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Empirical Investigation of the Effect of the Door's State on Received Signal Strength in Indoor Environments At 2.4 GHz

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***Abstract*—Due to the wide deployment of indoor wireless local area networks (WLANs), the indoor planning became a research of interest for IT as well as networking researchers. As a result of this wide deployment, many IT applications and services started relying on the ready implemented WLAN infrastructure. Therefore, there is a need for reliable propagation models which are able to predict the WLAN signal strength in indoor environments before starting the real world deployment which leads to an efficient and cost aware deployment process. In this paper we develop an empirical propagation model which focuses mainly on the effect of the door state on the propagated WLAN signal in indoor environments. The measurements were compared to other simulated results in literature. A new empirical parameter based on empirical measurements was introduced for a better estimation of the received signal strength (RSS).**

I. Introduction

Due to the rapid increase of WiFi indoor deployments, indoor wireless communications became a tremendous technology [7]. Therefore, there is a need to study the behavior of WiFi waves propagation in indoor environments. The complex structure of buildings and the layout of the rooms are the main factors that control the wave propagation in indoor environments. These factors create a multipath effect [7] where at the receiver, multiple signals are received with different strengths. Reflection, Scattering, and Diffraction are the main three propagation mechanisms [5].

A propagation model is a set of equations or algorithms that are used to calculate either the received signal strength (RSS) at the receiver or the path-loss power between the transmitter and the receiver. The propagation model calculates the received signal strength based on propagation mechanisms and the attenuation factors in a given environment. Indoor propagation models can be divided into 4 categories: deterministic, empirical, semi-deterministic, and semi-empirical models.

Deterministic, also called physical models, are used to calculate the received power at certain points using algorithms that simulate the propagation mechanisms. They make use of the laws and principles of physics in order to obtain realistic propagation models. The physical layout of the environment is taken into account when building the data for the received signal. These models can be either site specific or not site specific. A physical and not site specific model uses physical principles of electromagnetic (EM) wave propagation to predict signal levels in a generic environment in order to develop some simple relationship between the characteristics of that environment and propagation. Site specific channel model uses, in addition to the laws of EM waves, some techniques to map the real propagation environment into the model propagation environment. Ray tracing is one of the most used techniques in physical and site specific models especially for indoor propagation environments. Examples for Deterministic models are Ray optical propagation models [4] and Finite Difference Time Domain [8]

Empirical models represent models which are developed based on empirical measurements as the name implies. The basic idea of empirical models is to experimentally build a database of measurement data and to use this database to extract the relationship between the propagation environment and the expected received signal strength. In this technique, a lot of experiments should be conducted in the field in order to collect an efficient amount of measurement data which then can be used to derive the propagation model. The parameters used in these models are based on measurements and probabilistic relations. Empirical models need a calibrating phase where a lot of time is needed for taking large number of measurements. Therefore, the parameters of the empirical models can be used to calculate the signal strength at different environments if and only if they have the same structure and layout. One-slope and log-normal shadowing models are two examples of the empirical models [7].

A semi-deterministic model uses algorithms and empirical parameters to calculate the received signal. Compared to deterministic models, semi-deterministic models have higher computational speed but lower accuracy. The dominate path model [10] and motif model [6] are two different semi-deterministic models that simulate the resultant behavior of the waves.

Semi-empirical models are based on empirical equations which leads to a higher computational speed. Unlike the empirical models, semi-empirical models take into account the layout of the environment.

Our target is to improve the accuracy of semi-empirical and semi-deterministic models by taking into consideration the effect of opening and closing the doors in indoor environments even if there is a clear line of sight (LOS) between the transmitter and the receiver.

Our paper is organized as follows: In Section II, three different empirical models are illustrated as a background of our work. In Section III, we discuss briefly the results of other research efforts which studied the effect of doors on the wave propagation using semi-deterministic models. In Section IV we present our concept of the new propagation model. In Section V, we explain our the measurement process. The results are shown and analyzed in Section VI. We conclude the paper in Section VII.

