Correlation Analysis between Multi-Sources in Indoor Corridors and Tunnels

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Abstract ─ In this paper, a model is presented to simulate wave propagation in indoor corridors and tunnels with imperfectly conducting walls. The model is based on the waveguiding effect of corridors and tunnels. This approach is based on assuming that the boundaries of the waveguide section are constant impedance surface as the surface impedance of the wall is almost independent of the angle of the wave incidence onto the wall. An analytical approach for the calculation of the signal correlation between the transmitters and receivers elements in tunnels and indoor corridors is proposed. A new approach for determining the best locations of the indoor access points is introduced based on minimum correlation between sources with minimum cross talk. A scenario is considered in order to check the accuracy of this model. This scenario is verified by comparing experimental and numerical simulation results. Good agreement is achieved.

Index Terms ─ Indoor propagation, signal correlation.

I. INTRODUCTION

In recent years, a lot of attention has been drawn to modelling indoor wave propagation [1-2], in road and mine tunnels [3]. This is especially important in wireless applications because of the large dimensions compared with the operating wavelength and complex geometry of buildings. Predicting wave propagation in indoor environment is especially complicated problem due to the operating wavelength that 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. Different models have been developed to predict how indoor environment affects the wave propagation. These models are divided into empirical and theoretical models [4-10].

Recent advances on wireless communication have revived interest on correlation between sources in tunnels [11-18]. Results described in [16] have shown that angular spread of the rays are rather small and one can thus expect a strong correlation between antennas if arrays are used at both ends of the link. The correlation between the receiving array elements increases with distance, while a small correlation is obtained at small distances where the number of modes is large [17]. At large distance from the transmitter, the correlation increases since only few modes interfere; this correlation has a strong impact on the channel capacity [18]. Since small correlation between array elements is an important criterion for Multiple Input Multiple Output (MIMO) systems, in a tunnel, this can lead to arrays that may become prohibitively long [17].

In this paper, a model based on 3D waveguide model for simulating long corridor sections and tunnels is proposed. This approach is based on assuming that the boundaries of the waveguide section are constant impedance surface as the surface impedance of the wall is almost independent of the angle of the wave incidence onto the wall. An analytical approach for the calculation of the signal correlation between the transmitters and receivers elements is proposed. The effect of the transmitter and receiver locations on the signal correlation is presented. A new approach for determining the best locations of the indoor access points is introduced based on minimum correlation between sources and minimum cross talk. Full wave numerical analysis of the same problem based on FEKO [19] simulation is used to verify the obtained results. Experimental results are also conducted with a simple dipole antenna in a specific office corridor to verify the

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obtained theory.

II. MODAL ANALYSIS OF INDOOR PROPAGATION BASED ON CONSTANT WALL IMPEDANCE BOUNDARY CONDITIONS

Corridors in indoor environment and tunnels can be represented as a combination of multi-mode rectangular waveguide sections as shown in Fig. 1. The excitation source is assumed to be a dipole located at the waveguide section. The proposed model is introduced by Mahmoud [20-21]. The model is based on assuming that the boundaries of the waveguide section are constant impedance surface as the surface impedance of the wall is almost independent of the longitudinal phase constant k_z.

Following [20-21], consider a rectangular guide of width w and height h and the outer medium of complex relative permittivity $\varepsilon_c = \varepsilon_r - i\sigma/\omega\varepsilon_0$ as shown in Fig. 1 (b). When the operating frequency is sufficiently high such that the tunnel dimensions are much greater than the free space wavelength λ_0, the low order modes in the tunnel are characterized by $k_x \ll k_0$ and $k_y \ll k_0$, where k_0 is the free space wavenumber, k_x and k_y are the wavenumbers in the x and y directions. Under these conditions, the tunnel walls are accurately modelled by normalized constant surface impedance Z_s and admittance Y_s relating the transverse and longitudinal field components. The Z_s and Y_s are defined by [20]:

$$Z_s = 1/\sqrt{\varepsilon_r - 1 - i\sigma/\omega\varepsilon_0}, \quad (1)$$

$$Y_s = (\varepsilon_r - i\sigma/\omega\varepsilon_0)/\sqrt{\varepsilon_r - 1 - i\sigma/\omega\varepsilon_0}, \quad (2)$$

