Indoor Positioning Using Spatial Power Spectrum

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***Abstract*— A simple technique to estimate the position of a given mobile source inside a building is based on the received signal strength. For this methodology to have a reasonable accuracy, radio visibility of the mobile by at least three access points is required. To reduce the number of the required access points and therefore, simplify the underlying coverage design problem, we propose a new scheme that takes into account the distribution of RF energy around the receiver. In other words, we assume that the receiver is equipped with a circular antenna with beamforming capability. In this way, the spatial spectrum of the received power can be measured by rotating the antenna beam around the 360-degree field of view. This spatial spectrum can be used by a single receiver as a mean for estimating the position of a mobile transmitter. In this paper, we investigate the feasibility of this methodology, and show the improvement achieved in the positioning accuracy.**

I. Introduction

In recent years, technologies that find the location of mobile sources inside buildings are becoming an attractive area of research and development. A significant application of such technologies is in emergency situations where it is important to be able to locate or track the movements of the first responders inside closed environments. More commercial and public safety applications are also emerging every day.

The problem of finding locations of mobile sources inside buildings presents special challenges. Obstacles such as walls, furniture and other objects create a much harsher radio propagation environment. A variety of ranging and positioning techniques with different technologies such as RF, ultrasound, infrared, etc. have been proposed to solve this problem [1]. A simple technique to estimate the position of a given source is based on the Received Signal Strength (RSS). The general philosophy in this approach is to establish a one-to-one correspondence between a given position and the average received signal strength from at least three transmitters with known locations. One such system that has been implemented on the existing wireless local area network infrastructure is RADAR [2].

RADAR is a software-based localization system that operates by recording and processing RSS information from multiple access points (i.e. base stations). There are two main phases in the operation of this system: an off-line phase (i.e. data collection or training phase) and an online phase (i.e. mobile position estimation). In the off-line phase, a Radio-Map of the environment is created. The radio-map is a database of selected locations and their corresponding signal strengths received from several base stations. For example, an entry in the radio-map may look like $(x, y, z, RSS_{i(i=1,2,\ldots,n)})$ where (x, y, z) are the physical coordinates of the location where the signal is recorded and RSS_i is the average received signal strength of the base station i. In the on-line phase, the mobile measures the received signal strength from each of the base stations within range, and then searches through the radio-map database to determine the best signal strength vector that matches the observed one. The system estimates the location associated with the best-matching signal strength vector (i.e. nearest neighbor) to be the location of the mobile. This technique essentially calculates the L_2 distance (i.e. Euclidean distance) between the observed received signal strengths and the entries in the space defined by the radio-map. It then picks the RSS-vector that minimizes this distance and declares the corresponding physical coordinate as the estimate of the mobile's location. Alternative strategies such as averaging the k-nearest neighbors have also been considered.

Another interesting RSS-based localization methodology has been proposed in [3] where a probability distribution is constructed during the training phase. Then, a Bayesian inference approach is used to estimate the mobile's coordinates with the highest probability.

The general assumption in all of these RSS-based positioning systems is that the signal strength is recorded with an omni-directional antenna at the receiver. In a multipath environment, such as indoor, the mobile receives the transmitted signal from many directions due to possible reflections, diffractions and scattering phenomena. An omni-directional antenna is not capable of obtaining any information regarding the spatial (i.e. angular) distribution of the signal energy. The thesis of our research is that any information pertaining to the angular distribution of power can be used to increase the accuracy of an RSS-based localization methodology. For example, through the use of an antenna that has beamforming capability, more information can be extracted by measuring the signal strength in a given direction; therefore, instead of the average signal strength, a more general Spatial Power Spectrum (SPS) can be generated and used for position estimation. An array antenna with beamforming capability is able to steer the direction of its main beam toward any desired angle. In particular, a circular array, which has a 360-degree field of view, is an appropriate candidate for two-dimensional positioning application.

By using a more generalized and sophisticated radio-map that contains received signal strength information from various directions, the system would have the capability of estimating the mobile position with fewer access points and possibly higher accuracy. Section II describes the problem statement in more details. Simulation platform and various proposed solutions are investigated in Section III. System performance is discussed in Section IV and finally some concluding remarks are expressed in Section V.

