Navigating the Future: A Comprehensive Survey of 6G Indoor Localization

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***Abstract*—6G is a future standard for wireless communications that aims to transmit huge amounts of data in the least time possible, and its frequencies are planned in the range of 100GHz to 3THz. Localization is the process of determining the precise location of something or someone in a defined space. Indoor localization aims to locate precisely within 1cm in a 3D space. It is often achieved using technologies like Wi-Fi, Bluetooth, etc. Integrating 6G with indoor localization helps in creating environments that can be located with high precision and lower latency. Artificial Intelligence and Machine Learning algorithms help in evaluating vast amounts of data produced by 6G networks. This survey paper covers recent developments in 6G indoor localization. The goal of this survey paper includes developing more adoptable systems in enterprises, listing current technologies, and identifying challenges and limitations in implementing localization using 6G.**

***Index Terms*—6G, Indoor Localization, 6G Localization**

I. INTRODUCTION

Indoor localization technologies have numerous applications, ranging from emergency services to retail stock management to smart home automation services. GPS has matured and is mainly used to locate things in outdoor environments. However, indoor localization has become challenging due to the precision required to identify object locations and requires more sophisticated solutions.

In 6G, we may need more antennas and different encoding standards to support many symbols to support lower latency and higher data transfer speeds. Current 5G technology significantly improved indoor localization accuracy by using multiple antennas at a small distance to locate precisely. In 6G, Terra-Hertz frequency will be used to deliver high data speeds, higher reliability in case of network interruptions, and massive MIMO (Multiple Input Multiple Output), where we use multiple transmitters and receivers to increase data speeds. These features will significantly help in localization precision improvement as samples are taken at high frequencies and analyzed by ML algorithms. In 6G, the millimeter wave (mmWave) and terahertz (THz) communications have ultra-broad bandwidth so that the channel state information (CSI) will have a high resolution [7] [8].

In historical context, radio triangulation and RFIDs were used in limited indoor localization. As cell tower triangulation became much more accessible, location capability increased but focused more on outdoor localization. Wi-Fi wide adaption has increased accuracy in finding distance indoors using methods like RSSI and RTT, and Bluetooth's BLE beacons help in proximity detection using beacons.UWB emergence provided high accuracy in indoor localization due to its broad spectrum and fine time resolution. 5G innovations included MIMO and beam forming techniques, which lead to better localization precision due to lower latency and higher access point availability.

Challenges include signal attenuation, where building materials like concrete, glass, and metal significantly weaken signal strength as they pass through the surfaces, complicating accurate location detection indoors. Multi-path propagation of signals due to reflection off various surfaces like walls and floors can cause confusion in pinpointing signal identification and location accuracy due to signal phase shifts and time delay in reaching access points. Non-line-of-sight (NLOS) can reduce localization accuracy due to a lack of line-of-sight between transmitter and receiver. Density and scalability in places like shopping malls and stadiums can strain localization systems due to the sheer volume of locations. Indoor spaces have a high density of competing signals from various sources, such as Wi-Fi networks and Bluetooth devices. This noise can interfere with signals used for localization, reducing accuracy.

6G indoor localization applications include emergency services, retail business analytics, healthcare, smart buildings and IoT, and warehouse management. Indoor localization is an active area of research with a wide range of potential applications and opportunities. With a focus on smartphone-based implementations, this paper surveys the state of the art techniques used for indoor localization, including fingerprinting, triangulation, trilateration, hybrid Angle of Arrival (AoA)/ranging, and pedestrian dead reckoning techniques for Indoor Positioning Systems (IPS) using smartphone-based technologies [3].

Current technologies need help scaling due to infrastructure and deployment costs and high maintenance and upgrade costs. This survey paper explores the transformation of 6G wireless technology to improve indoor localization by providing current developments in space.

This survey paper will examine wireless network generations from 1 G to 6G and discuss the latest advances in indoor localization technologies. We will also explore weighted random forest algorithm-based localization for 6G indoor communication, the challenges and limitations of current systems, and future directions in 6G indoor localization.

