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Assessing the Performance of a Hybrid Geolocation Algorithm Integrating FP and TOA Techniques across Diverse Environmental Conditions

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Abstract: -This paper presents a validation study of indoor geolocation accuracies using a hybrid approach that combines fingerprinting (FP) and time of arrival (TOA) techniques. The investigation focuses on three dense environments, examining the influence of furniture density and multipath components on geolocation accuracy, particularly in non-line-of-sight (NLOS) scenarios. The results indicate that geolocation performance improves in denser environments with higher furniture density due to increased multipath components. Additionally, optimizing the hybrid method with a polygon size of 50 cm and sampling rate of 80 GHz leads to further accuracy enhancements. These findings underscore the significance of furniture density and demonstrate the effectiveness of the hybrid method in addressing NLOS challenges. The research contributes to the advancement of indoor geolocation techniques and provides valuable insights for designing precise indoor positioning systems across various applications.

Keywords*:indoor geolocation, non-line-of-sight, fingerprinting (FP), time of arrival (TOA).*

1. Introduction:

Keeping Accurate localization and positioning are crucial factors for both indoor and outdoor localization systems. While GPS is a well-known technology for outdoor applications [1]-[5], it is not suitable for indoor localization systems due to the complex nature of electromagnetic wave propagation in indoor environments [6]. Various obstacles present in indoor spaces cause diffraction, multipath fading, reflection, and other effects [7]-[10]. In order to overcome the obstacles of non-line-of-sight (NLOS) communication within indoor settings, a variety of commercially accessible technologies are employed, including RFID, Bluetooth, ZigBee, Wi-Fi, and ultra-wideband (UWB) [8]-[11]. Among these options, UWB is gaining popularity due to its superior performance in harsh and multipath environments [12]. Additionally, UWB offers advantages such as low power consumption and high accuracy [13]. Precisely, within the physical layer of IEEE 802.15.16, impulse radio ultra-wideband (IR-UWB) signals are delineated, featuring ultra-short nanosecond pulses. These signals offer the advantages of reduced implementation complexity and extended battery longevity [11][14].

Apart from employing distinct positioning methods like time-based time of arrival (TOA), the time difference of arrival (TDOA), fingerprinting (FP), and angle-based angle of arrival (AOA), there has been the development of hybrid approaches that integrate multiple techniques [15]. These hybrid methods can involve combinations like TOA and TDOA, TOA and FP, and so on. Moreover, the hybrid methodology allows for the integration of both indoor positioning systems (such as UWB) and outdoor positioning systems (like GPS). Furthermore, these hybrid methods can incorporate iterative techniques such as Steepest Descent, Gauss-Newton, and Levenberg-Marquardt, enhancing their effectiveness.

The primary objective behind employing hybrid methods is to leverage the individual advantages of each technique. Recently, a hybrid method combining iterative-TOA and channel impulse response (CIR)-based fingerprinting methods has been proposed [16]. This combined approach utilizes the initial estimation of time of arrival (TOA) from the fingerprinting method to enhance the accuracy of locating the test node. The Levenberg-Marquardt method is applied for the iterative process of the fingerprinting algorithm, further refining the geolocation estimation.

For precise estimation of indoor radio coverage and channel impulse response (CIR), the deterministic propagation modeling technique known as Ray Tracing (RT) is employed. By incorporating information on the positions and electromagnetic characteristics of indoor objects, RT can predict path loss, stationary impulse response, and RMS delay spread. Given that the effectiveness of indoor positioning systems heavily relies on multipath elements in non-line-of-sight (NLOS) scenarios, it is crucial to validate the proposed model across diverse geographical contexts.

In this paper, we conduct a comprehensive evaluation of the performance of the aforementioned hybrid model across three distinct indoor settings: indoor environment 1, indoor environment 2, and indoor environment 3. These indoor spaces exhibit varying densities of furniture, resulting in multiple signal paths between the transmitter and receiver. The performance analysis demonstrates that the proposed approach achieves higher geolocation accuracies in indoor environments characterized by dense multipath effects.

2. System Model

In this section, we introduce the system model employed in our study to facilitate precise indoor geolocation. The system model incorporates a polygonal system grid, which serves as a structured framework for representing and analyzing the indoor environment.

The system model entails a two-dimensional grid that overlays the indoor space, with each grid cell representing a polygonal region. The size of the grid cells is determined based on the desired level of resolution and accuracy required for geolocation purposes. In our investigation, we selected a polygon size of 50 cm, striking a balance between granularity and computational complexity.

