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Analysis of electromagnetic wave propagation inside a room with two field sources

Abstract. *The article presents the influence of the building structure on the propagation of electromagnetic waves. The model of the room was made of bricks, and included, e.g. a two-layer outer wall composed of hollow bricks and foamed polystyrene. Numerical calculations concerned checking the electric field intensity distributions at different locations of the field source. Two sources of the field, (e.g. WIFi, Bluetooth transmitters) operating at the same time, and in the same frequency range of 2.4 GHz, were also analyzed, and based on the results, the possibility of temporary signal loss was found, which the result of, among others, interference is. In order to perform the calculations, the Finite Difference Time Domain method based on Maxwell's equations was used. The analysis of the results and occurring phenomena will allow better planning of the deployment of wireless network transmitters in order to improve the quality of wireless communication.*

Streszczenie. *W publikacji przedstawiono wpływ konstrukcji budowlanej na propagację fali elektromagnetycznej. Model pomieszczenia wykonany został z cegieł i uwzględniał m.in. dwuwarstwową ścianę zewnętrzną złożoną z pustaków i styropianu. Obliczenia numeryczne dotyczyły sprawdzenia rozkładów natężenia pola elektrycznego przy różnych lokalizacjach źródła pola. Analizowano także dwa źródła pola (np. nadajniki WIFi, Bluetooth) pracujące w tym samym czasie i w takim samym zakresie częstotliwości 2.4 GHz i na podstawie wyników stwierdzono możliwość występowania chwilowych zaników sygnału, które są skutkiem m.in. interferencji. W celu wykonania obliczeń zastosowano metoda różnic skończonych w dziedzinie czasu (FDTD) opartą na równinach Maxwella. Analiza wyników i występujących zjawisk pozwoli na lepsze planowanie rozmieszczania nadajników sieci bezprzewodowej w celu poprawy jakości komunikacji bezprzewodowej. (**Analiza propagacji fali elektromagnetycznej wewnątrz pomieszczenia z dwoma źródłami pola**).*

Keywords: electromagnetic wave propagation, finite difference time domain method, wireless communication, civil engineering materials.
Słowa kluczowe: propagacja fal elektromagnetycznych, metoda różnic skończonych w dziedzinie czasu (FDTD), komunikacja bezprzewodowa, materiały budowlane.

Introduction

With the growing popularity of mobile devices, wireless technology are becoming more and more common, finding wide application in personal computers, laptops, PDAs, and mobile telephony [1-8]. The propagation of electromagnetic waves related to wireless communication, occurring inside building structures, is still an analyzed issue [10-20]. Analytical methods can only be used in simple cases where complex materials are not present. On the other hand, constructions occurring in today's construction technology contain many materials, that differ in terms of both electrical parameters and construction [9, 15, 19, 21]. Analysis of the quality of wireless communication inside structures containing, e.g. bricks with numerous hollows, insulating layers, or reinforcement that is intended to strengthen the structure must be made using numerical methods [22-24]. Accurate mapping of the model, adoption of appropriate assumptions and boundary conditions, will allow obtaining knowledge related to the propagation of EM waves. Thanks to this, it will be possible to mount devices related to wireless communication in places allowing for optimal signal quality. Multi-variant analysis will, to some extent, enable a better understanding of phenomena related to wave propagation, which will eliminate places associated with signal decay [2, 26, 27].

WiFi and Bluetooth are popular standards for wireless communication. Since both systems use the same frequency band, this leads to interference. The result is a decrease in network capacity, and in extreme cases - a complete cessation of work. In the face of modern applications requiring fast image and sound transfer, such devices reduce their chances of meeting the needs of users. Therefore, efforts are made to reduce the negative effects of both networks on each other. WiFi and Bluetooth operate on the same wave frequency range, so there is a high risk of interference [28]. Both technologies use the 2.4 GHz frequency. The results of research conducted by Texas Instruments confirm the negative impact of interference on the throughput of both networks. They indicate that the strength of this interaction depends on the distance between the transmitters.

