A Building Architecture Model for Predicting Femtocell Interference in Next-Generation Networks

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***Abstract*—This work considers the development of an indoor-to-outdoor signal propagation model, which can be used to analyze and reduce the interference in various wireless communication networks, particularly 4G networks with femtocells and macrocells. The developed model is based on generating a large number of floor plans with random, but realistic, designs and use signal attenuation models to analyze the statistical properties of the signal at a certain distance from the indoor transmitter after penetrating through several layers of construction materials such as wall, doors and windows. Further studies conducted using the developed model demonstrated that the walls and buildings could be exploited to act like a shield that reduces the mutual interference of indoor and outdoor transmitters as in the case of femtocells. As an application, the proposed model is used to investigate the effect of the placement of an indoor transmitter on the signal level outdoors. The obtained results demonstrated that optimizing the location of the indoor transmitter can reduce the power leakage to the outdoor environment by about 18.5 dB.**

I. Introduction

One of the main goals of the fourth generation (4G) wireless networks is to offer high data rates to all users anywhere inside the coverage area. However, delivering high data rates to indoor users, *i.e.,* users inside buildings, is proved to be a challenge as passing through buildings' walls greatly attenuates the signal power. An effective solution is to install local base stations, called femto base stations (femto BS) in WiMAX or Home NodeB (HNB) in 3GPP terminology, inside the buildings to cover the interior of the building and deliver high-quality broadband service to indoor users.

Depending on the availability of unused spectrum, femto BSs can work in dedicated channels or share the spectrum with existing networks [1]. In the latter case, incorporating femto BSs inside a macrocell may deteriorate the performance of femto users and the macro users who are close to the femto BS due to the mutual interference between the two systems. Although the femto BSs' maximum transmit power can be dynamically adjusted according to macro base station signal interference, such process is not trivial and includes several trade-offs to consider. To achieve the desirable result of femtocells, a receiver inside the building should get a high signal-to-interference and noise ratio (SINR) anywhere inside the building while the leakage of the femto BS signal to the outside world should be kept to minimum. Achieving such two conflicting gaols simultaneously could be very challenging without considering the signal attenuation due to the propagation through walls and other buildings materials. In other words, buildings act as a shield that reduces the mutual interference between the macro and femto users. However, wall attenuation changes considerably in a broad range from 5 dB to 20 dB or more, based on the wall properties such as the type of material used and thickness. Furthermore, a signal transmitted through windows or doors is attenuated less than 3 dB. Consequently, analyzing the interference in such networks using ray tracing [2] or Finite-Difference Time-Domain (FDTD) methods [3] would be highly complex, time-consuming, and it will be valid only to the case in study. Thus, a simple model capable of capturing the fundamental properties of such scenarios is indispensable.

In the literature, most of the works focused on the outdoor-to-indoor propagation models, aimed at extending the coverage of an outdoor transmitter to indoor receivers, and in fact a few paper considered the indoor-to-outdoor case. A comprehensive study of the outdoor-indoor interface that includes the effects of different materials is reported in [4]. The final report of the European Co-Operation in the field of Scientific and Technical research, Action 231 (COST-231) [5] also includes a model for penetration inside buildings. The model is calibrated empirically and it takes several factors into account such as frequency and distance. Oestges *et al.* [6] proposed a similar model however the effect of the angle of incident was included, several measurements were used to calibrate the model at 2.5 GHz. Another model which considers the distance and carrier frequency is explained in ITU-R M.1225 [7]. The models in [8] calculate the indoor path loss as a linear function of indoor distance. Extensive research was conducted to deterministically model the propagation in mixed outdoor-indoor scenarios using ray-tracing or other methods [3], [9]–[11]. Such methods require a large amount of details including the topography and digitized 3D map of the city and their results are site-specific. In [12], the authors modelled the transmission of a signal from the rooms that have external walls or the rooms adjacent to them. The measurements

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have been taken in several frequencies from 0.9-3.5 GHz. The proposed frequency-dependent model also considers the number of walls between the transmitter and outside. Although this work is unique, it does not model the transmitters farther from the external walls which limits its applicability.

