UHF Propagation in Indoor Hallways

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***Abstract*— A new model for UHF propagation in large buildings is presented. This model relies on knowledge of the interior arrangement of the building without requiring much detail. The guiding of radiation along hallways is the most significant propagation process at distances of more than 10 m from the transmitter. The waveguide model predicts the power loss rate along the hallways, which is affected by the coupling among the propagating modes. The coupling results from the roughness of the surfaces in the building; it is predicted in an average manner using the average deviation of the walls from perfect smoothness.**

I. Introduction

Understanding indoor radio propagation is important in the design and layout of mobile data and voice systems. A good model should provide insight into the propagation mechanism, in addition to predicting power levels throughout the building. Current models of propagation in the UHF band (300 MHz–3 GHz) are based on ray tracing with strong diffraction effects [1], [2], or on empirical distance power laws [3].

Ray tracing provides accurate predictions of power levels, when detailed information on the geometry and materials of the building is available . It is less useful when an overall picture is needed of the propagation, or when the geometry of the building is given without much detail.

Measurements show that despite the relative transparency of wall materials, hallway guidance is the most significant propagation mechanism at medium and large distances from the source (starting at a radius of about 10 m). A waveguide model was suggested for hallways by *Kyritsi and Cox* [4], but they assumed perfectly smooth walls, with no mode coupling. In this paper we suggest a more sophisticated model, that takes into account coupling among the waveguide modes, caused by the roughness of the walls. We investigate the effects of coupling on power levels in a building, in the hallways and adjacent rooms. Our model offers insight into observed phenomena, in particular the effect of hallway junctions on measured power levels.

The measurement results are presented in section II, followed by the model in section III and discussion in section IV.

II. Measurements

Measurements were taken in the 850 – 950 MHz band, in the basement of the Packard building in Stanford University. The power was measured with a 250 kHz resolution, with an accuracy of 1 dB. The antennas were quarter wave monopole with a magnetic mount, standing over a 0.3×0.3 m^2 ground plane.

The setup consisted of two polyethylene carts which were placed in the hallways or in the rooms. One cart held the transmitting antenna and the other the receiving antenna and other equipment. The source was the tracking generator of a spectrum analyzer, and a computer was used to record the received power spectra.

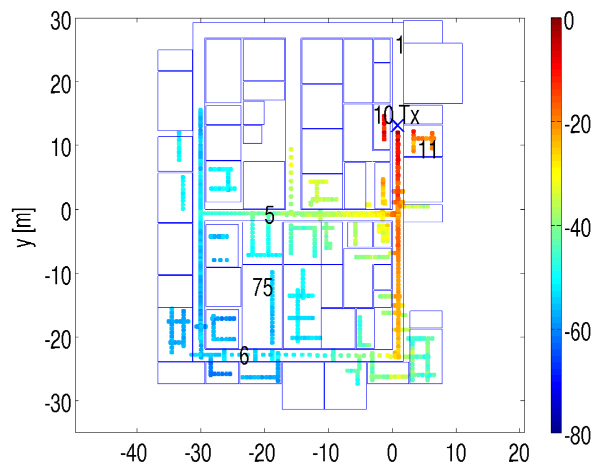

Fig. 1. Locations of the transmitter and receiver in the Packard basement, with median power level at each receiver location [dB]. The single digit numbers indicate hallways and the two–digit numbers indicate rooms in the building. Details of the walls and doors were omitted.

The Packard Building is an office and laboratory building in the Stanford University campus, built around 1999. The ceiling is floating with metal plates between the basement and the ground floor of the building, and the floor is concrete. The interior walls are mostly drywall with aluminum studs at 16" intervals, some walls are reinforced with concrete.

A. Results

This section shows power levels measured along the hallways and in adjacent rooms. The median power level over the band (850–950 MHz) is shown for each measurement location, where the median was taken over the dB power levels. Taking the median over the frequency band has a similar effect as taking a median over single frequency measurements over a small (spatial) neighborhood.

