A Practical Path Loss Model For Indoor WiFi Positioning Enhancement

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***Abstract*— Positioning within a local area refers to technology whereby each node is self-aware of its position. Based on empirical study, this paper proposes an enhancement to the path loss model in the indoor environment for improved accuracy in the relationship between distance and received signal strength. We further demonstrate the potential of our model for the WiFi positioning system, where the mean errors in the distance estimation are 2.3 m and 2.9 m for line of sight and non line of sight environments, respectively.**

I. INTRODUCTION

Wireless technologies are becoming increasingly important for flow of information. IEEE 802.11 technologies have started to spread rapidly, enabling consumers to set up their own wireless networks. This paper describes use of Wireless LAN (WLAN) technology, IEEE 802.11b, to determine the position of a mobile device, in an indoor environment. Location based services are provided based on such positioning applications. Global Positioning System (GPS), a worldwide satellite-based navigation system does not work indoors [1].

Local positioning is done utilizing many different properties. Some use physical properties of the signal, while others use the time taken for the signal to reach the destination node. Some common positioning methods are summarized as follows.

Angle of Arrival (AOA) refers to the method that the position of a mobile device is determined by the direction of the incoming signals from other transmitters whose locations are known. Triangulation technique is used to compute the location of the measured mobile device. However, a special antenna array is required to measure the angle [2].

Cell Identity (CI) makes use of the radio coverage of an identified cell to indicate the location of a mobile device. This identified cell may be stationary or mobile, but its location at the time of detection must be available. The main drawback of this method is its accuracy since usually the coverage of a cell is wide. Moreover, the presence of high rise buildings and many stationary points in an urban setting make this method inaccurate due to multi-path propagation and signal reflection [4].

Time of Arrival (TOA) method measures the round-trip time (RTT) of a signal. Half of the RTT corresponds to the distance of the mobile device from the stationary device. Once the distances from a mobile device to three stationary devices are estimated, the position of the mobile device with respect to the stationary devices can easily be determined using the intersecting circles of trilateration. TOA requires very accurate and tightly synchronized clocks since 1.0 μs error corresponds to a 300 m error in the distance estimate [2]. Thus inaccuracy in measuring time differences should not exceed tens of nanoseconds since the error is propagated to the distance estimate [4].

Time Difference of Arrival (TDOA) method is similar to Time of Arrival using the time difference of arrival times. However the synchronization requirement is eliminated though high accuracy is still an important factor. As in the previous method inaccuracy in measuring time differences should not exceed tens of nanoseconds [2].

Power based wireless positioning method utilizes the signal attenuation property of the radio wave propagation to estimate location of a mobile device. One common approach employs surveying of signal strength information in a particular area. This information forms a database describing the *signal strength finger print* of that area. The database is later used to determine the location of a mobile device by a particular pattern matching algorithm [3]. However, such a method requires the time consuming survey procedure.

Another power based wireless positioning approach uses a path-loss model to estimate the relationship between the signal strength and distance from transmitters. The estimated distances from three or more transmitters are used to trilaterate the final position of the device, [4]. This is the wireless positioning method that has been explored in details in this paper. In the next section, we revisit the characteristics of the IEEE 802.11b WLANs. Section III discusses the indoor path loss model, followed by the introduction of our proposed enhancement to the path loss model in Section IV. Applications and benefits of our proposed model are discussed in Section V.

II. THE IEEE 802.11 WLAN ENVIRONMENT

The IEEE 802.11 is one of the most utilized WLAN technologies. The standard defines both physical and MAC

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layer protocols [5]. The standard delineates both ad-hoc and infrastructure topologies. The 802.11b specification is the focus of this project since it is most commonly deployed. This version has a link rate of 11 Mb/s [6]. IEEE 802.11 defines the maximum transmit power at 1 W and antennae gain is limited to a maximum of 6 dB.

The maximum defined transmit power results in a cell size of tens of meters indoors and over a hundred meters outdoors. Therefore the previously described CI method is very inaccurate using this technology. Numbers of overlapping WLAN cells should improve accuracy. However overlapping cells are unlikely due to high network throughput, relatively high price of AP and a narrow frequency band which allows only three networks or APs to exist without interference [7].

IEEE 802.11 defines a synchronization function that keeps timers of all terminals synchronized. In the infrastructure topology, all terminals synchronize to the AP clock by using the timestamp information of beacon frames. The timer resolution is 1 µs, which is too inaccurate for time based positioning. In addition, the synchronization algorithm of 802.11 maintains synchronization at the accuracy of 4 µs which is also inadequate for time based positioning [6].

