Ray Optical Simulation of Indoor Corridor Propagation at 850 and 1900 MHz

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Abstract: In indoor propagation, the decline in field strength with distance has been modeled as inversely proportional to r^n, where n is found empirically. In this paper, the field strength in a 50 m hospital corridor is computed by geometrical optics. The computed field strength is well represented as declining as $1/r$, for $r<1$ m, and as $1/r^n$ at distances greater than 1 m, with n chosen to minimize the error between the computed field and the r^n approximate model. Values of n are found for four wall constructions, at 850 and 1900 MHz.

Introduction

The field strength of an antenna in free space declines as $1/r$. In indoor propagation, the field can undergo many reflections before it reaches the observer. The field may penetrate one or more walls or doors. Typically, the field strength varies rapidly as the location of the observer changes. It has been found useful to model this very complex behavior with the approximation

$$E(r)=\frac{E_o}{r^n} \qquad \ldots(1)$$

where E_o is the antenna's field in free space at 1 m distance, and n is dependent on the frequency and the construction and geometry of the walls. Where there is a line of sight path, the field attenuates more slowly than in free space and $n<1$. Morrow's value [1] for a metalworking factory with a line-of-sight coupling path corresponds to $n=0.8$ at 1.3 GHz. Where the field must propagate through walls or partitions, the field declines more rapidly than in free space and $n>1$. Morrow's data for an office including wall partitions at 900 MHz corresponds to n=1.2. Rappaport [2] gives values in various environments.

This paper studies the decline in field strength in the corridor of Fig. 1, which is 50.6 m long and 1.925 m wide. The floor and ceiling are concrete slabs 30 thick, with a ceiling height of 2.48 m. The transmitter is operated 1.2 m from one end of the corridor, on the corridor's centerline, at a height of 1.4 m above the floor. The doorways in Fig. 1 play the important role of permitting energy to escape from the corridor.

In the computation, the transmitter is a half-wave dipole oriented vertically, radiating 600 mW, with an isotropic level field strength of $E_i=\sqrt{\eta_0 P/(2\pi)}$ =6 V/m, where η_0 is the intrinsic impedance of free space. The dipole has a directivity of $D=1.64$ in the azimuth plane, hence the dipole's field strength at 1 m distance is $E_0=\sqrt{D}E_i$ =7.686 V/m. The receiver is moved along the centerline of the corridor on the dashed line shown in Fig. 1, at a height of 1.4 m above the floor. Graphing the field strength of the antenna in free space in dBV as a function of the log of the distance obtains the short dashed straight line in Fig. 2. The solid line in Fig. 2 shows the computed field strength with sheetrock walls. The long dashed line is the approximation and is discussed in the following.

Computing the Field with Geometrical Optics

The field in Fig. 2 is computed with geometrical optics, accounting for the direct ray from the source to the observer, and rays reflected once or many times from the floor, ceiling and walls. A three-dimensional geometrical optics computer program was written for this project, called GO_3D[3]. Walls are modeled as layered structures, where the electrical parameters are uniform in each layer. The reflection coefficient and the transmission coefficient for a plane wave incident on the wall [4,5] are used to approximate the ray's interaction with the wall. The program accounts for the full vector interaction of the field when it encounters the wall, using the reflection and transmission coefficients for the actual incidence angles for each interaction.

The GO_3D code asks the user specify the minimum field strength or "threshold field" for a ray to be included in the computation. Then the code itself chooses the number of reflections that must be traced to account for rays having field strengths above the threshold. The code constructs an image tree [6] including all image sources leading to fields above threshold. The tree is built once and then used to find the field at all observer locations. The user sets the threshold field strength as T dB below the transmitter's isotropic level field strength.

