A Study of the Application of Sectorized Antennas in RF-Based Indoor Localization Systems

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1. 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 track the movements of the first responders inside closed environments. More commercial and public safety applications are also emerging every day.

GPS provides such capability outdoors, where there exist line-of-sight propagation paths to GPS satellites; however, it cannot be used in an indoor environment where ceilings obstruct view of the satellites. The problem of finding locations of mobile sources inside buildings presents special challenges. Obstacles such as walls, furniture and other objects found in buildings create a much harsher radio propagation environment. A variety of ranging and positioning techniques with different technologies such as RF, ultrasound, infrared, DC electromagnetics, etc have been proposed to solve this problem [1, 2]. Accordingly, various levels of localization accuracy and resolution versus cost and complexity have been reported by such methodologies.

A simple technique to estimate the position of a given source is based on the received Signal Strength (SS). The general philosophy in this approach is to establish a one-to-one correspondence between a given position and the received signal strength from at least 3 transmitters with known locations. One such system that takes advantage of the existing WLAN infrastructure and therefore, does not require any specialized hardware is RADAR [3,4].

RADAR is a software-only localization system built over an off-the-shelf RF Wireless Local Area Network (WLAN). It operates by recording and processing Signal Strength (SS) information from multiple access points (i.e., base stations). It consists of two major phases. First, an off-line phase (i.e., data collection phase) followed by the online phase, i.e. finding the location of a mobile in real-time.

In the off-line phase, a “Radio Map” of the environment is created. A “Radio Map” is a database of locations and the signal strengths from the base stations as received at those locations. For example, an entry in the radio map may look like (x,y,z, $SS_{i\ (i=1,2,....,n)}$) where (x,y,z) is the physical coordinates of the location where the signal is recorded and SS_i is the received signal strength of the *ith* base station.

In the on-line phase (i.e. locating the position of the mobile in real-time), the mobile measures the signal strength of each of the base stations within range; and then searches through the Radio Map database to determine the signal strength tuple that best matches the signal strengths, it has measured. The system estimates the location associated with the best-matching signal strength tuple (i.e. nearest neighbor) to be the location of the mobile. This technique basically calculates the Euclidean distance in signal space and then picks the SS tuple that minimizes this distance in the signal space and declares the corresponding physical coordinate as its estimate of the mobile’s location. Alternative strategies such as averaging the k nearest neighbors have also been considered.

Another SS-based localization methodology has been proposed in [5,6,7] where a Bayesian Inference approach was used to find the position coordinates with the highest probability

The general assumption in all of these SS-based localizations 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 phenomenon as shown below:

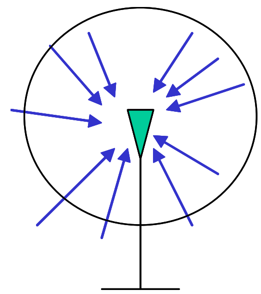

Figure 1: An omni-directional antenna

Through the use of a multi-sector antenna (or equivalently an antenna that has beamforming capability), more information can be extracted by measuring the signal strength in a given sector (or direction); therefore, a more sophisticated radio map can be built. In the next section, we will describe the problem that we would like to investigate.

2. Problem Statement

Our thesis is to consider the combined direction and signal strength information for localization purposes. Although driving the fine-grained spatial distribution of signal in a multipath environment is practically difficult, a coarse approximation of such distribution (power vs. direction) can be obtained with a sectorized antenna, beamforming or other types of smart antennas. An omni-directional antenna that is used in a pure SS-based localization is incapable of determining the direction in which the dominant path (or paths) is arriving at the receiver; equivalently, directions from which there are no signal energy could also be important to infer more information about RF propagation inside buildings. This added information that can be obtained by a sectorized antenna (see Figure 2), consequently, could be exploited to increase the efficiency of a localization system.

