Indoor Positioning Systems

A survey on Indoor Positioning Systems for IoT-Based Applications,

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Agenda

- Indoor positioning system (IPS) concepts and approaches
- IPS methods, techniques and technologies
- Discussion, challenges and solutions
- Application, services and vendors (Paper)
- Case Study

Overview

- **Key Tech:** To improve IoT services is positioning systems because accurate location data is essential for intelligent IoT applications such as smart hospitals, asset tracking in factories and indoor navigation systems.
- **GPS:** is ineffective indoors, making IPS critical for accurate tracking in closed environments

Key Components

- **Localization:** It determines the location of an object relative to a reference point
- **Localization systems:** have two main components
  - **Fixed reference nodes (RNs)**, also known as anchors (e.g. satellites in GPS)
  - **Mobile nodes (MNs)**, called as beacons or tags, which need to be localized

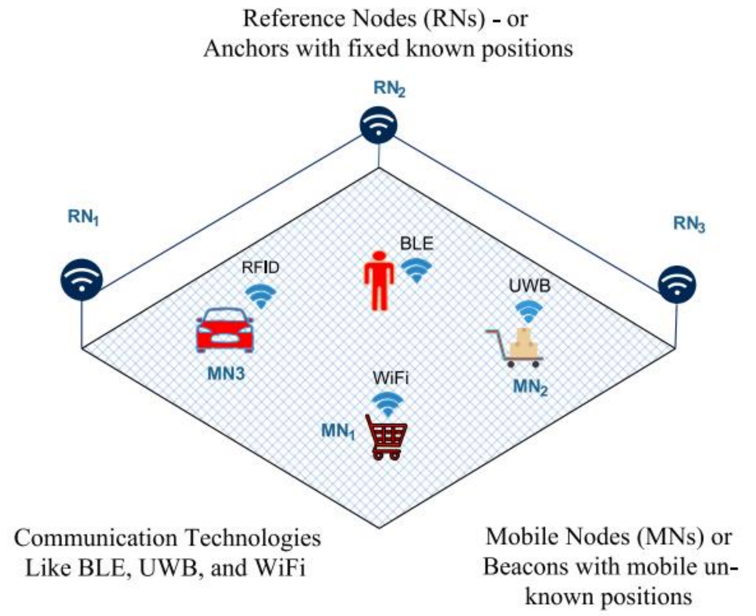


Fig. 1. IPS schematic: RNs (RN_1, RN_2, and RN_3) receive or emit signals to determine the position of MNs.

Key Components

- **Positioning systems:** refers determining the object’s coordinates in space
  - **Global (e.g. Global navigation satellite systems** like GPS, Galilea,GLONASS, BeiDou**)** covers large areas but has limitations in indoor and covered environments
  - **Local (Local Positioning Systems, LPS)** is designed for indoor and restricted environments using short-range communication technologies (e.g. Wi-Fi) or long-range options (e.g. Sigfox, cellular) for wider coverage. Both can be merged for hybrid positioning
- **Positioning services:** offered by IPS include:
  - **Tracking**: External parties track an object’s location
  - **Navigation**: Users actively use devices (e.g. smartphones) to find their own location relative to anchors
  - **Proximity**: Notifies users when they are near a Point of Interest (PoI), often used in public spaces and museums
  - **Inertial measurement**: Uses sensors (accelerometer, gyroscope, magnetometer) to measure motion, often found in mobile devices, complementing other positioning methods in indoor spaces