1) Wall Penetration: Figure 2 shows the power received in the near environment of the transmitter in the hallway and in two adjacent rooms. The geometry is shown in figure 1. The measurements in room 11 show considerably lower power than room 10, the reason is the concrete wall separating room 11 from the hallway. In room 10, power levels are very similar to the hallway level. The difference is within the accuracy margin of our measurements, that is limited by temporal variations and the inaccuracy of the equipment. A reliable estimate of the

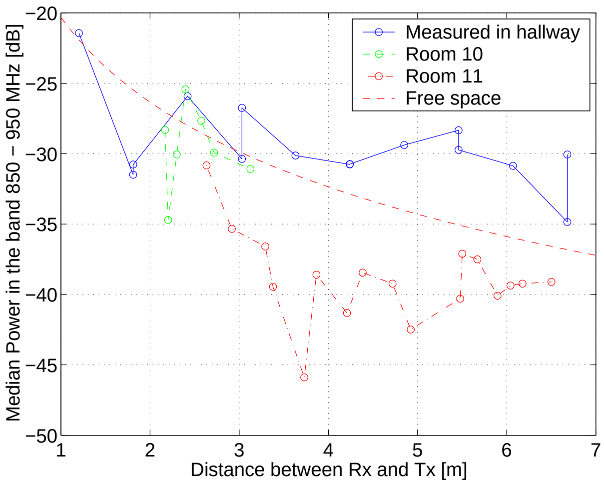

Fig. 2. Power received near the transmitter; The geometry is shown in figure 1. The free space curve is an estimation based on measurements at close range.

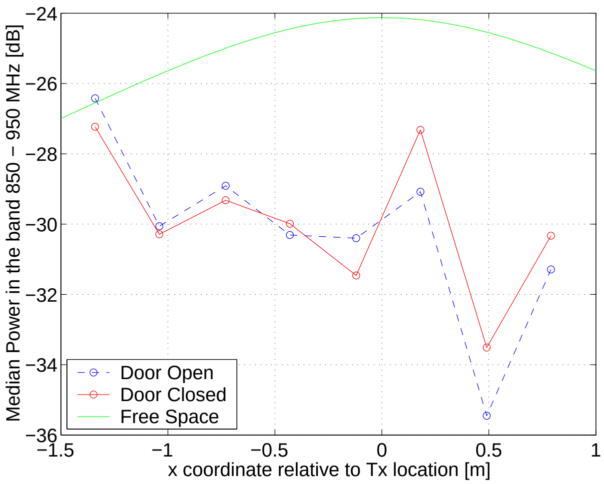

Fig. 3. Power received across a wall; The geometry is shown in figure 4. The free space curve is an estimation based on measurements at close range.

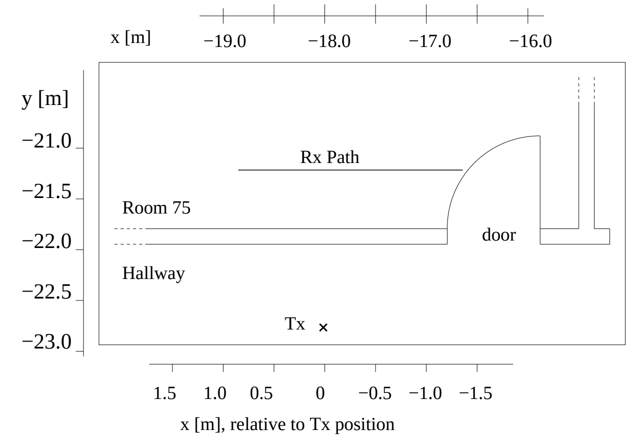

Fig. 4. Geometry of the measurements near room 75.

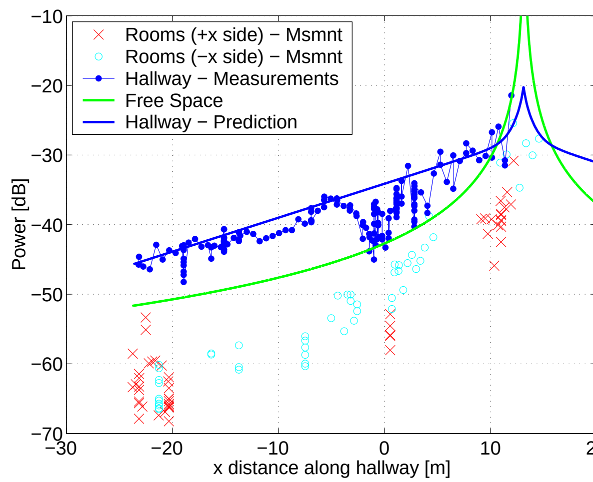

Fig. 5. Median power in hallway 1 and adjacent rooms. The hallway data are at points 0.5 m or more from both walls. The room data are at points between 1 m and 5 m from one of the hallway walls. The geometry is shown in figure 1. Model parameters are $\epsilon = 3$, $\sigma = 0.085$ S/m, $D = 2$ m, $s^2 = 0.2$ m^2 and hallway width is 1.8 m. The power distribution at the transmitter is a vertical narrow source in the middle of the hallway.

