Investigation of Three Dimensional Empirical Indoor Path Loss Models for Femtocell Networks

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Abstract. Femtocell which is a home access point that installed by end consumers inside their houses is an important parameter and a promising technology in future wireless networks. It is proposed as a solution to the indoor propagation problems and to increase the indoor bandwidth. However, many challenges need to be addressed before deployment of femtocell. One of these challenges is the indoor propagation. Most of the available models are for long range communication like macro and micro cellular networks. Models for femtocell networks where the effects of walls and floors are appeared are necessary. In this paper eight different models of indoor propagation were studied and compared with measured data. Measurements were conducted in three story building. Four different scenarios with different numbers of penetrated walls and floors were considered. The results were statistical analysed by calculating the average error and the error standard deviation.

1. Introduction
Femtocells provides a scalable and cost efficient solution to overcome the dramatically increase in the demand of indoor wireless bandwidth. As the deployment of femtocells increases [1], it is necessary and very important to predict the effects of the new deployment on existing and adjacent networks. Moreover, it is important for energy consumption and frequency reuse techniques to calculate the minimum required power to transmit from a given femtocell at a given frequency, and in the same time provides acceptable coverage to the served users. During the signal propagation between the transmitter and the receiver, the signal strength degrades due to the interaction with the surrounding environment which is called path loss. Therefore, predicting the path loss is important in order to evaluate the wireless communication system. Moreover, path loss is a significant parameter that really curbs and reduces the efficiency and the coverage of the cellular networks.

In literature different types of propagation models were proposed. Most of the proposed models are for outdoor environment and for long rang networks like macro and microcellular networks. According to Saunders [2], these models are not accurate enough to be applied in small cells like femtocell. In short range networks it is more accurate to consider more specific details in addition to the direct path between the base station and the user equipment (UE). In this case the number of floors and walls in addition to the furniture are severely curbing the signal strength. Some site specific models were proposed in the literature [3, 4]. These models are based on simulation, ray tracing and
finite difference time-domain technique. However, site specific models are memory and time consumption. Moreover, these models are not suitable for other scenarios with different topology. Therefore, general site models which are based real measurement and experiment are still widely used [5-11]. Recently researches discussed the indoor to outdoor propagation [12-14]. However, indoor to indoor propagation is more significant. Letourneux et al [15] and Lee et al [16] applied the Cost231 multi walls multi floors model for indoor path loss calculations.

In this paper eight different models of indoor propagation were studied and compared with measured data. Measurements were conducted in three story building. Four different scenarios with different numbers of penetrated walls and floors were considered. This paper is organized as follows: the open literature indoor propagation models are presented in the next section. Experimental setup is explained in Section 3. Section 4 shows a comparison between models and measurements. Finally, a conclusion is given in Section 5.

2. Indoor Path Loss Propagation Models

In the last decades many of indoor path loss measurements were carried out in different indoor environments, such as houses, corridors and offices. In this section, Indoor propagation models that are proposed in literature are presented, these models could be studied and discussed from different points of view such as slope, line of sight (LOS) or non line of sight (NLOS), one dimension or three dimensions. Some of these models considered the reference point at one meter for the indoor propagation and others are based on the free space losses (FSL). Next subsections discuss the available models: Cost231, multi walls multi floors (MWMF), ITU-R P1238, IEEE802.11, WINNER II, and ITU-R M2135.

2.1. Cost231 Models

This model was proposed based on real measurements conducted in European cities at two different frequencies 900 and 1800 MHz, then the model were scaled for other frequencies. Three different models for path loss were presented [5]. The Cost231 one slope model where the path loss is calculated as:

$$PL = L_0 + 10n \log(d)$$

where $L_0$ is the path loss (dB) at the reference distance which is one meter for indoor scenarios. It is calculated as in (2), $n$ is the power decay index, and $d$ is the distance between access point and UE in meter.

$$L_0 = 20 \log \left( \frac{4 \pi}{\lambda} \right)$$

The second model is Cost231 linear attenuation model which is expressed as:

$$PL = L_{FSL} + \alpha d$$

This model indicates that there is a linear relation between the path loss and the access point-UE distance. $L_{FSL}$ is the free space losses (dB) as in (4), $\alpha$ is the attenuation coefficient (dB/m), and $d$ is the distance between the access point and UE (m).

$$L_{FSL} = 32.4418 + 20 \log(d) + 20 \log(f)$$

where $f$ is the frequency in GHz and $d$ is the distance in meter.