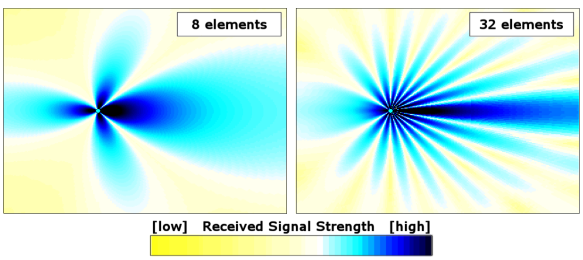

Fig. 1. Sample beam patterns of a circular array with beamforming

II. Problem Statement and Modeling

In this paper, we propose to follow the same two-phase approach as the general RSS-based localization mentioned in the previous section. However, in the training phase, instead of recording the received signal strength, a circular array antenna with beamforming capability records the Spatial Power Spectrum (SPS) of the received signal. The SPS is basically a two-dimensional graph of the received power versus angle (e.g. azimuth). Each point on this graph indicates the received power when the main beam of the antenna is directed toward a given azimuth. The beam of the array antenna is electronically controlled to point toward a desired direction (see Fig. 1). Consequently, by rotating the main lobe in the 360-degree field of view and recording the received power, an SPS graph for a given position is generated.

Now, the problem is to first form a database of the measured spectrums at the points of interest (e.g. set of grid points over the layout). This is the training phase which essentially yields a more sophisticated radio-map of the building where positioning is desired. Next, for any given position, the generated SPS can be compared to all the entries in this database and the position of the best match would be a good candidate for the unknown position.

In this paper, we investigate the feasibility of this approach by implementing a simulation platform that matches the condition of an indoor environment. The main difficulty in simulating an indoor RF channel is the strong dependence of the received signal on the layout of the building (e.g. multipath channel). In particular, all walls, windows and other objects that affect the propagation of RF waves will directly impact the signal strength and the directions from which RF signal is received. Empirical, statistical and deterministic models have been used to describe the behavior of such multipath channels [4]. In our study, we have elected to use a sophisticated ray-tracing tool to accurately predict the received signal in the indoor RF channel [5], [6]. Wireless System Engineering (WiSE) is a ray-tracing tool that has been developed and verified by Bell Laboratories. It is capable of considering the effect of dielectric properties of the wall material in the multipath profile generated at the receiver. We realize that even such models have limitations in their accuracy and are subject to errors when there are changes in the environment such as furniture moving, or even people walking through the building; however, this approach will give us the opportunity to create a testbed that to the extent possible mimics the conditions of indoor channels in real life.

The received power in an array antenna with a directional beam is a function of the azimuth angle where the main beam is pointing. For a given layout, wall material, transmitter-receiver locations, frequency and array size, the spatial power spectrum at the receiver coordinates can be obtained by rotating the main beam around the receiver using a beamforming algorithm. In order to further verify the accuracy of the obtained SPS, a simple experiment was conducted to compare sample measurements to the predicted values of the ray-tracing tool (See Appendix).

