WAVEGUIDE MODEL OF WIRELESS COMMUNICATION CHANNELS INSIDE BUILDINGS

Yelena Chaiko

Riga Technical University Institute of Industrial Electronics and Electrical Drives
1, Kalku Street, LV-1658, Riga, Latvia

krivcha@inbox.lv (Yelana Chaiko)

Abstract

A plenty of wireless data transmission networks now works inside of buildings.
Specifics of electromagnetic waves propagation of in these conditions are:
Presence of possible obstacles in a propagation path of a signal;
Multiple propagation paths of a signal because of numerous reflections.
The models communication channels offered at present time inside of buildings do not fully consider these specifics therefore do not possess satisfactory accuracy of calculation. Besides disadvantage of these models is their "instability" to amount of initial data. Initial data for creation of mathematical model of radio channels inside buildings is the plan of this building. The "steady" model allows to estimate roughly a level of a signal using the minimal amount of initial data about a building or city and leads to improvement of accuracy in the process of data specification. Models applied at the present moment start to work only after initial data about a lay-out of a building or city are full enough and these models do not give substantial improvement of accuracy at their updating.
The analysis of existing radio waves propagation models is performed in this paper.
The task of signal transmission between transmitter and receiver located in the random points inside the building is resolved.
New developed mathematical model of radio waves propagation inside buildings is called wave model.

Keywords: Mathematical model, propagation, radio channels.

Presenting Author's biography

Yelena Chaiko. In 2004 – Doctor of Science in Telecommunication " Mathematical models of radio wave propagation in woodland for mobile communication systems". From 2006.01.10. Riga Technical University as head researcher, Institute of Industrial Electronics and Electrical Drives. Research interests: Telecommunication systems, Electronics. Riga Technical University, 1, Kalku Street, LV-1658, Riga, Latvia, e-mail: krivcha@inbox.lv .

1 Methods of modeling of communication channels inside of buildings

The models of signals propagation inside of buildings offered at the present time can be divided into 3 groups:

Statistical models; not demanding the detailed information on a building except for the general description of its type: an industrial building, hotel, hospital, shopping center, a building of old construction, etc. [1-2].

Empirical single- or multibeam models; based on the analysis of one or several beams connecting transmitting and receiving antennas, for an estimation of a level of an received signal [1], [3-5].

Beam models; in which kvasioptic representation of signals propagation processes is used and reflections from room walls and diffraction at corners [6-8] are considered.

In models of 1-st group losses signal propagation L_p have dependence from distances between antennas d kind

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

where the exponent n is defined by type of a building.

Such model is applied in a software package [9] and characterized by speed of calculations at which performance it is required to determine only distance between antennas - all other parameters and constants concern to all building as a whole and are set preliminary.

Models of 2-nd group (Montey Keenan [3], Multi-Wall-Model [1]) are based on addition to (1) losses in all walls on a way between receiving and transmitting antennas. In model DPM (Dominant Path Model) [10] concerning the same group to the basic beam the additional beams which are passing through the next rooms in relation to that lay on the main way are added. Thus exact search of points of reflection of a signal is not made.

Models of 3-rd group [6-7] whenever possible fully consider the information on a lay-out of a building. According to them, all probable ways of a signal from the antenna of the transmitter to the antenna of the receiver are defined. For reduction of calculations time some ways of acceleration of computing process [7] are offered.

There are two versions of realization of the given sort of the models, named by trace of beams (ray tracing) and creation of beams (ray launching). The number of considered iterations (reflections, obstacles) depends on computation power of a computer.

The majority of models is limited by a maximum by 6-th iterations, including no more than 2 obstacles.

Difractional losses of a signal along each way pay off with use of the geometrical theory of diffraction [10], and factors of reflection - by means of Fresnel formulas [11]. It is possible also to use empirical ratios, calibrated by means of experimental data.

The basic disadvantage of models of 3-rd group is their sensitivity accuracy to the initial data [7-8] as already was marked. In cases when it is inexact data about parameters of walls [11] are specified or to their site, results of calculation essentially worsen [12].