The polygonal grid system enables the subdivision of the indoor environment into discrete regions, allowing for the characterization of furniture density and identification of multipath components within each polygonal cell. This detailed representation facilitates a comprehensive analysis of the influence of furniture distribution and multipath effects on geolocation accuracy.

To populate the polygonal grid with pertinent data, we compiled an extensive dataset comprising measurements of signal strength, time of arrival, and geometric information obtained from various locations within the indoor environments under examination. This dataset forms the foundation for constructing the fingerprint database and calibrating the TOA ranging parameters.

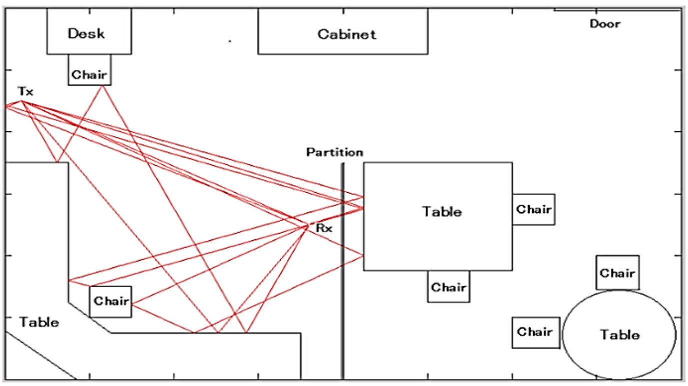

Figure 1 Visualization of Indoor Propagation Modelling Using Ray Tracing

The figure 1 illustrates the simulation of ray propagation paths within the indoor environment, providing a visual representation of the multipath effects and signal propagation characteristics. The ray tracing technique aids in understanding the complex interactions between the transmitted signal and the environment's objects, further enhancing our analysis of geolocation performance.

By harnessing the advantages of the polygonal system grid and incorporating ray tracing simulations, our study aims to provide valuable insights into optimizing geolocation performance within specific grid-based indoor systems. The utilization of this system model, along with the visual representation provided by the ray tracing figure, enables a more accurate and context-aware evaluation of the hybrid FP-TOA method's capabilities in diverse dense environments.

Subsequent sections will delve into the experimental setup, data collection process, and assessment of the hybrid method's geolocation accuracies within the polygonal grid system. This analysis will shed light on the influence of furniture density, multipath components, and the effectiveness of the hybrid approach in addressing non-line-of-sight (NLOS) challenges within structured indoor environments.

3. Enhanced Approach for Pre-Set Processing of UWB Geolocation

The geolocation estimation process in fingerprinting (FP) methods involves two distinct phases: the training phase and the geolocation phase. The FP geolocation process relies on a database for pattern matching and necessitates the presence of reference nodes. However, as the number of reference nodes increases, the computational complexity of FP geolocation calculations also escalates. On the other hand, a smaller number of reference nodes simplifies the calculations but compromises the accuracy of geolocation estimates.

To address this trade-off between computational complexity and accuracy, we propose an approach that utilizes polygonal shapes to represent the reference nodes. This optimized approach, which is elaborated in reference [16], aims to enhance the efficiency of geolocation calculations while optimizing the number of reference nodes used. By employing polygonal shapes as representations, we can strike a balance between computational efficiency and accurate geolocation estimates.

In the training phase of the fingerprinting (FP) method, unique signatures or fingerprints, represented as $m = h(l, t)$, are estimated and recorded for various reference locations $l \epsilon R$ within the designated region of interest (R). The location of a node or tag in the two-dimensional horizontal plane is defined as $l(x, y)$, employing Cartesian coordinates.

In the positioning phase, an estimation l0 is derived for the actual instantaneous position l0 by utilizing the corresponding estimated channel impulse response (CIR), $h(\hat{l}_0,t)$. However, the estimated CIR is subject to corruption from channel noise.