drywall attenuation cannot be obtained from our measurements, except to say that the penetration is very good. Measurements in [5] and [6] show attenuation of 0.1–0.5 dB for perpendicular incidence on drywall boards of various widths.

Another indication of the penetration through drywall is shown in figure 3, that presents the power measured along the wall of room 75, with the wooden door open and closed. The geometry of this measurement is shown in figure 4. The state of the door (open or closed) has a very small effect on power levels, and this indicates that most of the radiation penetrates directly through the wall.

Although penetration through the walls is very strong, the measurements shown below indicate that guidance along the hallways is a very important mechanism.

2) Power in and near the Hallways: Figure 5 shows the power measured in hallway 1 and the adjacent rooms, at distances up to 5 m from the hallway. Hallway 1 contained the transmitter so locations in it, which have line of sight to the transmitter, receive more power than locations in the rooms. The theoretical curves in figure 5 are discussed in section III.

One phenomenon seen in hallway 1 is the increasing difference between the hallway power levels and the room power levels, at increasing distances from the transmitter. At locations close to the transmitter, the difference in power levels is small (0 dB for the negative x and about 5 dB for the positive x). The walls in the positive x side are concrete in this area. At large distances from the transmitter, the difference between the hallway and the room levels is in the order of 15–20 dB for both sides.

The power in and near hallway 5 is shown in figure 6, where the transmitter was located in hallway 1 (figure 1). As in hallway 1, the power levels in the rooms are similar to the levels in the hallway in the area closest to the transmitter (right of figure), with the difference growing as the receiver moves away from the transmitter. The difference between the hallway levels and the room levels is small for the rooms in the positive y side, and some rooms get higher power levels because of direct penetration through the walls. The power levels in the rooms on

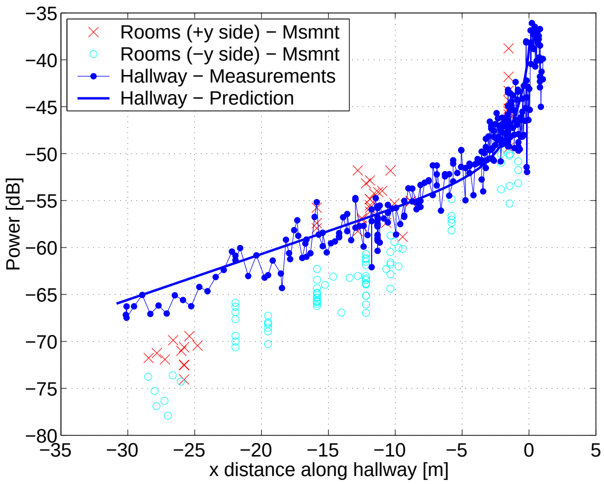

Fig. 6. Median power in hallway 5 and adjacent rooms. The hallway data are at points 0.5 m or more from both walls. The room data are at points between 1 m and 5 m from one of the hallway walls. The geometry is shown in figure 1. Model parameters are $\epsilon = 3$, $\sigma = 0.085$ S/m, $D = 2$ m, $s^2 = 0.2$ m^2 and hallway width is 1.8 m. The power distribution at the junction is uniform.

both sides of the hallway are similar for distances bigger than about 20 m from the junction with hallway 1.

Another important effect is the sharp decrease of power at areas near the junction and the considerably lower rate of power loss at areas further from the transmitter.

III. The Model

The simple model we present here consists of a slab waveguide. The walls of the waveguide are made of a lossy dielectric material (figure 7). The waveguide is filled with air, so between the walls we assume the electrical properties of free space. With this simple model, we ignore the effects of any objects within the waveguide.