User’s Role

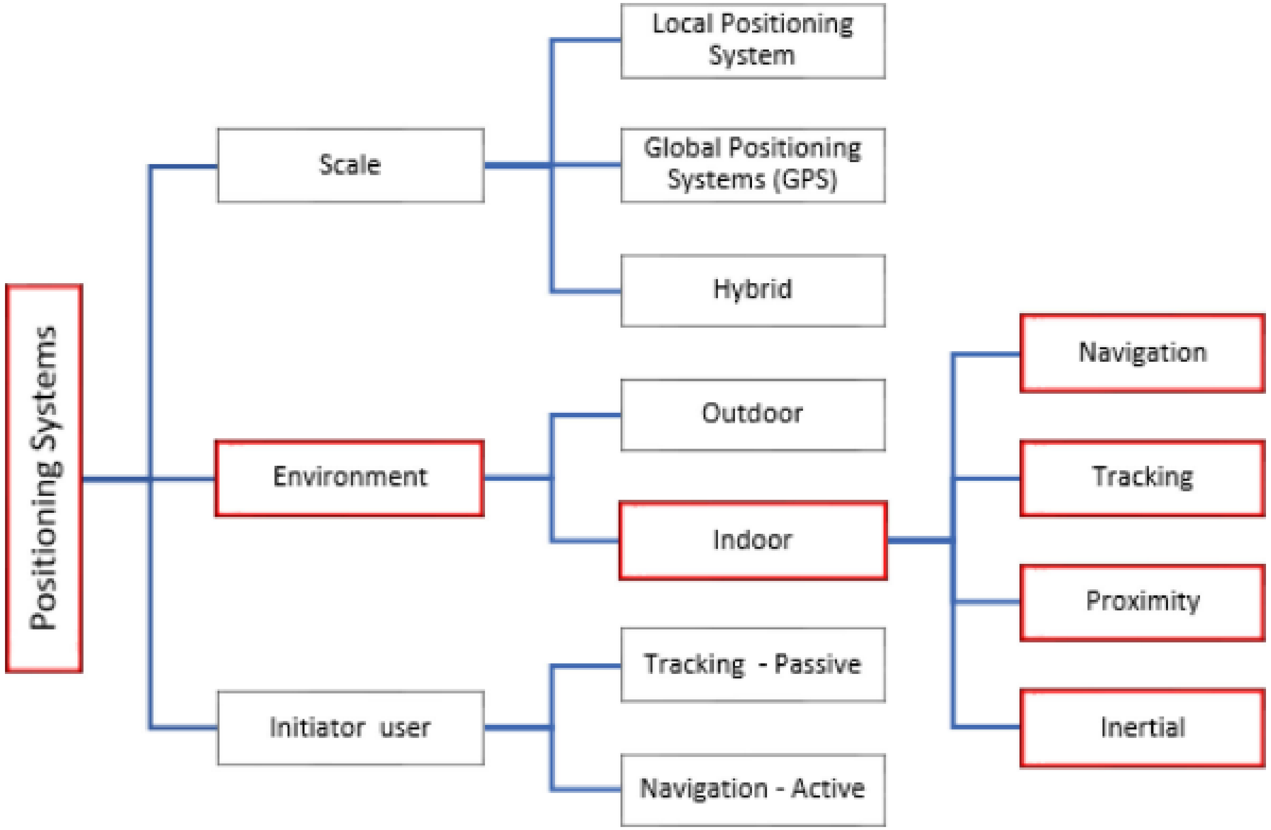


Fig. 2. Positioning system classification.

Topologies

- **Mobile-Node-Based-Localization (MNL):** it determines its location relative to surrounding RNs. Where MN acts as a initiator, receiving signals from RNs and managing the localization process. It is used for navigation systems.
  - **Advantages** relies on the MN for processing, as it reduces traffic congestion and signal interference on the RNs
  - **Disadvantage** resource limitations on the MN side such as energy, processing power, storage capacity. Where data processing and analysis can be offloaded to local cloud server.

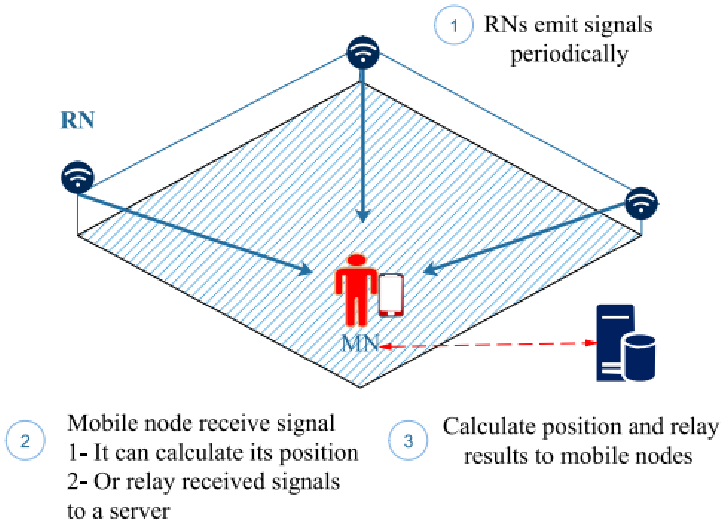


Fig. 3. MN-based localization system schematic.