The problem is that one of the devices is interfering with the reception of data by the signal sent by the other (WiFi or Bluetooth). Most applications, such as printing or synchronizing the PDA with a personal computer, require short connections that do not significantly affect the stability of the WiFi network. For this reason, the dominant approach so far has been come to terms with this phenomenon. Problems arise with larger Bluetooth networks. These types of installations are most common in large enterprises, allowing employees to work more mobile. With such a large scale and intensity of use, the interaction of both networks is inevitable. Another example is voice streaming applications. The growing popularity of VoIP (Voice over IP) or VoWLAN (Voice over WLAN) makes it necessary to operate both networks within one device.

The article analyzes the phenomena related to the propagation of EM waves inside a room made in a standard building technology. The distribution of the electric field in the analyzed area, at two different locations of the field source, was checked and compared with the distribution with simultaneous presence of the field sources. Using the above, it would be possible to estimate the phenomena of overlapping waves coming from neighboring base stations and check the possibility of temporary signal loss. The aim of the article is to analyze the physical phenomena occurring inside the area consisting of, e.g. hollow bricks and insulation. This type of analysis already at the design stage can be of great importance for the optimal placement and location of various sources of electromagnetic field.

Construction of walls in a typical single-family housing

In two-layer walls, the wall is a structural element, and insulation is the main barrier to excessive heat leakage from the house, thanks to which the house can be energy-efficient. External walls with a two-layer structure consist of a load-bearing brick part, an insulating layer (mainly mineral wool or polystyrene), and thin-layer plaster or other facade cladding [15, 29, 30].

In the case of a two-layer wall, each layer has different functions assigned to it: load-bearing - transfers forces from other elements of the structure; thermal insulation - provides adequate thermal insulation, and protects the construction layer against the destructive influence of external conditions. It is popular to construct houses in two-layer technology, in which the thermal insulation parameters of external walls are ensured by a properly selected layer of thermal insulation material. The need to insulate external walls is due not only to economic reasons, because the better the walls are insulated, the warmer the house, and therefore the lower heating costs. The second issue is the requirements for wall insulation. According to the regulations in force, the heat transfer coefficient of external walls should not exceed 0.20 W/(m²·K). Two-layer walls are built mainly of hollow bricks and blocks. Ceramics is a natural material that allows you to build walls with high thermal insulation.

The ETICS system is one of the most popular methods of finishing building walls, known as the seamless thermal insulation system (BSO), and even earlier as the "light wet method" [31-32]. Its main task is to improve the thermal insulation properties of the walls of both newly built and existing buildings, which require reducing the demand for thermal energy. It consists of several products, which complement each other, and create a barrier, that protects the house against unfavorable external factors. The basic materials for insulating two-layer walls are polystyrene and mineral wool. The wall is finished with plaster, where the layer depends, among others, on the function that the wall is to perform. For example, for internal walls, the plaster layer is 10 mm, while for external walls; the thickness of this layer is from 15 mm to 20 mm [31]. Mineral plasters are the most commonly used. They have the form of a dry mixture containing white cement, which must be mixed with water before use. They are characterized by good vapor permeability and high durability. Their hardness increases with time. You also need to strictly observe the proportions, when adding water to them. Ordinary mineral plasters are not very flexible, and are not resistant to cleaning with high-pressure water.

Description of building construction

Various construction technologies used today allow, above all, improving construction properties, such as energy efficiency. Other aspects related to construction techniques are compliance with standards, minimization of construction costs, and high efficiency [33, 34]. By using appropriate materials in the construction of single-family houses, it is also possible to ensure energy efficiency, or even create an intelligent building in which wireless communication plays an important role. In connection with this issue, the structure of the room was considered with the use of commonly used building materials. The electrical parameters of these materials are presented in Table 1.

