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THE APPLICATION OF RAY-TRACING TO MOBILE LOCALIZATION USING THE DIRECTION OF ARRIVAL AND RECEIVED SIGNAL STRENGTH IN MULTIPATH INDOOR ENVIRONMENTS

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Abstract—This work presents a new indoor localization method based on the fingerprinting technique. The proposed method uses a ray-tracing model that provides information about multipath effects. This information is stored in a dataset during the first stage of the fingerprinting method. The direction of arrival (DOA) and received signal strength (RSS) are used in the fingerprinting technique as a hybrid system. The localization estimation is calculated while taking into account the Euclidian distance between the DOA and the RSS from each unknown position and the information of the fingerprints. Numerical calculations were performed to show the mean and the standard deviation of the estimated error.

1. INTRODUCTION

Recently, there has been interest in the positioning of wireless terminals. Many people in academia and industry are currently involved in researching and developing 3D-radiolocalization methods for indoor environments with line of sight (LoS) and non-line of sight (NLoS) conditions [1, 2]. The application for this kind of system is commercial, because radiolocalization methods can be used in airports, hospitals, hotels, the military, medical, industrial and public safety settings. In fact, mobile phone positioning has become one of the most important features of communication systems because of its multiple applications. Hence, the demand for indoor localization systems has increased considerably in the last few years.

Indoor localization is not an easy problem to solve because of multipath effects [3, 4], NLoS conditions and other considerations such

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as reflecting objects, the presence of moving people and furniture. Moreover, due to the development of new radio access standards, such as Wi-Max, it is necessary to explore new techniques to improve the precision of localization using alternative detection methods.

Many proposed localization methods and algorithms were based on the computation of the time of arrival (TOA) [5–7], time differences of arrival (TDOA) [8], direction of arrival (DOA) [9–11] and the received signal strength (RSS) [12, 13]. Conventional methods based on these four measurements increase in error with multipath propagation because they require LoS conditions between the access points and the mobile stations. For instance, [3] tries to minimize the multipath disturbance on the accuracy of the system and [2] studies NLoS error mitigation techniques for time-based location systems. Another important factor to consider is the implementation cost and the need for expensive additional hardware. Normally, the measurement process requires the transmission and reception of signals between hardware components of the system. Also, most of the traditional approaches need expensive measurement campaigns to obtain information regarding RSS, TOA and DOA.

Many hybrid methods have also been developed in this research area. For example, [14] proposes a hybrid TDOA/DOA location scheme for wideband CDMA wireless communication systems and [1] gives a holistic approach by utilizing a bidirectional measurement of the TOA and DOA data at both the reference and mobile devices. A survey of wireless indoor positioning methods is provided in [16].

Ray-Tracing analysis is used for several localization methods in order to obtain information about propagation in for indoor environments [17]. There are many works in the literature that focus on ray-tracing [18–24]. For example, [18] proposes a localization technique that makes an accurate measurement of DOA, TOA and the Doppler shift by using ray-tracing. In [19], a 2-D ray-tracing procedure for the localization of EM field sources in urban environments is explained. The proposed method in [20] combines the spatial characteristics estimated from data measurements and a ray-tracing analysis. The use of a ray-tracing analysis presented herein enables site-specific location using only a single base station. Most of these above systems rely on additional sensory hardware installations and thus are not cost and time efficient.

Herein, a hybrid localization method is implemented. The location estimation is calculated considering the Euclidian distance between the DOA and the RSS from each unknown position and the information from the fingerprints. The main contribution of the current paper is to present a novel method that uses multipath effects to obtain better performance for the radiolocalization method and minimize errors in the localization process. The information about the multipath propagation can be obtained with a ray-tracing technique [25, 26]. This deterministic technique is able to predict the propagation channel parameters in indoor environments. Most approaches need expensive measurement campaigns, but our system is able to obtain all of the required information with a ray-tracing technique; the cost of this step is very low. The characteristics of our ray-tracing model will be described in next sections. Another advantage of the proposed approach is that while most of the previously developed approaches locate the mobile station in a 2D-space [4, 19], our method is able to find the mobile station position in 3D-space. Moreover, our proposed method does not require the installation of an extra sensor network.

A fingerprinting technique is also included in the proposed localization method. The information obtained by ray-tracing is stored in a dataset during the first stage of the fingerprinting technique. During the second stage, the position of a mobile station can be calculated by comparing the measured parameters (DOA and RSS) with the values stored in the dataset. The processed signals are available from the wireless devices that comprise the Wi-Fi (IEEE 802.11) and Wi-Max (IEEE 802.16) standards. In this paper, WLAN technology is used because this technique can obtain the required radio map grid spacing to reduce the location error. Moreover, the received signal strength (radio frequency) is available in all WLAN interface equipments.