where ε_r is the corridor walls relative permittivity and σ is the corridor walls conductivity. The total fields(E, H) are expressed as a sum over the natural modes in the corridor/tunnel. For a TM_y, or a vertically polarized mode, $E_x = 0$ and E_y may given, for an even mode by:

$$\mathbf{E}_y^{TM}(x, y, z) = \sum\sum A_{mn} e_{mn}(x, y)\, exp(-jk_z z), \quad (3)$$

where A is the excitation coefficients and $e_{mn}(x, y)$ are the transverse eigenfunctions, given by:

$$e_{mn}(x, y) = \cos(k_{xm}x)\cos(k_{yn}y), \quad (4)$$

where k_x and k_y are the transverse wave numbers in the walls given as below [20]:

$$k_{yn}h = n\pi[1 + j2Y_s/k_0 h], \quad (5)$$

$$k_{xm}h = m\pi[1 + j2Z_s/k_0 w], \quad (6)$$

where m and n =1,3, … are odd integers for the even modes considered. In the above: $k_y^2 + k_x^2 = k_0^2 - {k_z}^2$ because the guide is oversized relative to the wavelength, both k_x and k_y are $\ll k_0$ and k_z for the low order modes. The E_z component is obtained from the divergence equation $\nabla \cdot \bar{E} = 0$, hence,

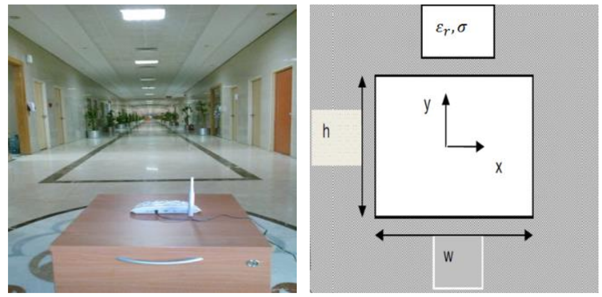
$$jk_z E_z = \partial E_y/\partial y, \quad (7)$$

which shows that E_z is of the first order smallness relative to E_y. The magnetic field components are obtained as:

$$\eta_0 H_x = -k_z E_y/k_0\,, \eta_0 H_y \approx 0, \text{ and}$$

$$\eta_0 H_z = j\partial E_y/k_0 \partial x, \quad (8)$$

where terms of the second order smallness have been neglected (such as $k_x k_y/k_0^2$). Same analysis can be followed to obtain the TE, horizontally polarized case.



(a) (b)

Fig. 1. (a) Schematic drawing of an example for an indoor corridor environment, and (b) equivalent waveguide representation [20].

Full wave numerical analysis based on FEKO Ray Launching Geometrical Optics (RL-GO) [19] simulator is used to verify this technique for long corridor section. FEKO's RL-GO [19] method is a ray-based technique that models objects based on optical propagation, reflection and refraction theory [23-24]. GO (ray launching) is formulated for use in instances where electrically very large (>20λ) metallic or dielectric structures are modelled. Ray-interactions with metallic and dielectric structures are modelled using Huygens sources, placed at each ray, contact point on material boundaries. The ray-launching process is easily controlled, based on the angular spacing (for localized sources) or transverse spacing (for plane wave sources) of the rays and the number of multiple interactions allowed.

Figure 2 shows the electric field distribution for a corridor section with imperfectly conducting walls. The operating frequency is assumed to be 0.90 GHz corresponding to the lower GSM band. The length, width and height of the corridor are assumed to be 100 m, 5 m and 3 m respectively. The permittivity of the walls is 3 and conductivity is σ=0.01 s/m [22]. The section is excited by a unit y-directed dipole which is located at the point (2.5 m, 1.5 m, 0.5 m).