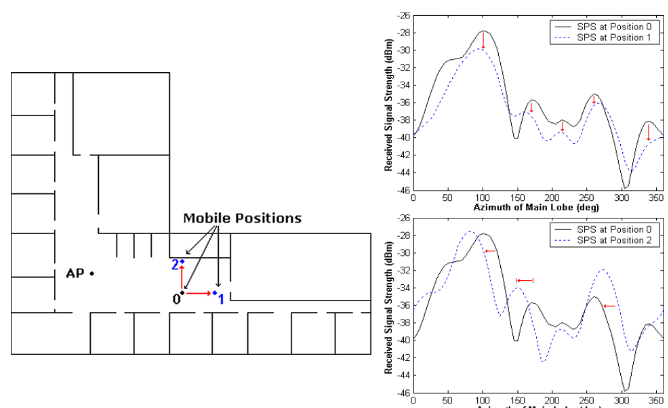

Fig. 2. Variation of the spatial signature

Once the SPS data for a set of predetermined points is collected, the test and verification phase of the positioning system can begin. Essentially each SPS graph that is obtained can be regarded as a spatial signature that signifies the position coordinates of the mobile as seen by an access point. On the contrary to the RSS-based methodology, where an L_2 distance is used to establish a metric between two RSS vectors, the problem of finding the closest match to a given SPS is not so obvious in this case. To further elaborate on this problem, consider the scenarios depicted in Fig. 2. Here, the mobile is the transmitter and the access point is the receiver equipped with a circular array antenna. When the mobile position changes from 0 to 1, the mobile distance from the access point is increased; and the SPS graph decreases in magnitude (i.e. vertical shift) while generally maintaining its shape. On the other hand when the mobile position changes from 0 to 2, the distance of the mobile to the access point is almost unchanged; however, the direction from which the access points receive the RF signal is now different. This translates to a horizontal shift in the spatial signature. Therefore, physical closeness or proximity in mobile positions could translate to visual similarity in the spatial signatures seen by an access point. Although, it can be shown that this is not true in general, the positioning methodology outlined in this paper is still applicable under all circumstances.

III. Simulation Platform

The block diagram shown in Figure 3 describes the simulation system that was created to assess the performance of this positioning technique. Performance can be obtained for various input parameters such as building layouts, radio characteristics of the building materials and receiver/transmitter attributes such as power, frequency and antenna gain pattern. Also, various signature-matching strategies can be implemented as search mechanisms to identify the position estimate of the mobile.

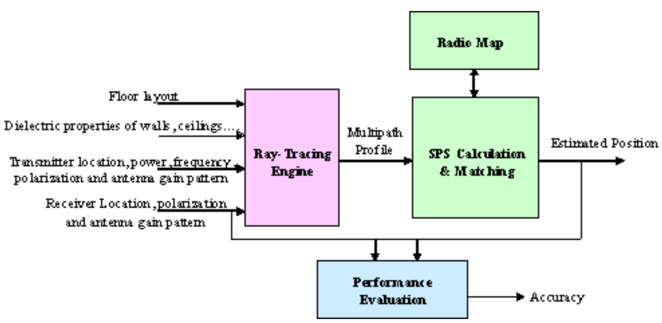

Fig. 3. Block diagram of the simulation platform

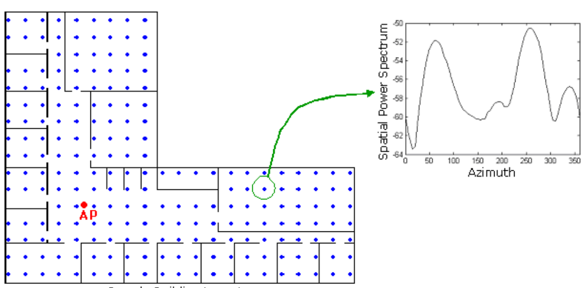

Fig. 4. Radio-map based on a grid overlay

To generate a radio-map for a given layout, we have defined a uniform grid of points as seen in Figure 4. For each point on the grid and for each access point a spatial signature is generated and stored. This constitutes the radio-map. Notice that if the antenna gain pattern for the receiver is taken to be omni-directional, then the system will behave similar to the RSS-based positioning. This special case is actually used as a benchmark to evaluate the gain associated with using SPS.

As previously mentioned, the main objective in this research is to study the applicability of using spatial power spectrum for indoor localization. For this purpose, a new approach for finding the best matching signal strength distribution should be found and implemented. Then, the performance of this system will be compared to the omni-directional case under various scenarios and parameters such as transmitter and receiver locations, building layout, number of receivers (i.e. access points), etc. To compare the signature of a test point to those included in the radio-map, an appropriate distance metric needs to be defined. We have considered three different metrics that are explained in the following subsections.

A. Minkowski Distance

Minkowski metrics are a family of distance measures, which are generalized from the Euclidean distance formula. It is often used as a similarity measure between two patterns that could be images, graphs, signatures or vectors. If $d_{L_r}(SPS_1, SPS_2)$ denotes the distance between two signatures SPS_1 and SPS_2, then Minkowski distance of order r is defined as:

$$d_{L_r}(SPS_1, SPS_2) = \left(\sum_{\theta} |SPS_1(\theta) - SPS_2(\theta)|^r \right)^{1/r}$$

At $r = 2$, this metric is the typical Euclidean distance that has been used for some of the RSS-based methodologies [2]. We chose to investigate the performance of L_1 and L_2 distance metrics for the spatial spectrum matching. These metrics essentially perform an element-by-element similarity measure between the two signatures SPS_1 and SPS_2, which might be ineffective for signatures that are circularly shifted versions of each other. This could be especially important when the radio-map grid resolution is low or there exist large open spaces in the layout (e.g. large conference room).