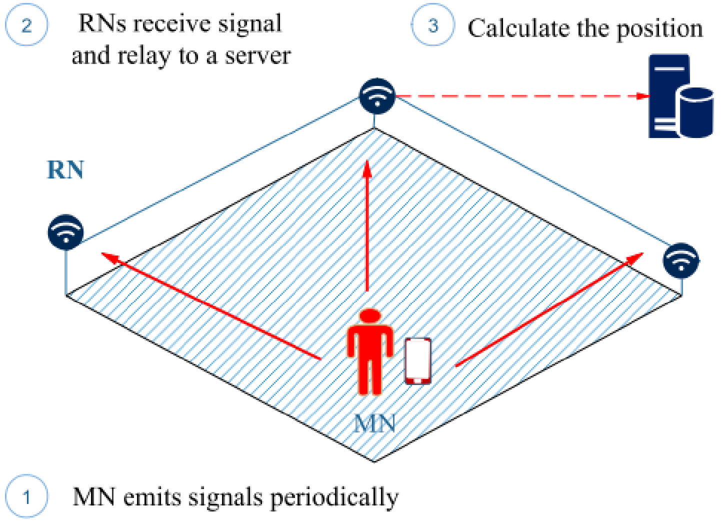


Fig. 4. RN-based localization system schematic: MN emits signal to RN and RNs relay-received data to server for localization.

Topologies

- **Reference-Node-Based-Localization (RNL):** Fixed RNs determines the position of the MN based on signals it sends. It is common in tracking systems, where RNs initiate the process, collect signals from MNs, and send the data to a server for localization
  - **Advantages** all processing and storage are handled by RNs,
  - **Disadvantage** congestion at the RNs leads to conflicts in handling data requests incase when many MNs

Topologies

- **Inertial Measurement Unit (IMU):** localization occurs at user device using three sensors, gyroscope(measures orientation), magnetometer(detects magnetic field), and accelerometer(measures acceleration along three axes)
  - **Advantages** complementary method for tracking movement, especially for athletes or behavior analysis,
  - **Disadvantage** system requires an initial position to start measurements and is prone to accumulated errors requiring correction algorithm

Topologies

- **Proximity based detection:** estimates the distance between an object and a point of interest (PoI), detecting when the object enters a defined vicinity
  - **Advantages** use case for context-aware services like advertising, shopping, and logistics. It is energy-efficient and cost-effective. Algorithms like MLE, k-nearest neighbor (kNN) are used to improve proximity zone detection. Bluetooth is often used in it e.g. covid 19 social distance measuring
  - **Disadvantage** not suitable for tracking or navigation that requires exact positions

Methods

- **Lateration:** it determines the position of an unknown object by measuring the distance from multiple known RNs. Object location found where circles/spheres intersect. Used for 2D spaces. More anchors more accuracy. Application is IoT environments
- **Angulation:** it uses angle of arrival technique to measure the signal angles from multiple RN. Object position is calculated based on the angles and distances from two or more RNs. Application is Bluetooth 5.1. Requires two RNs for 2D localization and three RNs for 3D localization
- **Scene Analysis and Pattern Matching:** Uses spatial information collected from specific points, forming a database. Measured values are compared with this database to estimate the object's location
    - **Fingerprinting (FP)**, in offline phase a map of the area is created by collecting RSSI values from reference points (RNs) and stored in a database and in online phase recent RSSI values are compared with the database to find the object's position

Methods

- **Proximity Based Detection:** the exact location is not required, instead the objects presence within a specific zone or PoI is detected. Beacons measure the proximity based on Tx-power e.g. Apple iBeacons. Crowded areas may affect accuracy. Applications are advertising, shopping and logistics.
- **Trajectory-Based Localization:** determines the object's position based on its movement from a known starting point. Movement data (direction, velocity) is tracked to find the next position. Common techniques are **dead reckoning (DR)** where current position is estimated based on the last known position and movement data (direction and velocity). **Pedestrian dead reckoning (PDR)** a variation that uses step length and direction for position estimation