TABLE I
ACRONYMS USED

Acronym	Full Term
6G	Sixth Generation
5G	Fifth Generation
IoT	Internet of Things
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
AI	Artificial Intelligence
ML	Machine Learning
RF	Radio Frequency
BS	Base Station
AP	Access Point
SNR	Signal to Noise Ratio
OFDM	Orthogonal Frequency Division Multiplexing
TDMA	Time Division Multiple Access
CSI	Channel State Information
RSS	Received Signal Strength
TOA	Time of Arrival
TDOA	Time Difference of Arrival
AOA	Angle of Arrival
NLOS	Non-Line-of-Sight
LOS	Line-of-Sight
GPS	Global Positioning System
GSM	Global System for Mobile Communications
RSSI	Received signal strength indication
RTT	Round-trip time
BLE	Bluetooth Low Energy
UWB	Ultra Wide Band
AoA	Angle of Arrival

II. EVOLUTION OF NETWORKS

A. First Generation (1G)

It was based on analog telecommunication standards. The most critical forerunner to 1G was a pre-network called 0G, which was relevant to mobile radiotelephones. In other words, transmissions were in analog form at frequencies over 150MHz; communications are exposed to eavesdropping due to encryption failure of voice services.

B. Second Generation (2G)

Some digital modulation techniques that played a significant role were Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) in the case of 2G. They have brought new data security features and allowed messaging services. These 2G networks had the Global System for Mobile Communications (GSM) standard. They brought signal protection through user data, using encryption, and providing authentication procedures with encrypted data. This was supported by the customer's SIM, which acts as the encryption key.

C. Third Generation (3G)

3G standards, which emerged at the start of this century, predicted that minimum data transfer speeds would reach two megabits per second. Further, it was built on the GSM model; 3G introduced further capabilities for security, which could fix vulnerabilities experienced by the 2G network, including bidirectional authentication and the use of the Authentication and Key Agreement (AKA) protocol.

D. Fourth Generation (4G)

Fourth Generation or Long-Term Evolution (LTE) networks, introduced in 2009, were humanly meant to provide up to 1 Gbps download speeds. 4G improved the efficiency of the spectrum and further reduced network latency to befit video calls, High Definition content, Digital Video Broadcasting (DVB), and a number of other services that need to be based on the internet.

E. Fifth Generation (5G)

While this paper is being written, 5G is still in the deployment phases, with many promises to offer speeds much higher than what LTE can offer. The security architecture is more robust and supports a very high number of devices connected concurrently.

F. Sixth Generation (6G)

6G is the sixth generation of wireless technology still in the research and development phase, expected to be rolled out around 2030. It aims to build on the foundations laid by 5G by providing even faster data speeds, lower latency, and more reliable connectivity

III. CURRENT TECHNOLOGIES AND METHODS FOR INDOOR LOCALIZATION

Current localization methods include Fingerprinting, Triangulation, and Trilateration.

A. Fingerprinting

Fingerprinting is an important technique used for indoor localization that utilizes the unique signal patterns at different points within a building to create a map. Fingerprinting involves signal strength recording at various points using multiple fixed access points. When a device needs to determine its location, it measures the signal strengths from nearby APs and matches this information against the fingerprint map to find the closest match and, thus, its location.

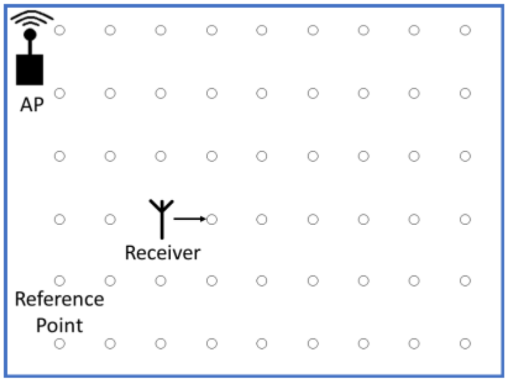


Fig. 1. Fingerprinting Method [3]

B. Triangulation

Triangulation is a geometric method used in indoor localization to determine the position of a device by measuring angles to it from known points at either end of a fixed baseline, rather than measuring distances directly. In triangulation, the location of a device is determined by forming triangles to it from known points. This is usually done by measuring the angle of arrival (AoA) of a signal emitted by the device from two or more APs. The intersection of these angles from the known points then determines the precise location of the device.