B. Earth Mover's Distance (EMD)

Earth Mover's Distance (EMD) was introduced in [7] as a distance metric with application in content-based image retrieval. An attractive property of this metric is its capability to match perceptual similarity better than other distance metrics used for image retrieval. This property is actually desirable in our application as well, since in most cases perceptual matching of spatial signatures would seem to apply in actual coordinate matching for indoor positioning.

The EMD is based on a solution to the transportation problem from linear optimization. It is a useful and flexible distance metric that measures the minimal cost that must be paid to transform one signature into the other. Signature matching is cast as a transportation problem by defining one signature as the supplier and the other as the consumer, and by setting the cost for a supplier-consumer pair to equal the ground distance between an element in the first signature and an element on the second. Intuitively the solution is the minimum amount of work required to transform one signature into the other. Alternatively, given two spatial spectrums, one can be seen as a mass of earth properly spread in space, the other as a collection of holes in that same space. Then, the EMD measures the least amount of work needed to fill the holes with earth. A unit of work corresponds to transporting a unit of earth by a unit of ground distance.

IV. System Performance

Using the simulation platform discussed in the previous section, we conducted simulation experiments for various layouts, array sizes, radio-map grid resolutions, antenna beam rotation step size and signature matching techniques. We have chosen an ISM band frequency of 2.4 GHz for the operation of system in simulation.

Table I summarizes the average position error obtained with different matching algorithms, number of access points and radio-map grid resolution. When the receiver antenna is selected to be omni-directional (i.e. array size is one), we will essentially have a pure signal-strength-based system where no directional information is included in the signatures and the radio-map. In this case, each spatial spectrum is replaced by a scalar that represents the total average received power. Performance of this omni-directional system with an L_2 distance metric has been chosen as the benchmark for comparison purposes.

Fig. 5 also displays the Cumulative Distribution Function (CDF) of error in the estimated position for different radio-map resolution. The performance of the SPS-based method with only one access point has been compared to the performance of the RSS-based method with one, two and three access points when the radio-map resolution is one meter. As observed, using the SPS approach, there is a significant improvement in accuracy when the number of access points is less than three. Fig. 6 visually demonstrates the advantage of using spatial spectrum for lower number of access points.

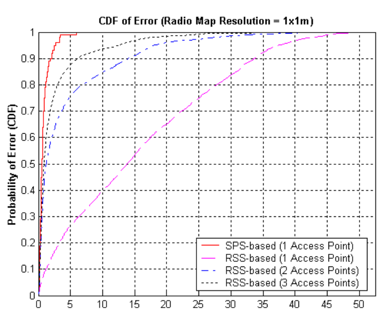

Fig. 5. CDF of the position error

The number of antenna array elements used for the simulation results in Table I is eight. As the number of array elements increases, the main beam of the antenna becomes

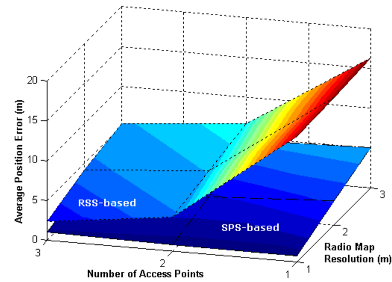

Fig. 6. Advantage of using SPS

narrower as seen in Fig. 1. The antenna in this case would be capable of measuring the fine-grained spatial multipath profile of the signal at the receiver location. However, it is not clear whether such fine-grained SPS would enhance the achieved positioning accuracy. For this reason, we have performed further studies to understand the effect of the antenna size on the average positioning error. We have observed that for a given radio-map resolution, building layout and matching algorithm; there might exist an optimal antenna array size that results in the minimum average position error. For a radio-map grid resolution of 3mx3m, step-size of 5 degrees, this has been displayed in Fig. 7.