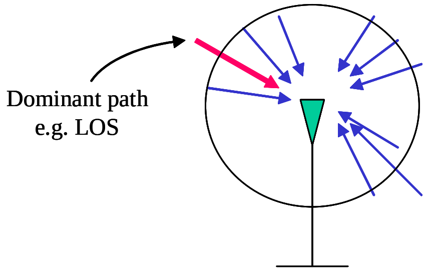

Figure 2a: Omnidirectional antenna

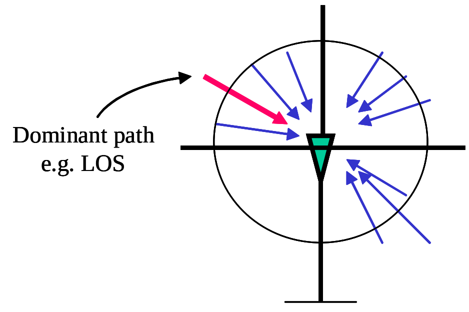

Figure 2b: An ideal 4-sector antenna

To investigate the feasibility of such methodologies, we will focus on antennas with ideal sectors as shown in Figure 2b (effects of imperfect beams or slices will be considered later). Although, any considered technique will also be applicable to outdoor environments, we are mainly interested in indoor environments where severe multipath and shadowing are the biggest channel impairments.

3. Modeling & Assumptions

The characteristics of a multipath channel are strongly dependent on the physical environment, e.g. layout of the building. In particular, all walls, windows and other objects that affect the propagation of RF waves will directly impact the received signal strength. Empirical, statistical and deterministic models have been used to describe the behavior of such multipath channels [8,9]. In our study, we have elected to use a sophisticated ray-tracing simulation tool [10] to accurately predict an indoor RF channel.

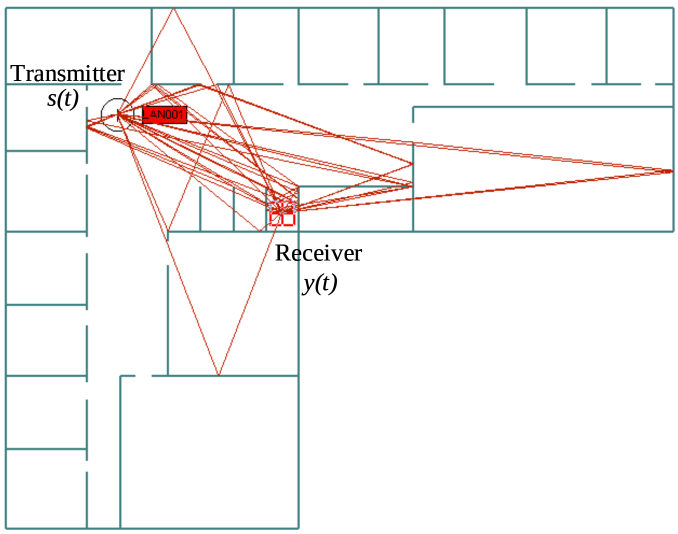

Figure 3: Sample output of EDX ray-tracing tool indicating Multipath Propagation

Figure 3 shows a sample of the multipath signal for a given floor layout and a given transmitter/receiver location. We realize that even such models have limitations in their accuracy and are also 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 an indoor channel in real life. It will also allow a user to (optionally) consider other related issues that are difficult to investigate with a statistical or empirical model such as interference from adjacent wireless systems.

The ray-tracing tool used in our study is capable of providing the impulse response of a stationary channel in the following form:

$$h(t) = \sum_{k=0}^{N-1} a_k \, \delta[t - t_k)]e^{j\theta_k}$$

where

$$\begin{aligned} &N : number\ of\ multipath\ components \\ &a_k : amplitude\ of\ the\ received\ impulse\ on\ path\ 'k' \\ &\theta_k : phase\ of\ the\ received\ impulse\ on\ path\ 'k' \\ &t_k : arrival\ time\ of\ the\ received\ impulse\ on\ path\ 'k' \end{aligned}$$

In addition to the above information, the ray-tracing tool also provides angle of arrival for each ray (i.e. spatial/angular distribution of the impulse response at the receiver).

Having the impulse response, the received signal $y(t)$ (for an omni-directional antenna) in response to the transmitted signal $s(t)$ can be easily found as:

$$y(t) = \int_{-\infty}^{\infty} s(\tau)\, h(t-\tau) d\tau + n(t) \qquad n(t): \text{Additive noise at the receiver}$$

Also, in the case of a non-omnidirectional antenna (for example, sectorized antenna as shown in Figure 4), having the ray's angle of arrival, the received signal power for any sector of space around the receiver can be obtained by considering those rays that fall inside the desired sector (or equivalently removing/filtering all the rays that are located outside the desired sector).