The default MAC protocol operation in IEEE 802.11 is based on a carrier sense multiple access with collision avoidance (CSMA/CA). To implement this protocol the physical layer measures the RF energy at the antennae and determines the strength of the received signal. The IEEE 802.11 standard specifies the Received Signal Strength Indicator (RSSI) that is the measure of the RF energy received by the radio. RSSI up to 8 bits (256 levels) are supported, but the absolute accuracy is not specified [5].

III. The Indoor Path Loss Model

This paper presents power signal based positioning method. However these power signals are complex radio waves whose aspects are described below.

A. Challenges in power based positioning

The many properties underlying electromagnetic wave propagation can be attributed to reflection, diffraction and scattering. The free space propagation model is used to predict received signal strength when the transmitter and the receiver have an unobstructed line-of-sight (LOS) path between them. The received signal power is well known and decreases with the square of the distance. However in many practical situations, indoor and outdoor, there is no LOS path between transmitter and receiver.

When a radio wave encounters another medium with different electrical properties, the wave is partly reflected and partly absorbed. The reflection coefficient is a complex function of the material properties and generally depends on the wave's angle of incidence, frequency and polarization. Diffraction allows the signal to propagate behind obstructions. Although the received signal energy decreases fast when moving deeper into the shadowed region, the diffraction component still produces a useful signal. The higher the frequencies used for wireless communications, the rougher the illuminated surfaces look from the wave's point of view. Instead of a single reflection, the energy then is spread out in all or at least many directions. This process is called scattering and is well known from radar techniques [8].

In real world situations, many objects, still and moving ones, produce reflections, diffraction and scattering. Attenuation of the signal is not only a factor of distance, but also of the obstacles between the transmitter and receiver. Even when position is not changed the signal strength can drop 2-3 dB. People moving in a room also affect signal strength. Multi-path propagation may result in dead spots where no signal can be received. These should be eliminated or minimized as much as possible, by choosing appropriate positions for the transmitters. Transmitters should be kept as far from each other as possible [8].

Thus RSSI measurements are sensitive to multi-path, fading, non line of sight measurements and diffraction. The errors inherent to the RSSI values affect the distance estimates once a path loss model is applied.

B. Revisiting Hata-Okumara model

Many researchers have shown, that propagation obeys to certain models, from which the log-distance model is one of the most simple. The following equation describes the large scale behavior of a propagation link quite well.

$$\log d = \frac{1}{10n}\left(P_{TX} - P_{RX} + G_{TX} + G_{RX} - X_{\alpha} + 20\log\lambda - 20\log(4\pi)\right) \tag{1}$$

In (1), d is the estimated distance between the transmitter and the receiver. P_{TX} (dBm) is the transmitted power level and P_{RX} (dBm) is the power level measured at the receiver. G_{TX} (dBi) is the antennae gain of the transmitter. Similarly, G_{TX} (dBi) is the antennae gain of the receiver. Also λ (m) denotes wavelength of the signal, n is a measure of the influence of obstacles like partitions, walls and doors. X_{α} is a normal random variable with a standard deviation of α [9].

The middle frequency of the 802.11b channel is 2442 MHz, and thus λ can be safely estimated to be 0.12m [4]. The standard deviation of X_{α} is in the range of 3 dB up to 20 dB, depending on building construction and the number of partitions the signal has to travel.

For free space, n equals 2, but for obstructed paths in buildings, n is between 4 and 5 giving a much smaller communication range for the same settings. Usually a simple prototype is developed to estimate the parameter n and to check that the values of antennae gain are as expected from the hardware documentation.

IV. Path Loss and WiFi Positioning Design

Empirical investigation has been a common methodology for the study of radio wave propagation and path loss modeling. Our research approach follows this methodology. A series of empirical studies are conducted to investigate the indoor path loss characteristics. Based on the results, we propose an enhancement for distance estimation given RSSI values. We also show the application of this enhancement to the WiFi positioning system.

A. *Distribution of the RSSI*

Since the RSSI value may fluctuate even while stationary (due to environment variables), the variation of the RSSI values was our first study. This was done by collecting a large number of RSSI samples from a single router to study the variation of the RSSI values. Though the standard deviation of the values was measured of the range 1.8 dB, the difference between the minimum and maximum RSSI values was large - up to 25 dB. The frequency distribution is shown in Fig. 1.