This paper presents a statistical model for indoor-to-outdoor path loss where the transmitter is a femto BS inside a suburban house. In particular, the randomness due to building floor plans and femto BS's position is modelled. The proposed model can be used to analyze the femtocell signal interference on macro users. The paper also investigates the issue of femto BS's placement to minimize the interference on macrocell users. The rest of the paper is as follows. Section II describes the signal propagation into buildings. The proposed propagation model is discussed in Section III. Section IV presents the building architecture model. The results on the effects of femto BS's position is reported in Section V and finally, Section VI concludes the paper and gives some ideas for further studies.

II. Signal propagation into buildings

Radio frequency signal propagation inside buildings is a combination of several complex physical effects. In practice, empirical models are used to calculate the signal strength. A successful mixed indoor-outdoor propagation model should consider the main characteristics that distinguish the channel from typical urban wireless channels. First, it should estimate the signal attenuation due to passing through walls, doors, and windows. Second, regardless of walls' attenuation, indoor channel should be modelled differently from the outdoor channel. Third, a method of transition between the models should be implemented

Modelling the mixed indoor-outdoor channel is beyond the scope of this work. Hence, we rely on widely-accepted channel models, such as COST-231 MultiWall Model (MWM) [5], which is an empirical model that has been augmented with some deterministic predictions, namely, the attenuation of walls. Most 3GPP recommendations used this model [1].

In this model, the signal attenuation can be computed as,

$$PL_i(d) = 20\log\left(\frac{4\pi d}{\lambda}\right) + k_f^{\left(\frac{k_f+2}{k_f+1}-0.46\right)} L_f + \sum_{i=1}^{N} k_{wi} L_{wi}, \tag{1}$$

where d is the travelled distance, N is the total number of intersected walls of type i, λ denotes the carrier wavelength, L_{wi} and k_{wi} are the attenuation and number of penetrated walls of type i, and L_f is the loss between adjacent floors. A 2D representation of the model concept is shown in Fig. 1. This work also assumes a 2D world and does not take the effect of different floors into account. Obviously, the attenuation of walls depends on their dimension as well as the constituting materials. Table I presents some approximate values of the attenuation of walls with typical dimensions at different frequencies.

The path loss in urban and suburban environments outside

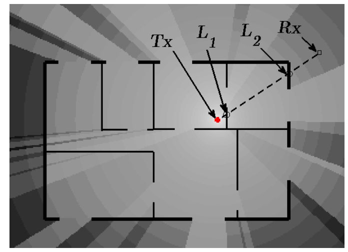


Fig. 1. Cost MultiWall Model (MWM) concept and a sample.

TABLE I
Attenuation of walls in different frequencies [6]

Wall Material	Attenuation (dB) in 900 MHz	Attenuation (dB) in 1800 MHz	Attenuation (dB) in 2.5 GHz
Wooden walls	8	10	12.3
Concrete walls	14-24	16-26	
Stucco walls			13.1

the high rise core of the cities can be calculated by [13],

$$\begin{aligned} PL_o(d) = {} & 40(1 - 4\times 10^{-3}\Delta h_b)(\log(d) - 3) \\ & - 18\log(\Delta h_b) + 21\log(f) + 80 \text{ dB}, \end{aligned} \tag{2}$$

where Δh_b is the BS antenna height measured in meters from the rooftop and f is the frequency in MHz. This model is useful in urban environments, however, according to studies reported in [14], the COST-231 path loss model is more accurate for short distances outside houses, like around buildings. For longer distances, which are used to model macrocell BSs' signal, the model in described (2) has to be used.

This work is based on the mixed indoor-outdoor interface proposed in [11], [12]. In this model, an imaginary boundary is placed around the building on the exterior walls. When the signal passes through the boundary, outdoor path loss model is applied. At the last step, the indoor and outdoor path loss components are added together to form the final result [12],

$$PL(d) = PL_i(d_i) + PL_o(d_o). \tag{3}$$

III. The Proposed Modelling approach

To design a model that can describe the femto BS's signal, the statistical properties of buildings are required. The signal transmitted from a femto BS passes through a number of different walls, doors, and windows before it reaches the outdoor environment. In particular scenarios, if the transmitter is close to an open window, the transmitted signal reaches outside without any significant attenuation. There are several models that explain the attenuation of a signal passes through walls built of different materials. However, to the best of our knowledge, there is no work conducted on modelling the randomness associated with different floor plans.