2. waveguide model of radio channels inside of buildings

Let's examine a problem about signaling between located in any points inside of a building a source and the receiver. To receive settlement ratio it is necessary to solve a regional problem about excitation of electromagnetic waves by the set source inside of a building. The decision of this regional problem we shall construct as follows. We shall break internal volume of a building into some final number of blocks so that each of them represented regular structure even along one axis and, probably, non-uniform along two other axes of three-dimensional system of coordinates, perpendicular the first (Fig. 1). Such blocks which we shall name elementary, depending on an internal lay-out of a building walls of the building, separate rooms or their parts, and also groups of several rooms. Actually, such approach means use of a method of partial areas (MPA) for calculation of an electromagnetic field inside of examined complex structure [13].

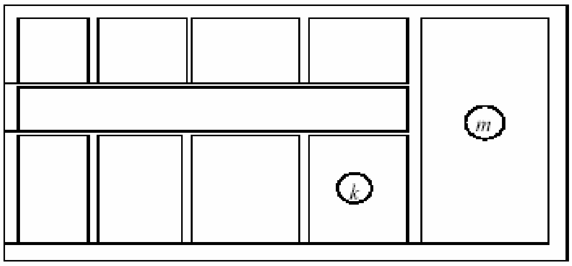

Fig. 1 Splitting of a building into elementary blocks

$\left\{\vec{E}_{kv}, \vec{H}_{kv}\right\}$ [13]:

$$\begin{cases} \vec{E}_k = \sum_H A_{êí}\, \vec{E}_{êí}, \\ \vec{H}_k = \sum_H A_{êí}\, \vec{H}_{êí}, \end{cases} \tag{2}$$

Having demanded equality of tangential making electromagnetic fields on borders of blocks

$$\begin{cases} \vec{E}_{k\hat{o}} = \vec{E}_{m\hat{o}} \\ \vec{H}_{k\hat{o}} = \vec{H}_{m\hat{o}}, \end{cases} \tag{3}$$

we shall receive system of the equations for unknown factors $A_{кн}$ in Eq..(2).

Generally elementary blocks into which the building is broken, represent structure, regular along one axis and is non-uniform filled along two others, perpendicular the first, axes. Thus, for successful application of an offered method of calculation of characteristics of signals extending inside of buildings it is necessary to investigate characteristics it is non-uniform the filled dielectric structures which commonly can be presented in the form of, represented on fig. 2. Problems of signaling in such structure are in detail examined in [14-15].

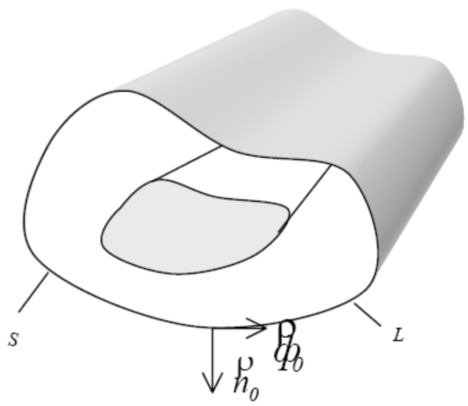

Fig. 2. It is non-uniform filled waveguide communication channel

As well as in case of beam models of 3-rd group, application waveguide inside of buildings with a complex lay-out is impossible for model of signals propagation without use of special procedures of acceleration of calculations. Such variant waveguide models is examined in following section.

2 The power formulation waveguide models

With the purpose of reception of calculation algorithm of signals propagation characteristics convenient for computer realization inside of buildings we shall examine a problem about excitation of electromagnetic waves in the elementary block - a parallelepiped $x_1 \times x_2 \times x_3$,

Homogeneously filled by not magnetic environment with known size *в=у/ще = tg∂* and

Surrounded by walls of infinite thickness with depth of penetration of a field [16] Δ_m, m=1..,6 Fig.(3). A source we shall consider dot, located in a point of M inside of a parallelepiped.

