Indoor Wave Propagation Prediction for Corridors Segments with Partially Reflecting Walls by Using 3D Waveguide Modal Analysis

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Abstract **─** In this paper, a model is presented to simulate wave propagation in indoor corridors with partially reflecting walls. The model is based on combination of modal analysis, dyadic Green's function, mode matching method and generalized scattering matrix. A new approach to simulate the effect of partial reflectivity of the walls of the waveguide model is proposed. This approach is based on approximating the fields inside the space of the actual waveguide section by equivalent waveguide sections of larger dimensions with PEC (Perfect Electric Conductor) walls. A simple scenario is considered in order to check the accuracy of this model. This scenario is verified by comparing experimental and numerical simulation results. The obtained results show that the proposed model is suitable for predicting accurate electric field strength due to an electromagnetic source in an indoor environment with partially reflecting boundaries.

Index Terms **─** Dyadic Green's function, indoor propagation, mode matching method, partially reflecting walls, waveguide model.

I. INTRODUCTION

Modeling indoor wave propagation for wireless communication is challenging problem because of the large dimensions compared with the operating wavelength and complex geometry of buildings [1-3]. However, understanding how electromagnetic waves propagate in indoor environments becomes increasingly important as wireless devices become more involved in lifestyle. Laptops, smart phones, tablet computers and others are overwhelming the market now more than ever and wireless networks have to work in all environments to satisfy the increasing demand. Predicting wave propagation in indoor environment is especially complicated problem due to the operating wavelength is usually much smaller than the size of different objects in the normal building in addition to the complicated shapes and structures inside indoor environment. Variations of room size, building materials and furniture placements as well as moving persons affect wave propagation in indoor environment in different ways. To predict how indoor environment affects the wave propagation, different models have been developed. These models are divided into empirical and theoretical models.

Empirical models represent traditional approaches for estimating signal power received from a source employing a stochastic approximation that combines all the surrounding environmental effects in a given location into a simple attenuation-distance relation [4]. Path-loss model requires very little computational resources as it does not incorporate any rigorous calculations of Maxwell's equations or wave equation. In this method loss parameters are extrapolated through the averaging of many physical measurement samples over a large area in an attempt to model an overall trend that estimates the decay of signal strength away from the transmitter. However, the time and resources saved by applying the simple decay equations are often offset by the effort required to gather enough on-site measurements for a more accurate estimation. Also, this method cannot accurately predict the power levels at every point in the environment considered. Different empirical models have been used for predicting the path loss along corridors in office environments [5-6]. On the other

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hand, deterministic models are based on solving Maxwell's equations, which can be done in different ways by making certain assumptions about the wave propagation and the geometry of the environment. Ray tracing [7-8] and waveguide model [9-13] are the most common theoretical models used to predict indoor propagation. Ray-tracing is based on the fact that at high frequencies the electromagnetic waves may be thought of as behaving like rays that travel in straight lines provided that the permittivity of the medium is homogeneous [14]. Geometrical optics (GO) [15] approximates the field strength at any point as the sum of the field associated with the direct ray from the transmitter to the receiver, plus the reflected and refracted rays from the surrounding walls. Reflection and refraction due to penetrable walls can be modeled generally by multiple rays. However, for simplicity single ray approximation is usually used. Discontinuities at the edges of the walls, doors and windows introduce additional diffracted rays. Geometrical Theory of Diffraction (GTD) and its uniform extension, Uniform GTD (UTD) are used to model diffracted rays from the edges [16]. The practical limitation of applying GTD to indoor propagation is that each diffraction point on an edge behaves as a secondary source giving rise to a new family of rays. Accounting for many such secondary sources becomes very time consuming and in many cases impractical.

It has been shown in simulations [13] and measurements [9-12] that corridors have a waveguiding effect. Basic theory of waveguide is already used to model corridors and tunnels. The advantage offered by the waveguide modeling approach over existing methods is that an overall picture of power levels in a large area can be obtained with very small computational and database requirements. The model requires very little detailed information about the environment, and provides accurate predictions of the major phenomena.

So far 2D analytical models treat corridors as perfect electric conducting boundaries [9]. Recently, dielectric waveguides with uniform cross-section have been developed to improve this 2-D waveguide model [11]. In the case of dielectric waveguide model the walls are modeled as infinitely thick [10]. This model is modified to be more realistic by using finite dielectric layer thickness to represent the surrounding walls [11].

In hybrid models theoretical models are combined with numerical models as FDTD (Finite Difference Time Domain) [11], [17]. For example, one can utilize ray tracing or waveguide model in simpler regions where these models are valid and can be applied efficiently. A more versatile and detailed numerical model is then used to solve for the field distribution in regions where the previously mentioned models cannot be used for accurate results. This saves computational time as the detailed numerical model are only required to be implemented in certain small regions.