II. Empirical Propagation Models

The basic idea of empirical models is to experimentally build a database of measurement data and to use this database to extract the relationship between the propagation environment and the expected received signal strength [10]. In this technique, a lot of experiments should be conducted in the field in order to collect an efficient amount of measurement data which then can be used to derive the propagation model. The methods of parameter estimation are used in order to find out an appropriate function which is fitted to the measurements. One critical point in this technique is the validity of the model for other transmission frequencies or environments. Usually additional measurements in the new environment and new frequency should be done in order to fit a certain model to this environment/frequency. In the following sections we present a group of the state-of- the-art Wi-Fi empirical models which have been presented in the recent publications.

A. One slope model

The One-Slope model is a fast and very simple way to predict the mean signal strength within an indoor environment without having a detailed knowledge about the layout of the environment. The path loss in dB is only dependent on the distance between the transmitter and the receiver:

$$L_{one-slope} = L_0 + 10nlog(d) \quad (1)$$

where L_0 in decibel is the path loss for $1m$, n is the power decay factor (path loss exponent) which defines the slope, and $d(m)$ is the distance. L_0 and n are experimental parameters which have different values in different environments. The value of the path loss exponent n is mainly dependent on the type of the buildings and the different materials composing the indoor environment. It is the main factor in the determination of the radio coverage. As an example, n = 2 in the free space. The penetration effect of multiple walls and multiple doors is modeled implicitly by increasing the power decay factor n. A more general model which is derived from the one-slope model is the two-slope model. In this model the path loss exponent is changing when the transmitter-receiver distance is greater than a defined break distance.

B. Motley Keenan Model

Motley Keenan model is more complicated than the one slope model but it gives more successful predictions. This model explicitly handles the presence of multiple walls and floors in the environment depending on their thickness and material. The path loss exponent is fixed as 2, like in free space, and additional loss factors are added in order to model the penetration loss of walls and floors intersecting the line of sight between the transmitter and the receiver. The path loss in dB is given by:

$$L = L1 + 20logr + n_f * a_f + n_w * a_w \quad (2)$$

Where $L1$ is the loss for 1m distance, r is the distance between the terminals, a_f and a_w are the attenuation factors (in decibel) per floor and per wall, n_f and n_w are the numbers of floors and walls respectively. The loss components of walls and floors are linear which means that the walls or floors from the same category add a constant delay to the path loss even if the signal has penetrated other walls or floors from the same type before. Recent measurements and simulation results indicate that the penetration loss of multiple walls or floors is not linear with the number of walls/floors. There is a nonlinear relation which makes the Motley-Keenan model not a precise model.

C. COST 231 Multi-Wall Model

The COST 231 Multi-Wall model of propagation within indoor environments uses a linear component to predict the penetration loss of multiple walls, but assumes a nonlinear dependence between the total penetration loss of multiple floors and the number of penetrated floors. A complex formula is added in which the penetration loss of floors increases more slowly as the signal goes through more floors after the first floor. The total path loss model (in decibels) is given by:

$$L_T = L_F + L_c + \sum_{i=1}^{w} L_{wi}n_{wi} + L_f n_f^{((n_f+2)/(n_f+1)-b)} \quad (3)$$

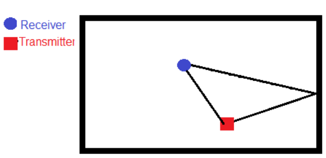
L_F represents the loss of the free space for a straight-line (direct) path between the transmitter and receiver, n_{wi} is the number of walls of type i which have been penetrated by the direct path, w is the number of different wall types, L_{wi} is the loss caused by a wall of type i, n_f is the number of floors which have been penetrated by the path and L_f is the loss caused by the floor. The constants b and L_c are experimentally coined depending on the environment. From the formula above it is clear that the additional loss per floor decreases with increasing number of floors.

III. Impact of Time Variance

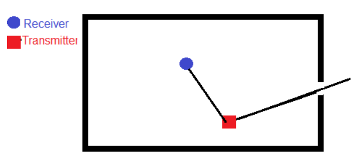
The main target of [9] was to investigate the inaccuracies of database to the prediction results using semi-deterministic models. Dominate path model and accelerated 3D ray tracing model were used. The ray tracing model was based on database preprocessing. In the preprocessing phase the environment is divided into tiles and the prediction grid is subdivided into receiving points. Then possible paths are computed via different algorithms for reflection and diffraction, and the RSS is calculated based on values in the database. Due to movements in indoor environments, time variance was required for the database. In the investigation, time variance was simulated in opening and closing doors states. Both algorithms proved that opening the doors will cause slow fading.