In their research on improving localization accuracy in urban disaster scenarios, the authors propose a novel geometric triangulation scheme that calculates the position of an object based on the angle of arrival between the object node and its reference points. By employing a least squares method to average position errors, their simulation results demonstrate an increase in position accuracy by up to 22.27% compared to previous triangulation schemes (P. Kristalina, A. Pratiarso, T. Badriyah and Erik Dwi Putro et al., 2016 [5]).

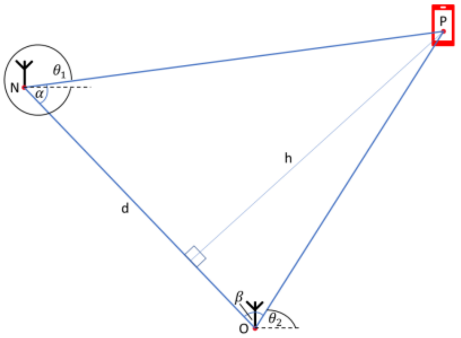


Fig. 2. Triangulation Method [3]

C. Trilateration

Trilateration involves using the known locations of at least three reference points.

Distance Measurement: The distances between the target and each of the known reference points are measured. This can be done using various methods such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), or Received Signal Strength Indicator (RSSI).

Circle Drawing: For each reference point, a circle is drawn around it with a radius equal to the measured distance to the target.

Intersection of Circles: The target's position is determined at the point where the three circles intersect. In a case where circle intersection is not possible Y. -B. Park and Y. H. Lee et al. proposed a novel method to find an intersection and verified using the Monte Carlo Simulation. [4]. Introducing 6G indoor localization leads to higher distance resolution measurements, rich environment data collection, near real time processing of localization data, improved network density and machine learning capabilities to improve trilateration technique.

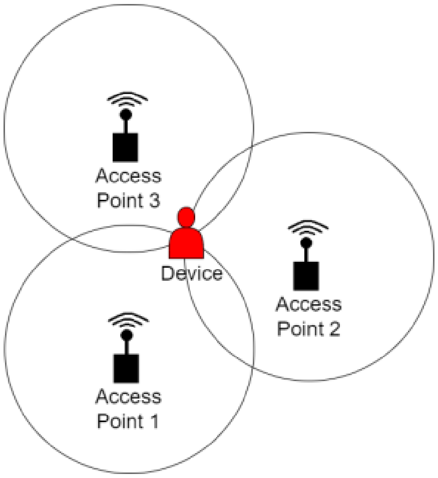


Fig. 3. Trilateration in two dimensions [3]

IV. TECHNOLOGICAL ADVANCES IN 6G FOR INDOOR LOCALIZATION

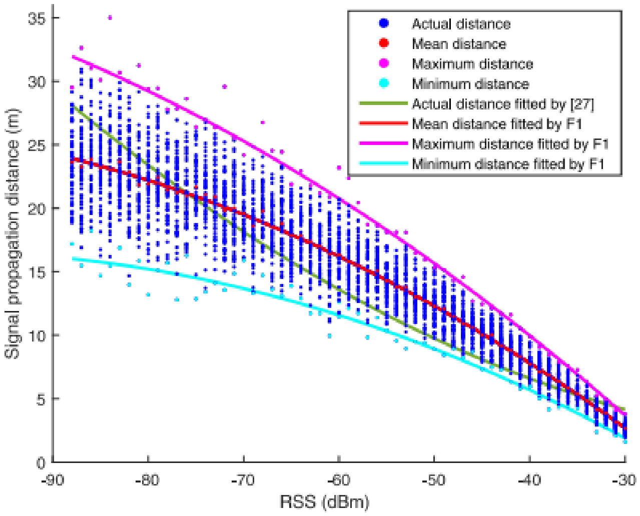
[9] **A Review of Millimeter Wave Device-Based Localization and Device-Free Sensing Technologies and Applications -** paper examines the adoption and advancements in mmWave communication and radar technologies for indoor localization and sensing, highlighting their application in 5G and 6G networks. It discusses key aspects of mmWave signal propagation, system design, and practical applications, addressing both device-based and device-free sensing systems. The study also explores the integration of machine learning algorithms and the development of mmWave-based simultaneous localization and mapping (SLAM), emphasizing the need for improved accuracy and robustness in various indoor environments.