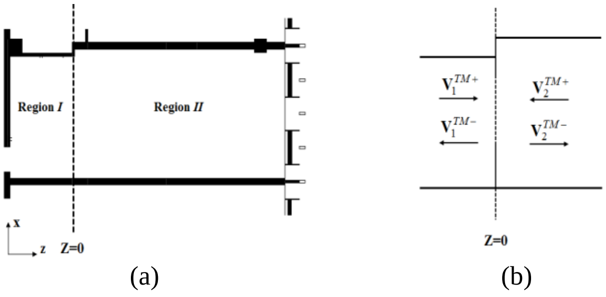
As it is mentioned, previous work based on waveguide model was only based on 2D analysis for the corridors segments [9-12]. The proposed model in the present paper is based on 3D waveguide model. This 3D waveguide model is suggested to be combined with mode matching method and generalized scattering matrix method to include the discontinuities inside the indoor environment. The antenna of the wireless system is presented as a small point source to excite the waveguide sections which represent the indoor environment. The guided waves in the corridors are presented in terms of the corresponding modes of a rectangular perfect electric conducting waveguide of the same dimensions of the corridors. Large number of modes are propagating in the corridor due to the short wavelength used in wireless communication and the large cross-section of the corridor. At intersections of waveguides with different cross sections, each mode is backscattered and transmitted in a different way. To determine the backscattered and transmitted fields for a large number of propagating modes, an effective mode matching method [20] is developed for dealing with three dimensional (3D) waveguide structures [21]. Mode matching method is used for analyzing transitions between waveguides with different cross section. Electromagnetic fields are then expanded in waveguide modes in each region. At the waveguide intersection the electromagnetic boundary conditions are applied to the field expansions for the different regions, then a generalized scattering matrix is determined. This scattering matrix relates the coefficients of incident, backscattered and transmitted modes.

In order to consider the effect of partial reflectivity of the walls a new approach is introduced as an extension of a paper by the authors [22]. The proposed method is based on using PEC waveguide model but the PEC waveguide sections in this case have larger dimensions such that the fields inside the equivalent waveguide would be nearly the same as the corresponding ones inside area of the original partially reflecting waveguide sections.

Full wave numerical analysis of the same problem based on HFSS (High Frequency Structural Simulator) simulation [19] is used to verify the obtained results based on modal analysis. Experimental results are also conducted with a simple dipole antenna in a specific office corridor. The measurements are presented at Wi-Fi frequency band 2.40-2.48 GHz.

II. MODAL ANALYSIS OF INDOOR PROPAGATION BASED ON PEC BOUNDARY CONDITIONS

Simple indoor environment can be represented as a combination of multi-mode rectangular waveguide sections as shown in Fig. 1. The excitation source is assumed to be an infinitesimal dipole located at one of these waveguide sections. The electric field at any point inside the waveguide containing the excitation source can be formulated as dyadic Green's function inside the waveguide section. The reflected and transmitted fields from one section to the directly connected sections can be obtained by using mode matching method. The interactions between all these waveguide sections are represented in the form of generalized scattering matrices. The following analysis is based on assuming that the boundaries of the waveguide section are PEC. Then the problem of 3-D waveguide model with partially reflecting walls is discussed.



(a) (b)

Fig. 1. (a) Schematic drawing of an example for an indoor environment. (b) Equivalent waveguide representation for an intersection between two corridors.

Following the same analysis in [18], electromagnetic fields inside rectangular waveguide section due to an infinitesimal point source can be represented in terms of a complete set of orthonormal eigenfunctions as follows:

$$\mathbf{E}_t(x,y,z)=\sum_m\sum_n V_{mn}^{TM}(z)\mathbf{e}_{mn}^{TM}(x,y)+\sum_m\sum_n V_{mn}^{TE}(z)\mathbf{e}_{mn}^{TE}(x,y), \tag{1-a}$$

$$\mathbf{H}_t(x,y,z)=\sum_m\sum_n I_{mn}^{TM}(z)\mathbf{h}_{mn}^{TM}(x,y)+\sum_m\sum_n I_{mn}^{TE}(z)\mathbf{h}_{mn}^{TE}(x,y), \tag{1-b}$$

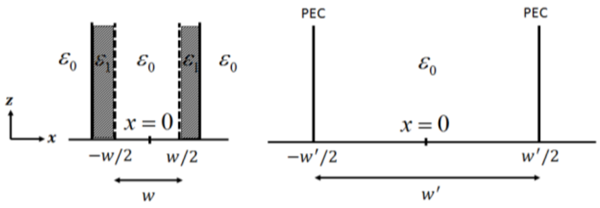
$$j\omega\varepsilon E_z(x,y,z)=-J_z(x,y,z)+\sum_m\sum_n V_{mn}^{TM}(z)\nabla\cdot\mathbf{e}_{mn}^{TM}(x,y), \tag{1-c}$$

$$j\omega\mu H_z(x,y,z)=\sum_m\sum_n V_{mn}^{TE}(z)\nabla\cdot\mathbf{h}_{mn}^{TE}(x,y), \tag{1-d}$$

where $\mathbf{e}_{mn}^{TE/TM}$ and $\mathbf{h}_{mn}^{TE/TM}$ correspond to the mnth electric and magnetic eigen TE/TM (Transverse Electric/ Transverse Magnetic) modes. Details of these eigen modes are discussed in [18]. For the case of an excited waveguide section, the amplitudes of these modes V^{TM}, V^{TE}, I^{TM}, I^{TE} are functions of the amplitudes and locations excitation sources inside the waveguide section, More details about the analysis method including mode matching technique and generalized scattering matrix are presented in [22].