In order to validate the proposed 3D-radiolocalization method, several realistic indoor scenarios have been analyzed. Numerical results demonstrate higher positioning accuracy with respect to traditional approaches.

This paper is organized as follows. In Section 2, the ray-tracing technique is explained. The basic concept of the proposed positioning method is described in Section 3. In Section 4, the estimation results obtained from the experimental data analysis are shown. Finally, Section 5 contains concluding remarks and directions for future work.

2. THE RAY-TRACING MODEL

Highly accurate ray-tracing analyses using three-dimensional terrain data have been carried out. In these studies, the terminals are accurately positioned using site-specific information for the measurement area. The ray-tracing model can be obtained by using the FASPRI simulation tool, a tool developed by our research group that analyses a 3D indoor environment via deterministic methods [25, 26].

The FASPRI is a code based on geometric optics and the uniform theory of diffraction (UTD). The electric field levels can be obtained using the direct, reflected, transmitted and diffracted fields. Thus, taking into account this variety of effects, the code provides good predictions [26]. These results can be used to examine the effect of varying certain sensing parameters on the precision of the system. The examined parameters include the number of antennas, the position of the antennas and the number of tracks.

Figure 1 shows the results of a FASPRI simulation. As shown in the figure, FASPRI uses a model of plane facets to describe the environment; the displayed rays travelling from the transmitter antenna to the observation point are depicted. All of the elements of an indoor environment are modeled by facets and the influence of the electromagnetic properties of the material of each facet is also included. However, the main problem associated ray-tracing approaches is that they need a great amount of time to obtain the multipath propagation. To avoid this inconvenience, FASPRI uses the angular Z-Buffer algorithm to accelerate the computation process [26]. In fact, FASPRI can simulate a great number of case-studies in a reasonable amount of time, as shown in [26].

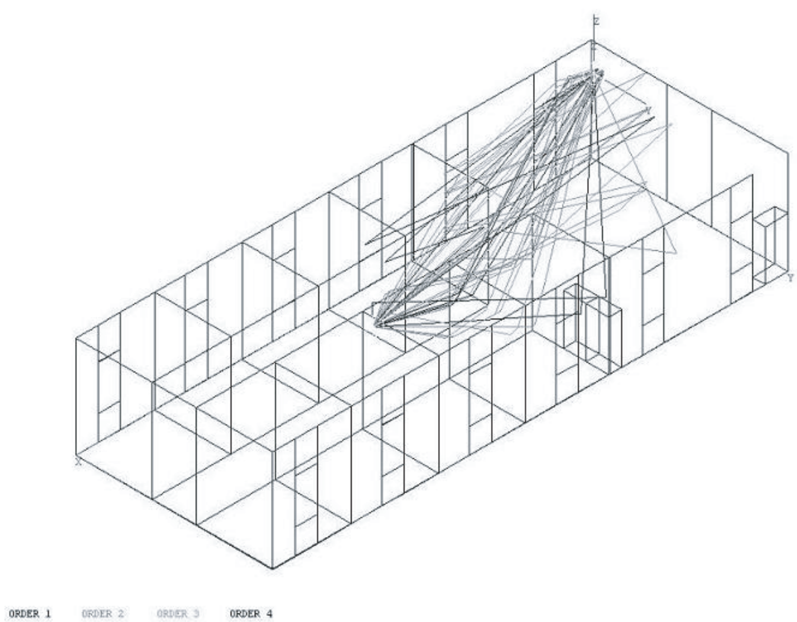

Figure 1. Results of a FASPRI simulation.

An advantage of using the ray-tracing technique is that, besides obtaining the power level of a series of points, information can also be obtained about multipath effects. This information can be used in a fingerprint method in order to improve the efficiency of the location system. To obtain the fingerprint database, FASPRI employs a 3D UTD propagation analysis and provides the location of the fingerprints in a reference grid.

3. THE FINGERPRINTING TECHNIQUE

The fingerprinting method [3] is used to overcome the errors caused by the absence of a LoS. The performance of indoor positioning is often degraded due to multipath propagation paths. For this reason, fingerprinting modelling has been included in our approach because it has high positioning accuracy in indoor environments.