The previous two models are not considering the numbers of penetrated walls and floors between the transmitter and the receiver as in the real scenarios. Therefore the Cost231 multi walls multi floors model (Cost231 MWMF) was proposed as follows:

$$PL = L_{FSL} + L_c + \sum_{i=1}^{l} K_{wi} L_{wi} + K_{f} \left[ \frac{k_f + \frac{2}{f} - 1}{k_f + \frac{2}{f} + 1} \right] L_f$$

In this model, the attenuation due to walls and floors is added to the free space loss, $L_c$ is a constant loss which determines from measurements results and it is close to zero [5], $K_{wi}$ and $k_f$ are the number
traversed walls and floors respectively, $L_f$ and $L_{wl}$ are the losses of penetrated walls and floors respectively, and $b$ is an empirical parameter.

2.2. The Multi Wall Multi Floor Model (MWMF)
This model is firstly proposed based on ray tracing at 5.2 GHz. Then it was verified using open literature results at different frequencies [6]. The path loss is expressed as

$$L_{MWMF} = L_0 + 10 \, n \log(\, d\,) + \sum_{i=1}^{J} \sum_{k=1}^{K_i} L_{wi} + \sum_{j=1}^{J} \sum_{f=1}^{K_f} L_{fj}$$

The difference between this model and the Cost231 model is the second term in the MWMF model where $n$ is determined between 1.96 and 2.03 while it is 4 in the Cost231 one slope model and 2 in the Cost231 MWMF model. Comparison between these models where $n$ is 4 was presented in [17]. In addition, The MWMF model shows a nonlinear relation between the traversed walls or floors and the penetration loss. $L_{wl}$ and $L_{fj}$ are the loss of $k^{th}$ wall and floor that has been traversed (dB), $K_w$ and $K_f$ are number of traversed walls and floors, $I$ is the number of wall categories, and $J$ is the number of floor categories.

2.3. ITUR P1238-7 Model
The ITUR P1238 model was proposed for a wide range of frequency, 900 MHz to 100 GHz [7]. Path loss is calculated as follows:

$$PL = 20 \log(\, f\,) + N \log(\, d\,) + L_f \,(\, n\,) - 28$$

where $N$ is the distance power loss coefficient, $f$ is the frequency (MHz), $d$ is the distance in meter between the access point and UE ($d > 1$ m), $L_f$ is the floor penetration loss factor (dB), and $n$ is the number of floors separate between the access point and UE. Since this model was proposed as a solution to the frequency reuse between floors, only number of floors is considered.

2.4. IEEE 802.11n Model
All the previous models could be defined as one slope models since only one value for $n$ is considered. This model defined a breakpoint (BP) distance where the path loss before this BP follows the free space loss $L_{FS}$ (slope of 2) as in (4) and after the BP the slope is increased up to 3.5 as [8]:

$$PL = L_{FS} \,(\, BP\,) + 10 \, n \log(\, \frac{d}{d_{BP}}\,)$$

The BP for the indoor scenario is 5 m.

2.5. WINNER II D112 V1.2 Model
The WINNER II channel mode was proposed for different scenarios of radio propagation such as indoor propagation, indoor to outdoor propagation, outdoor to indoor propagation, and outdoor propagation scenarios [9]. The model was applied at 2 and 5 GHz, then it was extended over frequency range 2-6 GHz. The model is divided to two parts, LOS part is presented as:

$$PL = 18 \cdot 7 \log(\, d\,) + 46 \cdot 8 + 20 \log(\, \frac{f_c}{5}\,)$$

The second part is NLOS is expressed as:

$$PL = 20 \log(\, d\,) + 46 \cdot 4 + 20 \log(\, \frac{f_c}{5}\,) + 12 n_w + F_L$$

$$F_L = 17 + 4 \,(n_f - 1)$$

where $f_c$ is the frequency in GHz, $d$ is the distance between the access point and the UE in meter, $n_w$ is number of walls, $n_f$ is number of floors. Equations (10) and (11) show that the relation of penetrated walls or floors and path loss is constant and linear. It is increased by 12 dB for each wall and 4 dB for each floor.
2.6. ITU-R M.2135-1/ 3GPP TR 36.814 Model
WIINER II model was modified and accepted by the ITU-R M.2135 [10] and the 3GPP for indoor femtocell scenario [11]. It was modified based on real measurement carried out in China [18-23]. The model is proposed for LOS as in (12) and NLOS as in (13).

\[
\begin{align*}
PL &= 16 \cdot 9 \log(d) + 32 \cdot 8 + 20 \log(f_c) \\
PL &= 43 \cdot 3 \log(d) + 11 \cdot 5 + 20 \log(f_c)
\end{align*}
\]

All previous models could be applied for three dimensional indoor environments. Next section is presenting the experimental setup where the measurements were carried out.

