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Mathematical Simulation of Indoor Wireless Networks

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Abstract

Maximum capacity of wireless network requires for optimum location of communicators, their correct configuration and preset operation modes. Solution of this problem inside buildings, where usually numerous transmitters operate in one frequency range, is impossible without computer aided tools of wireless network planning. One of the most important elements of automated system of wireless network planning, which provides accuracy of the obtained results, is a mathematical model of communication channel. Peculiar features of electromagnetic wave indoor propagation are restriction of wireless routes by various obstacles and diversity of signal propagation ways caused by its numerous reflections. Existing computer aided systems of automated wireless network planning are based on statistic model of radio wave propagation, which impairs reliability of the obtained results. This work demonstrates advantages of application of waveguide model of communication channels upon planning of indoor wireless network. According to this model overall structure is split into building blocks. In order to obtain rough estimations of the calculated parameters a building block can be presented by a group of similar rooms or even overall structure interior. In order to improve the accuracy of calculation a single room or even its sufficiently uniform portion should be considered as a building block. Each block is characterized by coefficient of bulk energy loss in it and coefficients of energy leakage via separating walls. Equations are developed for these coefficients, which enable their calculation by preset shape and pattern of block filling, as well as by thickness, dielectric permeability and conductance of wall material. Electromagnetic filed in building blocks is presented by superposition of natural waves propagating in them. In this regard solution, obtained using the waveguide model of signal indoor propagation, is close to asymptotic approximation at infinitely high amount of considered waves. The proposed approach has been applied upon planning of wireless networks for indoor data transmittance in various structures (educational, administrative, trading), varied greatly in their designs, type of internal and external walls. In all cases the experimental and calculated data agree well.

Keywords: wireless network, radio wave propagation, radio channel model, waveguide model, automated system.

INTRODUCTION

Numerous networks for data transfer operate nowadays indoor. In this case peculiar features of electromagnetic wave propagation are as follows:

– attenuation of radio signal by various obstacles;
– diversity of signal propagation ways caused by its numerous reflections.

Optimum allocation of communicators in such environment is impossible without computer aided automated systems.

Quality of automated system of wireless network planning is based on applied mathematical model of data propagation and conversion. Known mathematical models and software packages on their basis either does not provide calculation of a set of highly important properties of wireless network with required accuracy, or are complicated for implementation. Therefore, the problem of development of computer aided tool for planning of indoor wireless networks on the basis of accurate mathematical model of signal propagation, considered in this work, is urgent up till now.

One of the main requirements to an automated system is its stability with regard to the amount of initial data. In our case initial data are presented by building plan. Stable model enables rough estimation of signal level upon minimum amount of initial data on the building and provides improvement of accuracy with data clarification. Existing mathematical models start operation only after obtaining of sufficiently complete initial data on building plan and do not improve accuracy after obtaining of supplemental information. The mathematical model of radio wave indoor propagation, proposed in this work and known as waveguide model, satisfies completely this requirement.

MATHEMATICAL MODELS OF RADIO WAVE INDOOR PROPAGATION

The existing models of signal indoor propagation can be subdivided into three groups:

1. Statistic models which do not require for detailed data about building except for overview of its type: industrial building, hotel, hospital, trading center, earlier building and so on [1–6].
2. Empirical single- or multiple-ray models based on the analysis of one or several rays connecting transmitting and receiving antennas aimed at estimation of level of received signal [6], [7–9].

3. Ray models, which use quasi-optical presentation of signal propagation and consider for reflection from building walls and edge diffraction [10–12].

The models of the 1st group are described by Eq. (1):

$$L_p = L_{p0}(d_0) + n \cdot 10 \lg(d/d_0), \tag{1}$$

where the coefficient *n* is defined by the building type. Such model is characterized by rapid calculations when only distance between antennas should be determined – all other parameters and constants are related to overall building and set preliminary.

The models of the 2nd group (*Motley-Keenan* [7], *Multi-Wall-Model* [5]) are based on addition of loss on all walls between receiving and transmitting antennas to Eq. (1). In the *Dominant Path Model (DPM)* [13], also included in this group, supplemental rays are added to the main one, passing via adjacent rooms with regard to those on main path. Herewith, no accurate search for signal reflection point is performed.

The models of the 3rd group [10–11] consider as much as possible data on building plan. According to these data all possible signal paths from transmitter antenna to receiver antenna are determined. In order to reduce the involved time of calculations several methods of computation speedup are proposed [11].