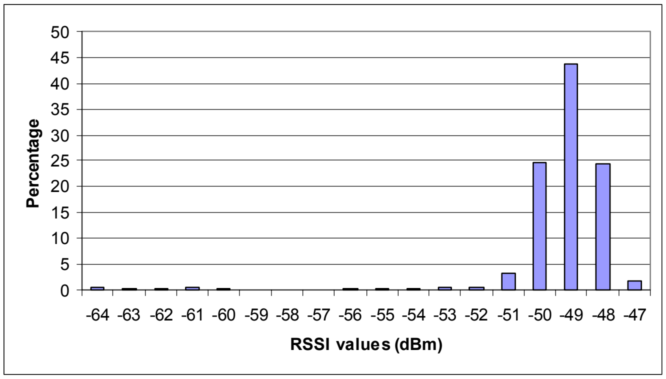

Figure 1. Frequency distribution of RSSI (LOS)

Thus, it can be seen from Fig. 1 that when large samples of signal strength values are collected over time the values have an approximate normal distribution. The results are left-skewed but for our purpose, it can be considered to be normally distributed. The results of these experiments are consistent with previously conducted experiments. It was found that the majority of the distributions in a LOS environment are slightly left-skewed [10].

The distribution of the RSSI values in a non LOS environment was also measured. In this case the stationary device was not visible to the mobile device. This was a particularly noisy environment. The frequency distribution of the RSSI can be seen in the figure below.

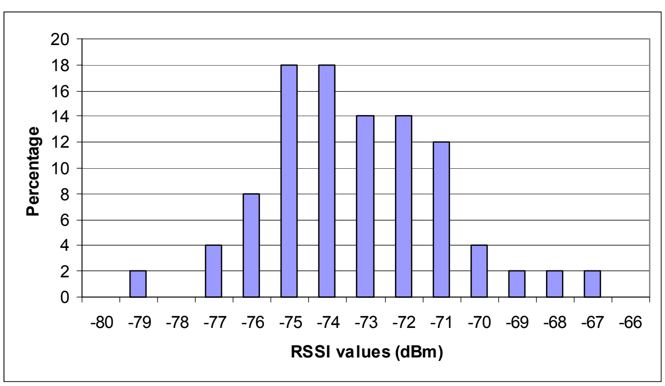

Figure 2. Frequency distribution of RSSI in (non LOS)

From Fig. 2, it can be seen that even in a noisy environment the samples follow a normal distribution and the left skew of the previous LOS distributions has decreased to a large extent. This implies that in a non LOS environment, RSSI distributions follow a normal distribution more closely. This result has been described previously in [10]. RSSI distributions are only slightly left skewed when the mobile device is at a significant distance from the transmitter and do not have a direct line-of-sight. Thus measurements in [11] report a normal distribution of RSSI values in an office environment where measurements are taken with no line of sight path.

The RSSI readings follow most natural phenomenon that can be described by normal distribution. This is due to the fact that these phenomena depend on a variety of independent factors. Similarly the RSSI value depends on the interference of multi-path signals, scattering, diffraction, obstruction by people and equipment. The combination of this variety of factors gives the RSSI value a normal distribution. Based on this fact and the results of our site survey, the normal distribution of RSSI values is a valid assumption.

B. *Relationship between RSSI and distance*

The initial study conducted involved setting up a single router in a lab and collecting RSSI samples while slowly moving away from the router. Samples at each position were collected in all orientations to cancel the effects of multi-path propagation. The experiment was conducted in a line of sight environment. The samples showed a trend of the RSSI decreasing with distance as is expected.

Antennas of a stationary device and a mobile device were placed on the same height. The distance between the antennas was increased step by step from 0.0 m to 18.0 m. The size of the step was 0.5 m. For each of the 36 distances a mobile device measured RSSI values of a stationary device 80 times.

The mean and the standard deviation of RSSI at each position are shown in the following figure.

