A Review of Indoor Positioning System Solutions for Industrial Applications to Analyze its Selection Criteria for a Given Application

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Indoor Positioning Systems (IPS) have caught popular attention in recent years as a result of their capacity to provide location-based services in interior locations where GPS signals are unable to provide meaningful information. However, with a plethora of IPS technologies available, selecting a fitting solution for a specific application can be a daunting task. The objective of this paper is to conduct a comparative analysis of the various forms of indoor positioning systems, such as Wi-Fi fingerprinting, Bluetooth low energy (BLE) beacons, ultrasonic, infrared, and magnetic-based systems based on their accuracy, reliability, deployment cost, scalability, and power consumption. The results show that the choice of IPS technology depends on the application requirements, with no single solution outperforming the others in all aspects. Based on this, a selection procedure has been devised to select the most appropriate IPS technology.

Keywords: Indoor Positioning Systems, Wi-Fi Fingerprint, BLE Beacons, Triangulation

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1. Introduction

Indoor positioning systems (IPS) have evolved into a critical instrument for providing location-based services in indoor settings. These are designed to provide accurate positioning information for indoor environments, where GPS signals [1] may be obstructed by buildings, walls, and other structures, and as a result, their accuracy may be affected. There are numerous techniques which can be used, such as Wi-Fi fingerprinting, BLE [2] beacons, ultrasonic [3] systems infrared systems [4], and many more. These systems enable tracking [5] and locating people or assets within a confined space, where global positioning system (GPS) signals are not accessible. There are various IPS technologies available, each with its own distinct set of characteristics and benefits, making it difficult to select the best solution altogether. Therefore, there is a need for a comparative analysis of the various IPS technologies.

In recent years, there has been a great amount of research and development in the field of Indoor Positioning Systems (IPS). Researchers have developed and evaluated various IPS technologies, including Wi-Fi-based IPS, Bluetooth Low Energy (BLE) IPS, Infrared IPS, Ultra-Wideband (UWB) IPS, and RFID-based IPS [6]. These technologies use various signals and sensors to detect the location of a user or object. Several different technologies are used for this among which the following five are the most used ones:

- **Proximity-based Systems:** Proximity-based systems [7] can determine the general location of a person or object within a facility at the room level. These are either reader-based or reference point-based systems and use tags and beacons.
- **Wi-Fi-based Systems:** Tags in a Wi-Fi positioning system [8] are Wi-Fi transmitters that distribute basic packets to several Wi-Fi access points throughout a facility. These access points send the time and strength of the reading to a back-end, which then utilizes algorithms to calculate the position and transmits it to the cloud.
- **Ultra-Wide Band (UWB) Systems:** UWB [9] is an interesting technology which uses three or more ultra-wide-band readers to send an extremely broad pulse throughout a GHz range. The readers then listen for super wide-band tag chirps and transmit extremely precise time data to a central server.
- **Acoustic Systems:** These systems use ultrasonic pulses from tags to locate things within an indoor environment. An acoustic system [10] functions similarly to UWB, but instead of radio waves, it employs sound. The tags emit an ultrasonic sound, which is picked up by the users to locate things.
- **Infrared (IR) Systems:** Indoor localization devices [11] based on infrared light pulses employ them to locate signals inside a building. Every room has an IR receiver, and when the tag pulses, the receiver gadget reads it.

Various algorithms and methods have been developed like machine learning algorithms, particle filters, Kalman filters [12], and Bayesian [13] approaches to improve the accuracy and efficiency of IPS systems. Fingerprinting techniques [14] involve creating a database of signal strength values from various access points or beacons. These values are then used to determine the location of a user or object. Different fingerprinting techniques, including RSSI-based fingerprinting and angle-of-arrival (AoA) fingerprinting have been explored. IPS has been integrated with other technologies, such as Augmented Reality (AR)[15], Virtual Reality (VR), and Geographic Information Systems (GIS). This has enabled new applications, such as indoor navigation, wayfinding, and location-based gaming. There are various metrics and evaluation methods such as accuracy, precision, and latency to assess the performance of IPS systems. Benchmarking datasets and competitions are also present to compare the performance of different IPS technologies and algorithms.