As mentioned earlier, the fingerprinting technique is carried out in two stages. In the first stage, the radio map or RF fingerprinting database for the target environment is obtained. The location fingerprints are obtained by analyzing the relative ray-tracing delay and signal strength from multiple access points over a defined grid. In second stage, the accuracy obtained in the localization process is analyzed. For this purpose, the developed technique uses a number of mobile stations in the area covered by the radio map and obtains the vector of received power and the directions of ray travel from different access points. In our studies, many mobile stations randomly distributed over the indoor space are considered. The position estimation is made by an algorithm that computes the Euclidean distance between the obtained vectors and each fingerprint in the radio map. The X, Y and Z coordinates associated with the fingerprint that results in the smallest Euclidean distance are returned as the position estimation of the mobile station using a simple algorithm.

The information provided by the ray-tracing tool FASPRI is stored in six vectors. Two of them, θ_h and φ_h, correspond to information on the angle of arrival at every fingerprint. The first vector contains the theta component of the direction of arrival from the M access points at the fingerprint h, and the second vector contains the phi component of the direction of arrival at the same point. The other two vectors θ_m and φ_m, contain the same information as the mobile stations m. Finally, the last two (RSSh and RSSm) vectors contain information about the RSS in each fingerprint, as well as information about the RSS of each mobile station. These vectors are calculated at the beginning of the process and stored in the fingerprinting database. In the second stage of the localization process, the Euclidian distance between each mobile station and every fingerprint is calculated by considering the two parameters: the DOA and RSS.

The location of a mobile station is evaluated using the following cost function, which uses the received signal strength and the estimated directions of arrival from the received signals:

$$D(X,\,Y,\,Z)=\sum_{n=1}^{N}\eta\left(D\hat{O}A_n-DOA_n^{RT}\right)^2+(1-\eta)\left(R\hat{S}S_n-RSS_n^{RT}\right)^2 \quad (1)$$

where

$$D\hat{O}A_n-DOA_n^{RT} = \sum_{i=1}^{M}\sqrt{\left|\left(k_x^m(i)-k_x^f(i)\right)^2+\left(k_y^m(i)-k_y^f(i)\right)^2+\left(k_z^m(i)-k_z^f(i)\right)^2\right|} \quad (2)$$

$$R\hat{S}S_n-RSS_n^{RT} = \sum_{i=1}^{M}\sqrt{\left|\left(E_x^m(i)-E_x^f(i)\right)^2+\left(E_y^m(i)-E_y^f(i)\right)^2+\left(E_z^m(i)-E_z^f(i)\right)^2\right|} \quad (3)$$

M is the number of access points, E is the received electric field value, N is the number of rays, and η is a weighting factor that indicates the ratio between the correlation of DOAs and RSSs and

$$k_x = \cos(\varphi)\sin(\theta) \quad (4)$$

$$k_y = \sin(\varphi)\sin(\theta) \quad (5)$$

$$k_z = \cos(\theta) \quad (6)$$

In the first part of expression (1), the DOA of every received ray in fingerprints and every received ray in mobile stations is compared. This comparison is made according to the number of access points; that is, if a fingerprint receives just one signal from access point number 1 and a mobile station receives just one signal from access point number 3, this information is not taken into account. This restriction is applied to all cases in this study. Note that the directions of arrival between fingerprints and the mobile station are compared as long as they receive the same number of rays from the same access points. Thus, a cost function is only applied if this condition is satisfied. The process is the same for all the mobile stations; therefore, the estimated position of each mobile station can be calculated.

In the second part of expression (1) the method compares the electric field values received from the signals from all the access points. These levels are compared with the electric field values previously stored in the fingerprint database. In this case, the comparison is only made if the number of rays received in the fingerprint is the same as the number of received rays in the mobile station. In other words, the location algorithm computes the Euclidean distance between the DOA and RSS samples received in the unknown position and each fingerprint in the database or radio map obtained using FASPRI.

Changing (X, Y, Z) inside the testing area, which is the point that minimizes the cost function, is used to estimate the position of the mobile station. Therefore, the estimated position $(\hat{X}, \hat{Y}, \hat{Z})$ is obtained as follows:

$$\left(\hat{X}, \hat{Y}, \hat{Z}\right) = \min D(X, Y, Z) \tag{7}$$

According to this expression (4), the position of the mobile station corresponds with the fingerprint whose Euclidian distance is the smallest. In order to measure the efficiency of this method, the physical distance between the estimated position $(\hat{X}, \hat{Y}, \hat{Z})$ of every mobile station and its real position (X, Y, Z) over the grid is calculated.