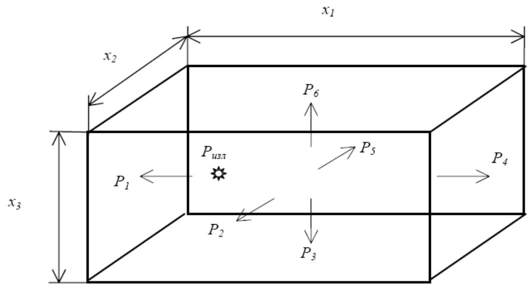

Fig. 3. The elementary block inside of a building

Field raised in examined structure we shall present in the form of superposition of fields of its own fluctuations as which we shall consider as fashions of homogeneously filled rectangular resonator with losses. Frequencies of the specified fashions are Eq.(4):

$$f_\nu = f_\nu^0 \left(1 + i(2Q_V)^{-1}\right) \tag{4}$$

where

$$f_\nu^0 = (c/2\pi)\left((n\pi/x_1)^2 + (l\pi/x_2)^2 + (j\pi/x_3)^2\right)^{1/2}$$

- own frequency of ν-th fashion of structure for the lack of losses, with c - speed of light, Q_ν - good quality of ν-th fashion, and a three of indexes *(*n, l, j*)* defines type and, accordingly, the index of ν-th fashion appropriated to it. The amplitude Aν from which ν-th fashion is raised, depends on capacity, type, polarization, the location of a source and inversely proportional differences of squares of frequency f_ν and frequencies of excitation f_0 [17] :

$$A_\nu = b_\nu / \left(f_\nu^2 - f_o^2\right) \tag{5}$$

where b_ν - a constant depending on an index ν.

To examined structure take place repeated reflections of electromagnetic waves from walls. At each reflection the part of energy leaves in a wall, and the remained part dissipates and collects in volume of a room. The size accumulated for the period of exciting fluctuation of energy is equal structure

$$W = \sum_q \left|A_q^2\right| W_q \tag{6}$$

where Wq - the electromagnetic energy reserved for the period of fluctuation by q-th fashion with individual amplitude (norm of q-th fashion).

Summation in Eq.(6) should be spent on all fashions of the block. However, presence of quickly decreasing denominator leads to fast convergence Eq.(6) at increase in a difference of frequencies $|f_\nu - f_0|$. For this reason at calculation of the sum of some Eq.(6) it appears sufficient to keep final (though also big enough) number of the fashions belonging set with own frequencies laying in narrow strip Δ of frequencies f in a vicinity of frequency f_0, $\Delta f \leq f_0$:

$$\Omega = \left\{ f_H : \left| f_H - f_0 \right| \leq \Delta f / 2 \right\}.$$

After the termination of transients in structure there comes power balance for averages for the period of exciting fluctuation of powers: power, given by source $P_{изл}$, it appears to the equal sum of powers disseminated in volume P_0 and leaving in surrounding walls P_{cm}:

$$P_{изл} = P_0 + P_{cm} \tag{7}$$

Power P_{cm} in Eq.(7) develops of powers P_m leaving in each of six surrounding structure walls

$$P_{cm} = \sum_{m=1}^{0} P_m \tag{8}$$

At $P_н/щ_н$ << $|A^2_н|W_н$ entering in Eq.(7) – Eq.(8) powers are determined by following ratio:

$$P_{изл} = \sum_{н\in\Omega} P_н, \quad P_0 = \sum_{н\in\Omega} P_{н0}, \quad P_m = \sum_{\nu\in\Omega} P_{\nu m} \tag{9}$$

where P_ν, $P_{\nu 0}$ and $P_{\nu m}$ - corresponding powers of losses in case of when one is raised in structure at ν-th a fashion with amplitude $A_н$.