There are two variants of implementation of such models, known as *ray tracing* and *ray launching*. The number of considered iterations (reflections, obstacles) depends on PC capacity. Most of the models are restricted by not more than six iterations including not more than two obstacles.

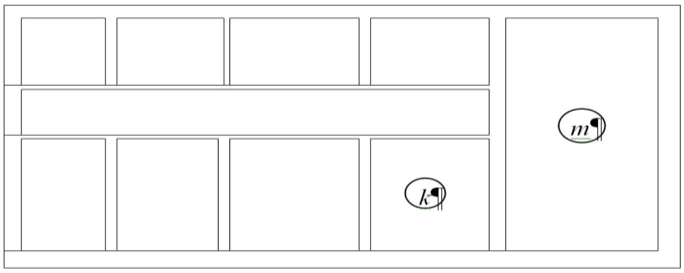
Diffraction loss of signal along each path are calculated using geometrical theory of diffraction [13], and the reflection coefficients by the Fresnel equations [14]. It is also possible to apply empirical equations calibrated by experimental data.

The main drawback of the models of the 3rd group, as already mentioned, is their sensitivity to the accuracy of initial data [11–12]. When the data on wall parameters [14] or their positions [15] are not accurate, the calculation results are significantly impaired.

WAVEGUIDE MODEL OF SIGNAL INDOOR PROPAGATION

Let us consider the problem of signal transfer between randomly positioned indoor source and receiver. In order to obtain calculated relations it is required to solve the boundary problem of excitation of electromagnetic waves by preset indoor source. Solution of this boundary problem will be as follows. Let us subdivide internal building space into certain finite number of blocks, so that each of them is a regular structure at least along one axes and, possibly, heterogeneous structure along two other axes of 3-D coordinates, perpendicular to the first axis (Fig. 1). Such blocks, referred to as building blocks, depending on interior layout, will be building walls, individual rooms or their portions, as well as groups of several rooms.

Aiming at development of suitable for computer implementation algorithm of calculations of properties of signal indoor propagation let us consider the problem of excitation of electromagnetic waves in a building block: parallelepiped $x_1 \times x_2 \times x_3$, uniformly filled with non-magnetic medium with known $\beta = \sigma / \omega\varepsilon = tg\delta$ and surrounded by walls of infinite thickness with the field penetration depth [16] Δ_m, m = 1,..,6 (Fig. 2). We will assume a point source located in the point M in the parallelepiped.



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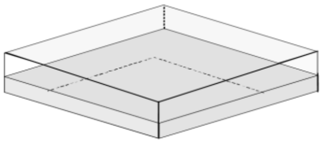

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Figure 1: Blocking of structure.

Let us present the field, excited in the considered structure, in the form of superposition of fields of its eigen oscillations (modes), which are assumed to be modes of uniformly filled rectangular resonator with losses. Frequencies of the mentioned modes are described by Eq. (2):

$$f_\nu = f_\nu^0 \left(1 + i(2Q_\nu)^{-1}\right), \tag{2}$$

where $f_\nu^0 = (c/2\pi)\left((n\pi/x_1)^2 + (l\pi/x_2)^2 + (j\pi/x_3)^2\right)^{1/2}$ is the eigen frequency of the ν^{th} mode of structure without losses, *c* is the speed of light, Q_ν is the Q-factor of the ν^{th} mode, and the three indices (*n*, *l*, *j*) define the type and, respectively, the assigned index of the ν^{th} mode.