A. Approximation of partially reflecting walls in modal analysis

A new approach is proposed in order to simulate the effect of partial reflectivity of the walls forming indoor environment by using the PEC waveguide model. The basic idea of the proposed method is that the field distribution inside a waveguide section with partially reflecting boundaries can be approximated by the field distribution of a PEC waveguide of the same cross section configuration and larger size as shown in Fig. 2. Figure 3 shows schematically how the field distribution of larger PEC waveguide can be used as an approximation for the field distribution inside a smaller waveguide section with partially reflecting boundaries. It should be noted that, this approximation is valid only inside the cross section area of the partially reflecting waveguide section.



(a) (b)

Fig. 2. Geometry of the problem of 2D waveguide section: (a) actual waveguide section with partially reflecting boundaries, and (b) equivalent waveguide section with PEC boundaries.

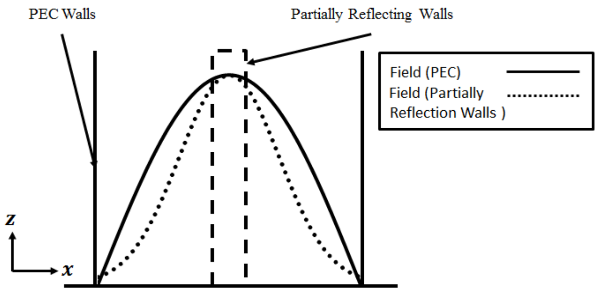


Fig. 3. Sample electric field distribution for PEC walls and partially reflecting walls.

To verify this technique numerically, a simple example based on single mode is studied. The transverse electric field mode TM_1 for a parallel plate with PEC boundaries as shown in Fig. 2 (b) is given by:

$$\mathbf{E}_t(x)=\cos\frac{\pi x}{w'},|x|\le w'/2\,. \tag{2}$$

On the other hand, the corresponding transverse electric field mode for partially reflecting boundary as shown in Fig. 2 (a) is given by [23]:

$$\mathbf{E}_t(x)=\begin{cases} cos(k_{x1}x), & |x|\le w/2 \\ e^{k_{x2}(w-|x|)}, & |x|\ge w/2\text{'} \end{cases} \tag{3}$$

where k_{x1} is given by:

$$k_{x1} = \frac{\pi}{w}\left[1 + 2j\,\bar{Z}_s/k_0 w\right], \tag{4}$$

and $\bar{Z}_s = 1/\sqrt{\varepsilon_r - 1 - i\sigma/\omega\varepsilon_0}$ is the wall impedance normalized to the free space wave impedance η_0 with wall's permittivity ε_r and conductivity σ [23].

Equation (3) represents the actual field distribution inside and outside the partially reflecting waveguide structure. The field inside this waveguide in the region $|x| < w/2$ can be approximated by using (2) with larger value of w'. In this case the optimum value of w' can be obtained by minimizing the error function given by:

$$\varepsilon(w') = \int_{-w/2}^{w/2} \left|\cos k_{x1}x - \cos\frac{\pi x}{w'}\right|^2 dx. \tag{5}$$

Figure 4 shows an example for this approximation technique where $\bar{Z}_s = 0.4 + j0.25$, $w = 0.5\,m$ and the operating frequency is $f = 0.9$ GHz. In this case, it is found that the optimum value of the equivalent waveguide section is $w' = 1.2\,w$ for dominate mode as shown in Fig. 4.

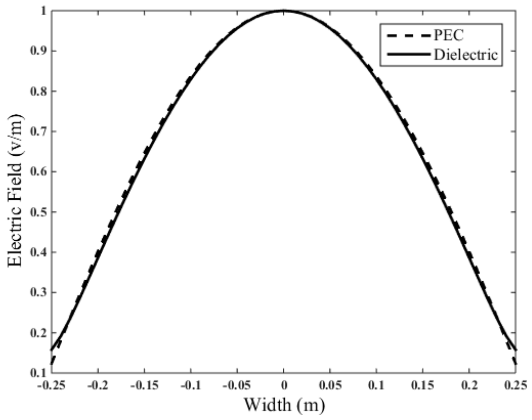
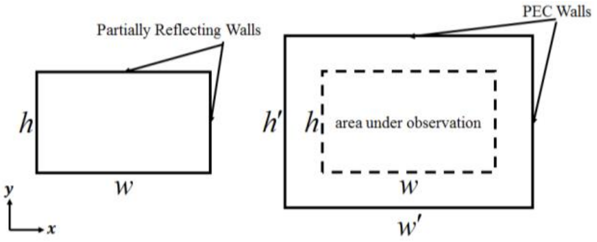


Fig. 4. Actual and approximate field distributions inside a parallel plate waveguide with partially reflecting boundaries.