Figure 2 (a) shows the magnitude of the normalized electric field in the plane parallel to the ground at a height 2.25 m. On the other hand, Figure 2 (b) shows the corresponding normalized electric field distribution for the equivalent constant impedance walls rectangular waveguide section. The percentage of the difference between Fig. 2 (a) and Fig. 2 (b) is calculated by using Mathematica. By comparing the simulation and model results, it is found that the error is about 8.57%. The model is developed in Matlab which runs on a laptop with an Intel 2.4 GHz processor, 8 GB of RAM and Windows 8.1 64-bit; the total program runtime for the above example is only 2 minutes. On the other hand, the same example is simulated using simulation package FEKO version 7.0 with the same computer resources. It is found that the simulation takes about 23 minutes using FEKO RL-GO solver. It can be noted that the proposed model is faster than the simulation package and the difference will be increased by increasing the dimensions or operating frequency.

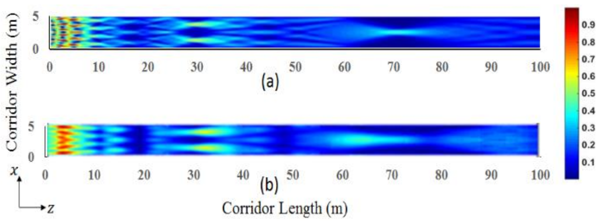


Fig. 2. Magnitude of normalized electric field, x-z plane, for two corridor segments at frequency band 0.90 GHz: (a) FEKO model, and (b) constant wall impedance model.

III. SPACE AND FREQUENCY CORRELATION BETWEEN MULTI-SOURCES

In this section the correlation between the electric field excited by two array elements is discussed [11-15]. This is a critical tool for optimizing the location of the transmitters with minimum cross talk as to obtain best coverage and minimize dead zones. The correlation coefficient $\rho^E_{j_1 j_2}(z)$ between the electric field produced by the transmitting elements j_1 and j_2, and received in a transverse plane at an axial distance z is obtained by:

$$\rho^E_{j_1 j_2}(z) = \frac{\iint_{xy} E_{j_1} \cdot E^*_{j_2}\, dx\, dy}{\sqrt{\iint_{xy} \left|E_{j_1}\right|^2 dx\, dy \iint_{xy} \left|E_{j_2}\right|^2 dx\, dy}}, \tag{9}$$

where E_{jx} is electric field for the corresponding source which can be obtained using the proposed model.

The correlation between sources is calculated for space diversity in the transverse and axial planes, where in the transverse plane both the source elements are fixed in the transverse plane with Δd spacing between them and the correlation is calculated between the electric field received in the transverse plane, x-y plane, at distance z from the transmitters, while for the latter one, the transmitters are in the axial plane with Δz and the correlation is calculated between the to the electric field received in the x-z plane. On the other hand, frequency correlation between sources is calculated at different frequency bands, channels, as to optimize the operating frequency channels of the sources with minimum cross talk and phase difference between received signals.

A. Transvers correlation

Transverse correlation is the correlation between sources that are located in the corridor/tunnel transverse plane [13] and it is calculated from the values of the electric field in a transverse plane. In order to verify the proposed formula for the correlation of Equation (9), a comparison with previously published results is presented. Figure 3 shows the correlation coefficient between adjacent elements at 0.9 GHz band for two cases, where the elements are λ and 2λ apart [12]. The tunnel is rectangular in shape with width and height of 4 m and 4.5 m, respectively. The maximum axial distance from the transmitter is 600 m. The transmitters in the tunnel are 50 cm from the ceiling and at 1/8 of the tunnel width from the side wall.

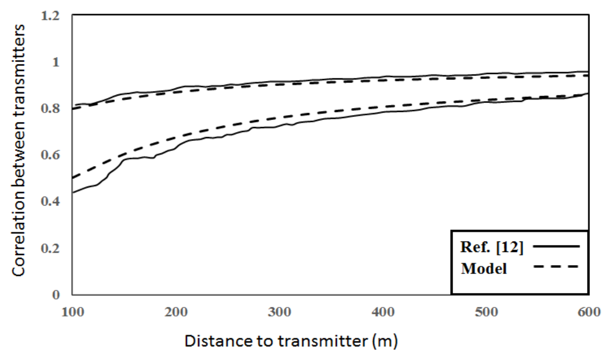


Fig. 3. Average correlation between the electric field produced by the two transmitters in the a tunnel for different spacing$(\lambda, 2\lambda)$, f =0.90 GHz, $\varepsilon_r = 5, \sigma = 0.01$.