The channel spatial correlation is defined as for $n = h(\hat{l}_0,t)$ and $m = h(l, t)$:

$$R_l^{m,n} = \frac{E\{mn\} - E\{m\}E\{n\}}{\sqrt{[E\{|m|^2\} - |E\{m\}|^2(E\{|n|^2\} - |E\{n\}|^2)]}}$$

In this context, where E{.} represents the expectation operator, the node's position is estimated by maximizing the correlation coefficient, $R_l^{m,n}$. The equation is given by:

$$\widehat{l_0} = argmax_l \epsilon R \left| R_l^{m,n} \right|$$

Due to imperfect channel estimation at the receiver, the ideal correlation cannot be achieved. Consequently, a correlation threshold R_{th} is employed to ensure that$R_l^{m,n} \geq R_{th}$. Thevaluesof$R_l^{m,n}$crosses $R_{th}$$are$definedas$R^{m,n}$= $[R_{l1}, R_{l2}, ...R_{lk}]$, where k is the number of values where$R_l$crossesR_{th}.The values of $R_l^{m,n}$ are arranged in descending order and associated with their respective location coordinates. The determination of the node's location involves calculating a weighted average of the coordinates from the top three locations in the index. This assumption is grounded in the proximity of these three locations to the node, emphasizing their significance in the calculation.

3.1 Hybrid Algorithm

To achieve precise estimation of node locations, a hybrid algorithm that combines CIR-based fingerprinting (FP) and iterative-TOA methods is employed in this study. The node location estimation process begins with the FP method, which provides an initial estimate for the node's location. This initial estimate serves as a starting point for the iterative-TOA method, which refines and improves the accuracy of the node's location estimation. The iterative process is facilitated by the utilization of the Levenberg-Marquardt equation, which aids in the convergence of the estimation algorithm.

For a more detailed explanation of this hybrid algorithm, including a comprehensive flowchart and mathematical details, we recommend referring to our previous article [16]. Within that article, you will find an in-depth description of the method, providing a step-by-step breakdown of the algorithm's execution.

The evaluation of the modified FP method's performance in this study is conducted using specific parameter values, which can be found in Table 1 of the aforementioned article [16]. Additionally, Table 2 within the same article provides essential information regarding the properties of materials used in the ray tracing (RT) technique, which is integral to the geolocation process.

4. Implementation of Modified Hybrid Approaches in Different Environments

4.1 Defining Three Different Indoor Environments

In order to validate our proposed model, we included a range of environments in this study. The selection of these environments was based on the presence and density of furniture within the rooms. The study encompasses analysis of several distinct environments, each described as follows:

Table 1 Parameter values for evaluating performance of modified FP method

Variable	Numeric
Channelbandwidth	2GHz
UWBsignaltype	Gaussianmonopulse
AWGN	SNR=10dB
Fingerprintingpolygonsize	20,30,40,50,60,70,and80cm
Area	10mx8m
Number of Access point	4

Table 2 Properties of materials employed in RT technique

Substances	σ[S/m]	ϵ_r	Thickness[cm]
Concretewall	**0.01**	**9**	**7.5**
Table,chair,cabinet, (wood)	10^{-5}	**13**	**3.0**
Window(glass)	10^{-1}	**7.6**	**3.0**

4.2 Indoor environment-1

To ensure a comprehensive representation of the complex multipath elements and non-line-of-sight (NLOS) scenarios, our study took into careful consideration a wide variety of furnishings present within the depicted environment, as visually depicted in Figure 2. By incorporating these extensive environmental factors, we aimed to accurately capture the intricacies of signal propagation. The abundance of furniture in the environment played a significant role in increasing the occurrence of reflections, thereby adding to the complexity of the geolocation problem.

In a previous study [16], we conducted simulations to assess the performance of both fingerprinting (FP) and hybrid techniques, with a specific focus on indoor environment-1. The outcomes of this investigation provided valuable insights into the capabilities and limitations of these methods, shedding light on their effectiveness in addressing the challenges posed by indoor environments characterized by multipath effects and NLOS conditions.

4.3 Indoor environment-2

In this particular environment, the presence of furniture is comparatively lower than in environment-1. As a consequence, the occurrence of multipath reflections is reduced. However, it is expected that non-line-of-sight (NLOS) conditions would be more prevalent in this setting. Figure 3 visually represents these conditions, highlighting a higher likelihood of signal blockages and obstructions within the environment. By specifically considering this environment, our study aimed to investigate the challenges posed by increased NLOS scenarios and their impact on geolocation accuracy. The presence of fewer furniture elements and the increased likelihood of NLOS conditions present unique difficulties for accurate geolocation estimation, necessitating the development and evaluation of appropriate methods to address these challenges.

4.4 Indoor environment-3

Within this specific environment, it is important to note that, apart from a centrally positioned cabinet as depicted in Figure 4, there is a distinct absence of any additional furniture. Consequently, the multipath component is primarily attributed to reflections originating from the surrounding walls. When comparing this environment (referred to as environment-2) to environment-1, it is observed that the number of transmitted signals is notably reduced. This distinction in the signal transmission characteristics between the two environments further emphasizes the unique challenges and characteristics associated with each setting, highlighting the need for tailored geolocation approaches and strategies.