4. EXPERIMENTAL RESULTS

In order to evaluate the localization performance of the proposed approach, an indoor environment (Politecnica building in Madrid) has been analyzed with different grid densities. The geometrical model of the scene is shown in Figure 2. The tests were performed for LoS and NLoS situations.

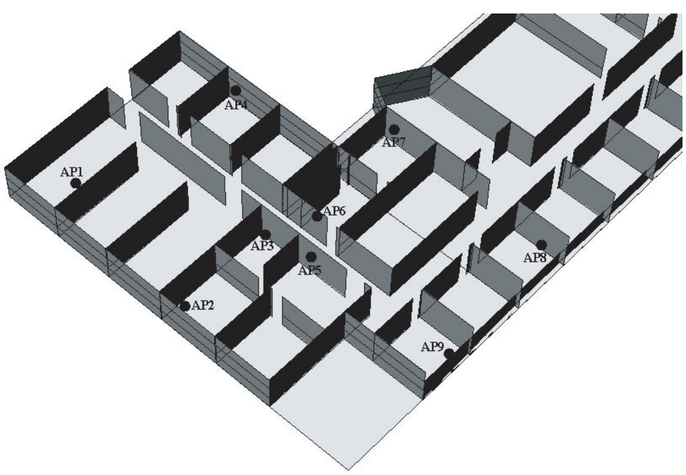

Figure 2. 3D view of the Politecnica building.

The experiments consider two grids consisting of 36×36 and 72×72 fingerprints at a frequency of 2.4 GHz. The simulations also use 9 access points and 99 mobile stations randomly distributed over the grids. Figure 3 shows the top view of the 830 m^2 area where the simulations take place, as well as the positions of the access points. The grid is formed by evenly distributed points, representing the 36×36 fingerprints; the nine triangles represent the nine access points and the circles represent the 99 mobile stations. Note that X and Y coordinates are measured in meters. The Z coordinate is always set to 1.5 meters and corresponds with the height of the mobile station from the floor. Despite this constant Z value, the method is 3D because the rays can reach any height (reflection on the floor, ceil, walls, diffraction, etc.). The nearest fingerprint to each mobile station is found by using this method.

The information available in each fingerprint and mobile station are parameters that affect the precision and reliability of the location process. For this reason, a study taking into account the number of received rays in fingerprints and in mobile stations has been performed. For this study, the results from two kinds of simulations are compared. First, information is generated using the 36×36 grid is analyzed; the distance between each fingerprint is 0.8 meters. Second, information is generated using the 72×72 grid is analyzed; the distance between each fingerprint is 0.4 meters.

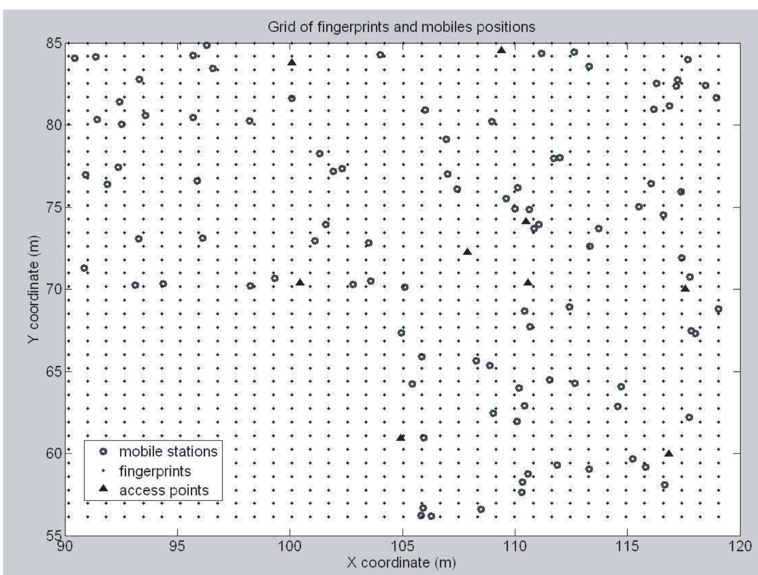

Figure 3. Top view of the Politecnica building, with the 36×36 grid.