B. Axial correlation

One of the most important challenges in indoor propagation is to determine the location of the transmitters or access points (AP), so as to guarantee maximum signal coverage. Axial correlation is an important tool for determining such locations of the APs with minimum cross talk as it is calculated from the values of the electric field in the axial plane, x-z plane, due to transmitters with Δz spacing along the axis of the corridor. To study this point, it is required to calculate, for a given frequency, the amplitude ρ of the complex correlation coefficient between two sources (j_1,j_2) with Δz separation down the corridor axis using Eq. (9), where the electric field in the x-z plane is calculated due to sources along the corridor axis and numerically integrated to calculate the correlation between the two sources.

Figure 4 shows the electric field correlation coefficient for two transmitters along the corridor axis with different spacing. The adjacent sources are 1 m to 85 m apart. The corridor width, height and length are 3 m, 3 m and 100 m, respectively. The walls permittivity is 3 and conductivity is 0.01 S/m [22]. It can be noted from Fig. 4 that, the correlation coefficient has peaks at some points. These points should be avoided when designing the locations of the access points. In order to check the effect of the correlation value on the electric field distribution, the electric field is calculated using FEKO for the mentioned corridor with two sources, where the calculation is repeated for two cases; in the first case the sources are 25 m apart and the second one the sources are 45 m apart.

Figure 5 (a) shows the magnitude of the simulated electric field in the plane parallel to the ground at a height 1.5 m from the ground with transmitter locations at z = 1 m and 46 m, respectively. On the other hand, Fig. 5 (b) shows the magnitude of the electric field with transmitter locations at z = 1 m and 26 m, respectively. It can be noted that the zones with almost no signal are less in Fig. 5 (a) than in Fig. 5 (b). Thus, electric field distribution for the case of minimum correlation between the transmitters is better than the case with higher correlation. It can be concluded from the above discussion, that the correlation coefficient between transmitters is a good tool for planning appropriate wireless links in indoor environment with optimum access point location.

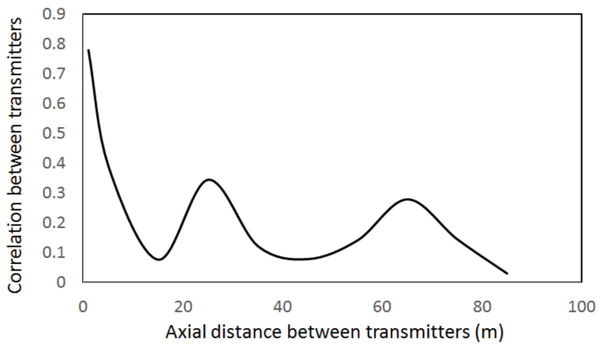


Fig. 4. Average correlation between the electric field produced by the two Transmitters in the corridor for different spacing (from 1 m to 85 m apart), $f = 0.9$ GHz, $\varepsilon_r = 3, \sigma = 0.01$.

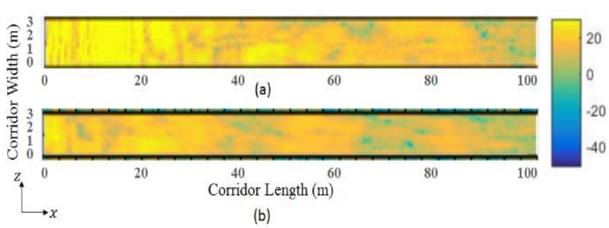


Fig. 5. Electric field distribution in $dB\mu V/m$ for x-z plane. (a) Field distribution for transmitter at locations at z = 1 m and 46 m. (b) Field distribution for transmitter locations at z = 1 m and 26 m.

C. Frequency correlation

Frequency correlation between sources is calculated at different frequency bands or channels, in order to optimize the operating frequencies for minimum cross talk between received signals. The same simulation example previously discussed is repeated for two frequency bands to calculate correlation between two sources with frequency steps Δf, where the two sources are at same position while the operating base frequency for the first band is $f_0 = 0.9\ GHz$ and for the second case $f_0 = 2.4\ GHz$. One of the two sources will be configured to operate in the base band while the other source is operating with higher frequency $f = f_0 + \Delta f$, where Δf is changed from 10 MHz to 100 MHz.