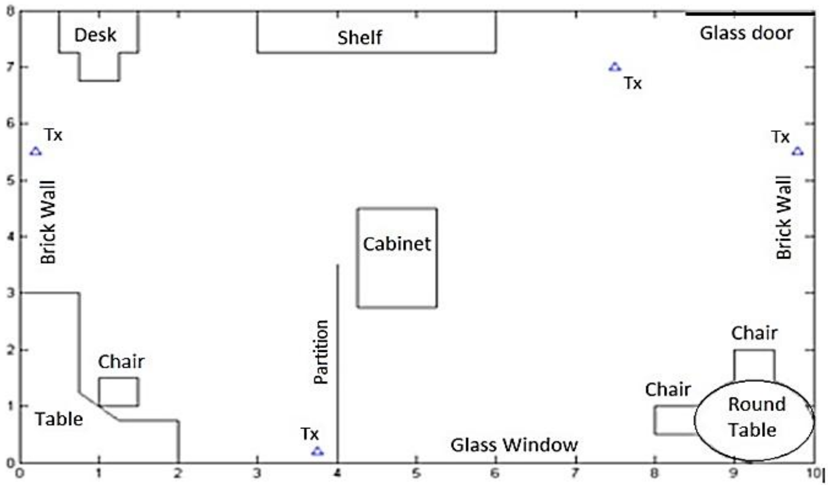

Figure 2 Spatial Layout of Indoor Environment-1 (Dimensions: 10m x 8m)

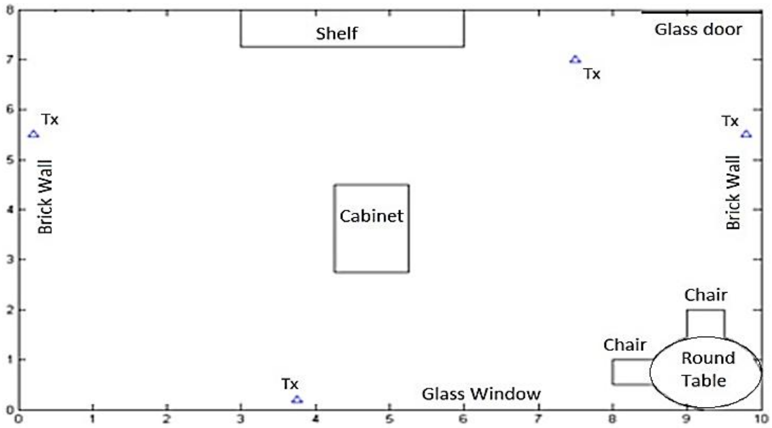

Figure 3 Spatial Layout of Indoor Environment-2 (Dimensions: 10m x 8m)

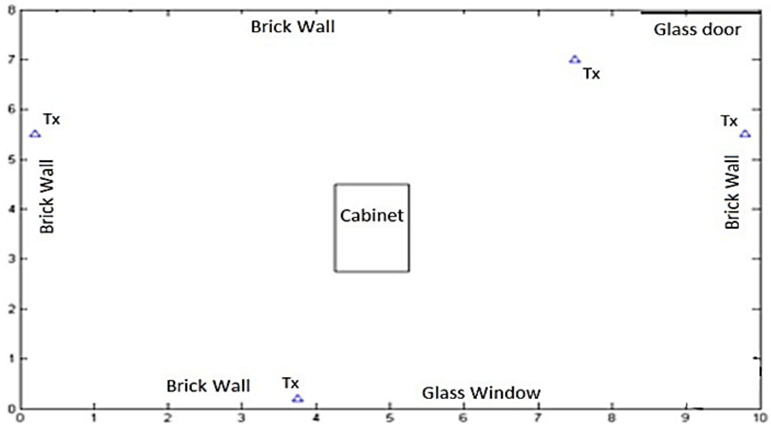

Figure 4 Spatial Layout of Indoor Environment-3 (Dimensions: 10m x 8m)

5. Evaluation of FP and Hybrid Methods' Performance in Indoor Environment-2

Based on our foundational understanding, it is established that multipath components tend to experience longer delays as they travel greater distances. In environment-2, which has a lower density of furnishings compared to environment-1, the received signals travel longer distances due to the scarcity of furniture. As a result, the received signals at the receiver predominantly consist of reflections from the walls, leading to extended time delays. These prolonged time delays contribute to a diminished match between the channel impulse response (CIR) of the test nodes and the database used for fingerprinting. Moreover, the reduced presence of obstacles, such as furniture, in environment-2, combined with varying relative positions of access points (APs) and mobile stations, increases the likelihood of encountering non-line-of-sight (NLOS) conditions. The prominence of NLOS conditions adversely affects the accuracy of node localization, as the fingerprinting patterns based on CIR fail to align with the reference databases. The absence of distinct furniture-based reflections and the prevalence of NLOS scenarios in environment-2 pose challenges to achieving accurate geolocation estimates.