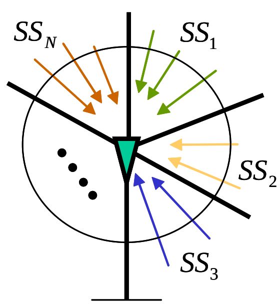

Figure 4: An ideal N-sector antenna, SS_i = Signal strength at sector i=1,2,…N

4. Plan of Study

A simulation platform with the ray-tracing tool (i.e. EDX) will be created to assess the performance of the localization system. The high-level block diagram of this system is shown in Figure 5.

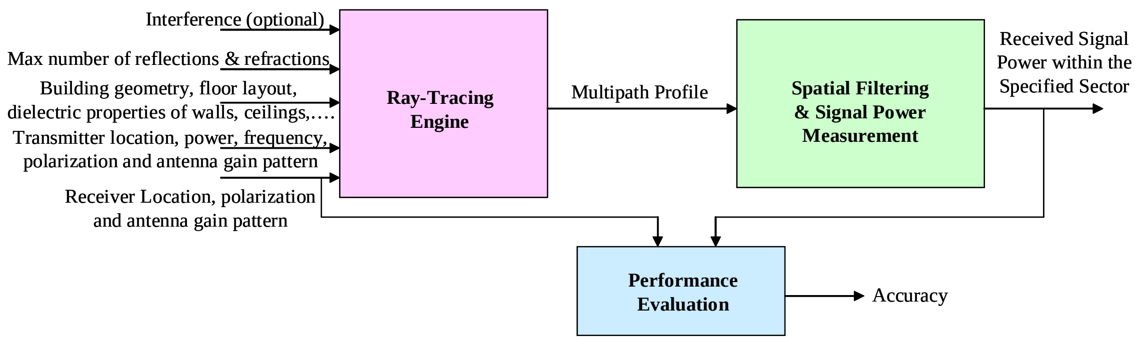

Figure 5: Block diagram of the test Platform

Having this platform, the performance of the localizer can be obtained for various strategies and parameters. The "Spatial Filtering" allows for considering only those rays that are within a specified arrival-angle interval (i.e., sector) in order to calculate the received signal strength. For example, a system with one 360 degrees sector is equivalent to a pure SS-based localizer. This system would serve as a reference (i.e., benchmark) for comparison purposes. This benchmark system is conceptually similar to RADAR; however, there exist substantial differences as listed below:

1) The radio maps are created using the ray-tracing tool as opposed to measurements with WLAN cards.
2) The system can operate at any frequency as opposed to the 2.4GHz normally used for WLAN.
3) The signal strength at each point is a deterministic value as opposed to random nature of measurements in RADAR, so the methodology for creating the radio maps will be different.

Several algorithms will be coded in MATLAB [11] to process the output of the ray-tracing engine. These algorithms implement the strategy in generating the proper radio maps and search mechanisms to identify the position estimate of the mobile. A sample radio map for a single transmitter and a receiver with an omni-directional antenna is shown in Figure 6.

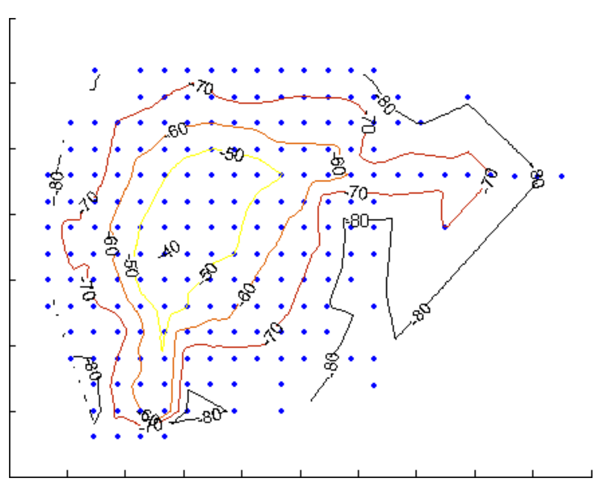

Figure 6: A sample radio map with a single transmitter (signal strength contours in (x,y))

As mentioned earlier, the main objective in this research is to study the effect and application of non-omnidirectional antennas (or other related types of smart antenna) 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 transmitters (i.e. base stations), noise, etc.

5. References

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