This technique can be generalized to simulate wave propagation inside indoor environment with partial reflecting boundaries as shown in Fig. 5. In this case, Fig. 5 (a) shows the cross section of the original corridor with partially reflecting walls and Fig. 5 (b) shows the equivalent PEC model which introduces nearly the same field distribution inside the area of the original corridor.

Full wave numerical analysis based on finite element analysis by using HFSS simulator is used to verify this technique for 2-D waveguide section. Figure 6 (a) shows the normalized electric field distribution for a waveguide section with partially reflecting walls. In this case wave port excitation of dominant mode only is used as the excitation. The dielectric constant of the wall of this waveguide is $\varepsilon_r = 3$ and the conductivity is $\sigma = 0.01\ s/m$. The inner dimensions of this waveguide are $w = 1m$ and $h = 0.5m$. The thickness of the walls of this waveguide is 0.1 m and the operating frequency is 0.9 GHz. On the other hand, Fig. 6 (b) shows the corresponding normalized electric field distribution for the equivalent PEC rectangular waveguide section. In this case the optimum equivalent waveguide with PEC boundaries is found to be $w' = 1.23$ m. It should be noted that the width of the waveguide h in this case does not change because the field distribution is independent on this direction in this case.



(a) (b)

Fig. 5. Equivalent waveguide representation for partially reflecting walls: (a) corridor section with partially reflecting walls, and (b) equivalent PEC representation.

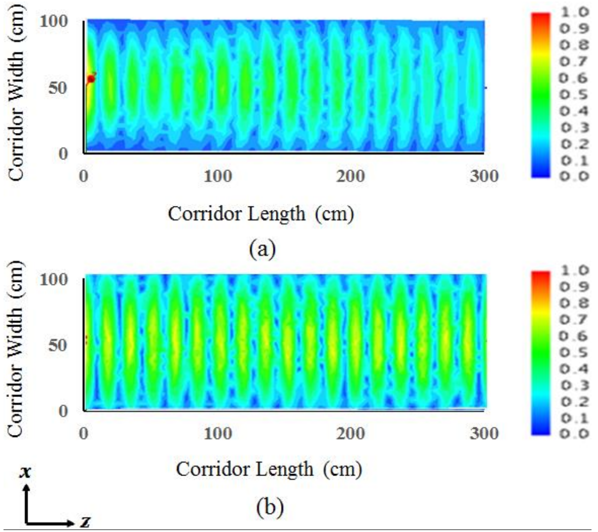


Fig. 6. Magnitude of normalized electric field, x-z plan, for corridor segment at frequency band 0.90 GHz: (a) HFSS model for partially reflecting walls, and (b) PEC model.

III. SIMULATION RESULTS

In this section sample results are presented to verify the accuracy of the proposed model by comparing the obtained results with both simulations and experimental results. Numerical simulations of indoor structures are obtained by using ray tracing technique based on FEKO software [24]. Different configurations of the excitation sources are presented to show the effect of the polarization on the indoor wave propagation.

A. Vertically polarized dipole

The first example here is based on a vertical dipole parallel to the y axis as shown in Fig. 7. The field is calculated at a plane parallel to the ground. Figure 8 (a) shows the electric field distribution for a waveguide section with partially reflecting walls. The operating frequency is assumed to be 0.90 GHz corresponding to lower GSM band. The length, width and height of the corridor are assumed to be 15 m, 3 m and 3 m respectively. The permittivity of the walls is 3 and conductivity is $\sigma = 0.01$ s/m [11]. The thickness of the wall is 10 cm. The dipole is located at the point (1.5 m, 1.5 m, 0.5 m). Figure 8 (a) shows the magnitude of the normalized electric field in the plane parallel to the ground at a height 2.25m. On the other hand, Fig. 8 (b) shows the corresponding normalized electric field distribution for the equivalent PEC rectangular waveguide section. In this case the optimum equivalent waveguide with PEC boundaries is found to be $w'=1.02\ w$ and $h'=1.33\ h$. It should be noted that the bottom and upper walls have more effect on the field distribution in this case than the side walls. This explains the small ratio of w' compared with the corresponding ratio h'.