IPS has been applied to a wide range of real-world applications, including indoor navigation, asset tracking, indoor mapping, location-based advertising, and healthcare. These applications have the potential to improve user experience, safety, and efficiency in indoor environments. The work done in the domain of IOT has been extensive and diverse, covering various technologies, algorithms, evaluation methods, and applications due to which revolutionizing advancements in IPS systems have been observed.

In this research paper, a comparative analysis of different types of IPS technologies is presented based on the accuracy, reliability, deployment cost, scalability, and power consumption. The goal of this study is to provide a complete assessment of IPS technologies and to evaluate the strengths and limitations of each technology. Comparative analysis can provide a systematic and objective evaluation of the strengths and weaknesses of different IPS systems, helping to identify the most suitable and cost-effective technology for a particular use case.

2. Techniques to Locate an Object using IPS

In this section, various algorithms and methodologies are discussed which can be used to segregate indoor environments from outdoor environments and estimate the position of sensor nodes in order to improve accuracy.

2.1 Triangulation Method

Triangulation [16] is a technique used in IPS to estimate the location of a device or person by measuring distances from multiple reference points as shown in Fig 1. The triangulation method involves using signals from multiple sources, such as Wi-Fi access points or Bluetooth beacons.

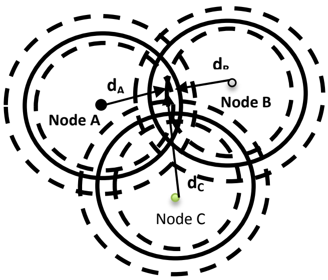

Fig. 1. Representation of Triangulation Method in 2D plane

The distance between the device and each reference point is calculated based on the strength of the signal received. By combining the distances from multiple reference points, the location of the device can be estimated. Triangulation is a widely used technique in IPS due to its accuracy and flexibility. One common algorithm used for triangulation is called trilateration [17]. It involves finding the intersection point of circles (in two dimensions) or spheres (in three dimensions) centered at the reference points with radii equal to the distances from the device to each point. The mathematical expression for the triangulation method is based on this principle.

For example, in two dimensions, consider three reference points with coordinates (x_1, y_1), (x_2, y_2), and (x_3, y_3), and distances r_1, r_2, and r_3 from the device to each reference point, then the distance from each reference point can be expressed as:

$$r_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2} \quad (1)$$

$$r_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2} \quad (2)$$

$$r_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2} \quad (3)$$

The location (x,y) of the device can be found by solving these equations using algebraic manipulation and substitution. Similar expressions can be derived in three dimensions, where spheres are used instead of circles, and four or more reference points may be required.

2.2 Time of Arrival (TOA)

Time of Arrival (TOA) [18] is used to determine the location of a device based on the time it takes for a signal to travel from a transmitter to the device. The transmitter emits a signal, such as an ultrasound or radio frequency (RF) wave, which is received by the device, which measures the time it takes for the signal to travel, known as the time-of-flight (TOF) [19]. The distance between the transmitter and the device can then be calculated using the speed of the signal. Let's assume there are N transmitters, and the device measures the TOF from each transmitter. The distance between the device and the i^{th} transmitter, di, can be calculated as:

$$d_i = c \times t_i \tag{4}$$

where c is the speed of the signal, and ti is the measured TOF. The distance between the device and each transmitter can also be expressed as:

$$d_i = \sqrt{[(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2]} \tag{5}$$

where (x_i, y_i, z_i) are the coordinates of the ith transmitter, and (x, y, z) are the coordinates of the device. By combining equations (4) and (5), we get:

$$c \times t_i = \sqrt{[(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2]} \tag{6}$$

Squaring both sides of equation (6), we get:

$$c^2 \times t_i{}^2 = (x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 \tag{7}$$

Rearranging the terms, we get:

$$(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 - c^2 \times t_i{}^2 = 0 \tag{8}$$

Such systems have several advantages, including high accuracy and precision, and it can work in both line-of-sight and non-line-of-sight environments. However, it also has some limitations, including the need for synchronized clocks between the transmitters.