Power P_ν, $P_{\nu 0}$ and $P_{\nu m}$ are defined by means of full Q_ν, and partial Qv_0 and $Q_{\nu m}$ good qualities at-ν-th fluctuation

$$P_н = щ_н \left| A_н^2 \right| W_н / Q_{н,} \tag{10}$$

$$P_{н0} = щ_н \left| A_н^2 \right| W_н / Q_{н0,}$$

$$P_{нm} = щ_н \left| A_н^2 \right| W_н / Q_{нm,}$$

$$щ_н = 2pf_{н,} \quad 1/Q_н = \sum_{m=0}^{6} \left(1/Q_{нm} \right).$$

In conformity with Eq.(6) – Eq.(10), power of losses in the structure, numerically equal $P_{изл}$, is distributed on set of raised fashions under the law

$$P_н = \frac{щ_н \left| A_н^2 \right| W_н / Q_н}{\sum_q щ_q \left| A_q^2 \right| W_q / Q_q} P_{изл} \tag{11}$$

In case of $л_{изл}$ << x_1, x_2, x_3 at run an index q on set of frequencies Ω in Eq.(11) takes place fast oscillation constants $|A^2_q|W_q/Q_q$. Summation in a denominator Eq. (11) carries out a role of operation of averaging specified oscillations owing to what it appears possible not breaking equality Eq. (7) to consider in Eq. (11) identical sizes $|A^2_q|W_q/Q_q$ for all $q\in\Omega$. Then, considering, that $|щ_q|\approx щ_{изл}$ for all fashions from Ω, the ratio Eq. (11) becomes:

$$P_н = P_{изл} / \partial_н \tag{12}$$

where

$$\partial_i = \left\{ \left[\left(f_i^0\right)^2 - \left(f_{èçë}^0\right)^2 \right]^2 + \left(f_i^0 / Q_i\right)^4 \right\} \sum_{q\in\Omega} \left\{ \left[\left(f_i^0\right)^2 - \left(f_{èçë}^0\right)^2 \right]^2 + \left(f_i^0 / Q_i\right)^4 \right\}^{-1}$$

By means of Eq.(7) - Eq. (12) making powers of losses in examined structure can be written down in the form of

$$P_m = g_m P_{изл} \tag{13}$$

where factors g_m (m=0..,6) are defined by the form of the examined block, character of its filling, characteristics of walls surrounding it, but do not depend on the location and characteristics of an orientation of a source of an electromagnetic field and are equal:

$$g_m = \sum_{i\in\Omega} \frac{Q_i}{\partial_i Q_{iò}} \tag{14}$$

Independence in Eq.(13) - Eq.(14) powers P_m from the location and characteristics of an orientation of a source is consequence of transition from Eq.(11) to Eq.(12). Physical preconditions of the given phenomenon are connected with repeated redeflection waves from walls block. This statement concerns only total sizes of powers, but does not concern to density of streams which, as shown further, pay off by means of the specified characteristics of a source.

Let's find ratio for calculation of good qualities $Q_{\nu m}$, by means of which factors g_m in Eq. (13) are defined.

Entered for the characteristic of absorbing properties of environment filling volume the parameter β is meaningful a tangent of a corner of losses dielectric with losses [17] owing to what partial good quality $Q_{\nu 0}$ is equal

$$Q_{н0} = в^{-1} \tag{15}$$

For calculation partial good qualities $Q_{\nu m}$ at m> 1 we shall take advantage of a ratio

$$Q_{нm} = \mathrm{Re}\left(f_н\right) / \mathrm{Im}\left(2 f_н\right) \tag{16}$$

where f_ν, - Eq.(4) frequency calculated on the formula at ν-th a fashion provided that in examined structure there are no other losses of energy except for its outflow through m-that wall.