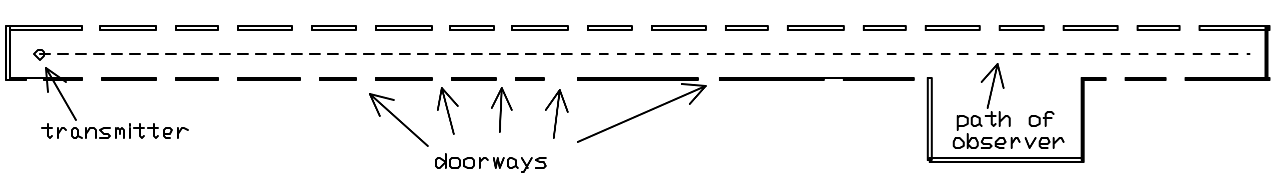
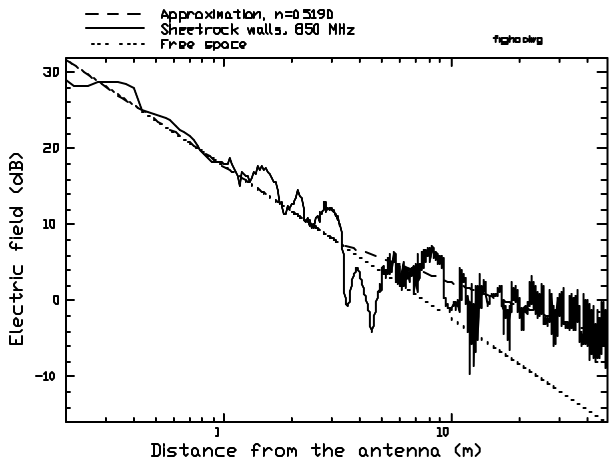
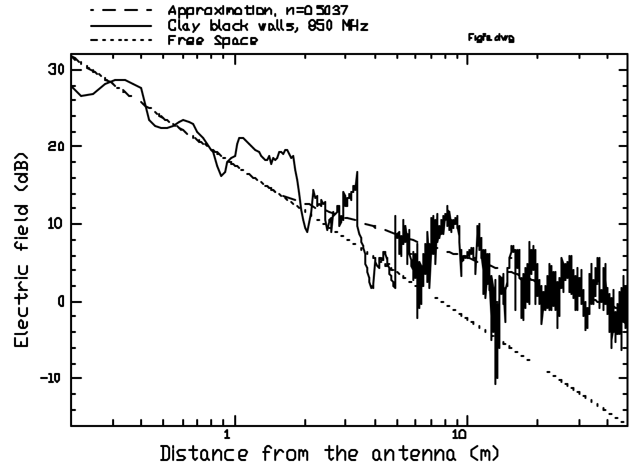


Fig. 1 [0]The 5th floor corridor model, of overall length 50.6 m.



(a) Sheetrock walls.



(b) Clay block walls.

Wall Construction

Four types of wall construction are examined in this paper. A "solid brick" wall consists of a 12 cm layer of brick, with $e_r = 5.1, s = 10$ mS/m at 850 MHz. A "sheetrock" wall consists of surface sheets of drywall 1 cm thick, separated by a 12 cm air layer. The drywall is represented with the electrical properties of concrete, $e_r = 6.1, s = 60.1$ mS/m. A "clay block" wall models construction using hollow clay blocks with a wall thickness of 8 mm, faced with plaster. This is represented as a layered structure with a 1.5 cm plaster (concrete) facing, a 0.8-cm brick wall of the clay block, a 9.4 cm thick air space inside the clay block, the 0.8-cm block wall and the 1.5-cm plaster facing on the other side of the wall. Some clay-block walls have metal screen embedded within the plaster. The "plaster and wire" wall models this construction with a 1 cm thick plaster (concrete) layer backed by a very highly conducting metal layer. Such walls are almost perfectly reflecting. The end walls in the corridor are 12 cm layers of glass $(e_r = 6, s = 0)$, which model decorative glass-block walls.

The reflection coefficient at a wall surface is a function of the frequency and the angle of incidence of the plane wave. For normal incidence on solid walls made of low loss materials such as brick, the wall is almost transparent at frequencies where its thickness is an integer multiple of the half-wavelength. At these frequencies, the wall behaves as a "radome" and the field passes through it. For fields incident at the Brewster angle, single-layer wall models behave as a "Brewster window" with zero reflection. Multiple-layer walls can also have "radome" and "Brewster window" behavior.

To characterize the reflective properties of walls in a single number, the reflection coefficient can be averaged over all angles of incidence. The reflection coefficient of a 10-cm wood door averaged for incidence angles from 1 to 90 degrees is 32%. The lightest wall construction is sheetrock, with an average reflection coefficient of 52%, hence about half of the amplitude of the incident field is reflected. The next heavier construction is the clay block wall, which reflects about 83% of the field incident on it. The heaviest construction is the brick wall, but at 850 MHz, the average reflection coefficient is 64%, less than the brick wall. The plaster-and-wire wall reflects 99.4% of the field, on the average. Note that the intuitive notion that heavier wall construction leads to a larger reflected field is incorrect and can be misleading. The fraction of the field that is reflected is dependent on the thickness of the various layers in the wall, on their electrical properties, on the angle of incidence, on the polarization, and on the frequency.