Figures 5 and 6 provide a comparison between the performance of the fingerprinting method and the hybrid method in terms of NLOS conditions. The hybrid method demonstrates superior performance, albeit with lower accuracy when NLOS conditions are less prevalent. Figure 7 illustrates the performance comparison of three methods: hybrid, fingerprinting (FP), time of arrival (TOA), and iterative TOA.

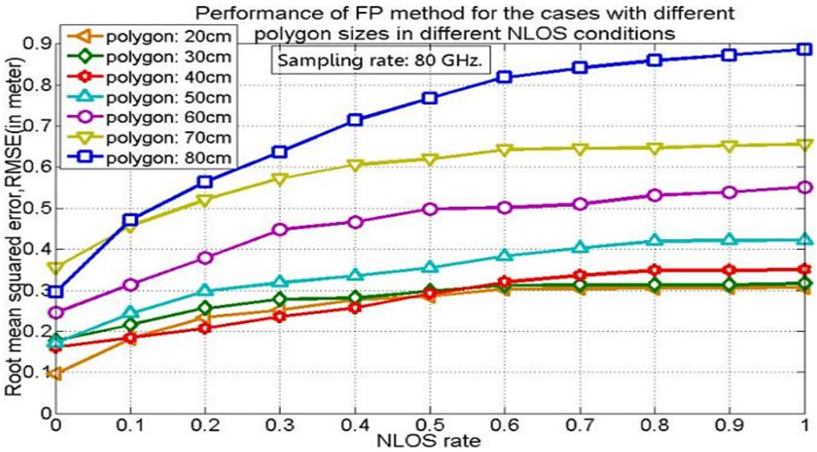

Figure 5 Localization Accuracy in FP Method for Different NLOS Rates and Polygon Sizes in Indoor Environment-2

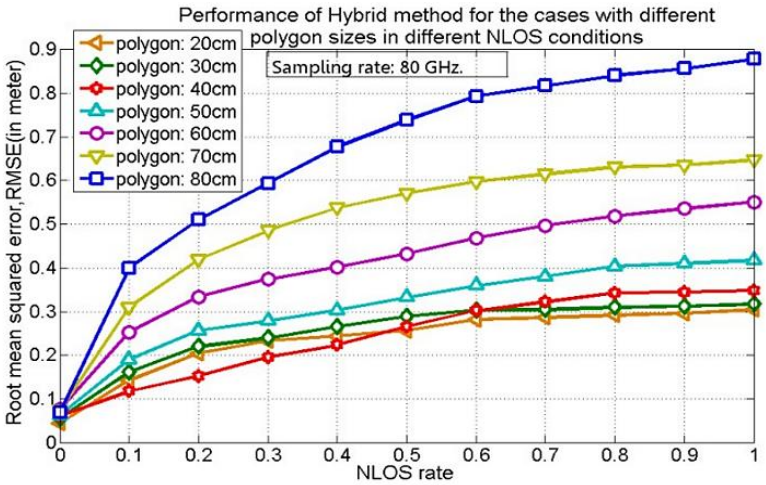

Figure 6 Positioning Accuracy in Hybrid Method for Different NLOS Rates and Polygon Sizes in Indoor Environment-2

Among the geolocation methods considered, the hybrid approach demonstrates the best performance. Interestingly, the FP method proves to be just as accurate as the hybrid method, despite both methods utilizing precalculated databases during the training phase. This suggests that the FP method could serve as a viable alternative to the hybrid method, particularly in scenarios where computational resources are limited. However, the TOA and iterative TOA methods, which do not rely on databases, exhibit lower geolocation accuracies. Furthermore, in environment-2 with smaller furniture elements, multipath components experience longer time delays compared to environment-1. Consequently, the TOA methods, which are affected by these extended time delays, exhibit more pronounced geolocation errors in environment-2 compared to environment-1. The presence of these longer time delays in environment-2 emphasizes the challenges faced by TOA-based methods when dealing with environments characterized by smaller furniture elements and the associated multipath effects.