A possible approach to model the effects of buildings' floor plans is to set up a mobile measurement testbed. The transmitter will be placed in a certain point inside the building, several measurements are then recorded at different locations around the building. Then, the transmitter location is changed and the process is repeated. Finally, this tedious process should

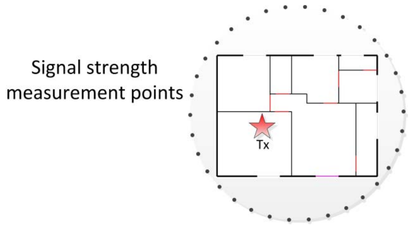


Fig. 2. Simulation setup.

Fig. 3. A sample floor plan automatically generated by the BPG algorithm.

be repeated for several buildings. Obviously, such approach is infeasible because of the tremendous effort required. Such experiments are unusually performed for one transmitter location at one building [10] and the results are site-specific.

As an alternative to the exhaustive measurements approach, we design an automatic floor plan generator algorithm to generate a number of floor plans enough to build a statistical model. The algorithm, namely Building Procedural Generation (BPG) [15], is able to generate realistic floor plans based on some parameters that can be estimated in each neighborhood. Having the floor plan, a well-accepted deterministic analysis tool is used to calculate the signal strength in the predetermined measurement points. This method allows us to develop the femtocell signal model based on a large number of samples, which can never be obtained by any measurement campaign. Consequently, the resulting model would be applicable to more general scenarios.

A concise summary of the BPG algorithm is brought here to illustrate its mechanism:

1) The number of rooms is generated randomly according to the data that can be obtained from the neighborhood or census.
2) The area of each room is randomly generated based on its functionality.
3) The area and outer shape of the house is determined.
4) The rooms are placed in the house.
5) A connectivity graph that demonstrates the doors is produced.
6) A corridor to connect the rooms together is added, if necessary.
7) Windows and doors are added randomly according to the connectivity graph.

A sample of the resulting floor plans is depicted in the Fig. 3. We have introduced some extra details and furnished the floor plan to provide a designer's look. For detailed explanation refer to [15].

Next, a transmitter is dropped at a random point inside the house. Using existing models of indoor signal propagation, and including the attenuation of walls, the radio frequency field strength is calculated and the signal power at the measurement points are estimated. The process is run several times in a Monte-Carlo manner to construct the sample set.

In general, the exact location of femto BS inside the house is unknown to the operator. Thus, the model should be independent of the exact location of the transmitter. Towards this goal, the measurements are gathered on a circle that enclosed the house and co-centered with it as depicted in Fig. 2. From the network planning point of view, it is possible to remove the house from the calculations and abstract the femto BS inside the house as a single point transmitter at the center of the house, with random gain in each direction in far field. *i.e.,* a transmitter with random pattern. A sample pattern for a particular floor plan is extracted from one simulation run is depicted in Fig. 4. The abrupt changes in the signal power, which is a result of passing through walls is clearly shown in the figure. As it can be noted from the above discussion, the proposed model gives a statistical representation of the femto BS signal with all the complexities due to buildings' floor plan without explicitly modelling the building itself. This enables the optimization of various design trade-offs and evaluate the performance of the next generation wireless networks more accurately.

IV. Constructing femtocell signal propagation model based on Building Architectural Model (BAM)

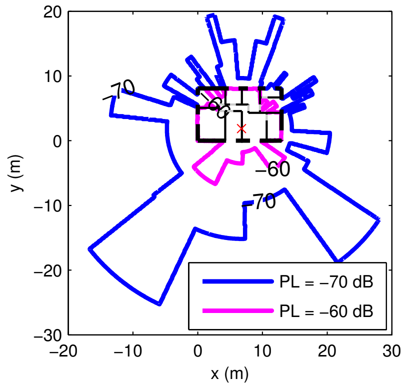
In order to calculate the femto BS's signal strength in and around the house, the COST-231 model, described in Section II is adopted as the main model. Since, the objective is to find the interference caused by femto BS's signal around the house, the model is also applied for short distances around the house. Therefore, the path loss can be calculated as,

$$PL(x) = PL_m(d_c) + PL_{ex}(x), \tag{4}$$

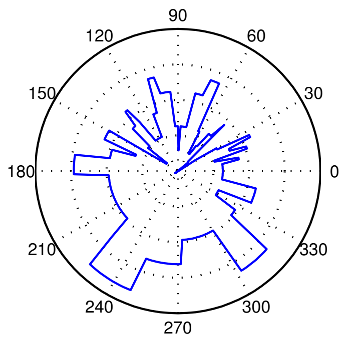
where $PL_m(d_c)$ is the path loss estimated by the main path loss model of the medium at distance d_c from the center of the house, and $PL_{ex}(x)$ is the excess path loss experienced at point x. For short distances around the house, the excess path loss models the effect of error in the transmitter position as well as the signal attenuation due to walls.