Table 1. Electrical properties of building materials [19, 35]

Building material	Relativity permittivity (ε_r)	Relativity permeability (μ_r)	Conductivity (σ) [S/m]
ceramic block	4.44	1	0.01
foamed polystyrene	2.55	1	0.00001
plaster layer	2.2	1	0.00001
glass	5	1	0.012
wood	2.5	1	0.003

The analysis of the EM field distribution was performed in a living room with dimensions of 2.7×4.5×0.5 m in the x, y and z directions, respectively (Fig. 1). All walls are made of ceramic block, which contain drills (Porotherm 18.8 P + W). The outer wall is made of two layers (ceramic layer - Porotherm 18.8 P + W and foamed polystyrene) [31, 32]. The model also took into account the plaster layer on each wall. The external plaster layer (on the external wall) was 0.02 m, while the thickness of the plaster on all other walls was 0.01 m).

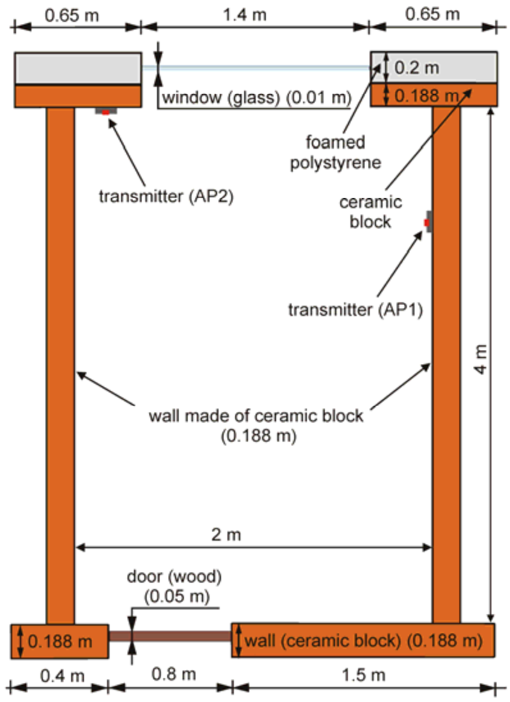

Fig.1. Geometry and dimensions of the analyzed room

The field source was generated by an access-point (AP) that was mounted on the inside of the wall. The source of the field was a transmitter generating a harmonic wave with the frequency of f = 2.4 GHz [22, 36]. The influence of the building material, and the AP location on the distribution of electromagnetic field was checked. Three variants were considered: AP1, AP2 and the situation with two field sources (AP1 and AP2 simultaneously).

Numerical model

For the analysis of electromagnetic field distribution differential methods are often used, e.g. Finite Difference Time Domain (FDTD) [4, 23, 26, 37], as well as the Finite Element Method (FEM) [38, 39]. To determine the electric field intensity, the finite difference method with direct integration of Maxwell's equations in the FDTD time domain was used [22, 23, 36].

When considering electromagnetic phenomena in building structures, the field distribution is described by Maxwell's equations [22, 26, 36]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{1}$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t}, \tag{2}$$

where: **E** is a vector of the electric field intensity, **H** is a vector of the magnetic field intensity, **D** is a vector of electrical induction, **B** is a vector of magnetic induction, σ is a conductivity.

After decomposition, equations (1) - (2) are presented in the form of six coupled first-order differential equations describing the individual components of the electric and magnetic field [36]:

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x \right), \tag{3}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right), \tag{4}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \right), \tag{5}$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right), \tag{6}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right), \tag{7}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right). \tag{8}$$

In FDTD method, the field distribution in the analyzed area is calculated by applying direct differentiation methods in time and space. In space, the differential diagram is realized by the correct distribution of the electric and magnetic field intensity vectors within each cell. The vectors of the electric field intensity associated with the cell Yee are hooked in the centers of the respective edges, and the vectors of the magnetic field intensity - in the midpoints of the sidewalls. The determined spatial distributions of physical quantities $\{E_x, E_y, E_z, H_x, H_y, H_z\}$ are assigned at selected points of the area (x, y, z), taking into account the discrete, finite size of the integration step over the area (Δx, Δy, Δz). Each component of the electric field intensity vector is surrounded by corresponding components of the magnetic field intensity vector rotating around it. In the case of the components of the vector **H** the notation is analogous.

