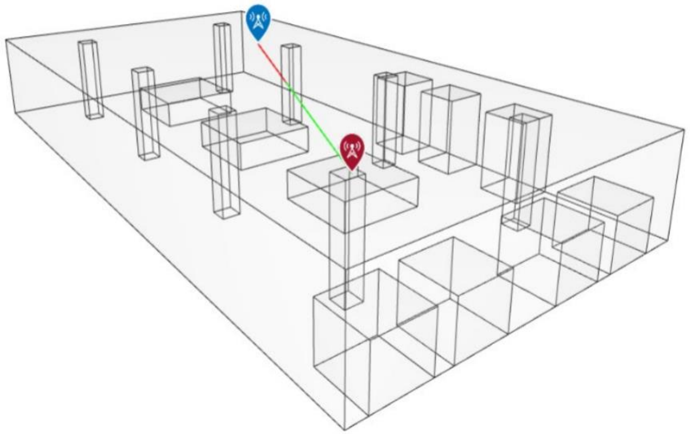
Problem Formulation

Optimal deployment of sensors

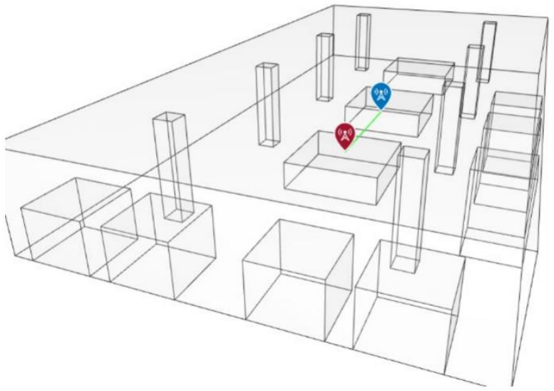
Given the environment, we need to optimally place the sensor nodes to achieve:

1. Lowest deployment cost for deploying $\boldsymbol{S}$ sensors based on the $\boldsymbol{dc}$ metric
2. K-coverage of target points $\boldsymbol{M}$

$$K - coverage_{m \in M} = \sum_{s=1}^{S} \{s | s \in S \ \wedge m \in Sphere(s, r_s) \ |LOS(m, s) \ \wedge RSSI(s) \geq RSSI_{threshold}\}$$



a) No LOS



b) LOS

Optimal deployment of sensors

3. Quality of communication between sensors to the BS given the least acceptable RSSI between any two nodes.
4. Full connectivity