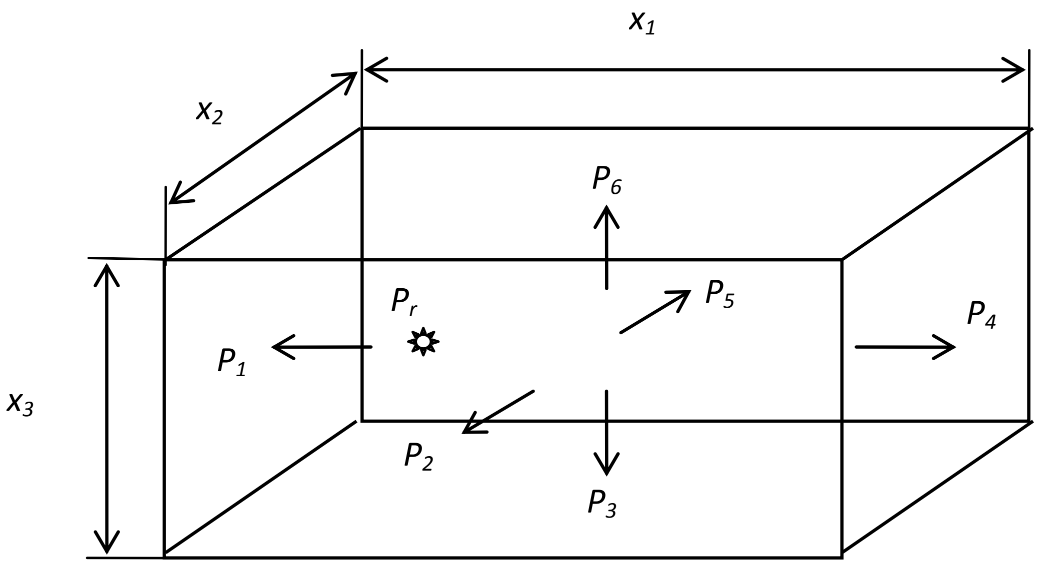

Figure 2. Building block.

The amplitude A_ν, at which the ν^{th} mode is excited, depends on power, type, polarization, source location and is inversely proportional to the difference of squares of frequency f_ν and excitation frequency f_0 [17]. The amplitude A_ν is calculated by Eq. (3):

$$A_\nu = b_\nu \big/ \left(f_\nu^2 - f_0^2 \right) \tag{3}$$

where b_ν is the constant depending on index ν.

In the considered structure there are numerous reflections of electromagnetic waves from walls. Upon each reflection a portion of energy is absorbed by wall and the remaining portion is dissipated and accumulated in the room space. The energy accumulated in the structure during a period of exciting oscillation is defined by Eq. (4):

$$W = \sum_q \left| A_q^2 \right| W_q \tag{4}$$

where W_q is the electromagnetic energy accumulated per a period of oscillation by the q^{th} mode with unity amplitude (norm of the q^{th} mode).

Summation in Eq. (4) should be carried out over all block modes. However, existence of rapidly decreasing denominator leads to rapid convergence of Eq. (4) with increase in the frequency difference $\left| f_\nu - f_0 \right|$. Hence, upon calculation of sum of series (4) it is sufficient to maintain finite (though, rather high) number of modes belonging to the set with eigen frequencies in narrow frequency range *Δf* in the vicinity of frequency f_0 , $\Delta f \le f_0$ (5):

$$\Omega = \left\{ f_\nu : \ \left| f_\nu - f_0 \right| \le \Delta f / 2 \right\} \tag{5}$$

After completion of transient processes in the structure there is established energy equilibrium for average powers for a period of exciting oscillation: the power transferred into the k^{th} block, P_k^+, equals to the sum of powers dissipated in the space of this block, P_{k0} , and absorbed by surrounding walls, P_{kw} (6)

$$P_k^+ = P_{k0} + P_{kw} \tag{6}$$

The power P_{kw} in Eq. (6) is comprised of the powers P_{kwm}, absorbed by each of six walls surrounding the structure, Eq. (7):

$$P_{kw} = \sum_{m=1}^{6} P_{kwm} \tag{7}$$

The power, transferred to the k^{th} block, P_k^+, is comprised of the powers transferred to it via the walls from adjacent blocks, P_k^a, and , probably, the power of transmitter P_k^r, if it is located in this block, Eq. (8):

$$P_k^+ = P_k^a + P_k^r \tag{8}$$

(if there is no transmitter in the k^{th} blocj, then P_k^r is assumed to be zero).

The power P_k^a, transferred to the k^{th} block from adjacent blocks, is proportional to the powers escaping via their walls with the coefficient of attenuation depending on the wall thickens and absorption in material of these walls.
The power P_k^a, transferred to the k^{th} block from adjacent blocks via common walls, can be written as follows:

$$P_k^a = \sum_{i=1}^{N} c_{ki} P_{wi} \ , \tag{9}$$

where N is the number of all blocks in the building, the elements c_{ki} are the attenuation coefficients of power P_{wi}, escaping from the walls of the i^{th} block and transferred into the k^{th} block. The elements c_{ki} are calculated as follows, Eq. (10):

$$c_{ki} = \begin{cases} 0 \ , \ \text{if the k-th and i-th blocks have no common wall,} \\ \dfrac{S_{ki}}{S_{il}} g_{il} \exp\left\{-2d_{il} / \Delta_{il}\right\} \ , \text{if the k-th and i-th blocks have common wall,} \end{cases} \tag{10}$$

where S_{il} is the surface area of the l^{th} wall of the i^{th} block; S_{ki} is the surface area overlapping with the k^{th} block of a portion of this wall; g_{il} is the coefficient calculated as follows [17-18]: $g_{il} = \bar{S}_{il} \Big/ \left(\beta_i V_i + \sum_{m=1}^{6} \bar{S}_{im} \right)$; $\bar{S}_{\mathrm{im}} = S_{im} \Delta_{im}$, β_i is the coefficient of bulk losses in the i^{th} block; Δ_{im} is the penetration depth of electromagnetic field into the m^{th} wall of the i^{th} block $m = 1 \ldots 6$; V_i is the volume of the i^{th} block.