Integrating Maxwell's equations in the time domain is based on the use of a two-step scheme. At selected moments of time, in which the electric field distribution is determined, the values of the components of the magnetic field intensity vector are shifted by the time $\Delta t/2$ in relation to them. Determination of the components of the electric field intensity vector: E_x, E_y, E_z is possible thanks to the earlier calculation of the components of the magnetic field intensity vector: H_x, H_y, H_z in the previous time step of the algorithm and the previous values of the components of the electric field intensity vector E_x, E_y, E_z. The described sequence of steps was called the leap-frog process (Fig. 2).

As a result of the partial derivatives approximation, the Maxwell equation is obtained in the differential form. E.g. equation (5) takes the form presented below:

$$\frac{E_z\big|_{i,j,k}^{n+1} - E_z\big|_{i,j,k}^{n}}{\Delta t} = \frac{1}{\varepsilon}\left(\frac{H_y\big|_{i+1/2,j,k}^{n+1/2} - H_y\big|_{i-1/2,j,k}^{n+1/2}}{\Delta x} - \frac{H_x\big|_{i,j+1/2,k}^{n+1/2} - H_x\big|_{i,j-1/2,k}^{n+1/2}}{\Delta y} - \sigma E_z\Big|_{i,j,k}^{n+1/2} \right). \tag{9}$$

The E_z component is expressed in an observation point (i, j, k) in the time n+1 by some components of the magnetic field in the previous moment t, in the suitable points of space [22, 36, 39].

In the calculated cases the area was composed of cubic Yee cells 10×10×10 mm. In the EM wave propagation, analysis reflections from both ceiling and floor were disregarded, in this case Mur's absorption conditions of the first order were applied [14].

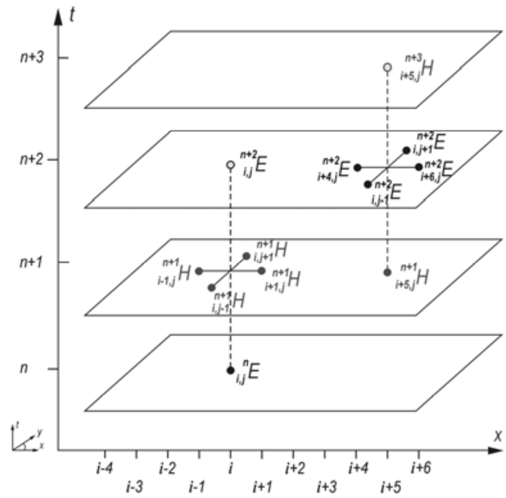

Fig.2. FDTD – the leap-frog process

The results of the analysis

The analysis of the electric field intensity, and phenomena related to the propagation of the EM waves, was performed using the FDTD method using the QuickWave 3D program. Calculations were made for the XY plane. Figures 3-5 show the instantaneous field intensity distributions in the entire analysis area in the same time step in which the steady state was reached. Figures 3-5 show the distribution of the E_z component at a distance of 0.3 m below the transmitter. The highest field value was obtained for the system with two field sources (Fig. 5). However, the difference between the variants with one field source (Figs. 3-4) is small. The most interesting is how the EM wave propagates near the walls, and how the waves overlap, as a result of reflections from the walls of the structure. As a result of such phenomena, temporary signal loss or amplification may occur. The most uniform field distribution is when the field source is in position AP1 (Fig. 3). If the field source is placed in the AP2 position (Fig. 4), then as can be seen, the wave front is broken into two bands, between which there are lower values resulting from the superimposition of the waves reflected from the right wall. Placing the field source on the wall near the window (AP2) results in transferring more energy to the structure of the upper wall, and as a result, there is less coverage of the room with the signal (Fig. 4).