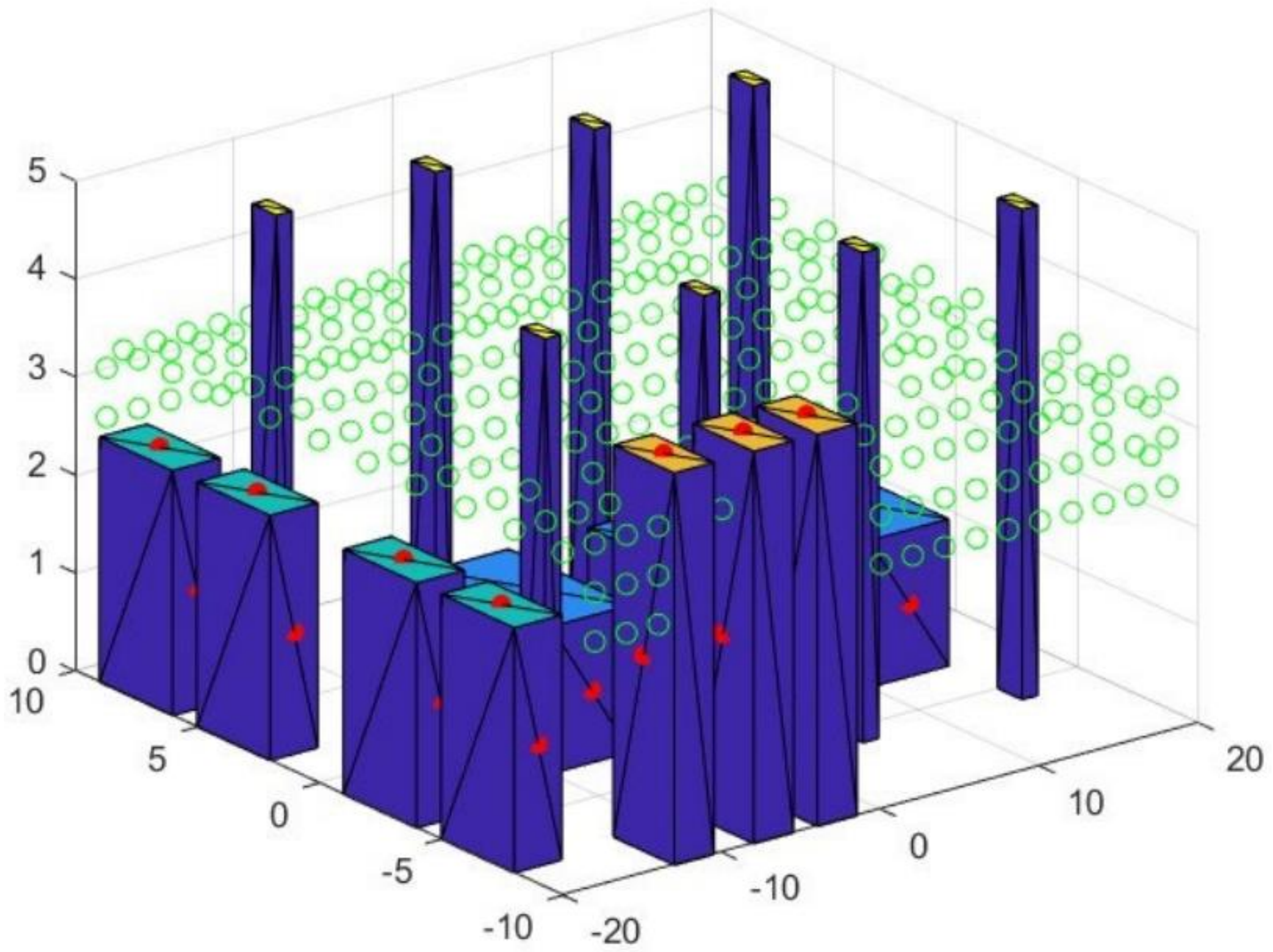
$$\forall s \in S, connected(s, BS) = true$$

Full Connectivity constraint

Optimization Framework

Initial deployment phase

Given the $3D$ environment and the grid step Δ, the algorithm calculates the $3D$ Euclidean coordinates of the monitoring points $\boldsymbol{M}$ and the deployable points $\boldsymbol{D}$.