$$\begin{aligned} PL_{ex}(x) = 20\log\left(\frac{4\pi d_x}{\lambda}\right) \\ + \sum_{i=1}^{N}(k_{wi}L_{wi}) - 20\log\left(\frac{4\pi d_c}{\lambda}\right), \end{aligned} \tag{5}$$

where d_x is the distance between point x and the receiver. Since the network operator is not aware of the internal architecture of the house and the transmitter position, the modelling idea is to assume that transmitter is at the center of the house and use the main path loss model to calculate the path loss. The error due to position of the transmitter and the walls' attenuation is then added as the excess path loss. After some



(a) Power footprint of a femto BS.



(b) Antenna pattern representation of the house.

Fig. 4. Angular pattern representation of a femto BS's signal leaking outside the building.

straightforward simplifications we obtain,

$$PL_{ex}(x) = 20\log\left(\frac{d_x}{d_c}\right) + \sum_{i=1}^{N} k_{wi} L_{wi}. \tag{6}$$

The proposed model considers two types of walls: light walls which are not bearing load such as plasterboards, particle boards or thin (<10 cm) concrete walls that has an attenuation factor $L_{w1} = 7$ dB, and heavy walls made of concrete or bricks,which has an attenuation factor $L_{w2} = 15$ dB [16]. The proposed model can be extended to include other types of walls, if needed. It is assumed that windows and doors attenuation factors are $L_{win} = 1$ and $L_d = 3$ dB, respectively [16].

To build the model, 500 different floor plans were generated using the BPG algorithm and the signal strength is sampled at 75 points with different angles as depicted in Fig. 2. The basic parameters of the software such as the number of rooms and bedrooms in each house are extracted from the recent Census data [17]. The complimentary parameters that are necessary to generate floor plans are adjusted to model a suburban dwelling.

The frequency distribution function of the excess loss is shown in Fig. 5. The peaks shown in the graph are clearly due to the attenuation of walls. The more walls, the signal passes, the more loss it would endure. The histogram composed of several parts, each of them can be modelled by a Gaussian distribution. Therefore, we will model the data with Gaussian Mixture distribution.

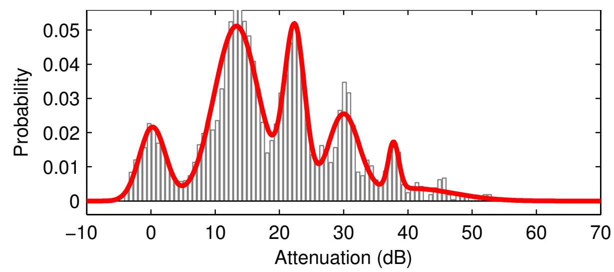


Fig. 5. Probability distribution function of building attenuation.

TABLE II
GMM PARAMTERS

i	1	2	3	4	5	6
μ_i	0.25	13.31	22.36	29.94	37.77	40.53
σ_i	4.19	12.20	2.60	5.95	0.68	45.16
ω_i	0.11	0.45	0.20	0.15	0.03	0.06

A. Estimating the attenuation with Gaussian Mixture distribution

The probability distribution function of a Gaussian Mixture distribution is the weighted sum of the probability distribution function of M Gaussian distributions as,

$$p(x|\lambda) = \sum_{i=1}^{M} \omega_i \, g(x|\mu_i, \sigma_i), \tag{7}$$

where $g(x|\mu_i, \sigma_i)$ represents the probability distribution function (PDF) of a Gaussian random variable with mean μ_i and standard deviation σ_i. It is basically several Gaussian random variable added together with weight ω_i. It is obvious that $\sum_{i=1}^{M} \omega_i = 1$. Expectation Maximization (EM) algorithm has been used to find the proper coefficients. The parameters of the resulting Gaussian Mixture Model (GMM) are given in Table II. The probability density function and cumulative density function of the distribution are shown in Fig. 5.