Techniques

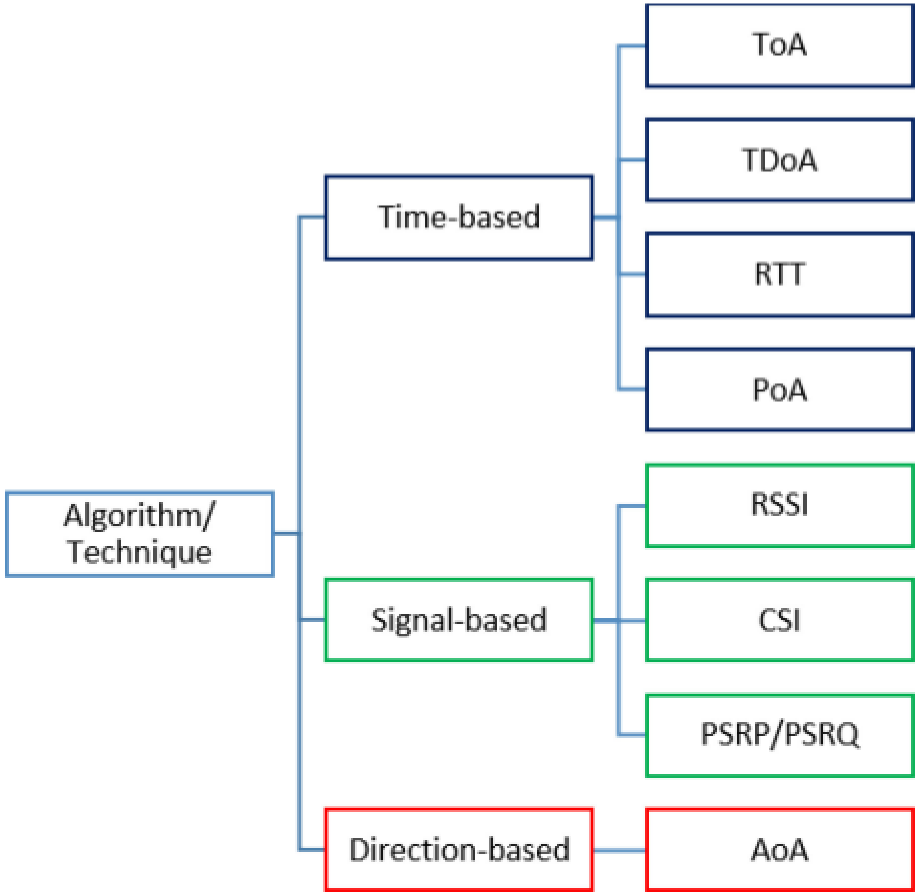
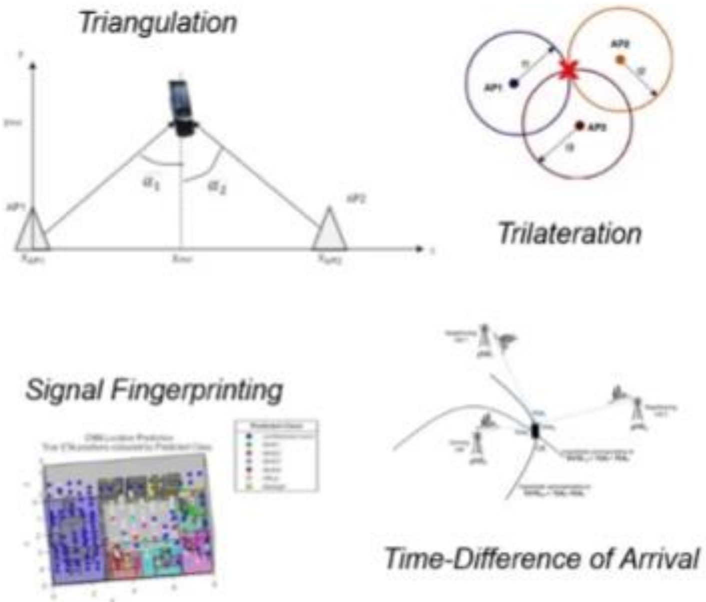


Fig. 7. IPS algorithm classifications.

Common Methodologies

- Power or signal strength-based
  - Bluetooth: Received Signal Strength Indicator (RSSI)
- Time based
  - Wi-Fi: Time of Arrival (TOA)
  - LTE, 5G: Time Difference of Arrival (TDOA)
  - 5G: Round Time Trip (RTT)
- Space based
  - Bluetooth: Angle of Arrival (AOA)
- Fingerprinting
  - Wi-Fi