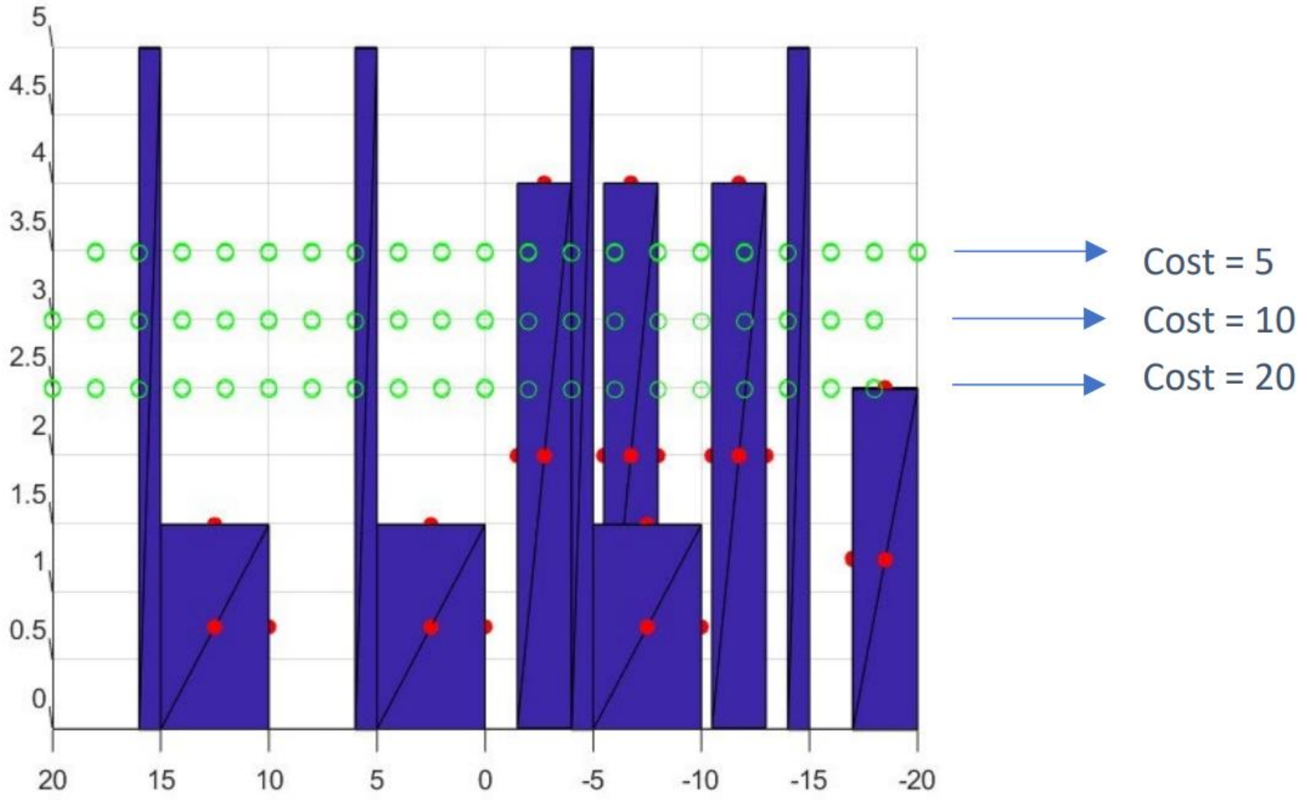


Monitoring points and deployable points in the industrial environment

Initial deployment phase

Deployment cost is assumed to depend only on the height