2.3 Time Difference of Arrival (TDOA)

Time Difference of Arrival (TDOA) [20] is used in IPS to determine the location of a device based on the time difference between the arrival of a signal at different receivers. In TDOA-based IPS, multiple receivers are placed at known locations, and a signal is emitted from a transmitter. The signal is received at different times by the receivers due to the difference in distances. The difference in arrival times between the signals is used to determine the location of the device. Let's assume there are N receivers, and the signal is emitted from a transmitter at coordinates (x_s, y_s, z_s). The TDOA between the i^{th} and j^{th} receivers can be expressed as:

$$TDOA_{ij} = t_i - t_j \tag{9}$$

$$t_i = \sqrt{[(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2]} \tag{10}$$

$$t_j = \sqrt{\left[\left(x_j - x_s\right)^2 + \left(y_j - y_s\right)^2 + \left(z_j - z_s\right)^2\right]} \quad (11)$$

where t_i and t_j are the times of arrival of the signal at the i^{th} and j^{th} receivers, (x_i, y_i, z_i) and (x_j, y_j, z_j) are the coordinates of the i^{th} and j^{th} receivers, and c is the speed of the signal.
Thus, equation (9) can be written as:

$$TDOA_{ij} = \frac{1}{c}\left(d_i - d_j\right) \quad (12)$$

where,

$$d_i = \sqrt{[(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2]} \quad (13)$$

and

$$d_j = \sqrt{\left[\left(x_j - x_s\right)^2 + \left(y_j - y_s\right)^2 + \left(z_j - z_s\right)^2\right]} \quad (14)$$

are the distances between the transmitter and the i^{th} and j^{th} receivers, respectively.

2.4 Angle of Arrival (AOA)

Angle of Arrival (AOA)[21]is used in IPS to determine the location of a device based on the angle of arrival of a signal at different receivers. In AOA-based IPS, the angle of arrival of the signal at each receiver is measured and used to determine the location of the device. AOA-based IPS requires a directional antenna at each receiver to accurately measure the angle of arrival. Let's assume there are N receivers, and the signal is emitted from a transmitter at coordinates (x_s, y_s, z_s). The AOA between the i^{th} receiver and the transmitter can be expressed as:

$$AOA_i = \tan^{-1}\left[\frac{y_i - y_s}{x_i - x_s}\right] \quad (15)$$

where (x_i, y_i, z_i) are the coordinates of the i^{th} receiver.

3. Classification of IPS based on its Features

3.1 Proximity-based Systems

Proximity-based Indoor Positioning Systems (IPS)[22] use sensors to detect the proximity of mobile devices to fixed beacons or anchors. These systems are intended to provide users with location-based services and navigation in indoor environments.

- **Use of Beacons or Anchors:** These systems rely on beacons or anchors placed at fixed locations. These beacons emit signals, which are received by mobile devices equipped with proximity sensors. The beacons or anchors can be Bluetooth Low Energy (BLE) beacons, WiFi access points, or RFID tags.
- **High Accuracy:** These systems can provide high accuracy, as the distance between the mobile devices and the beacon can be accurately measured. The accuracy can be further improved by using multiple beacons.
- **Seamless Integration with Mobile Apps:** These systems can be seamlessly integrated with mobile apps, enabling location-based services and navigation. They can be used to provide customized content, such as product information or promotions, to users based on their location.

3.2 Wi-Fi-based Systems

Indoor Positioning Systems (IPS) based on Wi-Fi utilize Wi-Fi signals to locate mobile devices in indoor environments. These systems utilize Orthogonal Frequency Division Multiplexing and Channel State Information [23] and consist of three main components: access points (APs), mobile devices, and a positioning server. APs are responsible for transmitting Wi-Fi signals and collecting CSI measurements from mobile devices. Mobile devices receive Wi-Fi signals and extract CSI information, including amplitude, phase, and delay characteristics. The collected measurements are sent to the positioning server for calculation of the user's position. They undergo several signal processing techniques to mitigate noise, interference, and multipath effects. Filtering and synchronization are applied to enhance their quality. Channel estimation algorithms estimate the channel response, enabling the separation of the desired signal from interference and multipath components. OFDM-specific techniques such as pilot-based estimation and equalization are utilized to improve their accuracy and reliability. Fingerprinting techniques create a database of CSI fingerprints associated with known reference locations, enabling the system to match received patterns to the stored fingerprints. Machine learning algorithms, such as k-nearest neighbors or support vector machines, can also be utilized for classification-based positioning. Trilateration or multilateration methods, utilizing the received signal strength or time of arrival, can further enhance positioning accuracy.