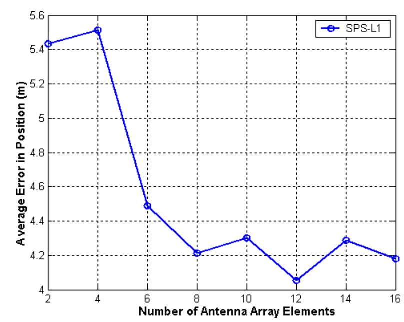

Fig. 7. Average error versus antenna array size (400 test mobile positions)

V. Conclusion

The underlying philosophy in this paper is that exploiting the information in the spatial distribution of RF energy around a receiver results in better estimates of the location of a mobile. This spatial spectrum basically represents a signature that only depends on the relative location of the transmitter with respect to the receiver and the environment surrounding them. It can be easily seen that in free space, there is a one-to-one correspondence between the transmitter position and the received SPS. If the receiver is assumed to be at the origin of a polar coordinate system, the received spatial signature is a function of the polar coordinates of the transmitter. If the receiver-transmitter pair is planted inside a building, the layout and the construction material of the walls dictate the flow of energy; and therefore, the shape of the signature. However, the uniqueness of the SPS signatures is still maintained in an indoor environment. Therefore, if a database consisting of a set of representative

TABLE I

AVERAGE POSITION ERROR (ARRAY SIZE = 8, STEP SIZE = 5 DEGREES)

	Radio-Map Res. 1x1m			Radio-Map Res. 2x2m			Radio-Map Res. 3x3m		
	AP = 1	AP = 2	AP = 3	AP = 1	AP = 2	AP = 3	AP = 1	AP = 2	AP = 3
SPS - L_1	0.99	0.83	0.82	3.10	2.48	2.12	5.07	4.58	2.90
SPS - L_2	1.06	1.03	0.86	3.20	2.46	2.34	5.05	4.11	2.77
SPS - EMD	1.18	1.05	1.02	3.22	2.59	2.28	5.95	4.49	3.07
RSS - L_2	15.8	4.37	2.50	16.0	5.54	4.32	16.4	6.66	5.53

points (i.e. radio-map) in a building is made, then, any inquiry to the whereabouts of a mobile can be answered by comparing the received SPS with the entries of the radio-map.

RSS-based methodologies also follow the same strategy; however, for them to have a reasonable accuracy radio visibility of the mobile by at least three access points is required. This would create a difficult coverage design problem, which would be eliminated if SPS signatures were used instead. In other words, an advantage of using the SPS signatures as opposed to RSS (i.e. pure signal strength) is that even single receiver with beamforming capability delivers good accuracy; and as a result, complicated triple coverage by three access points is no longer required.

Throughout this paper, we have considered the case where the stationary access point with the circular array is the receiver and the mobile is the transmitter. If there are many transmitters available, a multiple access scheme has to be in place to differentiate between the signals of different transmitters. It is also possible to consider the case where the mobile is the receiver capable of generating spatial signatures; however, it should be noted that in this case, the mobile requires an electronic compass (or a similar device) in order to have a reference frame for the azimuth angle. In this way, many mobiles can estimate their locations simultaneously without the need for a multiple access scheme.

APPENDIX

In order to justify the use of the ray-tracing tool for performance analyses of the SPS-based approach, verification of the accuracy of the simulated spatial power spectrum with real measurements was necessary. Therefore, a simple experiment was set up that involved a directional antenna located on a rotating platform (details of the hardware experiment have been omitted for brevity). The SPS was generated by taking the measurement of the received power when the azimuth angle of the directional antenna was pointing at 0, 10, 20, ..., 350 degrees. Fig. 8 demonstrates the comparison made between the measured SPS and the ray-tracing estimate. The measured SPS corresponds to a single physical coordinate; and therefore, exhibits the effects of multipath fading. By averaging the sample SPS corresponding to a few nearly co-located positions, a closer match to the smoothed outcome of the ray-tracing tool was observed. Averaging four such measurement samples provided good match in the experiment. The authors realize that in general such hardware measurements should replace the results obtained by the ray-tracing tool to further validate our conclusions and we hope to implement a prototype of the proposed scheme in the near future.

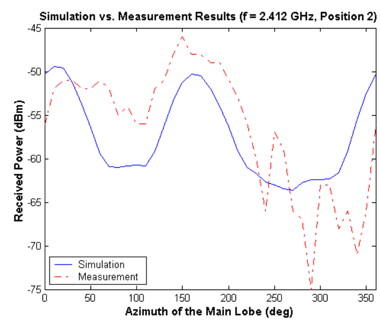

Fig. 8. Comparison of the measured SPS with the ray-tracing estimate

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