UWB indoor positioning system proposed by D. B, T. Veeramakali, S. Revathi, H. R. R, A. D and E. G. V et al. uses Time of Flight (TOF) and Time Difference of Arrival (TDOA) algorithms for accurate range measurements, aiding the trans-receiver (TAG) plane position algorithm in pinpointing locations [10]. Incorporating 6G into this system can help in reducing latency in transmitting positioning data, consistent connection in densely built areas, where UWB signals might be susceptible to interference and multi path distortions. 6G includes THz bands that could provide higher resolution and accuracy in signal processing.

Exploring the enhancement of WIFI-based indoor localization, researchers have introduced a **novel fingerprint positioning technology known as KV**, which utilizes a vision-guided definition to boost both the accuracy and stability of localization. The methodology uses two stages: WIFI-based coarse localization and fusion localization. The first stage employs a two-metric adaptive k-nearest neighbor (KNN) method that uses a difference-based approach to intelligently determine the optimal K value, moving away from manual selection. In the fusion localization stage, a multiangle unsupervised fusion technique that integrates WIFI and visual data is applied, significantly enhancing positioning accuracy and stability. Experimental results demonstrate a localization accuracy of 1.24 meters, with 60% of positioning errors within 0.8 meters, surpassing other state-of-the-art methods and highlighting its practical significance for multisource indoor positioning technologies. [11]

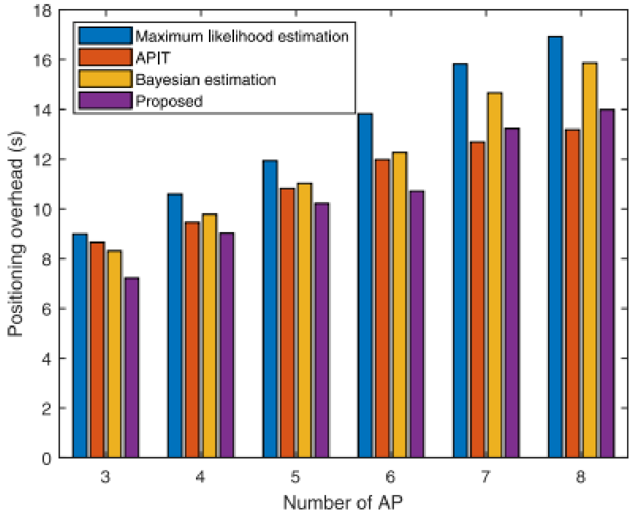
A novel method for **indoor positioning utilizing cellular signals** as a signal of opportunity has been developed, leveraging the capabilities of indoor base stations (BSs) for enhanced signal coverage. This method employs the time of arrival (TOA) for ranging, capturing cellular signals to estimate the distance from user equipment (UE) to a single BS. However, traditional TOA approaches limit the positioning to one-dimensional data. To overcome this, the proposed method integrates fingerprint positioning, utilizing TOA and one-reflection path as fingerprint features, enabling two-dimensional (2D) localization with just one BS. The study includes a comprehensive signal processing flow and utilizes ray tracing to generate channel parameters, ensuring the proposed algorithm's practical applicability and accuracy. Simulations at 100 GHz, adhering to 6G standards, demonstrate a mean positioning error of 0.312 meters with a fingerprint interval of 0.5 meters, offering a viable solution for 6G indoor positioning scenarios. [12]

M. Zhou, X. Li, Y. Wang, S. Li, Y. Ding and W. Nie et al., proposed **multisource information fusion-based indoor positioning approach using Gaussian kernel density estimation**. This paper addresses challenges posed by the evolving network technologies and the consequent complexity of indoor environments and rising number of wireless access points (APs). These factors contribute to signal propagation distance estimation issues due to the variability in received signal strength (RSS), resulting in diminished positioning accuracy and robustness. Initially, a heuristic distribution model is formulated to depict the relationship between RSS from diverse Wi-Fi APs and signal propagation distances. Subsequently, Gaussian kernel density estimation is applied to ascertain the signal propagation distance distribution. Integration of this distribution into the Dempster–Shafer (D–S) evidence theory facilitates the fusion of multisource RSS information following the D–S evidence synthesis rules. The synthesis also aids in selecting matching reference points (RPs) via a trust function. A fuzzy decision algorithm is then employed to pinpoint the optimal matching RPs for enhanced positioning accuracy. [13]



[13]

Fig. 4. Relationship between the RSS and the signal propagation distance.