If two field sources are placed in a room (Fig. 5), the EM field intensity increases in the entire area, thanks to which the signal value is higher even in the lower part of the structure (at the door). As a result of the resulting physical phenomena related to the propagation of EM waves from two sources (e.g. interference, reflections), a mutual increase in the instantaneous values of the electric field in close proximity to the field sources is visible in comparison to solutions with single field sources (Figs. 4-5). Even stronger is the field inside the structure adjacent to the field source. In Fig. 5, a temporary and targeted reduction of the field intensity at the height of the window is very noticeable, which is the result of the overlapping of waves from both sources. It can even be assumed, that in these areas, it is possible to experience temporary signal loss. As can be seen, despite the close proximity of both field sources, signal decays and temporary field intensity gains are desirable.

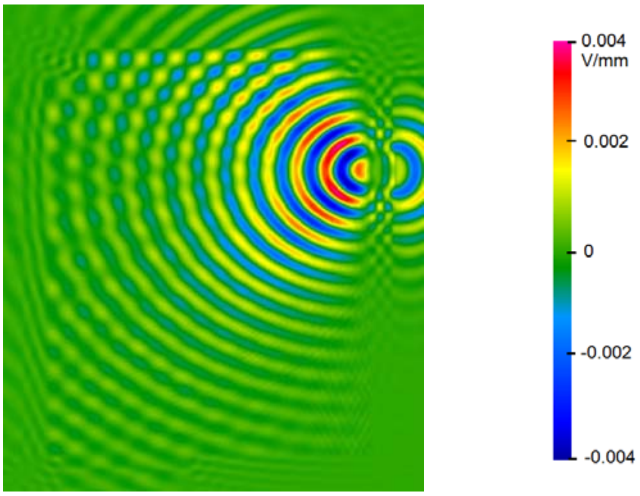

Fig.3. Temporary distribution of E_z component in the model with AP1 (maximum value is 0.003 V/mm)

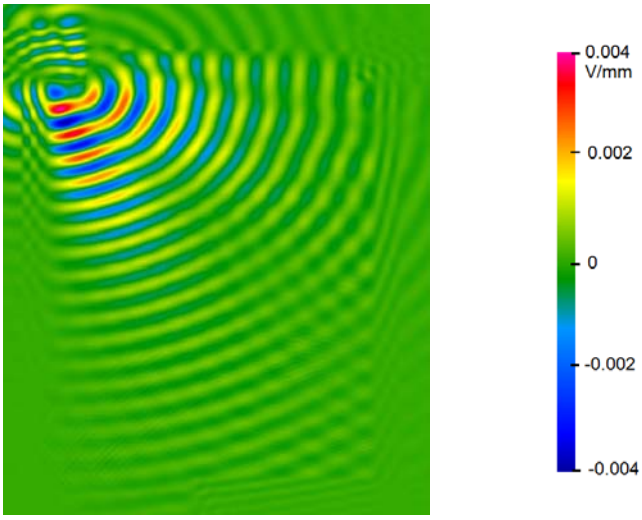

Fig.4. Temporary distribution of E_z component in the model with AP2 (maximum value is 0.0033 V/mm)

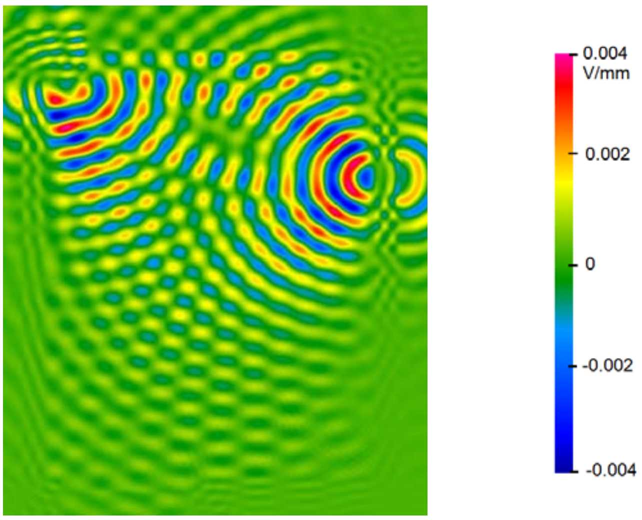

Fig.5. Temporary distribution of E_z component in the model with two access points: AP1 and AP2, (maximum value is 0.0034 V/mm)