Techniques

- **Time-Based Localization:** it measures the time of signal propagation to estimate the distance between MNs and RNs.
  - **Time of arrival (ToA):** measures the time it takes for a signal to travel from the transmitter to the receiver. The distance is calculated by multiplying the signal propagation time by the speed of light. Difficulty is to measure precise time synchronization between Tx and Rx. Accuracy depends on bandwidth and sampling rate.
  - **Time different of arrival (TDoA):** only measures the difference in arrival time between anchor nodes. Requires synchronization between anchors. Where at least three anchors are needed to find the receiver’s position in the intersection
  - **Round trip time of flight (RTT):** measures the time it takes for a signal to travel to the receiver and back. Precise clocks are required at both ends
  - **Phase of arrival (PoA):** measures the phase of the incoming signal to estimate distance, often used in combination with other techniques. It reduces impact of multipath interference
- **Signal-Based Localization:** it is based on signal strength
  - **Received signal strength indicator (RSSI):** estimates the distance between devices based on the signal strength received. Higher signal strength typically indicates a shorter distance. Used with methods like trilateration, scene analysis and proximity detection. Prone to multipath effects
  - **Channel state information (CSI):** provides detailed channel information and it is more accurate than RSSI but more computationally expensive to capture its application is fingerprinting
  - **Reference signal received power/quality (PSRQ and PSRQ):** measures the power and quality of LTE reference signals in cellular networks. Used in cellular networks for positioning with BTS

Techniques

- **Direction/Angle Based Localization:** it rely on measuring the angle of arrival (AoA) of signals and determining the position based on multiple bearings.
  - **Angle of arrival (ToA):** measures the direction from which the signal is received. The position is calculated based on the intersection of bearings from multiple anchor nodes. Anchors must have directional antennas and precise calibration. Synch not required between transmitter and receiver. Accurate for short distances. Applications are VLC, UWB and Bluetooth uses AoA for positioning

Techniques

Comparative Summary	
Accuracy	ToA, TDoA and CSI are very accurate. AoA not as precise as the others, can reach centimeter-level accuracy when paired with modern technologies like Bluetooth 5.1.
Trade-offs	RSSI easy to implement but less accurate due to multipath interference. CSI offers better accuracy than RSSI but is more complex
Cost and implementation	RSSI is cost-effective but limitated in accuracy, Time-based methods (ToA, TDoA, and RTT) are more complex but suitable for higher accuracy, AoA requires specialized antennas and can be costly but is ideal for high precision and short range positioning

Technologies

Data Transmission: IPS rely on various communication technologies to transmit data between the sender and receiver. These enabling technologies can be categorized based on the type and range of the signals used for communication. The key signal types in IPS are

- **RF** (2-5GHz, e.g. Wi-Fi, Bluetooth, Zigbee),
- **Light and optical communication** (visible light and IR e.g. Li-Fi and IR based systems. They offer high-speed communication but often have limited range and require line of sight)
- **Sound based communication** acoustic and ultrasonic signals, where ultrasonic waves are used for short-range, low power positioning and are useful in environments where radio frequencies might not be ideal e.g. hospitals or sensitive areas
- **Magnetic based communication** magnetic based positioning is often used in environments where RF signals may not be ideal, such as in places with heavy interference or shielding (e.g. basements or industrial settings)

Technologies

Short Range: it covers distances from a few centimeters to a few hundred meters, making them ideal for localized, indoor areas such as homes, offices and malls. Used in real time human tracking, navigation in constrained spaces and object localization in smaller environments

Wi-Fi most common for IP. Wi-Fi 6 can achieve high speed and low energy consumption, especially in IoT contexts. Under ideal conditions its accuracy is around 2m in commercial app and below 1m using RTT for localization

MATLAB:

- **https://ww2.mathworks.cn/help/wlan/ug/802-11az-indoor-positioning-using-super-resolution-time-of-arrival-estimation.html**

BLE its latest version covers upto 400m but its accuracy ranges from 1-2m for human and object tracking. It operates in the 2.4GHz ISM band. It includes AoA and AoD which gives cm level accuracy about 10cm

MATLAB:

- **https://ww2.mathworks.cn/help/bluetooth/ug/bluetooth-le-based-positioning-using-direction-finding.html**
- **https://ww2.mathworks.cn/help/bluetooth/ug/bluetooth-le-node-tracking-using-direction-finding.html**

Technologies

Short Range: it covers distances from a few centimeters to a few hundred meters, making them ideal for localized, indoor areas such as homes, offices and malls. Used in real time human tracking, navigation in constrained spaces and object localization in smaller environments

UWB it is low power and high data rate tech, usually operates in 3.1-10.6GHz spectrum. It can achieve sub-20cm accuracy and is highly resistant to multipath effects, making it ideal for industrial IoT and IP.