of the deployable location.

There are 3 levels for deploying sensors.



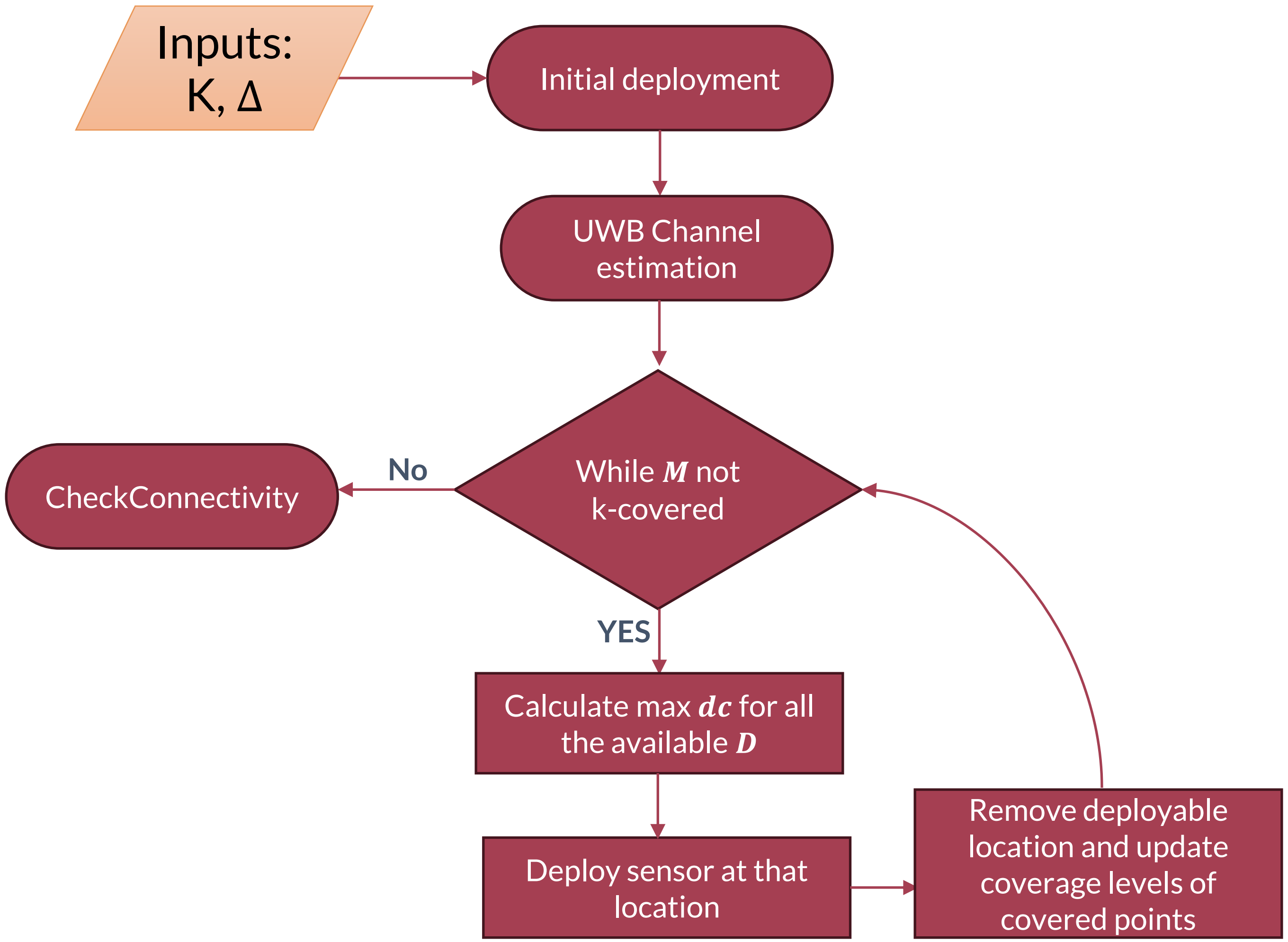
(Side-view) Deployable locations at different heights with different costs