Walls surrounding structure are characterized by an impedance [17]

$$Z_m = c_m \left[1 - i y_m / \left(щ e_m \right) \right]^{-1/2},$$

where c_m =(е/м)$^{1/2}$, σ_m and ε_m - characteristic resistance, electric conductivity and dielectric permeability of a material of which m-that wall is made, μ - its magnetic susceptibility accepted identical to all materials in examined structure, ω=2πf. Considering a ratio for depth of penetration of a field in a material of m-that wall [17]

$$\Delta_m = \frac{\sqrt{2}}{k_0}\left\{\left[1 + y_m^2/(щe_m)^2\right]^{1/2} - 1\right\}^{-1/2} \qquad (17)$$

where $k_0 = щ\ (e\ м)^{1/2}$ =2р/л, л - length of a wave in the environment filling volume of the block, the valid and imaginary parts of impedance Z_m can be written down in the form of:

$$\operatorname{Re} Z_m = \frac{c_m k_0 \Delta_m}{\sqrt{2 + (k_0\Delta_m)^2}} \cos u_{m,} \qquad (18)$$

$$\operatorname{Im} Z_m = \frac{c_m k_0 \Delta_m}{\sqrt{2 + (k_0\Delta_m)^2}} \sin u_{m,}$$

where $u_m = \frac{1}{2}\arctan\left(\frac{2}{k_0\Delta_m}\sqrt{1+(k_0\Delta_m)^{-2}}\right)$

Named by a parameter of refraction of environment size n_m =c/c$_m$=(e$_m$/e)$^{1/2}$ always it is more, and as a rule, it is much more 1, owing to what the maximal value of the module of impedance $|Z_m|$ much less than characteristic resistance ρ the environment filling volume of examined structure ρ. For this reason value Z_m=0, m=1.., 6 it is used for calculation of initial approximation of resonant frequencies $f^0_н$ (see (4)) which, then, is specified by means of a method of indignation:

$$\operatorname{Re} f_i = f_i^0 + \frac{\partial f_i}{\partial Z_m}\operatorname{Im} Z_m \approx f_i^0, \qquad (19)$$

$$\operatorname{Im} f_i = f_i^0 + \frac{\partial f_i}{\partial Z_m}\operatorname{Re} Z_m .$$

where the derivative $\partial f_н/\partial Z_m$ undertakes in point $Z_1 = Z_2 = \ldots = Z_6 = 0$.

In [18-19] the formula for a derivative $\partial f_н/\partial Z_m$

$$\frac{\partial f_н}{\partial Z_m} = -\frac{1}{k_0 c k^э_{нm}}\frac{\partial f_н}{\partial h_m} \qquad (20)$$

where $h_m = V/S_m$ - the size of the block on a normal to m-th wall, V - its volume, S_m - the area of m-that wall is received,

$$k^э_{нm} = 1 - \int_{S_m} e|E_{нn}|^2 dS \Big/ \int_{S_m} м|H_{нф}|^2 dS$$

$E_{нn}$, $H_{нф}$ - normal to m-that wall of a component electric and a tangent to it component of a magnetic field at ν-th a fashion.

At $Z_m=0$, m=1.., 6 in examined structure degeneration E-and H-takes place aashions with an identical set of indexes n, l, and j. Believing as well as at transition from (11) to (12), that for frequencies from set Ω of fashion E-and H-type with equal $f^0_н$ on the average bring the equal contribution to the energy saved up in the block and using formulas for components field E- and H-fashions, we receive [20-21]

$$\frac{1}{k^э_{нm}} = \frac{1}{\left(k^э_{нm}\right)^E} + \frac{1}{\left(k^э_{нm}\right)^H} = 1 + \frac{k_0^2}{k_{нm}^2} \qquad (21)$$

where $k_{нm}$=ор/h_m, ξ - an index n, l or j, defining number of variations of a field of ν-th fashion in a direction, perpendicular m-that wall.