3. Experimental Setup
The measurements were conducted in three story building. The received power was measured continuously with one meter separation between two consecutive measurements. The experiment equipment in Figure 1 is including TP-LINK modem router and Dell Inspiron laptop in addition to free open source networks scanner which called “inSSIDer” that measure the received signal strength and display the information as graphs and numbers.

![Figure 1. Experiment equipments.](image)

The wifi access point was used instead of the femtocell since the femtocell works on licence spectrum and it is very difficult to order and deploy. LTE networks in Malaysia operate at 2.6 GHz. Therefore, there is no significant difference between using wifi at 2.4 GHz and the femtocell access point.

The building consists of three floors with 4.3m ceiling height. The first floor is including three rooms as in Figure 2, while the second and the third floors have different dimensions and layout as in Figure 3. The access point was fixed in the first floor one meter above the ground, centered between the left and right walls, and one meter distance from the rear wall. Then using the laptop, the received signal strength was measured and converted to the path loss as:

\[
PL = P_t + G_t + G_r - P_r
\]

where \( P_t \) is the access point transmission power which is 19 dBm, \( P_r \) is the received power at the UE terminal, \( G_t \) is the transmitter gain which is 3 dBi, and \( G_r \) is the receiver gain which is 1 dBi.
At each location 10 measurements were taken. Then the mean value of measurements at each point was compared with results obtained with the empirical models: Cost231, MWMF, ITU-R P1238, IEEE802.11, WINNER II, and ITU-R M213. After that the measurements were statistically compared with the empirical models as shown in next section.

4. Results and Discussions

The first scenario where is the access point and the UE are in the same room and LOS connection occurs between the transmitter and the receiver. The maximum distance is the length of the room which is 7.4m. The access point was one meter next to closest wall. The path loss exponent n for the Cost231 MWMF model is 4 [5] and for the MWMF model is 2 [6]. The distance power loss coefficient $N$ in the ITUR model equals to 28 [7]. The value of the attenuation coefficient $\alpha$ in Equation (3) is 0.62 [5].

Results of measurements as well as predictions of path loss are given in Figure 4. It is noticed that the measured data is higher than all models at the reference distance. Then it is close to the one slope model at $d$ equals 3 m. After $d$ equals 5 m, the Cost231 one slope, ITUR 1238 and Cost231 linear models are overestimating the measured data. The IEEE802.11 model is close to the measured data while the rest models are underestimating the measured path loss.
The results were statistically proved as in Table 1. Prediction error standard deviation for Cost231 linear model is the lowest between other models, which means it is the closest statistically. The positive mean for the Cost231 one slope model shows that the model is overestimating the average measured data by 1.41 dB. The rest of the models underestimate the average of the measured data by different values. The worst model in this scenario is the Cost231 one slope model since it has the highest error standard deviation with 4.685 dB.

Table 1. Statistical analysis of the first scenario

| Model                  | Mean  | Standard deviation | Error standard deviation |
|------------------------|-------|--------------------|-------------------------|
| Cost231 one slope model| 1.41  | 10.57              | 2.11                    |
| Cost231 linear model   | -5.22 | 7.70               | 1.54                    |
| Cost231 MWMF model     | -7.39 | 8.59               | 1.72                    |
| ITUR 1238 model        | -4.31 | 8.01               | 1.60                    |
| ITUR 2135 model        | -8.40 | 9.11               | 1.82                    |
| WINNER II model        | -7.56 | 8.58               | 1.72                    |
| MWMF model             | -7.39 | 8.59               | 1.72                    |
| IEEE802.11 Model       | -6.93 | 8.53               | 1.71                    |

In the second scenario, the access point and the UE are in the same floor where the UE is moving from LOS connection to NLOS connection with maximum three walls. The maximum distance is the length of the floor which is 23.85 m. $n$, $N$ and $\alpha$ are same as in the first scenario. $L_w$ for Cost231 MWMF model is 6.9 dB [5]. $L_{w1}$ and $L_{w2}$ in the MWMF model are 16 and 14 dB respectively [6]. Figure 5 shows the results for the measured data and the prediction models. The effects of walls in this scenario are clear enough in the figure. The path loss at the reference distance still 13 dB higher than the predicted models as in the first scenario. Linear, ITUR 1238, IEEE802.11 and ITUR 2135 models are close to each other but none of them is fitting the measured data. The closest model to the data is the WINNER II model.
Table 2 shows the statistical data for the measurements and the empirical models. The mean values indicate that all models underestimate the average of the measurements. The error standard deviation reading proved that the closest model to the measurement is the MWMF model followed by WINNER II model and Cost231 one slope model.