Figures 4 and 5 show the results for various numbers of rays for the Politecnica building, using a 72×72 grid. The mean error is shown in Figure 4 and variance of the mean error is shown in Figure 5. The mean error is calculated as the Euclidian distance between the real position of the mobile station and its estimated position. The experimental results give a mean cost of about 0.3 m, as shown in Figure 4. Results are reasonable, since separation between each fingerprint is 0.4 m. The best results are obtained by considering 6 or 10 rays. In both cases, the mean error value is 0.261 m and the variance value is 0.09 m when η is different than 1. In other words, if the method only considers the DOA ($\eta = 1$), the results are not as accurate as other cases; other values of η do not affect the performance of the method. It is notable that the results are very similar for the rest of the η values. The same information is illustrated in Figures 6 and 7 for the case of the Politecnica building with a 36×36 grid. In this case, the separation between fingerprints is 0.8 m and the best result is obtained by considering 8 rays. The mean error value for 8 rays is 0.55 m and the variance is 0.19 m. Figures 6 and 7 show that the best results are produced if the number of rays is in the range between 6 and 10 again. Also, for this case $\eta = 1$ and the other three values provide similar results.

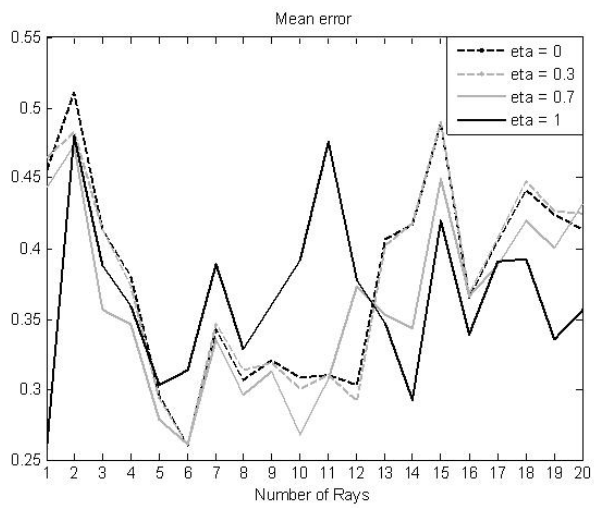

Figure 4. Mean error (meters) varying the number of rays taken into account in order to calculate the cost function depending on the η parameter. Results obtained for a 72×72 grid of fingerprints in the Politecnica building.

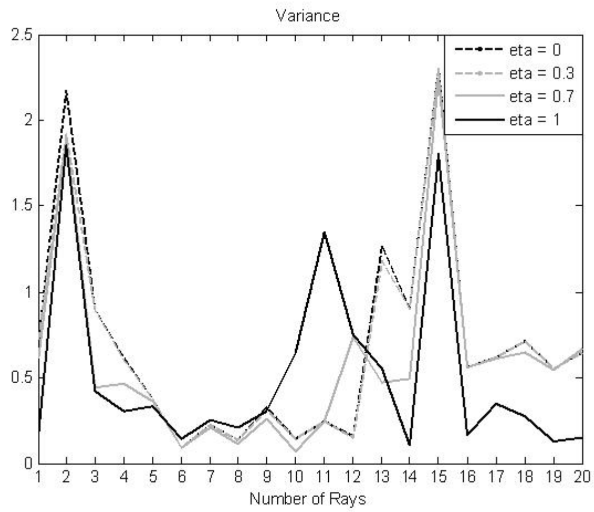

Figure 5. The variance of the mean error (meters) for various numbers of rays in order to calculate the cost function depending on the η parameter. The results are obtained for a 72×72 grid of fingerprints in the Politecnica building.

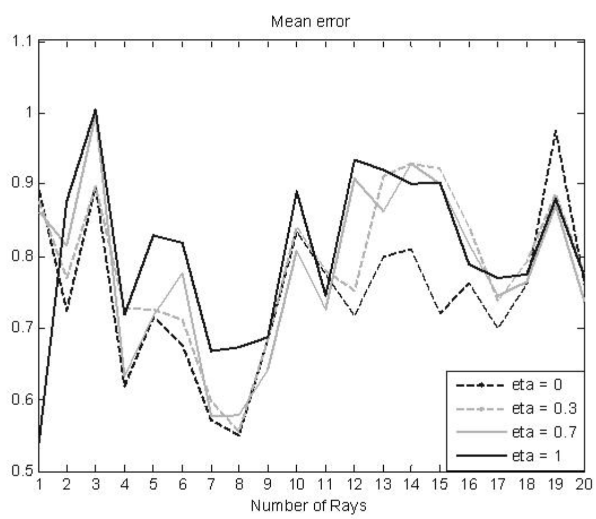

Figure 6. Mean error (meters) varying the number of rays taken into account in order to calculate the cost function depending on the η parameter. The results obtained for a 36×36 grid of fingerprints in the Politecnica building.