6. Evaluation of FP and Hybrid Methods' Performance in Indoor Environment-3

To further validate our model and evaluate its performance, we introduced a new geolocation scenario known as environment-3. This setup involves a single wooden shelf positioned at the center of the room, as depicted in Figure 3. In Figure 8 and Fig. 8 of our study, we present the positional accuracies obtained from the FP method and the proposed hybrid method, respectively, specifically for environment-3. Notably, the hybrid method demonstrates improved positional accuracies, particularly in scenarios with lower non-line-of-sight (NLOS) conditions. However, it is worth mentioning that both the FP method and the hybrid method exhibit comparable performance in situations with higher NLOS conditions. These observations align with our findings in the cases of environment-1 and environment-2, as previously discussed. The results from environment-3 further support the effectiveness of the hybrid method in achieving enhanced positional accuracies, especially in scenarios with fewer NLOS conditions. However, it is evident that the FP method remains a competitive alternative, demonstrating comparable performance in scenarios with higher NLOS conditions.

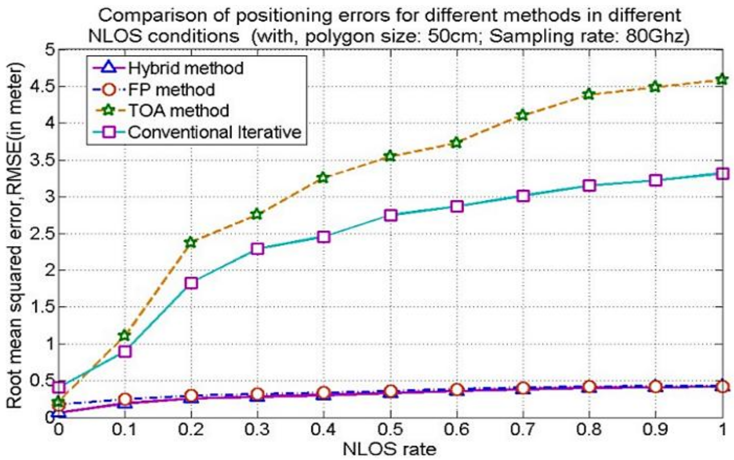

Figure 7 Localization Accuracy Comparison of TOA-only, FP-only, Conventional Iterative TOA, and Hybrid Methods in Indoor Environments with Varying NLOS Rates

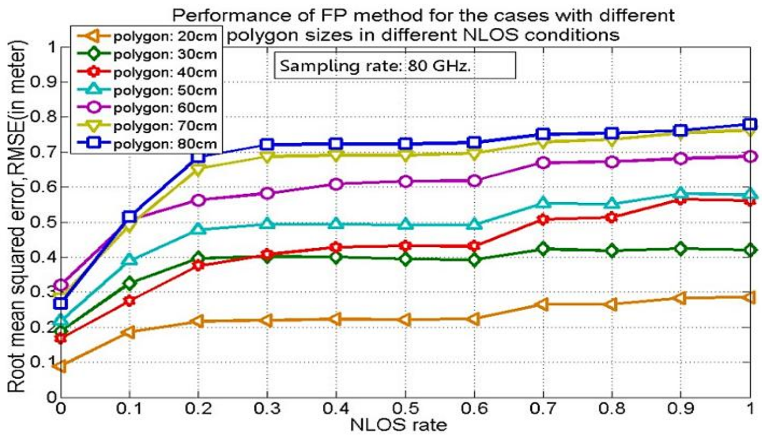

Figure 8 Localization Accuracy in FP Method for Different NLOS Rates and Polygon Sizes in Indoor Environment-3

Figure 10 illustrates a comprehensive comparison of positional accuracies achieved by the proposed hybrid method, the TOA-only method, the FP-only method, and a conventional iterative method specifically tailored for environment-3.

7. Comparative Performance Analysis of FP and Hybrid Methods in Diverse Indoor Environments

Considering the noticeable increase in geolocation errors in the time of arrival (TOA) method compared to the fingerprinting (FP) and proposed hybrid method across all analyzed geolocation structures, our primary focus centered on comparing the FP and hybrid methods. To ensure consistency, we adopted a polygon size of 50 cm and a sampling rate of 80 GHz, as they demonstrated superior performance in conjunction with the hybrid method, as discussed in reference [16].