- **Use of Wi-Fi Access Points:** These systems rely on Wi-Fi access points installed at fixed locations. These access points emit Wi-Fi signals, which are received by mobile devices equipped with Wi-Fi sensors and are used to determine the location of the mobile device.
- **Existing Infrastructure:** These systems can be easily deployed in environments that already have Wi-Fi access points installed. No infrastructure changes are needed, which reduces the deployment time and cost.
- **Security:** These systems can be designed to be secure by using encryption techniques and protect user privacy by using anonymous identifiers or pseudonyms.

3.3 Ultra-Wide Band Systems

UWB-based Indoor Positioning Systems (IPS)[24] utilize Ultra-Wide Band transmissions to identify mobile devices in indoor situations.

- **High Precision:** These systems provide high precision using Time of Flight (ToF) measurements of UWB signals.
- **Line of Sight Not Required:** These systems do not require a line of sight between the mobile device and the UWB anchor and can penetrate walls, objects, and other obstacles,
- **Low Interference:** These systems have low interference with other wireless technologies, such as Wi-Fi and Bluetooth as they use a frequency range that is not used by other wireless technologies.

3.4 Acoustic Systems

Acoustic Indoor Positioning Systems (IPS) use sound waves to determine the location of a mobile device in indoor environments. These systems are designed to provide accurate and reliable location-based services and navigation to users in indoor spaces. It relies on the propagation of sound waves to estimate the position of a target device. Various methods can be used, such as Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Angle of Arrival (AOA).

- **Low Cost:** These systems are relatively low cost compared to other technologies as they use microphones and speakers, which are affordable and readily available.
- **Non-invasive:** These systems are non-invasive and do not require any additional hardware to be installed. They use the existing ambient sound sources such as air conditioning units, fans, and other environmental noise.

- **Fast Response Time:** These systems provide fast response times as low as a few milliseconds. They use sound waves that have a short wavelength, enabling fast data transfer and reliable communication.

3.5 Infrared Systems

Infrared Indoor Positioning Systems (IPS) detect the location of a mobile device by using infrared light.

- **Non-Radiative:** Infrared signals are non-ionizing and non-radiative, making them safe for human exposure.
- **Multi-Purpose:** They can be used for various applications, such as asset tracking, indoor navigation, and location-based advertising.
- **Indoor Mapping:** Infrared IPS can be used to create indoor maps of a building or room, which can be used for navigation and location-based services.

4. Case Studies to Understand the Selection Criteria of Different IPS solutions.

In this section, detailed case studies are discussed where each kind of Indoor Positioning Systems can be used. Table 1 provides the comparison of the various IPS systems as described in the previous sections.

Case Study I: In a hospital, it is essential to monitor the location of medical equipment, staff, and patients.
By implementing a proximity based IPS system, hospital staff can quickly locate equipment, track patient movements, and monitor staff activities in real-time. For instance, let's say a patient has a medical emergency, and the hospital staff needs to respond quickly. With an IPS system in place, they can quickly locate the patient's room and determine the fastest route to get there. Additionally, if a piece of medical equipment is needed, staff can quickly locate it using the IPS system, ensuring that it is readily available when needed.

Case Study II: One example of where infrared-based IPS systems can be useful is in a museum or art gallery. In these environments, it is essential to track the location of visitors and ensure that they follow a particular path or do not touch the exhibits.

Table 1. Comparison of various kinds of IPS

IPS System	Technology Used	Range	Accuracy	Infrastructure quirement	Interference Susceptibility
Proximity based	BLE beacons, NFC, RFID	Up to 100 meters	Low	No additional infrastructure required	Susceptible to interference from obstacles and other radio signals
WIFI Based	WIFI Access Points	Up to 150 meters	Medium	Wi-Fi infrastructure required	Susceptible to interference from other Wi-Fi devices
Ultra-Wide Band	Radio Waves	Up to 200 meters	High	UWB infrastructure required	Resistant to interference due to wide

					bandwidth and low power
Acoustic	Sound Waves	Up to 50 meters	Medi um	Microphone Array, Sensor nodes	Susceptible to ambient noise and reverberation
Infrared	Infrared light	Up to 10 meters	High	Line of sight required; no additional infrastructure.	Susceptible to line-of-sight obstruction