[13]

Fig. 5. [13] Paper comparison of positioning overhead by different approaches.

The graph presented provides a comparative analysis of the positioning overhead associated with various localization estimation techniques as a function of the number of access points (APs). The techniques evaluated include Maximum Likelihood Estimation, APIT (Approximate Point-In-Triad), Bayesian Estimation, and a Proposed method. The results clearly illustrate that the positioning overhead, measured in seconds, increases with the number of APs for all methods, which is likely attributable to the increased computational complexity and data processing requirements as more APs are involved.

The section "Localization Systems" of the paper "**THz Systems Exploiting Photonics and Communications Technologies**" [14] explores the indoor localization technologies used in innovations, especially in the chipless radio frequency identification (RFID) systems and the Terahertz (THz) bands. This makes high-precision localization a key component of SAR (synthetic aperture radar) applications such as SLAM (simultaneous localization and mapping) systems for detailed mapping and navigation within indoor environments.

IEEE Transactions paper titled "**AutoLoc: Toward Ubiquitous AoA-Based Indoor Localization Using Commodity WiFi**", Xianan Zhang and colleagues introduce a novel system, **AutoLoc**, which uses Angle of Arrival (AoA) measurements from commonly available WiFi devices to achieve high-precision indoor localization. Addressing the primary limitations of prior AoA systems, which include the necessity for frequent re-calibrations and additional sensor inputs, AutoLoc implements a unique solution that removes the need for manual calibration by utilizing inherent signal properties. The system notably achieves decimeter-level accuracy by calculating relative Channel State Information (CSI) across different locations and deploying a confidence-aware localization algorithm. This innovation enhances the scalability and applicability of WiFi-based indoor positioning systems, making it a vital development in the context of emerging 6G technologies, where seamless and precise indoor localization is increasingly critical for applications ranging from automated inventory management to augmented reality experiences [16]. 6G technology could significantly enhance systems like AutoLoc by providing higher frequencies and greater bandwidth for improved localization accuracy, denser network infrastructure for finer granularity, and integrated advanced technologies for smarter, energy-efficient, and ubiquitous indoor positioning solutions.

The research by Wei, Wang, and Zhao investigates the latest approaches to improving indoor localization with passive Wi-Fi tags. The paper, entitled "**LocTag: Passive WiFi Tag for Rob-based Indoor Localization via Smartphones**, [18]" will look at the limitation of current indoor localization systems and propose a new system that can allow one to achieve robust location indifferent to the complexity and interference from WiFi access points (APs) at different indoor environmental conditions.

At the core of this study lies in the development of **LocTag**, a passive WiFi tag localizing commercial off-the-shelf smartphones. In stark contrast to traditional passive WiFi tags, which were developed with an emphasis on functional communication, LocTag functions by backscattering ambient WiFi signals designed for localization. As the name suggests, this method does not require the WiFi tag to have a transmitter in the first place, hence any cost and maintenance requirements are significantly reduced.

The key innovations introduced in this paper are in terms of source selection techniques, Wi-Fi compatible triggering, and a random multiple access protocol. This helps LocTag selectively reflect the signal from surrounding APs or smartphones, and hence it is not able to reflect surrounding signals, which allows it to avoid messing up signal reflection. The LocTag prototype is implemented using a Field Programmable Gate Array (FPGA) and its performance under normal office conditions. The results show that indoor localization of sub-meter level accuracy can be realized using LocTag and the project emanating, indicating that it has great potential for use in an environment in which conventional localization systems fail to give substantive results.

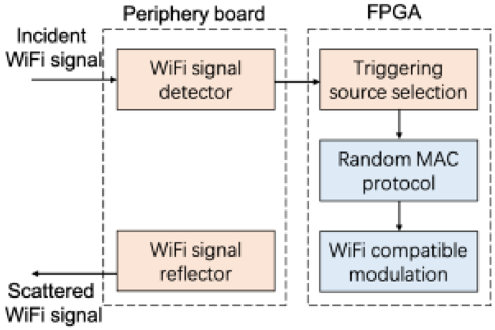


Fig. 6. Architecture of LocTag [18]

This work, therefore, does not only question the existing application boundaries of passive Wi-Fi tags but rather proposes integrating them into the emerging 6G landscape, where improved indoor localization can be key to afford seamless human-device interaction.