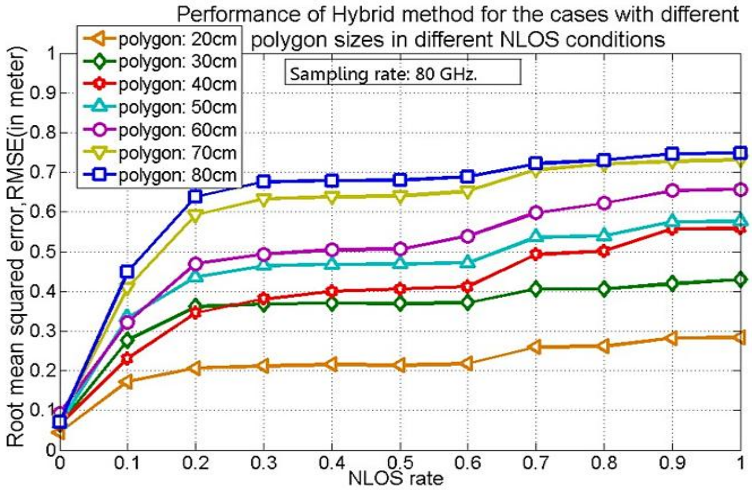

Figure 9 Localization Accuracy of Hybrid Method with Different Polygon Sizes and NLOS Rates in Indoor Environment

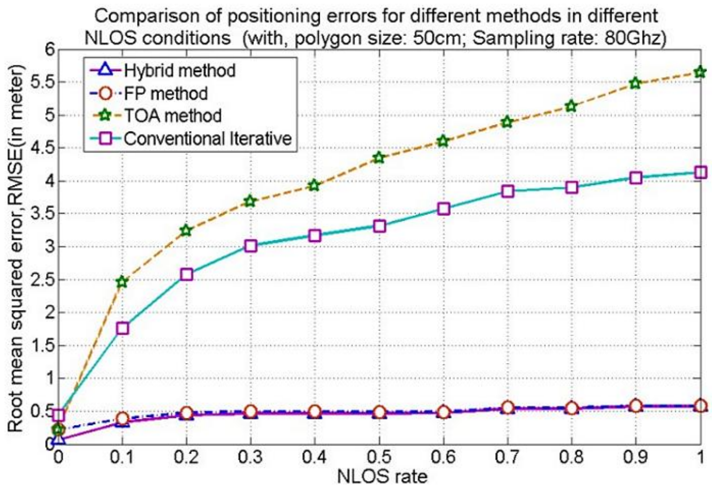

Figure 10 The Effect of NLOS on Localization Accuracy: A Comparison of TOA, FP, Iterative TOA, and Hybrid Methods

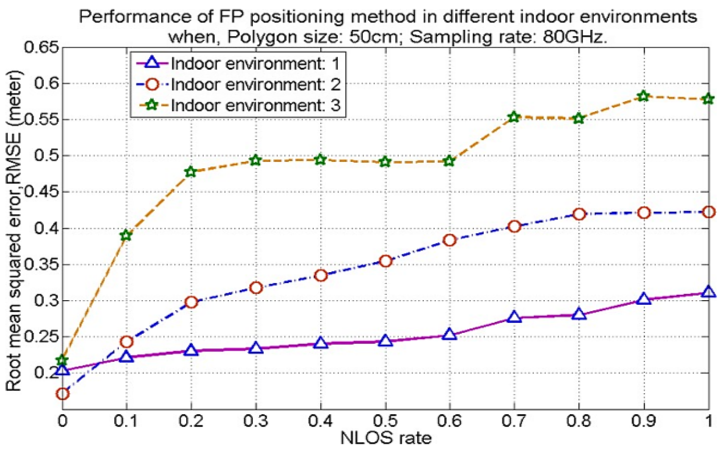

Figure 11 Performance Comparison of Fingerprint Geolocation Method in Different Indoor Environments with Polygon Size of 50 cm and Sampling Rate of 80 GHz