The waveguide can be defined in terms of its width and the relative complex dielectric constant of the walls ϵ:

$$\epsilon_r(x,z) = \begin{cases} 1 & -a \approx h(z) \le x \le f(z) \approx a \\ \epsilon & x < h(z) \text{ or } x > f(z) \end{cases} \tag{1}$$

where $\epsilon_r(x,z)$ stands for the relative dielectric constant of the smooth waveguide. The permeability is fixed at the vacuum permeability for the walls and interior of the waveguide and the wall roughness is given by $f(z)$ and $h(z)$.

The analysis starts with a smooth waveguide where $f(z) = a$ and $h(z) = -a$ in section III-A. This model is extended by considering rough (non-smooth) walls in section III-B. The waveguide model is two dimensional (it assumes no variation in the vertical direction), and the effects of the floor and ceiling are discussed in section III-C.

A. A Smooth Multi-Moded Waveguide

The hallway waveguide is normally multi–moded because the width of hallways is many times the wavelength in the UHF band. Our model is two dimensional, so there is no variation in the y direction. The lossy dielectric walls of the waveguide have the complex relative dielectric constant

$$\epsilon = \epsilon' + j\epsilon'' = \epsilon_r - j\frac{\sigma}{\omega\epsilon_0} \tag{2}$$

where ϵ_r is the relative permittivity of the walls, σ is their conductivity; ω is the angular frequency, the time dependence is $e^{j\omega t}$ and $\epsilon_0 = 8.85 \times 10^{-12}\,\frac{F}{m}$ is the vacuum permittivity. A few other definitions: $k = \frac{2\pi}{\lambda}$ is the free space wave number, where λ is the free space wavelength. β and $k_x = u/a$ represent the z and x components of the k vector for propagation inside the waveguide, where u is the normalized k vector in the x direction. $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$ is the vacuum impedance, and $\mathcal{H}$ is an arbitrary amplitude.

The field expressions for the transverse electric (TE) modes inside the waveguide $|x| <= a$ are brought from [7]:

$$\mathbf{E} = E_y\hat{\mathbf{y}} = j\frac{k}{k_x}Z_0\mathcal{H}\begin{Bmatrix} \cos(k_x x) \\ \sin(k_x x) \end{Bmatrix} e^{j\omega t - j\beta z}\hat{y} \tag{3}$$

The upper function in the curly braces apply to the symmetric modes and the lower to the antisymmetric modes, where the symmetry/antisymmetry characterizes the field component in the y direction. The field components not shown can be calculated using Maxwell's equations. A similar expression describes the magnetic field of the transverse magnetic (TM) modes.

Using the boundary conditions, the characteristic equation can be formulated in terms of u, the propagation constant in the waveguide, and the properties of the waveguide. The characteristic values of the real part of u (marked u') are as follows for the TE modes [7]:

$$u' = \pi(1-\eta)\frac{n}{2} \quad \text{where} \quad \eta = \frac{\epsilon''\lambda}{4\pi a(\epsilon'-1)^{3/2}} \;\;,\;\; n = 1, 2, \ldots \tag{4}$$

Odd values of n correspond to the symmetrical modes and even values of n correspond to antisymmetric modes. The propagation constant in the z direction is determined from $\beta^2 = k^2 - \left(\frac{u}{a}\right)^2$.

The number of significant modes N (for a single polarization) is determined by the condition $u' < ka$ and it can be approximated by $N \approx \frac{4a}{\lambda}$ (assuming $\eta << 1$). When both TE and TM modes are considered, the number of significant modes is $2N$.

B. A Rough Waveguide

The analysis of multi-moded waveguides and the coupling between the propagating modes started with a series of papers by *Marcuse* [8], [9], [10] and was extended by others [11], [12]. These works analyze a dielectric multi-moded optical fiber in order to predict the effects of production imperfections of optical fibers.

The two dimensional model is maintained. We characterize the wall perturbations statistically, using their correlation functions, where we assume that the perturbations on both walls are independent of each other and wide sense stationary, i.e., the

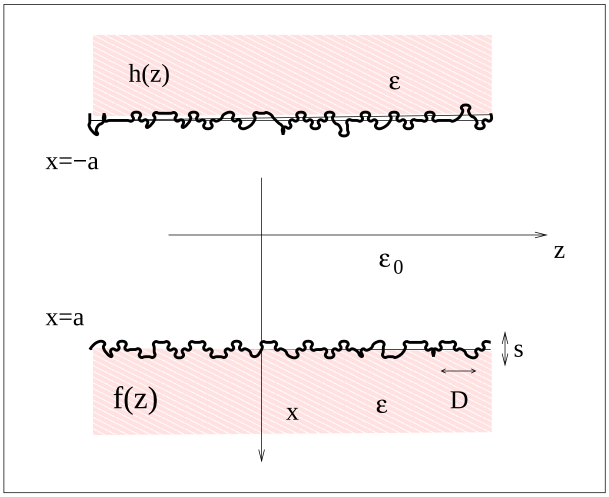

Fig. 7. A rough slab waveguide, $f(z)$ and $h(z)$ define the roughness of the walls.