The **SIABR (Structured Intra-Attention Bidirectional Recurrent)** method is an advanced deep learning approach designed to tackle the complexities of indoor localization using Terahertz (THz) signals. This method leverages the unique properties of the THz spectrum, characterized by ultra-broad bandwidth and high resolution in capturing *Channel State Information (CSI), such as Angle of Arrival (AoA), received power, and delay*. The core innovation lies in its two-tiered network structure. At the lower level, it uses a Bidirectional Long Short-Term Memory (Bi-LSTM) network enhanced with an intra-attention mechanism that efficiently processes the intricate details of multi-path THz signals. At the second level, it uses a residual network (ResNet) to extract and refine the spatial information, enabling precise 3D positioning. Tests demonstrate that SIABR can localize objects with a mean distance error as low as **0.25 meters**, proving its potential for high-accuracy applications in dynamic indoor environments (Fan et al., 2021) [17].

Md. Zahidul Islam Sifat et al. presented a study in "**An Improved Positioning System For 6G Cellular Network**" at the 26th International Conference on Computer and Information Technology (ICCIT) 2023, which focuses on enhancing indoor localization within the emerging 6G networks using signal fingerprinting combined with machine learning algorithms. This research utilizes the Received Signal Strength Indicator (RSSI) to achieve highly accurate indoor positioning. Implementing classic machine learning algorithms like k-Nearest Neighbors and Support Vector Machines, the study reports mean error distances as low as 0.08025523 meters, demonstrating an accuracy of up to 99.92%. These results underscore the potential of integrating advanced signal processing techniques and machine learning to significantly improve positioning accuracy in indoor environments, leveraging the unique capabilities of 6G technology. This approach not only enhances indoor navigation but also supports a wide array of applications requiring precise location tracking. [15]

TABLE II
COMPARISON OF POSITIONING SYSTEMS AS PRESENTED IN [15]

Parameter	**Wi-Fi and Bluetooth Approach**	**IoT RSSI Approach**	**Proposed GSM RSSI Approach with ML**
Technology	Wi-Fi and Bluetooth	IoT (RSSI)	GSM RSSI
Hardware Requirements	Multiple access points, Bluetooth devices	Diverse IoT hardware components	Existing GSM network infrastructure
Cost Analysis	Moderate to High	Moderate to High	Low
Signal Interference	Yes, due to coexistence	Interference due to crowded frequency band	Minimal interference, separate frequency band
Accuracy	Average mean error around 1.22 meters	Mean error around 0.664 for Wi-Fi, 0.753 for Bluetooth LE	Reduced absolute mean error to 0.08025523 and 0.10692412 meters in two test scenarios
Unique Features	Trilateration techniques	IoT integration, hardware dependent	Machine learning with GSM RSSI fingerprinting
Coverage	Limited to areas with Wi-Fi access points	Limited by hardware coverage	Extensive coverage due to GSM infrastructure
Future Compatibility	May face challenges in evolving Wi-Fi scenarios	Limited by IoT development	Compatible with evolving cellular networks (e.g., 6G)
Additional Hardware	Yes, requires Wi-Fi access points	Yes, requires diverse IoT components	No additional hardware required; uses existing GSM BSSs

The paper by Kaur et al., "**AI-enabled CSI fingerprinting for indoor localisation towards context-aware networking in 6G**" presents an innovative approach to indoor localization using AI-enabled CSI fingerprinting, a technique pivotal for the advancement of context-aware networking in 6G environments. This method exploits the detailed multi path characteristics captured by CSI, which provides a richer dataset compared to traditional RSSI-based systems. By applying machine learning algorithms, the system can accurately determine a device's location based on the unique fingerprint formed by the amplitude and phase differences of CSI across multiple channels. The approach transforms the traditional regression problem into a classification framework, thereby improving localization precision. Extensive experiments validate the superiority of this method over conventional techniques, demonstrating its potential to significantly enhance location-based services in next-generation networks [19].