MATLAB:

- https://ww2.mathworks.cn/help/comm/ug/uwb-localization-using-ieee-802.15.4z.html
- https://ww2.mathworks.cn/help/comm/ug/uwb-ranging-using-ieee-802.15.4z.html

RFID used for short range object tracking, RFID operates with active and passive tags that can communicate upto 100m (active) or 10m (passive). Not precise as other technologies and suitable for tracking the arrival and departure of objects in specific scenarios like warehouses and supermarkets

ZigBee is designed for low-cost, low data rate and low power applications. Covers distance upto 100m. It shares similarities with BLE and uses RSSI for positioning

Technologies

Long Range: those technologies are designed for wider coverage areas, capable of connecting thousands of devices across several hundred meters. Suitable for large-scale IoT applications such as smart cities, mega malls and campuses

LPWAN includes vast areas upto 40km, low bit rates, low energy consumption. It divides into cellular and non-cellular technologies

- **Sigfox** operates using ultra-narrowband (UNB) technology and can cover long distances rural areas 40km and urban environments upto 15km
- **LoRaWAN** its resilient to multipath and interference, LoRaWAN provides RSSI for positioning and TDoA for higher accuracy. Suitable for large scale localization in both indoor and outdoor environments with accuracy range 1.19m in LoS and 1.72m NLoS
- **NB-IoT and LTE-M** require mobile operator infrastructure but provide excellent battery life and are widely used for large scale IoT deployment. Also offer indoor positioning features in 4G and 5G standards

Cellular Networks (4G/5G) brings more advanced location-based services with enhanced accuracy and lower latency

MATLAB:

- **LTE Toolbox (Time Difference Of Arrival Positioning Using PRS)**
- **https://ww2.mathworks.cn/help/5g/ug/5g-new-radio-prs.html**
- **https://ww2.mathworks.cn/help/5g/ug/nr-prs-positioning.html**

Technologies

Comparison of Short-Range and Long-Range Technologies

Technology	Range	Accuracy	Power Consumption	Applications
Wi-Fi	Few meters to 100+ m	~2 m	Medium	Human tracking, IoT devices, ADL, indoor navigation
BLE	Up to 400 m	1-2 m (up to 10 cm with AoA/AoD)	Low	Commercial positioning, asset tracking, proximity services
UWB	10-100 m	~20 cm	Low	High precision, industrial IoT, robotics, asset tracking
RFID	Up to 100 m	10 m	Low	Object tracking, logistics, warehouses
LPWAN (Sigfox/LoRaWAN)	Up to 40 km (Sigfox) or 10-15 km (LoRaWAN)	1-2 m	Very Low	Large-scale IoT deployments, smart cities, agriculture
Cellular (4G/5G)	Several km (urban/rural)	5 m (LTE) to cm (5G)	Medium	Outdoor/indoor IoT, wide-area positioning