statistical propertied do not change along the hallway. for any point z_0 along the waveguide:

$$\langle [f(z_0) - a] [f(z_0 + z) - a] \rangle = s^2 e^{-\frac{|z|}{D}} \tag{5}$$

where s is the rms deviation of the wall from perfect straightness and D is the correlation length. The same statistics is assumed for $h(z)$, which defines the deviations of the wall near $x = -a$.

We now examine the deviation of the complex dielectric constant of the waveguide from the smooth waveguide. This deviation is given by

$$\Delta\epsilon(x, z) = \epsilon_r(x, z) - \epsilon_s(x, z) \tag{6}$$

where $\epsilon_r(x, z)$ is defined in (1) and $\epsilon_s(x, z)$ stands for the relative dielectric constant of the smooth waveguide.

The fields in the waveguide are solutions of the wave equation:

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + (\epsilon_s(x, z) + \Delta\epsilon(x, z))\,\epsilon_0 k^2 E_y = 0 \tag{7}$$

The modes of the smooth waveguide are solutions of

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + \epsilon_s(x, z)\epsilon_0 k^2 E_y = 0 \tag{8}$$

We express the fields in the perturbed waveguide in terms of the modal fields of the smooth waveguide and manipulate the wave equation to calculate the coupling among the modes. A low coupling assumption is used in the calculation, which means that the distances characteristic of the coupling process are significantly bigger than the wavelength. After considerable manipulation, the coupling among the modes is expressed by a linear set of coupled power equation:

$$\begin{aligned} \frac{dP_m}{dz} &= -\beta''_m P_m + \sqrt{\pi} 2 s^2 D \times \\ &\quad \sum_{n=1}^{2N} |K_{mn}|^2 \, e^{-\left[\frac{D}{2}(\beta_m - \beta_n)\right]^2} (P_n - P_m) \end{aligned} \tag{9}$$

where P_m is the power carried by the m^{th} mode,

$$K_{mn} = -(\epsilon - 1)\frac{k^2}{2ja}\frac{T_n(u'_n)}{\sqrt{\beta'_n}}\frac{T_m(u'_m)}{\sqrt{\beta'_m}} \tag{10}$$

and $T_n()$ is either $\cos()$ or $\sin()$, depending on the symmetry of the mode.

The coupling between TE and TM modes is not predicted by the model, because of the two dimensional assumption. We included cross polarization coupling in order to compensate for this over–simplification of the model.

The coupled power equations (9) can be expressed as a simple matrix equation, where the unknown is a vector containing the power level of each mode:

$$\frac{\partial \overline{P}}{\partial z} = -\Gamma \overline{P} \quad \text{where} \quad \overline{P} = \begin{pmatrix} P_1 \\ \vdots \\ P_{2N} \end{pmatrix} \tag{11}$$

Γ is an $2N \times 2N$ symmetric matrix which holds all the power coupling coefficients. We model the source as a distribution of power among the waveguide modes, and then solve (11) numerically. The results presented in section II are the total power along the waveguide predicted using this method, where the calculation was performed with the Matlab software.

C. *Floor and Ceiling*

The exact analysis of a third spatial dimension in our waveguide model creates considerable complications without changing the basic behavior. We take an approximate approach to the effects of the floor and ceiling on the hallway propagation, they are modeled by smooth surfaces made of very good conductors. Thus, their effects can be considered separately from the effects of the walls.

Using this coordinate separation, there is only a minor effect of the floor and ceiling on the behavior of the fields and the coupling among the modes. The graphs shown in section II-A were calculated with the two dimensional model.

D. *A Hallway Junction Model*

This section describes the model of hallway junctions, where power flows along one hallway (the ‘main’ hallway) into another (‘side’) hallway. We present here an intuitive explanation of the mode coupling mechanism, for thorough analysis see [13], [14].