Substituting Eq.(17) – Eq.(21) and following from Eq.(4) mode ratio

$$\frac{\partial f_i}{\partial h_ð} = -\frac{k_{ið}^2}{k_0^2}\frac{f_i^0}{h_ð}$$

in Eq.(16) for m=1.., 6 it is found:

$$Q_{нm} = \left(1 + \frac{k_{нm}^2}{k_0^2}\right)^{-1} \frac{V}{2S_m\Delta'_m,} \qquad (22)$$

where

$$\Delta'_m = \frac{n_m \Delta_m \cos u_m}{\sqrt{2 + (k_0\Delta_m)^2}}$$

By means of ratio Eq.(13) – Eq.(15) and Eq.(22) it is possible to calculate components of losses of energy in the examined block. And, owing to presence of weight factor $\partial_н$ in Eq.(12) satisfactory results on accuracy it is possible to expect even if in set of frequencies Ω on which the required field decays, to include only fluctuations with $|f^0_н - f_{изл}|/f_{изл} << 1$.

After the termination of transients in each block into which the building is divided, there comes power balance for average powers: the total power which has arrived in any, for example, to k-th the block P^+_k it appears to the equal sum of powers disseminated in its volume P^0_k and leaving in surrounding walls P^{cm}_k:

$$P_к^+ = P_к^0 + P_к^{cm} . \qquad (23)$$

And, power P^{cm}_k in Eq.(23) develops of powers P^{cm}_{km}, leaving in each of M_k surrounding the block walls

$$P_{к}^{cm} = \sum_{m=1}^{M_{к}} P_{кm}^{cm} \,. \qquad (24)$$

Power P^{+}_{k} , acting in k-th the block develops of the powers getting into it through walls from next blocks $P^{см}_{k}$ and, probably, powers of transmitter $P^{изл}_{k}$ if it is located in this block:

$$P_{к}^{+} = P_{к}^{см} + з_{к} P_{к}^{изл} \,, \qquad (25)$$

where $з_{к}$ it is equal 1 for the block in which the transmitter is located, and 0 for all others.

Power $P^{см}_{k}$ acting in k-th block from adjacent blocks with it, is directly proportional to size of powers following through their walls with the factor of easing depending on thickness and absorption in a material of which these walls are made.

Power $P^{см}_{k}$ acting in to k-th the block from the next blocks through the common walls, it is possible to present in the form of:

$$P_{к}^{см} = \sum_{i=1}^{N} c_{ki} P_{i}^{cm} \,, \qquad (26)$$

where N it is equal to number of all blocks a building, elements c_{ki} are factors of easing of power $P^{cm}{}_{i}$, following through walls of i-th block and getting in to k-th the block,

$$c_{ki} = \begin{cases} 0, & \text{if blocks with numbers k and i do not have a common wall,} \\ \dfrac{S_{ki}}{S_{il}} g_{il} \exp\{-2d_{il} / \Delta_{il}\} & \text{if blocks with numbers k and i have a common wall,} \end{cases} \qquad (27)$$

S_{il} there is an area of l-st wall of i-th block, S_{ki} - the area overlapped with to k-th the block parts of this wall, g_{il} - factor with an index l for i-th block, counted on the formula Eq.(14).

Elements C_{ki} make a matrix C from dimension N × N which is meaningful matrixes of connections of blocks of a building. Its elements are defined by the plan of a building, and also thickness and absorbing properties of its external and internal walls and blockings. At absence of the common wall between to k-th and i-th blocks the factor C_{ki} is equal 0. Having substituted Eq.(23) – Eq.(24) and Eq.(26) in Eq.(25) it is received N the equations of a kind:

$$P_{к}^{cm} = (1 - g_{k0}) \left[\sum_{i=1}^{N} c_{ki} P_{i}^{cm} + з_{к} P_{к}^{изл} \right], \qquad (28)$$
$$k = 1, \ldots, N$$

Ratio Eq.(28) represent the equations of balance of powers in all blocks of a building and can be considered as system N of the linear algebraic equations rather N by unknown persons P_{k}^{cm}.

Having solved Eq.(28) for each block we find powers P_{k}^{cm}, by means of which then on Eq.(24) and Eq.(26) it is possible to find powers P_{km}^{cm} and P_{km}^{cm} the m leaving and acting in to k-th the block through its m-th wall. Having divided them on the area of corresponding walls S_m, we find resulting average density of streams of power T_{km}^{cp} at each wall in everyone block.

$$T_{km}^{cp} = \left(P_{km}^{0} + P_{km}^{cm}\right) / S_{m} \,. \qquad (29)$$

Stream T_{km}^{cp} is directed perpendicularly to m-that wall to k-th the block. Positive sign T_{km}^{cp} means, that power acts in to k-th the block through its m-that wall, negative-that through this wall power leaves from to k-th the block.