Figure 6 shows the electric field correlation coefficient between the sources due to frequency diversity at two frequency bands. It can be noted that the correlation decreases at higher operating band.

It can be concluded that correlation between transmitters can be reduced by either using space diversity, frequency diversity or by combining both. It should be noted that the optimal locations of indoor access points in corridors are these locations with minimum correlation between transmitters where the cross talk between transmitters is minimum and signal quality is better.

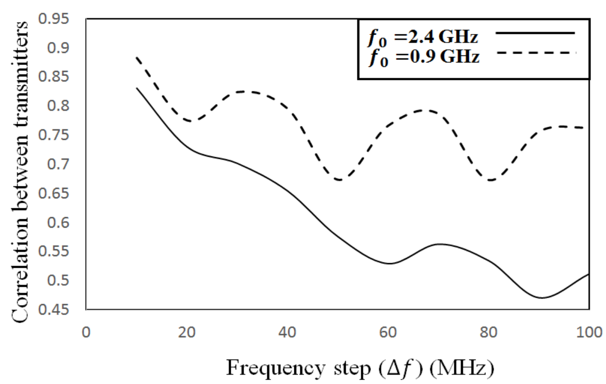


Fig. 6. Average correlation between the electric field produced by the two Transmitters in the corridor for different frequency bands, $f = 0.9$ GHz, 2.4 GHz, $\varepsilon_r = 5$, $\sigma = 0.01$.

IV. MEASUREMENTS

In this section sample results are presented to verify the accuracy of the present model by comparing the obtained results with measurement results. The proposed model is used to simulate indoor propagation in long corridor section with imperfectly conducting walls and to calculate the correlation between two sources.

This scenario of a straight corridor section is verified experimentally at Wi-Fi frequency 2.4 GHz in corridor of commercial building with gypsum walls. The experimental setup consists of three wooden carts. One cart is used to hold the first transmitting antenna and the transmitter and the second one is used to hold the second transmitter, while the third is used to hold the receiving antenna, the receiver and data collecting computer as shown in Fig. 7. TP-LINK TL-WA701ND access points with dipole antenna with gain of 5 dBi are used as transmitters. The transmitting and receiving antennas are kept vertically polarized. The measurements were taken with one transmitter located at a fixed location and the other transmitter moving into 5 m steps along a straight line away from the first transmitter, while receiver is moved along the corridor to measure the axial correlation between the transmitters. Figure 7 shows the locations of the transmitters and the receiver for the relevant measurements. The length of the corridor is about 100 m while the width and height are 3.7 m and 3.4 m, respectively. The building walls is gypsum walls with permittivity 2.4 and conductivity 0.08 [25]. The heights of both receiving and transmitting antennas are kept 60 cm above the ground.

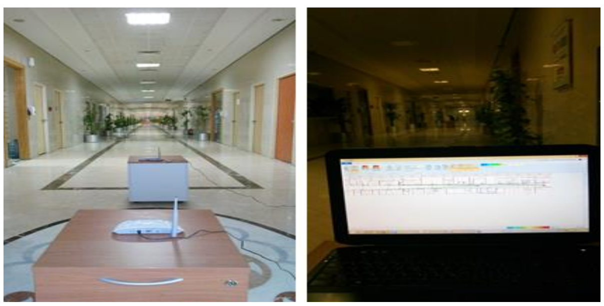


Fig. 7. Measurement setup in corridor section

Figure 8 shows a comparison between the measured received power in dBm and calculated power by using proposed modal analysis. Good agreement between the calculated and the measured power is obtained. The slight differences can be explained as errors in the positioning of the antenna and differences due to the boundary conditions of the actual corridor. The calculated error between the model and measured results is about 9.029%.

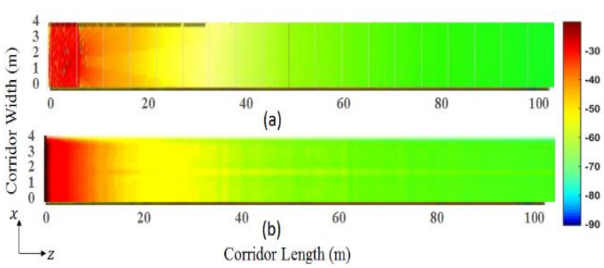


Fig. 8. Received power distribution (dBm) across the corridor. (a) Measured power strength, and (b) calculated power strength using modal analysis.