Approximating the Field in the Corridor

Fig. 2 shows the field in the corridor computed with geometrical optics for sheetrock and for clay block wall construction, at 850 MHz. The field was computed every 3 cm along the path. Very close to the antenna, the field of the direct ray dominates and the field is well approximated by the free-space value. Farther from the antenna, the field varies rapidly with the position of the observer, and on the average, declines more slowly than in free space. This behavior will be modeled with a *bi-linear* model, which uses the free-space field for distances closer than a "transition point", r_b, and for farther distances, using Equation (1). Thus,

$$E = \frac{E_b r_b}{r} \text{ for } r < r_b \qquad \text{…(2)}$$

and

$$E = \frac{E_b r_b^n}{r^n} \text{ for } r > r_b \qquad \text{…(3)}$$

where $E_0 = E_b r_b^n$, and the "transistion point" or switchover from Equation (2) to Equation (3) falls at distance r_b and field strength E_b. The product $E_b r_b$ is equal to the field strength of the antenna at a 1-m distance, which for a 600-mW half-wave dipole, is 7.686 V/m.

To find the value of n, Equation (1) is recast as a straight line by graphing the field in dB as a function of the logarithm of the distance. The slope of the straight line, $-n$, and the intercept, $20 \log E_0$, are chosen to minimize the mean-square error between the field in the corridor computed with geometrical optics and the approximation of Equation (1), at distances greater than 1 m Then the "transition point" is determined as the intersection of the free-space field, Equation (2), with the approximation found by linear regression, Equation (3). The accuracy of the approximation is assessed by computing the mean-percent error between the approximation and the actual field.

Table 1

Computed Values of *n* at 850 MHz

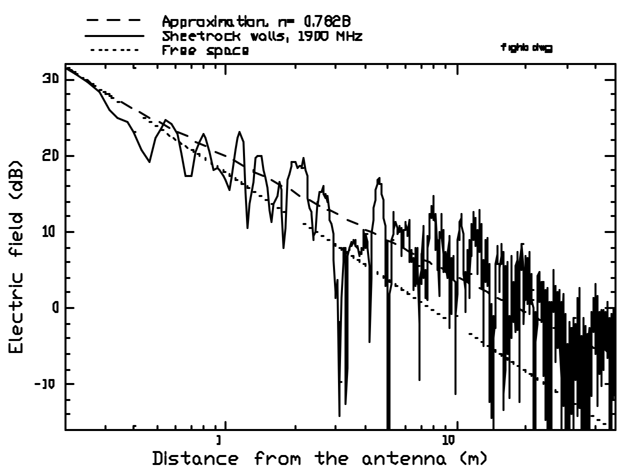
Wall construction	Average reflection coefficient	E_b	r_b	n	Mean % error
Sheetrock	52%	2.371	3.241	0.5190	19.3
Brick	64%	3.988	1.927	0.4679	30.6
Clay block	83%	4.802	1.60	0.5037	24.8
Plaster and wire	99.4%	9.375	0.8198	0.5833	36.1

Values of *n* at 850 MHz

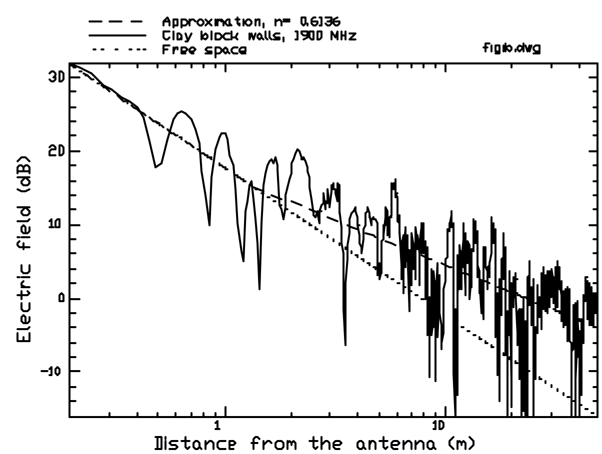
Fig. 2 compares the field in the corridor to the fitted bi-linear model. In part (a) for sheetrock walls, the field declines with $n = 1$ to a distance of $r_b = 3.2$ m, and then declines more slowly with $n = 0.519$ for farther distances. For clay block walls, part (b) shows that the break point falls at 1.6 m from the antenna, and beyond that distance the field declines with $n = 0.5037$. Comparing parts (a) and (b) in the figure shows that the more reflective clay block walls lead to a larger amplitude variation in field strength with distance. But on the average the field declines with about the same value of n for these two wall constructions. In the 50 m corridor geometry, when the observer is far from the transmitter, many of the reflections from the walls have near-grazing incidence angles, and then the reflection coefficient approaches unity, independent of the wall construction.