V. Optimal femto BS placement

The signal power of femto BS leaked to outside of the building depends on the floor plan of the building and position of the femto BS. A transmitter seated near a window would have the most powerful signal outside, whereas one placed in an enclosed room has a limited effect on macro users outside. In this section, we study the effect of femto BS's position and find the best possible position that minimizes the expected interference. The interference at a particular point can be minimized by;

$$\bar{I}_m = \min_{x_t} \int_c I(x_t, x_r)\, f_{X_r}(x_r) dc, \tag{8}$$

where x_t and x_r represent transmitter and receiver coordinates, respectively. $I(x_t, x_r)$ is the interference at x_r caused by a transmitter at x_t, and $f_{X_r}(x_r)$ is the probability density function of the receiver position. The interference is to be minimized on c which is defined as a circle around house with radius R centred at the center of the house. Assuming

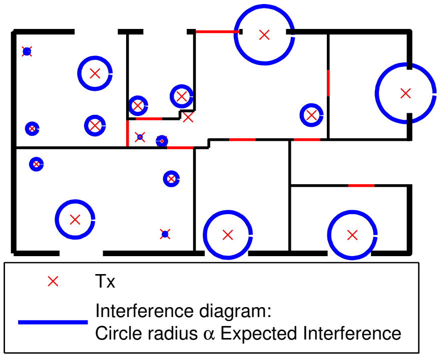


Fig. 6. Expected signal attenuation map of the house.

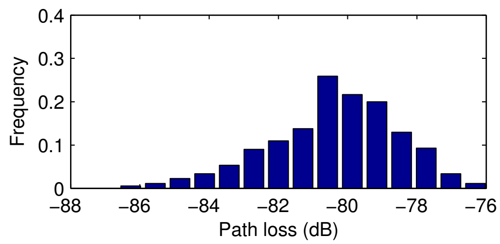


Fig. 7. The histogram of $\overline{I}_m$.

equal probability of receiving signal at each angle, we may write,

$$\overline{I}_m = \min_{x_t} \frac{1}{2\pi} \int_0^{2\pi} I(x_t, [R, \theta]) d\theta. \tag{9}$$

For every realization in the building database, an extensive search on every possible transmitted point results in the optimal position. The diagram in Fig. 6 illustrates the expected interference at some potential femto BS's position. Femto BSs are represented by red crosses. The radius of each circle is proportional to the expected interference. Large circles show high level of interference, whereas small circles indicates that little interference is expected, which could be potential candidates for placing a femto BS. High level of interference is expected around the windows, which makes this regions as the worst for placing femto BS. On the other hand, enclosed areas inside the house with no windows, like corridors or corner of rooms have a better chance of limiting interference to outside. To study the effect of femto BS's location, the calculations are repeated for 500 realizations and the interference is measured on a circle with radius equal to 15 m. The histogram of the expected path loss ($\overline{I}_m$) of a transmitter placed at the optimum point is shown in Fig. 7.

The average value of the path loss for optimal position over all realizations is 80.4 dB. Considering 62 dB path loss at the distance of 15 m, the mean excess path loss due to building is worked out to be 18.4 dB. The simulations also show that the expected interference can increase up to 22.9 dB by moving the femto BS in the house. These values can be used as a rule of thumb to consider the attenuation effects of the building.

VI. Conclusion and Future Works

This paper presented a novel model that considers the complex effects of buildings' floor plan on the signal power. The proposed model, namely Building Architectural Model (BAM), predicts the power of the femtocell signal leaking outdoors. It considers the main effects of the buildings, including signal attenuation due to passing through walls/windows/doors and a mixed indoor-outdoor channel. The model is based on widely accepted propagation models. However, validation of the results by measurements would be highly desirable.

The model can be used to derive several performance metrics of the network. Moreover, it can be used by the operator to predict the effect of the installation of new femtocells on its network. The proposed model was used to minimize the femtocell power leakage outside the building by optimizing the femto BS's placement and its interference. The achieved results confirmed that a proper placement of a femto BS can decrease the mean interference around the house by as much as 23 dB.

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