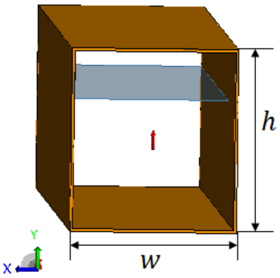
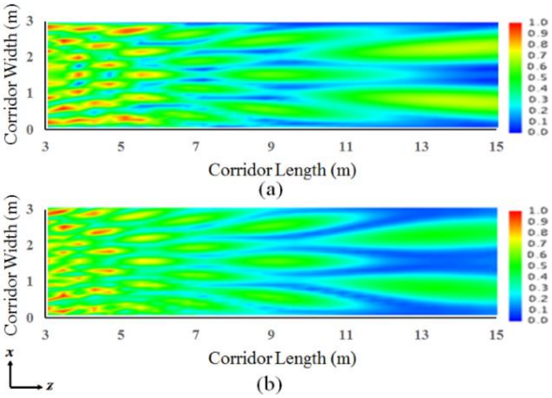


Fig. 7. Vertical polarization simulation model.

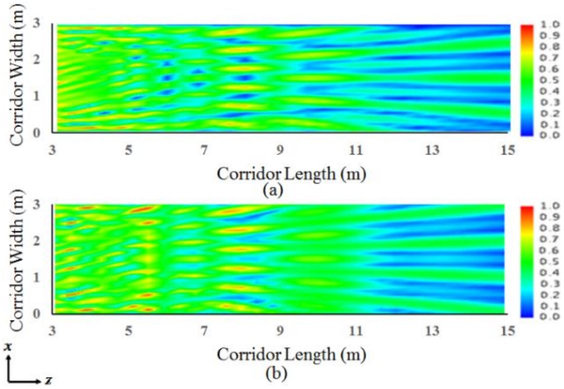


(a)

(b)

Fig. 8. Magnitude of normalized electric field, x-z plan y = 2.25 m for a corridor segment at frequency 900 MHz: (a) FEKO model for partially reflecting walls, and (b) equivalent PEC model.

This analysis is repeated for other two frequencies in the wireless communication band from 0.9 GHz to 2.5 GHz to cover most common applications for indoor propagations like WiFi and the upper GSM band. Figures 9 shows the same problem at frequencies 1.5 GHz, where Fig. 9 (a) shows the normalized electric field distribution for a waveguide section with partially reflecting walls in the plane parallel to the ground at a height 2.25 m. On the other hand, Fig. 9 (b) shows the corresponding normalized electric field distribution for the equivalent PEC rectangular waveguide section. In this case the optimum equivalent waveguide with PEC boundaries is found to be $w' = 1.02\ w$ and $h' = 1.15\ h$.



(a)

(b)

Fig. 9. Magnitude of normalized electric field, x-z plan, for corridor segment at frequency band 1.5 GHz: (a) FEKO model for partially reflecting walls, and (b) equivalent PEC model.

Figures 10 shows the same problem at frequencies 2.5 GHz where in this case the optimum equivalent waveguide with PEC boundaries is found to be $w' = 1.02\ w$ and $h' = 1.05h$. It should be noted that the bottom and upper walls have more effect on the field distribution in this case than the side walls. This explains the small ratio of w' compared with the corresponding ratio h'.

The error is calculated using Mathematica 10.3 by comparing the percentage difference between figures of the simulation and model results and it is found that the error is ranging from 13.3% to 14.9% for the proposed results. It can be noted the good accuracy of the modal analysis of equivalent PEC waveguide section compared with the FEKO simulation results of the partially reflecting wall waveguides. The relation between the dimensions of the equivalent PEC waveguide and the corresponding dimensions of original partially reflecting wall waveguide as functions of frequency is shown in Fig. 11. It is shown that the ratio of h'/h decreases by increasing the operating frequency to be nearly unity at the higher frequency limit. This can be explained due to the localization of the propagated waves inside the section of the waveguide at higher frequencies. Thus, the effect of the boundary walls would be decreased in this case. On the other hand, the ratio of w'/w is nearly unity in all cases for vertically polarized dipole. Thus this result is omitted here.

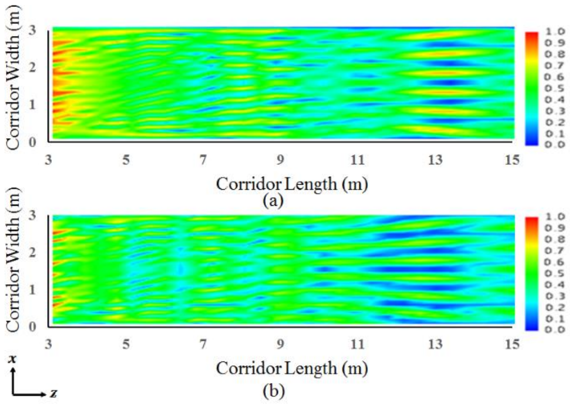


Fig. 10 Magnitude of normalized electric field, x-z plan, for corridor segment at frequency band 2.5 GHz: (a) FEKO model for partially reflecting walls, and (b) equivalent PEC model.