Optimization Framework

Node selection phase

The node selection phase deploys the sensors one-by-one according to the $\boldsymbol{dc}$ ratio.

After deployment the algorithm checks if every sensor is connected to the BS.



SIMULATION

Experimental Evaluation and Results

- Simulation settings
- Results
- Comparison

Simulation Settings

Assumptions and inputs

Assumptions used throughout the modeling and simulation of the optimization process are:

- Simplified environment model
- Discretized deployable and monitoring areas
- Communication range needs to be at least twice the sensing range to imply connectivity

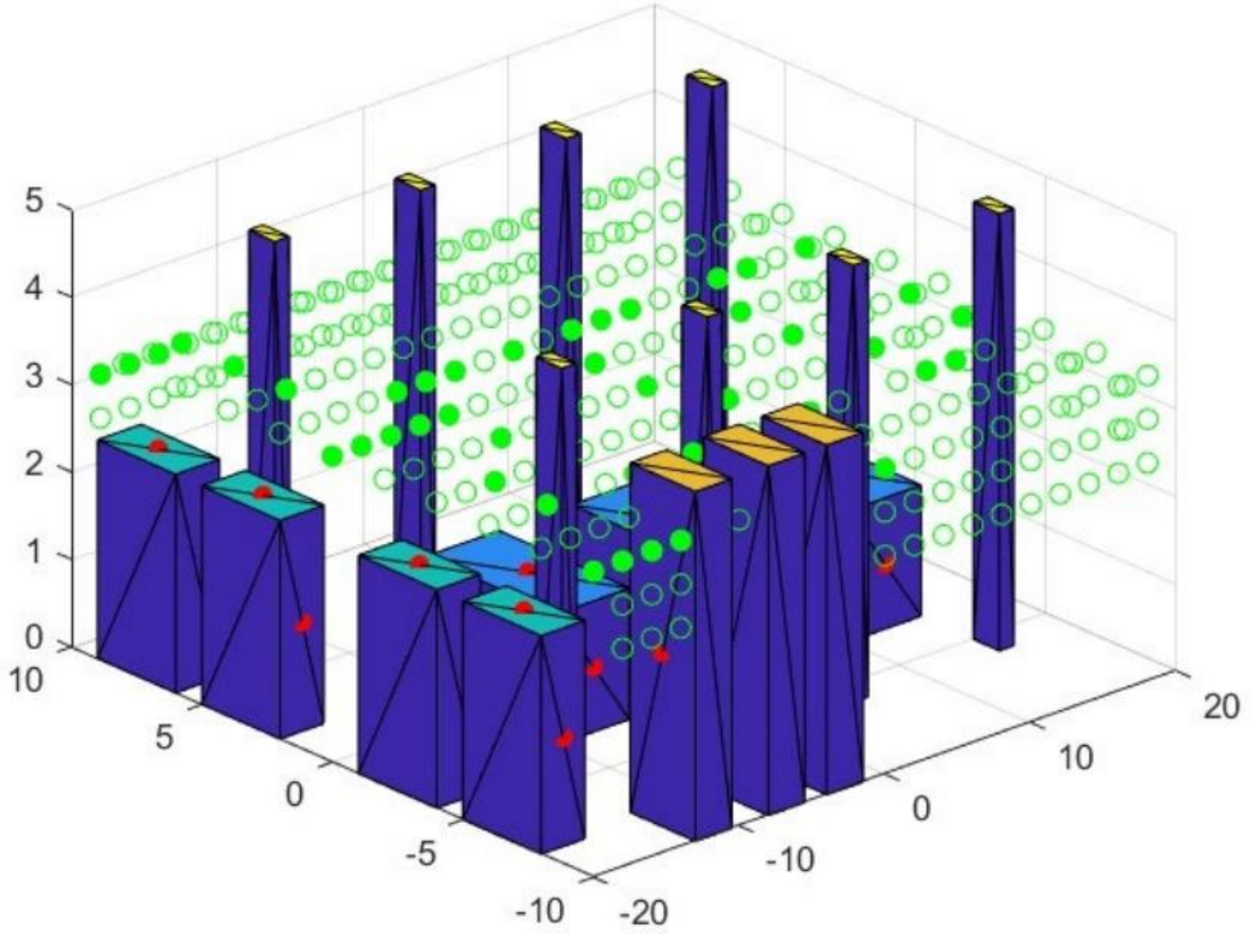
Target space	40m x 20m x 5m
k-coverage	3
Sensing rang r_s	5 m
Communication range r_c	10m
$RSSI_{threshold}$	-80 dBm
BS location	(0, 0, 5)
Δ	2 m
P_{tx}	10 dBW
f_c	4.25 GHz
BW	3 Ghz

Simulation parameters

Results

Deployment of sensor nodes

The algorithm took 67 iterations to finish the deployment of the 46 relay nodes to sufficiently cover all the target points.