IV. The Concept of the New Model

Up to our knowledge, the previous work has not examined the effect of the state of the doors (whether opened or closed) on wave propagation in indoor environments. They only considered the effect of doors as obstacles blocking LOS, yet the RSS inside the same room will also vary based on the door's state. Therefore, these models are not able to provide an accurate prediction of the signal strength inside a room.
To demonstrate this effect, a top view for a room in two different cases is shown in Fig. 1. In the closed door room



(a) closed door



(b) opened door

Fig. 1: Top view for reflected rays within the same room

as shown in Fig. 1a, there exists two different rays (direct ray between the transmitter and the receiver, and a reflected ray from the door). These two rays are added together at the receiver which results in either a constructive or a destructive interference.
In the second case in which the door is open as shown Fig. 1b, only one ray reaches the receiver which results in a different RSS value. In real life, there are multiple of reflected rays and only one direct ray. These reflected rays will certainly affect the RSS inside the room and should be taken into consideration when studying the signal propagation in indoor environments. Since the error in RSS could be severe in some applications, our target was to come up with a statistical model based on empirical measurements which takes into consideration the effect of the door's state when predicting the signal propagation in an indoor environment. This model could be later used to increase the accuracy of semi-empirical or semi-deterministic models.

V. Measurements

Measurements were held in two neighboring rooms at the Auditorium and Media Center (HMZ) in the Darmstadt University of Technology. During the evaluation, the two rooms were named room 'A' and room 'B'. The dimensions for room 'A' are 5.4 m x 5.5 m x 3.8 m, while the dimensions for room 'B' are 4.23 m x 5.5 m x 3.58 m. In other words, Room 'A' has a larger size than room 'B' as the two rooms have the same height and length but they differ in width. The layout of the two rooms is shown in Fig. 2. In each of them, one wall is made of glass and the other three lateral walls are made of concrete. Each room has one door made of wood.

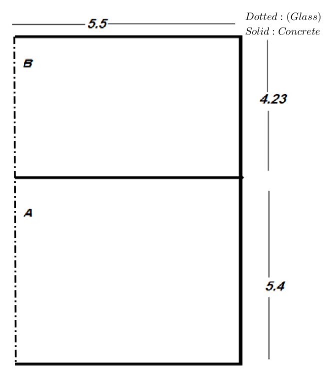


Fig. 2: Top view for Rooms A and B

During the measurements, both of the rooms were completely empty i.e. neither furniture nor people were inside. The transmitter was a wireless router of type "LINKSYS WRT54G v7" with a transmition rate of 54 Mbps [2]. It is supported with two external antennas for data communication and diversity. The installed firmware was "dd-wrt" which was configured to transmit at transmitting power of 20 mw. As a receiver, we used a laptop with an "Intel(R) WiFi Link 1000 BGN" [1]WLAN card. 'Homedale' software [3] was used to record the RSS measurements.

Inside both of the rooms, the transmitter has been placed at a height of 3 m from the floor. Furthermore and as shown in Fig. 3, it was placed at distance 0.65 m from the wall opposite to the glass wall, and 0.75 m from the nearest side wall to the transmitter.

To calculate the distance from the transmitter to a specific measuring point , Pythagorean equation in 3D was used

$$d = \sqrt{(length - 0.65)^2 + (width - 0.75)^2 + h^2} \qquad (4)$$

where

h : is the height between Tx and Rx in room 'A' and 'B' and =2.5
$width$: is max at 5.4 in room 'A' and max at 4.23 in room 'B'
$length$: is max at 5.5 in room 'A' and room 'B'