On the other hand, Fig. 9 shows a comparison between the measured and calculated correlation by proposed analytical model. The calculated error between the measured and model results is about 9.3%. It should be noted that the correlation is minimum at 40 m which can be the best location of the access point with minimum cross talk.

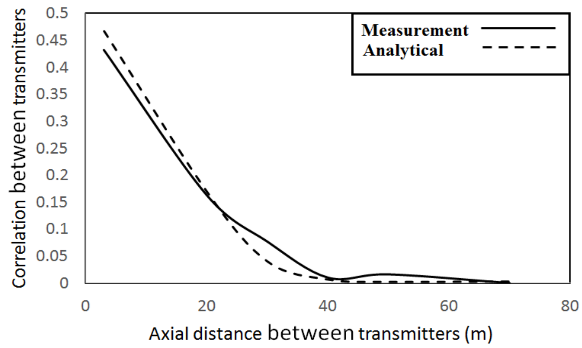


Fig. 9. Average correlation between the received power of two transmitters in the corridor with different axial spacing (from 3 m to 70 m apart), $f = 2.48$ GHz.

The same setup is used to test the model for corridor segment with another hotel building with brick walls with permittivity 3.73 and conductivity 0.37 S/m [25] as shown in Fig. 10. In this case the corridor width is 3.1 m and height is 2.8 m, while the length is about 35 m. The measurements were taken with one transmitter located at a fixed location and the other transmitter moving into 5 m steps along a straight line away from the first transmitter while receiver is moved along the corridor to measure the axial correlation between the transmitters. The axial distance between the transmitters is from 5 m to 30 m.

Figure 11 shows a comparison between the measured and calculated correlation by proposed analytical model. The calculated error between the model and measured results is about 8%. It should be noted that the correlation is lower than 0.2 at 15 m which can be the best location of the access point with minimum cross talk for location after 15 m aside.

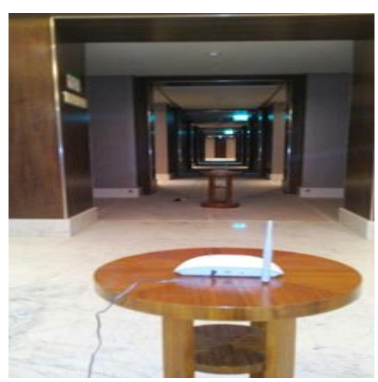


Fig. 10. Measurement setup in hotel.

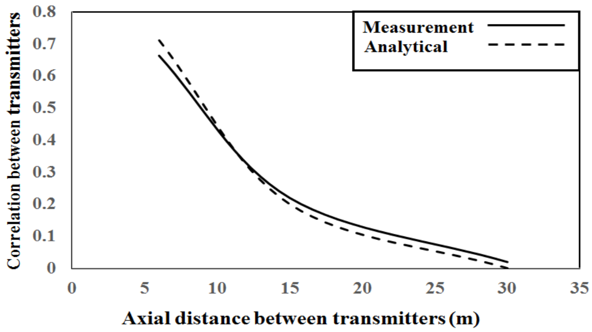


Fig. 11. Average correlation between the received power of two transmitters in the corridor with different axial spacing apart (from 5 m to 30 m apart), $f = 2.48$ GHz.

It should be deduced from the presented approach that designers of indoor wireless system should consider the optimal location of the access point that corresponds to minimum correlation between sources. Also it can be concluded that the proposed model is a good tool for designing indoor wireless system with high accuracy and low computational resources.

V. CONCLUSION

A model based on 3D waveguide model for simulating long corridor sections and tunnels is proposed. This approach is based on assuming that the boundaries of the waveguide section are constant impedance surfaces. Space and frequency correlation between transmitters are presented. A new approach for determining the best locations of the indoor access points is introduced based on minimum correlation between sources and minimum cross talk. It can be deduced, that the correlation coefficient between transmitters is a good tool for planning appropriate wireless links in indoor environment with optimum access point location. The results of the presented model are verified by comparison with numerical results and experimental results. Good agreements are obtained from these comparisons.

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