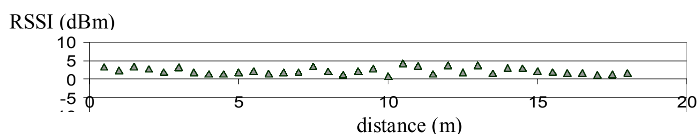

Figure 3(a). Standard deviation of measured RSSI

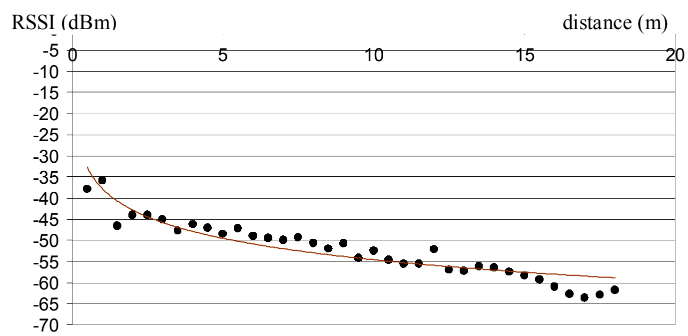

Figure 3(b). Mean of measured RSSI

Every value in Fig. 3(a) corresponds to standard deviation of the RSSI values collected at that position. It is observed that the variance of the signal at each position does not vary significantly with distance compared to the mean, shown in Fig. 3(b).

As expected from the Hata-Okumura radio propagation model the signal strength value shows an exponential decrease with respect to the distance [9]. The curve in Fig. 3(b) represents the mean of the RSSI values at a certain distance. The error in signal strength measurements results from multi-path propagation caused by reflections as discussed previously. The RSSI function of the WLAN adapter may also cause some unreliability.

C. *Tuning the Parameters of the Pathloss Model*

The RSSI values at each position were collected for a range of distances from the stationary device. These values were used to tune the parameters in the signal propagation model.

The key unknown in the path loss model in (1) for our application is the quantity n. Here, we seek empirical study to find n that gives accurate path loss estimation. The empirical results are presented in Fig. 4 where we plot distance versus RSSI according to (1) with various n values. We further plot the actual distance (in thick line) at each time of RSSI recording.

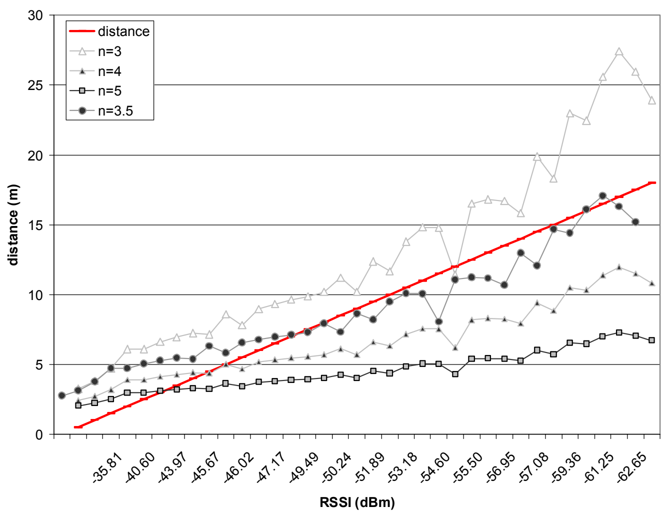

Figure 4. Distance trend lines

Based on Fig. 4, n=3.5 seems to be the appropriate choice for the path loss model for most of the RSSI readings. The values of G_{TX}, G_{RX}, the antennae gains, were tuned so that the model corresponded the measurements as precisely as possible. As expected by hardware documentation [5], antenna gains seemed to be of the range 2.5-3 dBi. For our prototype we estimate the gain at 2.5 dBi.

This model was developed in a line of sight environment. But in a typical indoor environment it is unlikely that the mobile device would be visible to the stationary access points. It is likely that the parameter n of the signal propagation model in (1) would need to be increased to account for a non line of sight environment, where there are typically obstructions such as doors and walls.

Also when we carefully examine Fig. 4, it is observed that for closer distances, the value of the distance is overestimated to an extremely large extent. Thus, to take care of this inaccuracy, we propose a multi model approach for the indoor path loss modeling.

D. *Modeling a two-function path loss model*

Rather than building a new path loss model, we choose to re-parameterize (1) for the indoor path loss model. From the empirical results we found that at closer ranges the n factor of the propagation model would take a higher value. Thus at this stage a dual path loss model is proposed. At closer ranges a different model would be used than for ranges greater than 5m. This is driven by the need to make the signal propagation model as accurate as possible since as mentioned previously a small difference in the RSSI value can make a significant difference to the distance estimate. A similar multi model approach has been suggested in [7] for differences between a LOS and non LOS environment.