Consider the plane wave decomposition of the modes, where each mode can be decomposed into a pair of plane waves propagating at equally oblique angles with the z axis. The lower order modes are decomposed into plane waves that propagate in an almost parallel direction to the z axis. High order modes travel in directions increasingly oblique to the z axis. When considering a perpendicular hallway corner, the low order modes in the main hallway couple strongly into high order modes in the side hallway and vice versa (figure 8).

The expected effect in the side hallway is a significant decrease of power level as the receiver moves away from the junction and power is re-distributed among the modes in the side street. At a certain distance, where the modal distribution of power reaches its steady state, the rate of decrease of power along the hallway resumes its low steady state value.

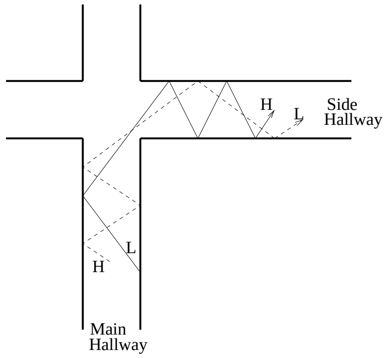

Fig. 8. A hallway corner model. The solid line represents a low order mode of the main hallway coupled into a high order mode of the side hallway. The dashed line represents a high order mode of the main hallway coupled into a low order mode of the side hallway.

IV. Discussion

The measurements along and near the hallways (figure 5 and 6) show that when the receiver is 10 m or further from the transmitter, power levels are stronger in the hallway than in the adjacent rooms. This is true even when the rooms are closer to the transmitter (as in the case of hallways 5 and 6). The power levels in the rooms may be higher than those of the hallway, in cases where the direct propagation from the transmitter to the rooms is normally incident on the intermediate walls.

Coupled modal theory predicts that for radiation along a hallway, the low order TE modes dominate at large distances, and that a steady state rate of power loss is reached beyond an initial high loss area near the source. The theory predicts that any distribution near the transmitter transforms to a field dominated by the low order modes at further distances. Simulation with the parameters that appear to characterize the Packard building (hallways 1.8 m wide, walls with $\epsilon = 3$, $\sigma = 0.085$ S/m, $D = 2$ m and $s^2 = 0.2$ m^2) shows that the steady state power distribution among the waveguide modes is dominated by the lowest order TE mode. The evolution from a uniform power distribution (over the modes) to the steady state one occurs over a distance of about about 10 m. Figure 5 shows the measurements in hallway 1, with the theoretical prediction for average power levels based on modal theory, where the initial power distribution (over the modes) described a narrow TE (vertical) source in the middle of the hallway.

Figure 6 shows power measurements in hallway 5, together with the theoretical prediction based on the waveguide model with uniform initial distribution. The model predicts a significant change in the distribution of power, when the receiver turns from one hallway to another. We used a uniform distribution of power over the modes as initial conditions after turning a corner. The power level used after turning a corner was determined in the simulation from the power level calculated for the intersecting hallway. In junctions where the main hallway (that guides power into the junction) continues after the intersection the power level at the cross hallway is half (-3 dB) of the main hallway level.

The power level in the rooms adjacent to the hallways can be deduced in the model from the penetration of the different modes through he walls. We note that the model considers only the hallway guiding effects, so it omits direct radiation from the transmitter into the rooms.

The penetration from a hallway to the adjacent rooms varies along the hallway, because the power distribution among the modes changes. The high order modes penetrate strongly into the walls, and they tend to be strong near the transmitter and hallway junctions, whereas the low order modes, that do not penetrate as well, dominate in the steady state power distribution.

V. Summary

This paper presented a new model for UHF propagation in large buildings, based on the guiding effects of hallways. The importance of the guiding mechanism was shown by comparing hallway and room power levels in an office building. The hallway power levels are higher in most cases, even when the hallway is further from the transmitter than the rooms. The model is based on the waveguide analysis of the hallways, where the roughness of the walls causes mode coupling which is analyzed in an average manner. The steady state distribution of power over the modes has most of the power in the lowest order TE mode. The evolution of the power distribution from the area of the transmitter or a junction, along the hallway, explains the sharp decrease of power levels in these areas, which evolves into a lower rate of power loss. The model suggests an intuitive explanation of the propagation mechanism, which is absent in other commonly used propagation models.

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