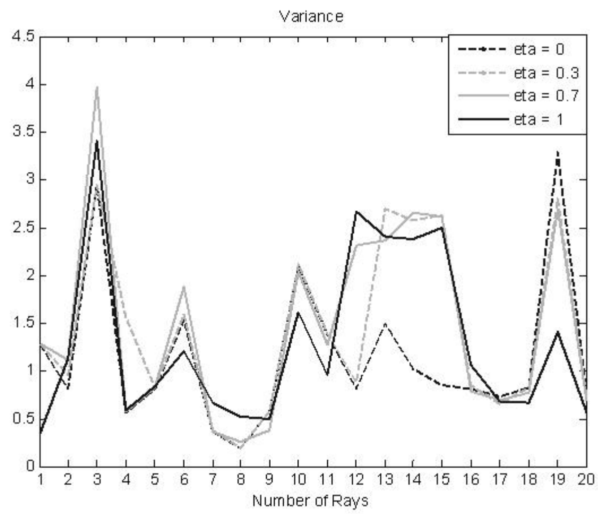

Figure 7. The variance of the mean error (meters) versus the number of rays account in order to calculate the cost function, which depends on the parameter η. The results are obtained for a 36×36 grid of fingerprints in the Politecnica building.

The results for the different grids can be compared to show the accuracy of the localization method depends on the density of the grid. The error for the grid with 72×72 points is 0.2828 m and the error in the case of the grid of 36×36 points is 0.5657 m. Hence, there is no improvement by increasing the number of points of the grid; when the distance between adjacent points is doubled the mean error is also doubled. Thus, it can be concluded that the accuracy of the location process is very similar for both grids. However, it should be noted that the mean error is not reduced when the number of rays is increased at a given frequency. In fact, the detection method using 8 rays provides better results than the detection method using 20 rays; when the number of rays is less than 4 or 5 there is not enough information to provide good results. As explained in Section 3, if a fingerprint receives just one signal from access point number 4 and a mobile station receives just one signal from access point number 7, the information is not considered. Thus, the information is only considered if the order of the rays is the same for both the fingerprint and the mobile station. That is, both rays must be generated in access point number 4 or in access point number 7. Where there are few rays, the cost function is evaluated a few times and thus the results are not as accurate. The opposite situation occurs when the number of rays is large (from 15 to 20). In this situation the information in the database is only considered if the order of the 15 rays in a fingerprint is the same as the order of the 15 rays in a mobile station. For example, if the first ray of a fingerprint is generated at access point number 2, the first ray of the mobile station must also be generated at access point number 2; this condition is applied to every ray of every fingerprint and every ray of every mobile station. Furthermore, it is probable that fingerprints and mobile stations do not contain information for more than 15 rays. Hence, it is quite difficult to find enough information when the order of access points is the same for the fingerprint and for the mobile station when the number of considered rays is very high. For this reason, results are not so good when the number of rays is increased.

5. CONCLUSIONS

The problem of radiolocalization for indoor scenarios has received much attention from the research community in recent years. Under NLoS conditions and multipath contributions, indoor localization increases in error and it is necessary to find innovative solutions allowing more accurate measurements. Moreover, indoor multipath characteristics can vary considerably-they depend on building dimensions, the transmitting/receiving range and the presence or absence of furniture. Due to propagation in complex indoor environments, multiple signals from different directions can be used to determine the location of the mobile terminal.

Our contribution is a novel approach using the multipath behavior by combining ray-tracing measurements (DOA and RSS) and a fingerprinting technique to determine the location of a mobile station. The location algorithm computes the Euclidean distance between the DOA and RSS samples received at an unknown position and each fingerprint is stored in the database. We compare the results of our detection method for several numbers of rays.

The proposed approach is quite simple and decreases errors due to the absence of LoS and multipath reflections. Also, our approach provides accurate results by using the widely available RF-based wireless LAN infrastructure. Its advantages are that it is very useful for practical applications and there is enhanced accuracy with respect to similar approaches, especially for mixed LoS/NloS conditions.

A fingerprinting technique using the direction of arrival and the received signal strength is relatively easy to implement and provides good results for the indoor location process. Also, the analysis presented above concludes that the method does not provide better results if the number of rays is increased and different values for η are used; it is notable that the results are very similar for all values of η. For the case where η is equal to 1, the method provides less accurate results. Thus, if the method does not consider the information about the received signal strength, the error in the location process will be slightly higher.

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