Table 2. Statistical analysis of the second scenario

| Model                  | Mean  | Standard deviation | Error standard deviation |
|------------------------|-------|--------------------|--------------------------|
| Cost231 one slope model| -0.22 | 9.77               | 0.51                     |
| Cost231 linear model   | -12.07| 15.49              | 0.82                     |
| Cost231 MWMF model     | -10.74| 13.19              | 0.69                     |
| ITUR 1238 model        | -12.21| 16.52              | 0.87                     |
| ITUR 2135 model        | -15.47| 17.88              | 0.94                     |
| WINNER II model        | -4.40 | 8.63               | 0.45                     |
| MWMF model             | -0.83 | 8.45               | 0.44                     |
| IEEE802.11 Model       | -14.38| 17.55              | 0.92                     |

In the third scenario, the access point is located in the first floor one meter above the ground as in the first scenario while the UE is moving in the second floor. One floor and some cases one wall are considered in the path loss calculations. The following parameters are considered: n for one floor is 4 [5], N is 28, α is 0.62, L_f in Cost231 MWMF model is 18.3 dB, and L_{f11} in the MWMF model is 19 dB [6].

Figure 6 shows that five of the models are close to each other but below the measured data. Two models are close to the data which are Cost231 one slope model and MWMF model. Lastly, the linear model is far and overestimates the measurement. In this scenario, the minimum distance between the transmitter and the receiver is 4.3 m. Therefore the difference between the measurement and the predicted results at the reference distance did not rise.
The third scenario statistical analysis results are presented in Table 3. It is confirmed that the only model that overestimates the measurements is the linear model while the rest are underestimation. Based on the error standard deviation, the closest model to the measurement is the MWMF model followed by the Cost231 one slope model. The worst predicted model for this scenario is the ITUR 2135 model.

Table 3. Statistical analysis of the third scenario

| Model                  | Mean  | Standard deviation | Error standard deviation |
|------------------------|-------|--------------------|--------------------------|
| Cost231 one slope model| -2.08 | 5.97               | 0.30                     |
| Cost231 linear model   | 6.64  | 18.94              | 0.95                     |
| Cost231 MWMF model     | -20.68| 21.06              | 1.05                     |
| ITUR 1238 model        | -20.20| 20.40              | 1.02                     |
| ITUR 2135 model        | -33.05| 33.28              | 1.66                     |
| WINNER II model        | -22.00| 22.36              | 1.12                     |
| MWMF model             | -3.98 | 5.63               | 0.28                     |
| IEEE802.11 Model       | -32.10| 32.21              | 1.61                     |

The last scenario considered the effects of traversed floors on path loss between the access that located in the first floor and the UE that moving in the second and the third floors. The parameters that considered in this scenario are as follows: $n$ for two floors is 5.2 [5], $N$ is 28, $\alpha$ is 2.8, $L_f$ in Cost231 MWMF model is 18.3 dB, $L_{f1}$ and $L_{f2}$ in the MWMF model are 19 and 15.2 dB respectively [7].

The comparison of the measurements and the predicted models is presented in Figure 7. It is shown in the figure that all the predicted models are below the measurements. The mean values in Table 4 are confirming this observation. It also noticed that the Cost231 and the MWMF model are fitting each other and have the same behaviour with the measurement. In addition, they are the closest models to the measurement as observed from Figure 7 and Table 4.
In brief, none of the empirical models predicted the measurement in the four scenarios. It is observed that the models which considered the traversed walls and floors are the closest to the measured data. Figure 7 shows one more interesting thing, where the path loss for the same type of floor is not constant with the number of traversed floors. The path loss is 30 dB for the first floor and 21.5 dB for the second floor. The same thing was observed in [6].

5. Conclusion
This paper compares eight indoor path loss models with measured data for different scenarios at 2.4 GHz. Measurements were carried out in three story building. For LOS scenario as in the first scenario, none of the models are predicting the measured data. This is very clear for the very short distances which close to reference distance. The empirical models seem not working properly for the short range connection. For other scenarios, the closest model to the data is the MWMF model. On the other hand, the worst model is ITUR M2135.

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