In our proposed solution we also split the signal propagation model in two parts. Based on the empirical data in Fig. 4, a model is suggested for distances less than 5m and a separate model for distances greater than 5m.

For distances less than 5m the estimated n is 5 which gives the least erroneous distance estimate. The higher value of n is estimated using Fig. 4 and may be caused by multi path interference. For distances greater than 5m we estimate n to be 4. The n value for greater distances is slightly increased from the observed value in Fig. 4 to increase the accuracy of the model in a non LOS environment, since the study was conducted in a LOS environment. The LOS values are used to estimate the model for closer ranges since it is likely that at closer ranges the mobile device and the stationary device would be visible to each other.

However in a real life scenario the position of the mobile devices relative to the stationary device is not previously known and is in fact the parameter that is to be estimated. Therefore using the empirical data that has been collected the signal strength corresponding to a 5m distance between the mobile and stationary device is used. For the lab environment this threshold value corresponds to – 49 dBm.

While the positioning application of the mobile device encounters a signal strength value stronger than or equal to – 49 dBm from a transmitting device, it uses Model A with n = 5 to estimate its distance from the transmitter. If however the signal strength value is weaker than – 49 dBm the distance estimated is according to Model B with n = 4.

V. Discussion of Results

Using the proposed path loss model, we add trilateration algorithm to estimate the location of a mobile device in a two dimensional plane. The experiments were conducted in two kinds of the environment in the lab. The first phase of experiments was conducted in a purely line of sight environment. Therefore all the stationary devices would be visible to the mobile device, and the signal would not be obstructed to a large extent. Later experiments were conducted in a non LOS environment. We consider four stationary devices in all our experiments.

A total of 20 experiments were conducted in a LOS environment. The average error of the results was 2.3m. This is a relatively low error which can be attributed to the fact that all the stationary devices were visible to the mobile devices, and thus the signal strength values were less affected by unpredicted obstructions. The RSSI values were generally higher and thus Model A was used typically. The setup of this experiment is illustrated in Fig. 5.

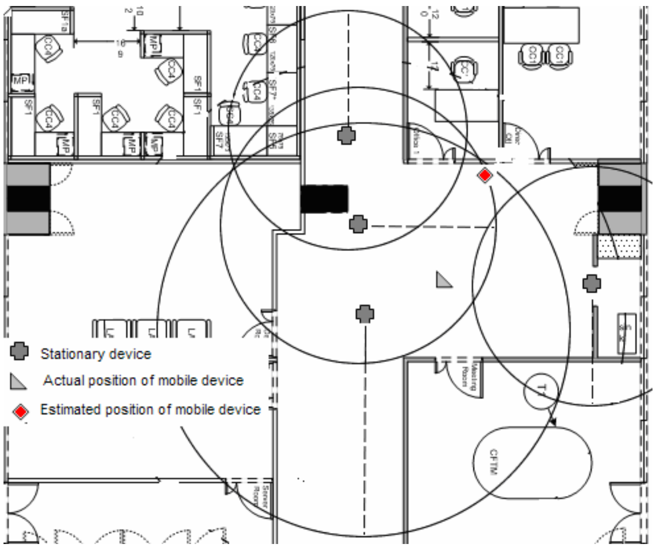

Figure 5. Example of a LOS experiment

However there were cases where the distance was overestimated since a low value of RSSI lead to Model B being used for distance estimation. Due to the relative close proximity the overestimated distance skewed the results to a large extent.

In a non LOS environment similarly 20 tests were conducted. The average error of the results obtained was 2.9m. The non LOS router configuration was such that a router was kept in four different rooms. Thus while testing inside the rooms; the probability of finding one router which would be in line of sight was quite high. Hence in many cases the distance from one router was estimated using Model A, whereas the distance from the rest three routers were estimated using Model B. This increased the accuracy of the final position estimates.

Thus, the accuracy of the measurements, apart from the accuracy of the positioning prototype, it is also due in part to the strategic positions of the stationary devices.

VI. Conclusion

The positioning prototype developed in this project showcases the use of an innovative signal propagation model to provide a high degree of accuracy in estimating the position of a mobile device in a wireless ad-hoc network. The dual signal propagation model implies that the system can adjust to a non line of sight environment to a large degree at larger distances, even though the typical case considered is that of a line of sight environment. The minimal sampling and high noise threshold ensures that the prototype can be used in real time applications.

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