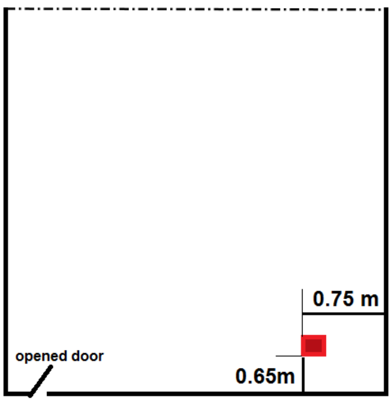


Fig. 3: Top view for transmitter's location: The transmitter is the red rectangle. It lies at a distance 0.75 m from the nearest side wall and 0.65 m from the back wall while the Rx height is 0.5 m

Two cases were tested twice. The two cases are Line of Sight (LOS) where transmitter and the receiver are at the same room, and Non Line of Sight (NLOS) where the transmitter and the receiver are at two different rooms. That yields four different case scenarios:

- LOS 'A' : Tx and Rx are in room 'A'.
- LOS 'B' : Tx and Rx are in room 'B'.
- NLOS 'A': Tx in 'B' and Rx in 'A'.
- NLOS 'B': Tx in 'A' and Rx in 'B'.

15 receiving point were chosen to cover almost the whole room. While collecting the measurements, the door was opened and the RSS readings were recorded, then the door was closed and RSS readings were recorded again before moving to another receiving point. The number of recordings per a receiving point were not less than 80 recordings to get the average of all recordings and make the results accurate as much as possible. By the end of the measurements, each receiving point had a correlation not less than 0.9 with its recordings.

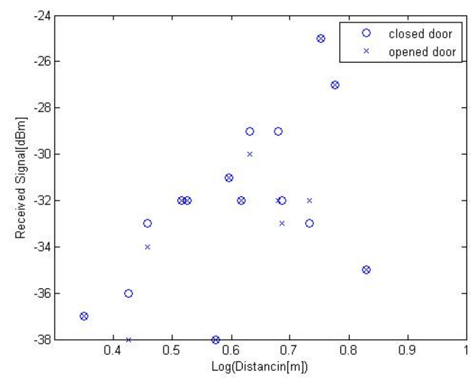
VI. Results and Analysis

As a first step we measured the effect of room size on the signal propagation using path-loss exponent for each room separately in both LOS and NLOS cases. The path-loss exponent for the two rooms is given by Table I. The close values in path-loss exponent show that all four cases will have a similar behaviour only at short distances. The increase in path-loss exponent in NLOS cases is due to the implicit addition of the separating wall in the path-loss exponent. The attenuation factor for concrete wall was measured explicitly and was equal to 8 dB.

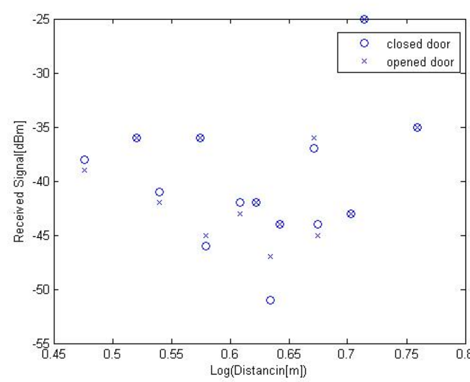
TABLE I: Path-loss exponent in the four cases

	Tx in room 'A'	Tx in room 'B'
Rx in room 'A'	1.97	1.6
Rx in room 'B'	2	1.5

As a second step we studied the effect of door's state (whether opened or closed) on the signal propagation in LOS and NLOS cases. As shown in Fig. 4 and Fig. 5, it was observed that the doors' state has a significant effect on the received signal strength. The signal strength was changed at some measuring points while at other points no change happened.



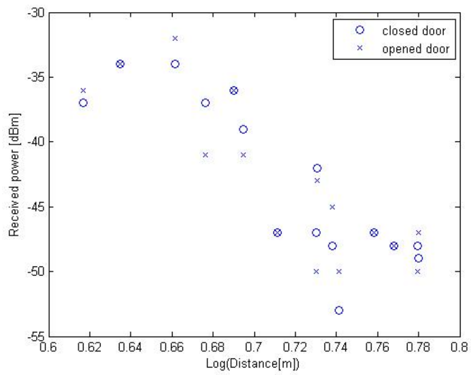
(a) LOS 'A'