The elements c_{ki} arrange the $N \times N$ matrix *C*, which is the matrix of couplings of building blocks. Its elements are defined by the building layout as well as by thickness and absorbing properties of exterior and interior walls and floors.

Substituting Eqs. (6), (7), and (9) into Eq. (8) we obtain *N* equations of the following type:

$$P_{wk} = \left(1 - g_{k0}\right) \left[\sum_{i=1}^{N} c_{ki} P_{wi} + P_k^r \right], \ k=1,...,N, \tag{11}$$

where $g_{k0} = \beta_k V_k \Big/ \left(\beta_k V_k + \sum_{m=1}^{6} \bar{S}_{km} \right)$.

Equations (11) are the equations of power balance in all building blocks and can be considered as a set of *N* linear algebraic equations with regard to *N* unknown P_{wk}.

Applying Eq. (11) to calculation of the power P_{wk} for each block, then, using Eqs. (7) and (8), it is possible to determine the power P_{wkm} and P_k^a, escaping and transferring into the k^{th} block via its m^{th} wall. Diving them by surface area of corresponding walls S_m, we obtain resulting average densities of power flows $\bar{T}_{km}$ near each wall in each block, Eq. (12):

$$\bar{T}_{km} = P_{wkm} / S_m \,. \tag{12}$$

The flow $\bar{T}_{km}$ is directed in perpendicular to the m^{th} wall of the k^{th} block. Positive sign of $\bar{T}_{km}$ means that the power is transferred to the k^{th} block via its m^{th} wall, negative sign means that the power escapes from the k^{th} block via this wall.

On the basis of known $\bar{T}_{km}$, using interpolation, it is possible to recover the value and direction of average density of power flow $\bar{T}$ in each point in any building block, and then to apply it to determination of average received power in the vicinity of this point by Eq. (13):

$$\bar{P} = G \bar{T} \lambda_r^2 / \left(4\pi\right), \tag{13}$$

where *G* is the coefficient of directed action of receiving antenna, λ_r is the transmitter wavelength.

In each block the law of variation of received power during passing along any line is of oscillatory pattern. In the vicinity of arbitrary point of block the received power achieves periodically maximum and minimum values, caused by wave interference upon their multiple repeated reflections. Equitation (13) determines average value of this power in the vicinity of the considered room point.

Across two–three walls from transmitter location the decisive factor in accuracy of calculations is the value of received power $\overline{P}_k$, averaged over the considered k^{th} room.

In this regard, in the first approximation it possible to avoid interpolation and to calculate average power of received signal in arbitrary point of the k^{th} room using Eq. (14):

$$P(r) = \overline{P}_k \left(r / r_{k0} \right)^{-n}, \tag{14}$$

where r is the distance between transmitter and receiver, $n = 1,5 \div 4$, $r_{k0} = \left(r_k^{\max} r_k^{\min} \right)^{1/2}$, $r_k^{\max}$, and $r_k^{\min}$ are the distances between transmitter and the farthest and the closest points of the k^{th} room (if transmitter is located in the considered room, then it is assumed that $r_k^{\min} \cong 5\lambda_{rad}$).

CONCLUSIONS

The developed model of indoor communication channels has been applied for forecasting of propagation loss in the frequency range from 430 MHz to 2400 MHz in various standardized buildings: R&D and higher education entities, trading centers, and the like. Multi- and one-storey buildings, brick and reinforced constructions have been applied for approbation of the model. While selecting single rooms of considered structures as building blocks the results of calculations of average loss of signal propagation in each structure differ from experimental data not more than by 2÷3 dB, which is a good index of at least the same accuracy as the results obtained elsewhere [1–15].

In addition, it should be mentioned that the developed model is calibrated well by measurements or, in other words, its parameters are easily identified by means of experimental data.

Analysis of the given examples evidences efficiency of application of the waveguide model to calculation of characteristics of signal indoor propagation.

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