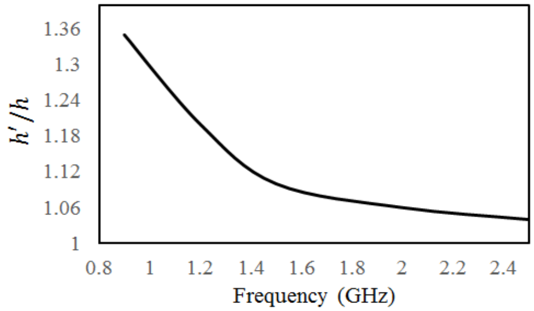


Fig. 11. Relation between corridor segment with partially reflecting walls and the corresponding PEC model.

B. Horizontally polarized excitation

The second example here is based on a horizontal dipole parallel to the x. The field is calculated at a plane parallel to the ground. Figure 12 (a) shows the normalized electric field distribution for a waveguide section with partially reflecting walls. The operating frequency is assumed to be 0.90 GHz corresponding to lower GSM band. The length, width and height of the corridor are assumed to be 15 m, 5 m and 5 m respectively. The permittivity of the walls is 3 and conductivity is $\sigma = 0.01\ s/m$ [11]. The thickness of the wall 10 cm. The dipole is located at the point (1.5 m, 1.5 m, 0.5 m). Figure 12 (a) shows the magnitude of the total electric field in the plane parallel to the ground at a height 2.25 m. On the other hand, Fig. 12 (b) shows the corresponding normalized electric field distribution for the equivalent PEC rectangular waveguide section. In this case the optimum equivalent waveguide with PEC boundaries is found to be $h' = 1.03\,h$ and $w' = 1.35\,w$. The calculated error between the model and simulation figures is about 15.6%. It should be noted that the bottom and upper walls have more effect on the field distribution in this case than the side walls. This explains the small ratio of h' compared with the corresponding ratio w'. This analysis is repeated for other two frequencies in the wireless communication band from 0.9 GHz to 2.5 GHz to cover most common applications for indoor propagations like WiFi and GSM bands.

It can be noted the good accuracy of the modal analysis of equivalent PEC waveguide section compared with the FEKO simulation results of the partially reflecting wall waveguides. The relation between the dimensions of the equivalent PEC waveguide and the corresponding dimensions of original partially reflecting wall waveguide as functions of frequency is shown in Fig. 13. It is shown that the ratio of w'/w decreases by increasing the operating frequency to be nearly unity at the higher frequency limit. This can be explained due to the localization of the propagated waves inside the section of the waveguide at higher frequencies. Thus, the effect of the boundary walls would be decreased in this case. On the other hand, the ratio of h'/h is nearly unity in all cases for vertically polarized dipole. Thus this result is omitted here.

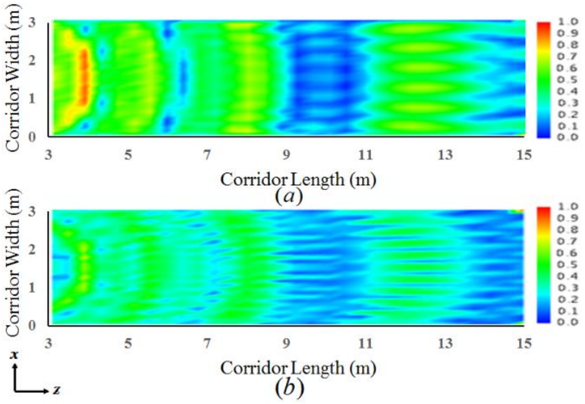


Fig. 12. Magnitude of normalized electric field, x-z plan, for corridor segment at frequency band 0.90 GHz: (a) FEKO model for partially reflecting walls, and (b) PEC model.

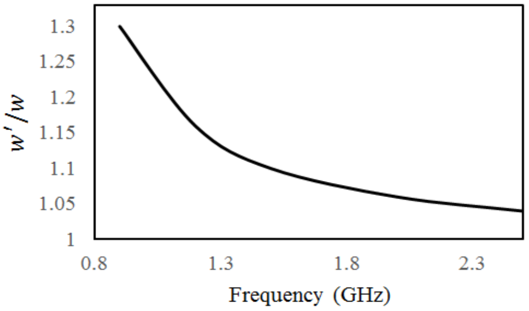


Fig. 13. Relation between corridor segment with partially reflecting walls and the corresponding PEC model.