On known T_{km}^{cp} using procedure of interpolation it is possible to reconstruct size and direction of average density of a stream of power T^{cp} in any point inside any block of a building and further with its help to determine average accepted power in a vicinity of this point under the formula

$$P^{cp} = G T^{cp} л_{изл}^{2} / (4p) \qquad (30)$$

where G - factor of the directed action of the reception aerial, $Л_{изл}$ - length of a wave of the transmitter.

In each block the law of change of accepted power at moving along any line has oscillatory character. In a vicinity of an any point of the block accepted power periodically accepts the maximal and minimal values caused by an interference of waves at their repeated redeflections. The formula Eq.(30) gives average value of this power in a vicinity of a an examined point of room. Having divided power of transmitter $P^{изл}$ on $P_{пр}^{cp}$, we find average losses of distribution signal in each block of a building.

Repeated redeflection waves in each room lead to absence of any primary direction of distribution partial waves. Therefore, at resulting fluctuations in each room approximately it is possible to count identical all numbers k_{vm} in Eq.(21) – Eq.(22):

$$k_{нm}^{2} = (1/3)(2p / л_{изл})^{2}, \quad m = 1, \ldots, M \qquad (31)$$

After substitution (31) in (22) and (14) it is received following simple formulas for calculation of factors g_{il} in (27):

$$g_{i0} = \frac{0.375 \beta_{i} V_{i}}{0.375 \beta_{i} V_{i} + \sum_{m=1}^{6} S_{im} \Delta'_{im}} \,, \qquad (32)$$

$$g_{il} = \frac{S_{il}\Delta'_{il}}{0.375\beta_i V_i + \sum_{m=1}^{6} S_{im}\Delta'_{im}} \qquad (l \geq 1)$$

As it was already marked, through two - three walls from the location of the transmitter a determinative in accuracy of calculations is the size of accepted power P_{k0}^{cp} average on all examined (k-th) room. In this connection as a first approximation it is possible to do without procedure of interpolation and to calculate average power of an accepted signal in an any point of k-th room under the formula

$$p^{cp}(r) = P_{k0}^{cp}\left(r / r_{k0}\right)^{-n} \qquad (33)$$

where r - distance between the transmitter and the receiver, n = 1,5÷ 4, $r_{k0} = (r_k^{max} r_k^{min})^{1/2}$, r_k^{max} and r_k^{min}- distances from the transmitter up to the points most removed and closest to them to k-th a room (if the transmitter is located in a an examined room it is necessary $r_k^{min} \approx 5\text{л}_{изл}$), and $P_{ко}^{cp}$ pays off on Eq.(30) for k-th room.

The conclusion

The developed model of communication channels inside of buildings will be realized in the form of the computer program and will find application for forecasting propagation losses of signals for frequencies of 900 and 1800 MHz in various types of uninhabited buildings: scientific and higher educational establishments, shopping centers. Among buildings to which approbation of model will be realized, can be multi-storey and one-storey, brick and concrete. Selecting the elementary block of separate rooms of a an examined building results of calculations of average signal propagation losses in each room should be compared to experimental data.

Thus it will be possible to estimate accuracy of the offered model.

3 References

[1] Damosso E., ed., Digital Mobile Radio: COST 231 View on the Evolution towards 3rd Generation Systems. Bruxelles: Final Report of the COST 231 Project, published by the European Comission, 1998.

[2] Gahleitner R., Radio Wave Propagation in and into Urban Buildings. Phd thesis, Technical University of Vienna,

[3] Motley A. J. and Keenan J. M., "Radio coverage in buildings," Bell System Technical Journal (BTSJ), vol. 8, pp. 19 - 24, Jan. 1990.