WSN deployment result

Deployment of sensor nodes

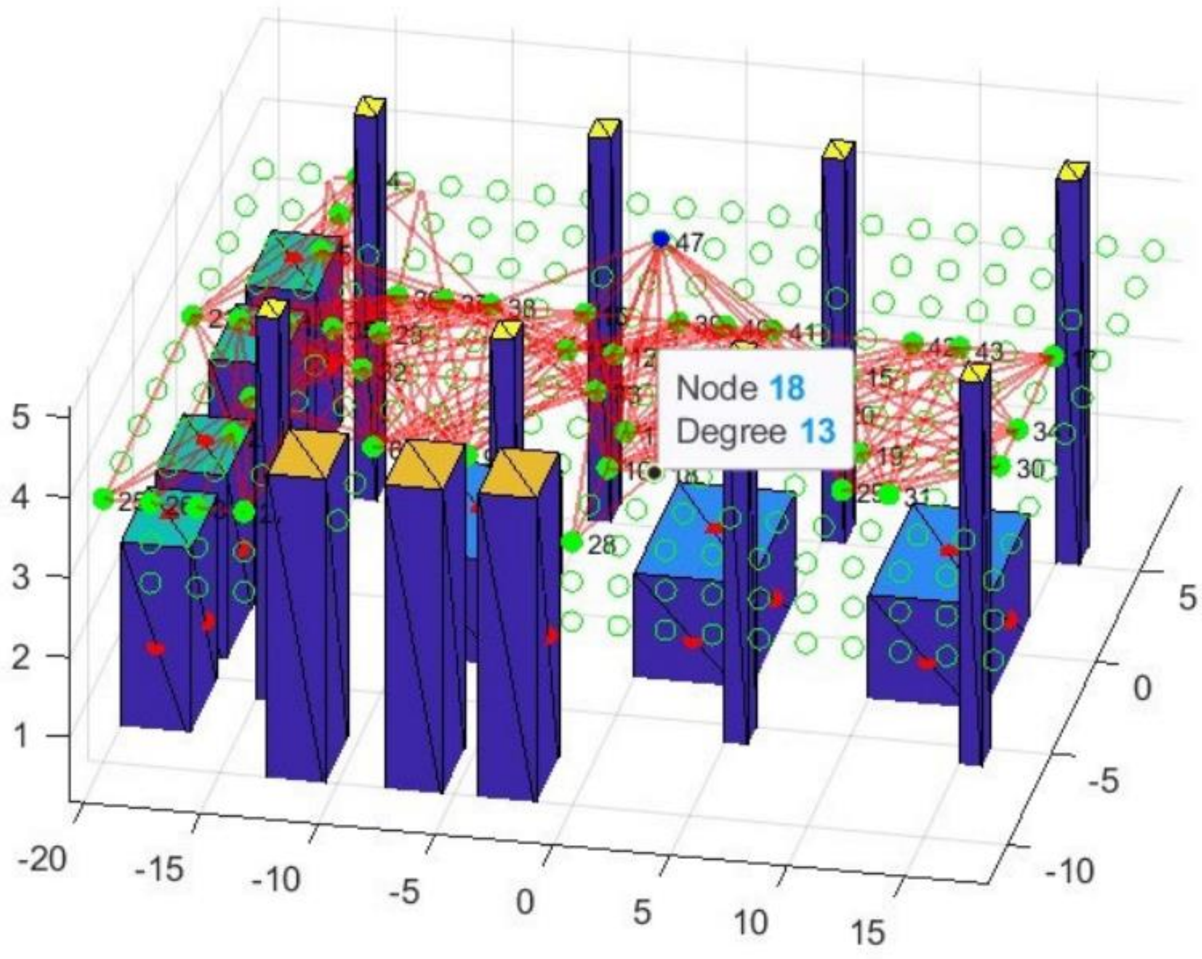
Each target point was successfully k-covered.

```
Columns 1 through 17

    5     3     3     5     3     4     5     3     3     5     3     5     3     3     3     3     3

Columns 18 through 32

    3     3     4     3     5     3     3     3     3     6     3     3     3     3     6
```

Coverage level for each target point/sensor

Deployment of sensor nodes

A connectivity check is run to check if every node can relay the information to the BS directly or through routing to other nodes



Connectivity plot of the deployed Sensors with the BS

Deployment of sensor nodes

```
ans =

  Columns 1 through 17

     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1

  Columns 18 through 34

     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1

  Columns 35 through 47

     1     1     1     1     1     1     1     1     1     1     1     1     1
```

$Conncomp$ MATLAB function output showing group of each sensor node

Comparison

Proposed algorithm vs “LowCost” algorithm

The “LowCost” algorithm was implemented in MATLAB and run with the same simulation settings to compare the performance and results of both.

Algorithm	Number of deployed nodes	Execution time (sec)	K-coverage percentage (%)	Connectivity (Sensor node to BS)	Mean RSSI (dBm)
Proposed	67	3116	100	Yes	-61
LowCost	85	162	78	Yes	-71.9

Proposed algorithm versus LowCost algorithm

FUTURE WORK

Limitations of the proposed approach and future suggestions

- Limitations of the proposed approach
- Future work

Limitations of the proposed approach

These limitations provide insights into areas that require further investigation and potential improvements:

- Model assumptions
- Scalability
- Dynamic environments
- Practical implementation challenges

Future work recommendations

Points of future research and improvements

- The refinement and extension of the optimization algorithm such as using Genetic algorithms.
- Investigate the integration of additional wireless technologies and protocols with the proposed approach.
- Improving the accuracy of the UWB channel modeling process.
- Considering the downlink channel and the integration of massive Multiple-Input Multiple-Output (MIMO) base stations.
- Considering the evolving landscape of Industry 4.0 and the Industrial Internet of Things (IIoT) , leveraging Artificial Intelligence (AI) and machine learning algorithms for real-time decision-making.


THANK YOU
ANY QUESTIONS?