C. Cascaded sections simulation

Real indoor environment, as shown in Fig. 14, can be presented as cascaded regions with different geometrical properties. In this case generalized scattering matrices are calculated independently for the intersection between each two connected regions. Then these generalized scattering matrices would be cascaded with appropriate phase delay matrix to compute the overall generalized scattering matrix for the entire indoor environment [20]. The above analysis is extended to simulate the intersection of two corridor segments with different widths by using mode matching. The width of the first segment is assumed to be 3 m while the width of the second segment is assumed to be 5 m. The height of both segments is assumed to be 3 m. The lengths of the two segments are 10 m and 10 m respectively. The operating frequency is assumed to be 900 MHz. The transmitting antenna is assumed to be vertically polarized and located at the mid of the first segment at a height 1.5 m. Figure 15 (a) shows the calculated electric field distribution at the plane parallel to the ground plane at a height of 2.25 m from the floor. Figure 15 (b) shows the corresponding PEC model with $h' = 1.3h$ for both sections. It can be noted the good accuracy of the modal analysis compared with the FEKO simulation results.

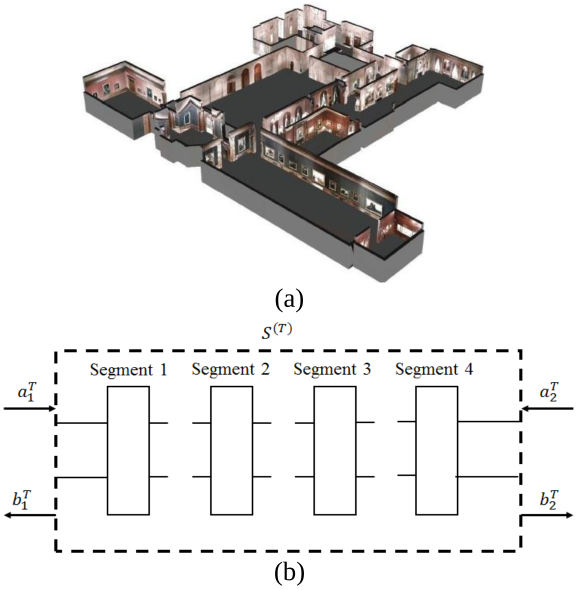


Fig. 14. (a) Schematic drawing of a real indoor environment, and (b) equivalent cascaded generalized scattering matrix for complicated multi-section indoor environment.

The model is implemented in Matlab which runs on a laptop with an Intel 2.4 GHz processor, 4 GB of RAM and Windows 7 64-bit, the total program runtime for the above example is only 9 minutes. The calculation of S-matrices is done for each corridor segment and every frequency sample while the cascade coupling is done once for every frequency. The mesh generation for the electric field is done for every corridor segment and frequency sample. The latter includes summing up the electric field for every mode at every x- and z-position in the corridor segment. The E-field mesh generation is the bottleneck in the numerical calculations and the largest influence on program speed is the mesh resolution and the number of modes included. On the other hand, the same example is simulated using FEKO version 7.0 with the same computer resources. It is found that the simulation takes about 41 minutes using FEKO Physical Optics (PO) solver. IT can be noted that the proposed model is faster than the simulation package and the differences will be increased by increasing the dimensions or operating frequency.

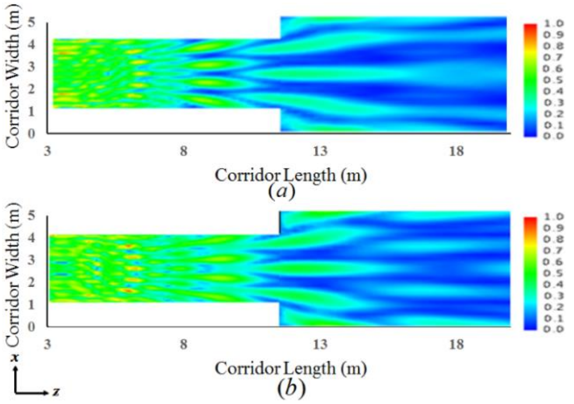


Fig. 15. Magnitude of normalized electric field, x-z plan, for two corridor segments at frequency band 0.90 GHz: (a) FEKO model for partially reflecting walls, and (b) PEC model.

IV. MEASUREMENTS

In this section sample results are presented to verify the accuracy of the present model by comparing the obtained results with experimental results. The proposed model is used to simulate simple cascaded sections of indoor propagation with partially reflecting walls and the equivalent PEC model.

This simple scenario of a straight corridor section is verified experimentally at Wi-Fi frequency 2.4 GHz for two different locations with different corridors dimensions in to verify the presented model in different buildings structures. The first scenario has been done in corridor of commercial building with brick walls. The experimental setup consists of two wooden carts. One cart is used to hold the transmitting antenna and the transmitter and the other one is used to hold the receiving antenna, the receiver and data collecting computer as shown in Fig. 16. Cisco Aironet 1242 access point with dipole antenna with gain of 2.2 dBi is used as transmitter. The transmitting and receiving antennas are kept vertically polarized. Most of the measurements were taken with the transmitter is located at a fixed location and the receiver is moved along the corridor. Figure 16 shows the locations of the transmitter and the receiver for the relevant measurements. The transmitter was fixed at certain position and the receive antenna was moved along a straight line away from the transmitter in steps of 30 cm. The length of the corridor is about 15 m. The height of both transmitting and receiving antennas is kept 60 cm above the ground. Figure 17 shows a comparison between the measures received power in dBm and calculated power by using modal analysis for partially reflecting walls. In this case, the optimum equivalent waveguide with PEC boundaries is found to be equivalent PEC width is 1.02 of the walls width while the equivalent PEC height is about 1.06 of the walls height. Good agreement between the measured and calculated power is obtained. The slight differences can be explained due to errors in the manual positioning of the receiving antenna and differences due to the boundary conditions of the actual corridor. The calculated error between the model and measured results is about 7.3%.