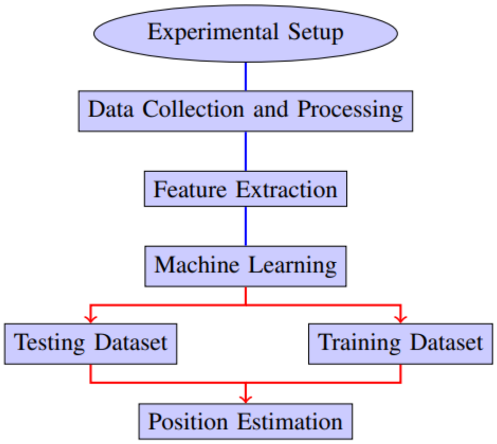


Fig. 7. Flowchart of the procedure in [19]

V. CHALLENGES AND LIMITATIONS

Signal Attenuation and Multipath Propagation: Indoor environments are notorious for their complex layouts and materials that cause signal attenuation and multipath propagation. Signals can be absorbed, reflected, or scattered by walls, furniture, and other obstacles, leading to inaccuracies in localization.

Cost of Deployment: Sub-terahertz systems and complex machine learning algorithms are examples of advanced indoor localization technologies that may necessitate large hardware and infrastructure expenditures. Deployment costs may be expensive, especially for smaller companies and organizations.

Complexity of Indoor environments: Due to the varied layouts, materials, and constructions, indoor settings are by nature complicated. It is difficult to achieve high localization accuracy in such a variety of scenarios, such as places with plenty of obstructions or multi-story structures.

Limited Accessibility for Maintenance: Indoor localization system calibration and maintenance can be difficult, particularly in large-scale installations or locations with restricted access. To ensure system performance, accessibility for regular maintenance and troubleshooting will be necessary.

Energy Consumption and Sustainability: High-resolution localization might require continuous transmission and processing of signals, leading to high energy consumption. Designing energy-efficient systems while maintaining high performance is a critical challenge.

VI. FUTURE DIRECTIONS IN 6G INDOOR LOCALIZATION

The evolution of 6G indoor localization is expected to focus on several strategic areas to enhance accuracy, reliability, and usability:

1) **Integration of Diverse Data Sources:** Future systems may utilize data from IoT devices, wearables, and infrastructure to improve contextual awareness and localization accuracy.
2) **Advanced Machine Learning Models:** The deployment of more sophisticated models, including deep neural networks and reinforcement learning, will handle the complexities of dynamic indoor environments.
3) **Use of Sub-Terahertz (THz):** Exploiting higher frequency bands could significantly enhance localization precision.
4) **Ubiquitous and Seamless Localization:** Techniques ensuring seamless outdoor-to-indoor localization transitions will provide continuous user experiences without service interruption.
5) **Energy Efficiency:** Developing methods to reduce the power consumption of localization systems will be essential, especially for portable and wearable technologies.
6) **Enhanced Robustness and Reliability:** Improvements in signal processing and network resilience will address challenges such as signal multipath effects and interference.
7) **Interoperability and Standardization:** Ensuring that different localization systems work seamlessly together will require standardized protocols and interfaces.
8) **Real-Time and Predictive Capabilities:** Future localization systems might predict user paths and adapt in real-time, using historical data to optimize navigation and services.

VII. CONCLUSION

This exploration of 6G indoor localization technologies covers the significant advances expected to greatly improve the accuracy and efficiency of indoor navigation systems. With the advent of 6G, we're looking at leveraging ultra-high frequency bands, increased data speeds, and advanced machine learning algorithms to improve localization accuracy and reduce response times. Our review examined current methods like fingerprinting and triangulation, and emerging techniques like AI-driven CSI fingerprinting and THz communications, all showing promise in pushing localization precision further.

However, implementing 6G isn't without its challenges. Issues such as how building materials can block or alter signal paths and the complexity of signal reflection in urban environments pose significant hurdles. Additionally, the infrastructure costs for these advanced systems need to be managed for them to be feasible on a large scale.

Looking ahead, the focus will be on integrating more diverse data sources, enhancing AI models for dynamic environments, and tapping into sub-terahertz frequencies. These advancements aim to not only improve how accurately we can pinpoint locations indoors but also to ensure a smooth transition between outdoor and indoor tracking systems. As we push forward, the goal is to develop robust, energy-efficient, and widely compatible 6G indoor localization solutions that can revolutionize how services like emergency response, healthcare, and retail operate, significantly boosting efficiency and safety in these areas.

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