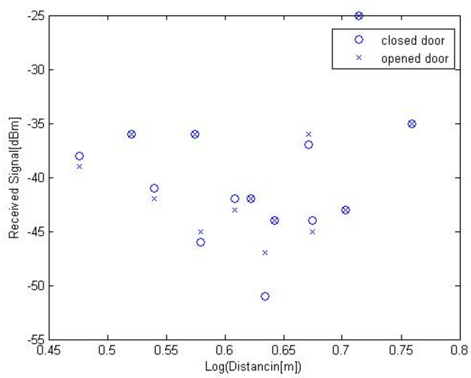
(b) LOS 'B'

Fig. 4: Measurments before and after opening the doors in the 4 scenarios

At some receiving points the effect of the door's state was significant as the rays reflected from the doors either caused a constructive or a destructive interference. For example in Fig. 4b, the difference between the received signal before and after opening the door at log(0.54 meter) was +1 dB, while the received signal at log(0.57 meter) was -1 dB. On



(a) NLOS 'A'



(b) NLOS 'B'

Fig. 5: Measurments before and after opening the doors in the 4 scenarios

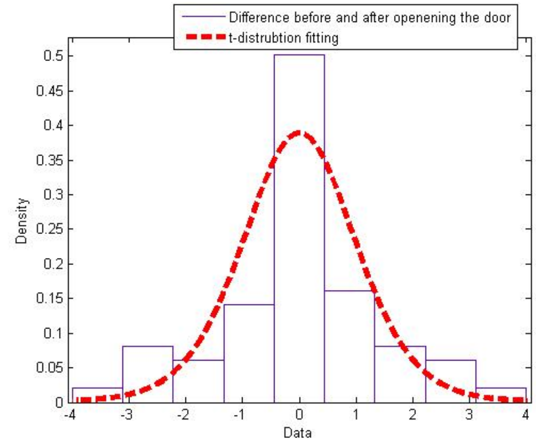


Fig. 6: Histogram of the door's effect vs. T-distribution

the other hand, there were other receiving points where the door had no effect as the rays reflected were attenuated due to multiple reflections till reaching the receiving point, i.e. they had insignificant value. This can be shown in Fig. 5a at log(0.71 meters) where the difference between the received signal before and after opening the door is 0 dB (i.e. both received signals were -47 dB). It is obvious from Fig. 4 and Fig. 5 that doors' state will affect the received signal strength regardless it is in LOS or NLOS.
In order to increase the accuracy of semi-empirical models, the effect of doors was represented by a random variable χ_d. To find out the properties of χ_d, a histogram was drawn using Matlab in Fig. 6.

The mean value was 0.03 dB with a variance of 3.5. T-test is used when the degrees of freedom in any statistical analysis is on tens units (i.e. less than 100). Therefore, t-test with 59 degrees of freedom was used and it validated that the χ_d distribution follows a normal distribution with zero mean and 5% significance. The significance value reflects that the data distribution is highly probable or reliable. In other words, there is a 95% chance being true. The χ_d could be used in some weighted network planning algorithms that rely on link quality. Unlike what was simulated in [9], the effect of doors' states is close to a shadowing effect than a slow fading. A possible explanation for the error in [9] is that in the preprocessing phase, the size of the tiles was large (or not small enough) to trace the effect of the constructive links (rays). It is expected that the effect of constructive links will appear as the size of tiles decreases. However, this will increase the computation time losing the advantage of speed. Therefore, it is a trade off between accuracy and speed. Skewness and kurtosis for χ_d were -0.083 and 3.5. Based on the t-distribution analysis, it is expected that the histogram will follow a normal distribution (skewness=0 and kurtosis=3) as the number of degrees of freedom approaches infinity.

VII. Conclusion

Our main goal in this paper was to study and analyze the effect of the doors' states on the signal propagation in indoor environments. Experimental results have shown that doors' states have a significant effect on the RSS in indoor environments. Instead of applying deterministic models with complex algorithms and low computational speed, an empirical parameter was modeled. The proposed empirical parameter increases the accuracy of estimated RSS by taking the door's effect into consideration. This investigation is expected to be of great importance to WLAN network planning as well as many real time applications whih started to rely on WLAN such as indoor localization.

Acknowledgment

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