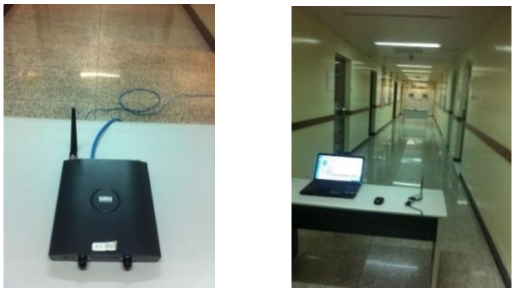

(a) (b)

Fig. 16. Measurement setup: (a) transmitter and (b) receiver.

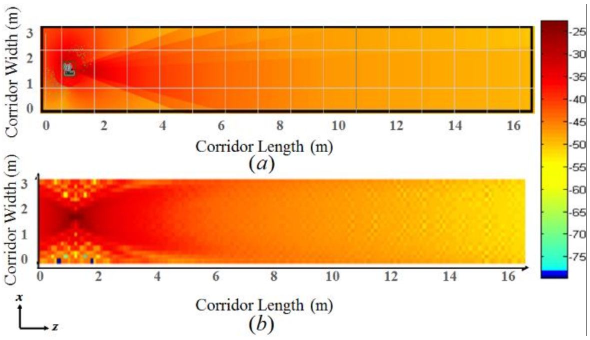


Fig. 17. Received power distribution (dBm) across the corridor. (a) Measured signal strength and (b) calculated signal strength.

On the other hand, the same setup is used to test the model for corridor segment with another commercial building of gypsum walls as show in Fig. 18 (a). The area under test is highlighted in Fig. 18 (b) in the structure layout.

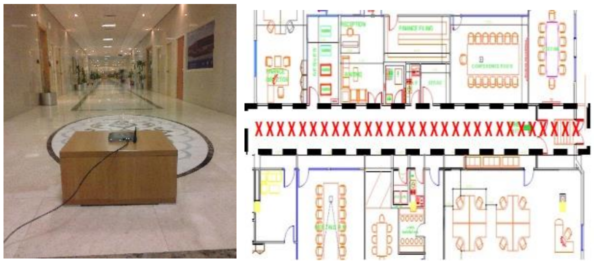

(a) (b)

Fig. 18. Corridor section of indoor commercial building: (a) transmitter and (b) structure layout.

Figure 19 shows a comparison between the measured received power in dBm and calculated power by using modal analysis for partially reflecting walls, the difference error between the two results is about 7.8%. It can be noted that the total field distribution is not confined within the hallway boundaries, resulting in significant illumination of the adjacent rooms. It should also be noted that there is considerable interference penetrating through the walls. This through-wall interference is distributed along the entire length of the side hallway.

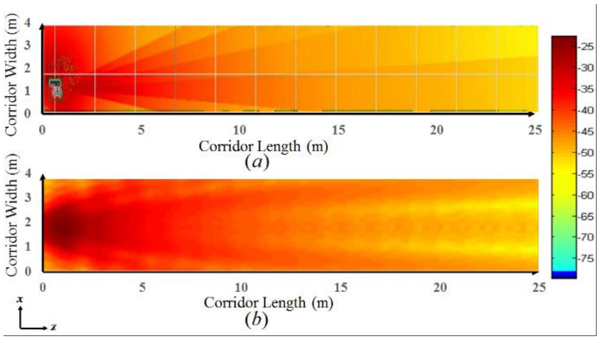


Fig. 19. Received power distribution (dBm) across the corridor. (a) Measured signal strength and (b) calculated signal strength.

V. CONCLUSION

In this paper, a new approach is proposed to simulate electromagnetic wave propagation in indoor environment with taking into consideration the effect of partial reflectivity of the walls forming indoor environment by using equivalent PEC waveguide model. The basic idea of the proposed method is that the field distribution inside a waveguide section with partially reflecting boundaries can be approximated by a field distribution of a PEC waveguide of the same cross section shape with expanded lateral dimensions. Vertical and horizontal polarizations are studied and it found that the bottom and upper walls have more effect on the field distribution in the case of vertically polarized excitation than the side walls while the reverse is true for the horizontally polarized excitation. The results of the presented model are verified by comparison with numerical results and experimental results. Good agreements are obtained from these comparisons. The present model represents a good tool for planning appropriate wireless links in indoor environment.

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