Technologies

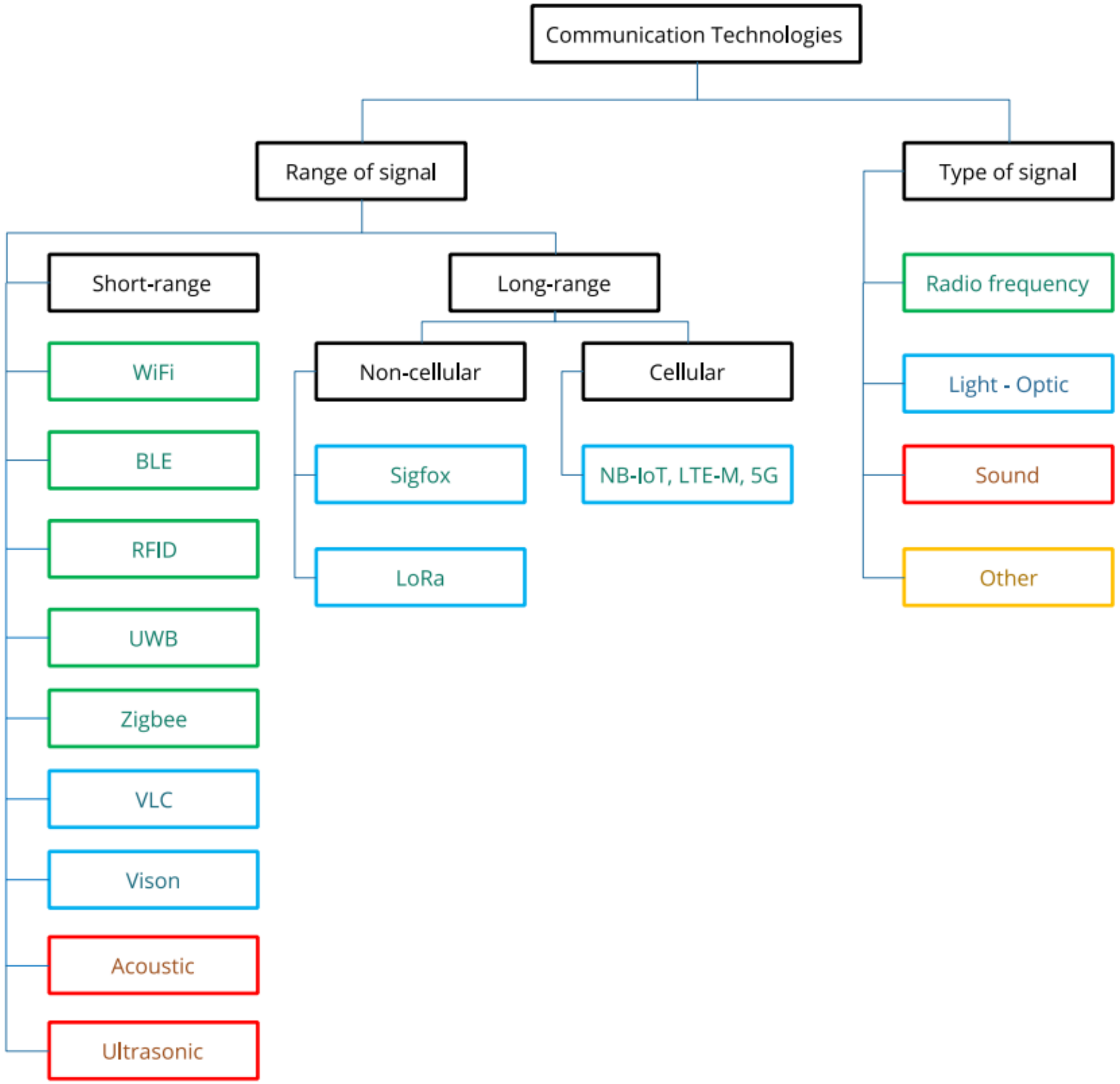


Fig. 8. Enabling communication technology.

Evaluation Metrics

Metric	Description	Importance
Accuracy	Closeness to the true position, minimizing system errors and noise.	Essential for reliable location data.
Precision	Repeatability of results, ensuring consistent performance.	Required for stable, long-term operations.
Availability	Accessibility of system/service, with no need for proprietary hardware.	Ensures widespread use and user adoption.
Cost	Total expenses including setup, maintenance, and operational costs.	Critical for market acceptance and scalability.
Coverage	Spatial extent covered by the system, influenced by node density and Tx-power.	Balances cost with performance over larger areas.
Energy Efficiency	Power consumption of devices and systems, crucial for battery-operated devices.	Extends device lifespan and reduces operational costs.
Latency	Time delay between request and response in real-time systems.	Crucial for time-sensitive applications.
Scalability	Ability to scale up or down without affecting performance.	Necessary for expanding IoT deployments.
Robustness	System's ability to function despite environmental challenges or signal degradation.	Ensures consistent performance in varied conditions.

Noise and obstacles

A major challenge in IPS is the disruptive impact of noise and obstacles on signal propagation. Moreover, environmental noise introduces unpredictability in signal strength, distance, and angle measurements making the real-world performance of IPS significantly differ from lab or simulation results. Two possible solutions

- **Noise and obstacle removal** includes mitigating environmental noises and removing or bypassing obstacles which is impossible to eliminate entirely
- **Signal manipulation** various filters and estimation algorithms used to reduce the impact of noise e.g. kalman filter, extended kalman filter, particle filter etc.