[4] Wolfle G., Landstorfer F. M., Gahleitner R., and Bonek E., "Extensions to the Field Strength Prediction Technique based on Dominant Paths between Transmitter and Receiver in Indoor Wireless Communications," in 2nd European Personal and Mobile Communications Conference

[5] Wolfle G. and F. Landstorfer M., "Dominant Paths for the Field Strength Prediction," in 48th IEEE International Conference on Vehicular Technology (VTC), (Ottawa), pp. 552-556, May 1998.

[6] Huschka T., "Ray Tracing Models for Indoor Environments and their Computational Complexity," in IEEE 5th International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 486 - 490, Sept. 1994.

[7] Carciofi C, Cortina A., Passerini C, and Salvietti S., "Fast Field Prediction Techniques for Indoor Communication Systems," in 2nd European Personal and Mobile Communications Conference (EPMCC), (Bonn), pp. 37 - 42, Nov. 1997.

[8] Degli-Esposti V., Carciofi C, Frullone M., and Riva G, "Sensitivity of Ray-Tracing Indoor Field Strength Prediction to Environment Modelling," in European Cooperation in the Field of Scientific and Technical Research (COST), COST 259 TD(97)049, (Lisbon), Sept. 1997.

[9] WINPROP, Software tool for the Planning of Mobile Communication Networks and for the Prediction of the Field Strength in Urban and Indoor Environments. http://winprop.ihf.uni-stuttgart.de, June 1999.Mathworks Inc., Natick, 1998.

[10] Landron O., Feuerstein M. J., and Rappaport T. S., "A Comparison of Theoretical and Empirical Reflection Coefficients for Typical Exterior Wall Surfaces in a Mobile Radio Environment," IEEE Transactions on Antennas and Propagation, vol. 44, pp. 341-351, Mar. 1996.

[11] Gibson T. B. and Jenn D. C., "Prediction and Measurement of Wall Insertion Loss," IEEE Transactions on Antennas and Propagation, vol. 47, pp. 55-57, Jan. 1999.

[12] Danielle P., Degli-Esposti V., and Falciasecca G. J. R. G., Frullone M., "Evaluation of the Reliability of a Ray Tracing Microcellular Field Prediction Model," in Progress in Electromagnetics Research Symposium (PIERS), (Innsbruck, Austria), p. 513, July 1996.

[13] Веселов Г.И., Раевский СБ. Слоистые металлодиэлектрические волноводы. - М.: Радио и связь . 1988 . 248 с.

[14] Гуреев А.В. О скорости переноса энергии электромагнитными волнами в регулярном экранированном волноводе // Журнал технической физики. 1990 . Т. 60 . N 11 . С. 23-28 .

ISBN 978-3-901608-32-2

[15] Гуреев А.В. Свойства нормальных и присоединенных волн в экранированных неоднородно заполненных волноводах // Изв. вузов. Радиофизика. 1990. Т.33. N 8. С. 954-964 .

[16] Г.Т.Марков, Б.М.Петров, Г.П.Грудинская. Электродинамика и распространение радиоволн - М.: Сов. радио, 1979 , 376 с.

[17] Вайнштейн Л.А.. Электромагнитные волны - М.: Радио и связь, 1988 г., 440с.

[18] Гуреев А.В. Метод учета потерь в металле при анализе экранированных резонаторов и волноводов // Радиотехника и электроника. 1985, т.30, 6, С. 1058-1062 .

[19] Гуреев А.В. Методы возмущения в задачах о распространении электромагнитных волн в регулярных волноводах // Журнал технической физики . 1991. Т.61. N 10. С. 139-146 .

[20] Гуреев А.В. Расчет потерь электромагнитной энергии в полых волноводах // Радиотехника . 1987 . N 9 . С. 59-61 .

[21] Гуреев А.В. Расчет добротности СВЧ резонаторов // Радиотехника . 1988 . N 5 . С. 79-81 .