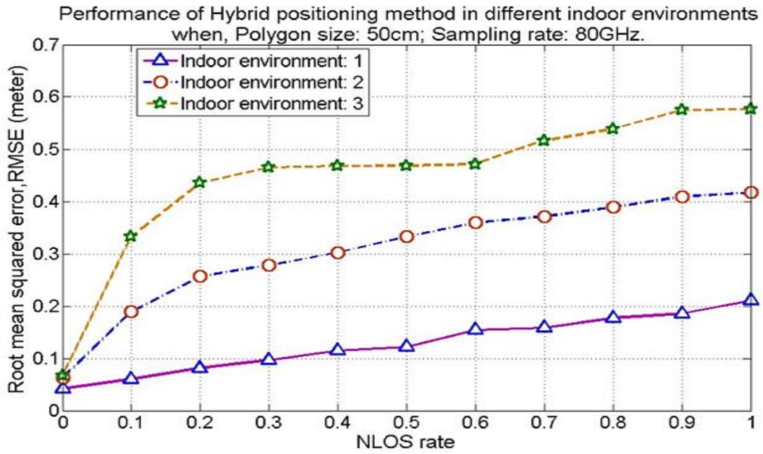

Figure 12 The Effect of Different Indoor Environments on the Accuracy of Hybrid Localization with a Polygon Size of 50 cm and a Sampling Rate of 80 GHz

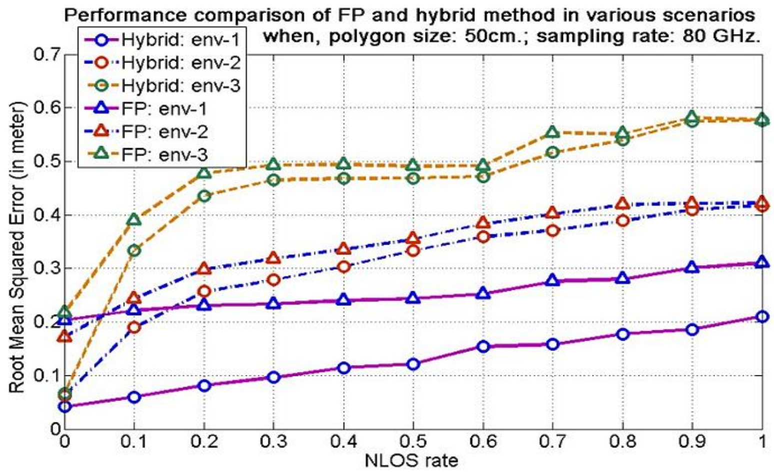

Figure 13 Performance Comparison of FP and Hybrid Localization Methods in Different Indoor Environments for Polygon Size of 50 cm and Sampling Rate of 80 GHz

To evaluate the geolocation performance of the FP method and the hybrid methods, we conducted separate assessments for all the environments under consideration. The results of these comparisons are presented in Figures 11, 12, and 13, respectively. From these figures, it is evident that the geolocation performance in environment 1 outperforms that of environments 2 and 3. This discrepancy can be attributed to the presence of a greater number of reflected multipath signals within environment 1, which provides more diverse and abundant information for accurate geolocation estimation. In contrast, in environment 3, where the density of furniture is lower, the geolocation performance is adversely affected by the existence of longer delayed multipath signals. The sparser presence of furniture in this environment leads to fewer opportunities for signal reflections, resulting in less information available for accurate geolocation estimation. As a result, the geolocation performance in environment 3 is comparatively poorer compared to the other two environments. These findings highlight the impact of furniture density and multipath characteristics on geolocation performance. The presence of numerous reflected multipath signals in environment 1 contributes to its superior performance, while the sparser furniture arrangement in environment 3 leads to increased reliance on longer delayed multipath signals, negatively affecting the geolocation accuracy.

8. Conclusion

The results obtained from our simulations, in which we examined three distinct geolocation structures with varying densities of reflection sources, have validated the efficacy of the proposed hybrid method that combines fingerprinting (FP) and time of arrival (TOA) techniques. Our findings indicate that in environments with a higher density of reflection sources, the geolocation accuracies significantly improve. To assess the performance of different geolocation methods, namely FP-only, TOA-only, iterative-TOA, and the hybrid approach, we conducted rigorous testing in three different geolocation structures. The objective was to determine which method excelled in accurately locating a signal. While both the FP and hybrid methods outperformed the conventional TOA-only and iterative-TOA methods, the hybrid method clearly demonstrated superior performance. The advantage of the hybrid method can be attributed to the synergistic combination of enhanced accuracies offered by both the TOA ranging and FP geolocation approaches. This advantage is particularly pronounced in dense multipath environments where the presence of numerous reflection sources poses challenges for conventional methods.

In summary, our study showcases the effectiveness of the proposed hybrid method, which seamlessly integrates FP and TOA techniques. The simulation results indicate that denser environments contribute to improved geolocation accuracies. The hybrid method surpasses alternative approaches, thanks to the collective strengths of TOA ranging and FP geolocation, making it the optimal choice for accurate signal localization, especially in complex and densely populated multipath environments.

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