By implementing an infrared based IPS system, museum staff can quickly locate visitors and ensure that they follow the designated path. For instance, let's say a particular exhibit is getting too crowded, and museum staff wants to redirect visitors to a different exhibit. With an infrared based IPS system in place, they can quickly locate visitors and direct them to the desired location, without disrupting other visitors or the exhibit. Table 1 provides a comparative analysis of the various IPS solutions based on the technology used, range, accuracy, infrastructural requirement, and interference.

5. Applications

Due to their capability to provide accurate and dependable location-based services in indoor environments, Indoor Positioning Systems are employed in a variety of applications, ranging from improving customer experience to increasing operational efficiency.

- **Indoor Navigation:** One of the most common applications of Indoor Positioning Systems is navigation. It gives users turn-by-turn directions and real-time location updates in interior contexts. Indoor navigation [25] is very helpful in vast indoor locations like airports, shopping malls, and hospitals. IPS technology can guide users to their desired location, reduce the time spent searching for destinations, and provide a better user experience.
- **Asset Tracking:** Asset Tracking [26] is another significant application of Indoor Positioning Systems. It allows organizations to track the location of assets, such as equipment, tools, and inventory, in indoor environments. It can help organizations improve asset utilization, reduce asset loss, and optimize asset management. Asset Tracking is particularly useful in industries such as manufacturing, warehousing, and healthcare.
- **Indoor Analytics:** Indoor Analytics [27] is the use of Indoor Positioning Systems to gather data on user behavior in indoor environments. IPS technology can provide insights on user traffic patterns, dwell times, and interactions with indoor environments. Indoor Analytics can help organizations understand user behavior, improve customer experience, and optimize operational efficiency. Indoor Analytics is particularly useful in industries such as retail, hospitality, and entertainment.
- **Location-based Advertising:** Location-based Advertising [28] is the ability of Indoor Positioning Systems to deliver personalized advertisements to users based on their location in indoor environments. IPS technology can provide advertisers with real-time location data on users, enabling them to deliver highly targeted advertisements. Location-based Advertising can help organizations improve marketing effectiveness, increase revenue, and provide a better user experience. Location-based advertising is especially effective in businesses like retail, hotel, and entertainment.
- **Emergency Response:** Emergency Response [29] is the use of Indoor Positioning Systems to improve emergency response times in indoor environments. IPS technology can help emergency responders locate individuals in distress quickly, reducing response times and improving safety. Emergency Response is particularly useful in environments such as hospitals, airports, and large public venues [30].

Based on the scenarios considered for the application of IPS system and the required features, recommended technology for each scenario is presented in Table 2.

Table 2. Applications, Features and Recommended IPS techniques for various scenarios

Applications	Features	Recommended Techniques
WIFI Positioning	Uses WIFI signals to triangulate positions	WIFI fingerprint trilateration
Bluetooth Beacons	Uses BLE beacons to identify locations	Triangulation, trilateration
Inertial Navigation	Uses motion sensors to track motions	Dead reckoning, sensor fusion
Ultra-Wideband (UWB)	Uses short radio waves for precise referencing.	Time-to-flight (ToF) ranging, Angle of Arrival (AoA)
Magnetic Field Positioning	Uses magnetic fields to identify position	Magnetic fingerprinting, trilateration
Computer Vision	Uses cameras to identify position based of visual landmarks	Feature detection, Optical flow, SLAM

6. Conclusions

Conclusively, the domain of Indoor Positioning Systems has been quickly expanding in recent years. This comparative study of various kinds of indoor positioning systems highlights the strengths and weaknesses of each system. It is evident from the analysis that there is no one-size-fits-all approach for IPS systems. The choice of IPS system depends on the specific application and the environment in which it will be deployed. Thus, in this research paper, we have tried to evaluate various techniques and select the best fit solution for indoor positioning, while presenting a comparative review, which might be a useful resource for researchers, engineers, and practitioners looking to design or install IPS systems for a wide variety of applications.

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