Energy efficiency

A critical concern for IoT based systems in particular MN where battery life is limited. More accuracy requires more power due to need of continuous signal reception and higher transmit power. Keeping the balance between accuracy and energy consumption a key issue

- **<u>Low power communication technologies</u>** like BLE and UWB in TDoA can help reduce energy consumption in passive and active modes
- **<u>Task outsourcing</u>** offloading positioning tasks to a server
- **<u>Lightweight Algo</u>** simple algorithms reduces energy consumption
- **<u>Transmit power and advertising time adjustments</u>** fine tuning the transmission power and the interval between signal broadcasts (advertising time) can help optimize energy consumption without significantly degrading performance

Security and privacy

As location data is sensitive and can expose users to threats such as tracking and unauthorized access

- **Lightweight security algo** may include encryption and authentication techniques tailored to low-power devices
- **Anomaly detection** using ML based approaches to identify fake nodes without burdening system resources
- **Privacy protocols** privacy enhancing techniques such as secure multi-party computation or homomorphic encryption can protect user privacy without compromising system functionality

Case Study

Indoor Navigation with a Smartphone

Intelligent Secure Trustable Things, Springer

Studies in Computational Intelligent, 2024

Overview

A smartphone navigation application that can provide accurate indoor localization without relying on GPS or any communication networks (such as Wi-Fi, LTE or 5G). The system used passive QR codes embedded in a building's infrastructure to help guide users for environments like hospitals, malls etc. to monitor emergency situations

- **QR Codes Based Localization** QR codes placed at various points in the building serve as markers that the smartphones app can scan. Where QR codes hold information about their respective position in other words those codes can store coordinates and relevant details about the surrounding area e.g. room numbers, point of interest. The app using camera of the smartphone to scan QR codes, by detecting the QR codes position. Therefore, computes user's position based on these codes, making independent of satellite or network based services
- **Advantages** low cost, offline functionality and user friendly

QR Code Types

Two distinct types of QR codes for different purpose of usage

- **Floor QR Codes** Usually placed at entrance of each floor. It represent a floor plan as an edge list used to create a navigation graph (with coordinates of destinations and navigation points, each labeled with a description e.g. room numbers, bathrooms, exit points). Due to limited space (3kB max), the data is first base64 encoded, then compressed using gzip
  - **Challenges** Dense QR codes, which slow down the recognition process and may not easily scanned under suboptimal lighting conditions
- **Localization QR Codes** Placed at destinations, intersections and key navigation points. It requires GPS or UTM coordinates. Other information includes room label, resident names or location specific information. It data size is smaller compared to Floor QR codes (3-4 times smaller) making the codes less dense and easier to scan
  - **Challenges** Such codes are more manageable in size so adequate for robust scanning, even under varying lighting conditions

Solution is AI or ML Mechanism The AI or ML mechanism used to aid in decoding can help with challenging lighting and recognition conditions. However, the mechanism is not fool proof and larger, clearer QR are still necessary for optimal performance. AI enhanced image processing algorithms to assist in decoding QR codes in challenging environments.

How navigation works?

- **Scanning the Floor QR Codes** user scans the floor QR code at the entrance to a particular floor. This code contains essential data such floor plan, navigation graph and the destination coordinates. The floor plan and graph are decoded from the compressed data and app reconstructs the map of the floor with the nodes representing various destinations, PoI etc.
- **Destination selection** after decoding the floor map, the user selects a destination and it identifies the destination point in the navigation graph which is a set of coordinates linked to other points of edges
- **Pathfinding with Dijikstra’s Algo** once destination is selected the app runs algo to find shortest path between the user’s location and the destination
- **Pedestrian Dead Reckoning for user localization** the app uses PDR to track user’s movement as they walk towards the destination based on step counting (accelerometer or gyroscope) and stride length (distance per step)
- **Direction of movement** the app uses IMU sensors (accelerometer, gyroscopes, magnetometers) to determine the direction of movement using smartphone’s orientation compass heading
- **Orientation display** compass heading or IMU sensor data is visualized on the screen with an arrow or indicator to show direction

Local to global transformation

The need sharing of local coordinates (derived from the PDR algo which measured in meters of points within the floor) to global GPS coordinates is necessary. They are compatible with public maps and outdoor navigation systems. Methodologies are

- **Inverse transverse Mercator projection (ITMP)** is used to project geographic coordinates onto a plane or Cartesian coordinate system. The inverse of this project would take plane coordinates and map them back to geographic coordinates. ITMP are highly accurate with minimal distortion particularly in localized areas but computationally demanding
- **Bilinear interpolation (BI)** is a simpler method where the latitude and longitude values at the corners of a rectangular floor are used to estimate the GPS coordinates at any given point inside the rectangle. This algorithm performs linear interpolation first in one direction x-axis and then in the perpendicular direction y-axis. Due to it simpler implementation it has less computation with faster results in comparison to ITMP. But less accurate.

Use Cases

https://www.mathworks.com/videos/wireless-positioning-and-localization-design-with-matlab-1653495227684.html