Table 1 gives the wall average reflection coefficient, the location of the "transition point" and the value of n for all four wall constructions. Note that the value found for n is about the same for sheetrock, brick and clay block walls despite the large increase in the average reflection coefficient. The very reflective plaster and wire construction leads to fields that decline more quickly with distance with $n \approx 0.6$.

The bi-linear model in Equations (2) and (3) results in mean errors in Table 1 that are between 20 and 36 percent. The least reflective wall, sheetrock, gives rise to the smallest amplitude variations in the field along the corridor, shown in Fig. 2(a), and the smallest percent error. Brick and clay block walls have higher average reflection coefficients and give rise to larger errors between the geometrical-optics field and the bi-linear model approximation. The plaster and wire-wall construction, with a reflection coefficient greater than 99 percent, leads to the largest amplitude variations in the field along the corridor and the largest percent error of about 36 percent.



(a) Sheetrock walls.



(b) Clay block walls.

Fig. 3 The field in the 50.6 m corridor at 1900 MHz.

Values of *n* at 1900 MHz

The computation of the field in the corridor was repeated at 1900 MHz, using the same electrical parameters for the wall materials. Fig. 3 shows the field in the corridor at 1900 MHz with sheetrock walls and with clay block walls. Comparing Fig. 3 with Fig. 2, it is evident that at the higher frequency the amplitude of the variation in the field is much larger. The average reflection coefficient for the sheetrock wall increases from 52% at 850 MHz, to 71% at 1900 MHz, leading to larger fields associated with reflected rays in the corridor. For clay block construction, the average reflection coefficient declines from 83% at 850 MHz to 75% at 1900 MHz.

Table 2

Computed Values of *n* at 1900 MHz

Wall construction	Average reflection coefficient	E_b	r_b	n	Mean % error
Sheetrock	75%	2.31	0.332	0.7828	46.3
Brick	57%	3.94	1.95	0.6662	47.8
Clay block	75%	5.73	1.34	0.6136	41.3
Plaster and wire	96.2%	25.78	0.298	0.7761	47.1

Table 3 gives the transition point and the value of n for each wall construction at 1900 MHz. For sheetrock walls, the transition point falls only 33 cm from the antenna, and the field declines with $n = 0.78$, more quickly than at 850 MHz, which has $n = 0.52$. For brick walls, n is also much larger at 1900 MHz, 0.67 compared to 0.47. In fact, for all four wall types, the value of n is substantially higher at 1900 MHz. Note that the errors in the approximation are all near fifty percent at 1900 MHz, larger than at 850 MHz. The amplitude of the variation of the field along the corridor is generally larger at the higher frequency, leading to larger errors in the approximation of Equations (2) and (3).

Conclusions

This paper has presented the field strength in a 50 m hospital corridor. The decline of field strength with distance is modeled as $1/r^n$, where n is found as a least-square error curve fit to measured or computed data. Computations were done for various wall constructions at 850 and 1900 MHz, leading to values of n between 0.47 and 0.58 at the lower frequency and between 0.61 and 0.78 at the higher.

The geometrical optics approximation is unrealistic in several ways, which may affect the usefulness of the results. Walls are modeled as sandwiches of uniform layers, ignoring interior features such as studs, which can be metal, and pipes, ducts and wiring. Diffraction from the edges of doorframes, which can also be metal, are ignored. The ceiling is represented as reflecting the field spectrally, whereas in fact a hanging ceiling conceals ducts, pipes and electrical conduits, which scatter the field. Furniture is not easily included in the model. Thus hallways can have wooden chairs and benches, which absorb the field, and metal lockers, which both reflect and scatter it. Nevertheless the geometrical optics model lends useful insights into the measurements done in the corridor, reported in a companion paper[7].

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