Figure 6 shows the distribution of the maximum values of the electric field inside the building structure itself. As can be seen, the construction of the right wall, which is made of hollow bricks, where there is both ceramics and air, causes a less smooth propagation of the EM waves, than in the case of the field source located in the AP2 position (near the window). Foamed polystyrene, which has a very low conductivity value, does not significantly reduce the field intensity inside this part. In this case, the field distribution gradually decreases. The biggest problem is the unpredictability of EM wave propagation in complex structures (e.g. in this case inside ceramic blocks). When we are dealing with a complex structure, where there is also variability in electrical parameters (as here: air and ceramics), we are not able to predict the field intensity distribution. Reflections from the boundaries of the areas, and later overlapping of waves, even those that passed through the ceramic material, are only possible to observe as a result of numerical analysis. This allows for a better understanding of the physical phenomena resulting from the propagation of the EM waves inside complex structures. Thanks to this, it is possible to better plan the assembly of EM field sources in order to ensure the best possible quality.

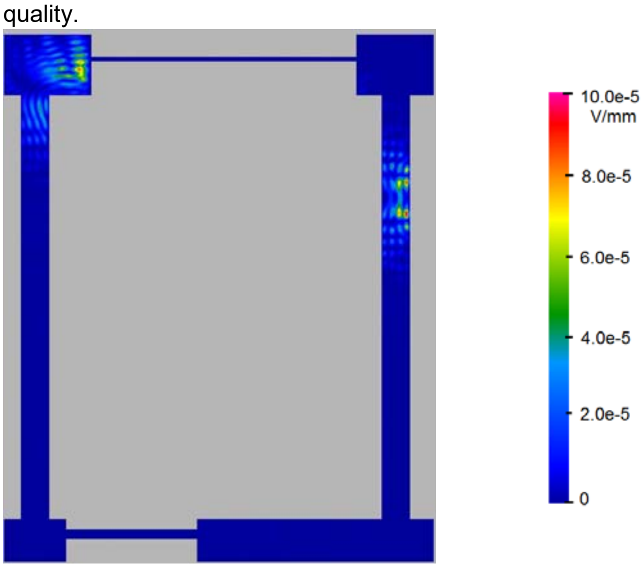

Fig.6. Distribution of E_z component inside the building construction with mounted two field sources in positions: AP1 and AP2 (maximum value is 9.98e-5 V/mm)

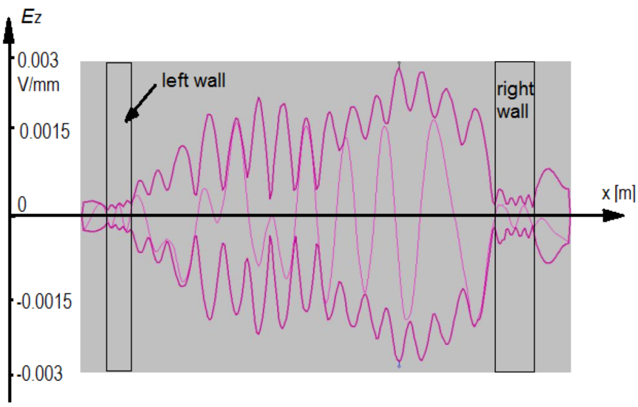

Fig.7. Distribution of maximum values of E_z component in the analyzed construction with mounted two field sources in positions: AP1 and AP2 along the X-axis, along the straight line Y=2 m (maximum value is 0.0029 V/mm)

Figure 7 presents the maximum values of the electric field intensity (field envelope) obtained after multiple passages of the EM waves, when the steady state has been reached. Values were taken along a straight line creasing through the location of the field source at the AP1 position. As can be seen, when there are two sources of the field, the field intensity values have similar values throughout the area due to the overlapping of the EM waves. However, the farther from the right wall and AP1 transmitter, there are visible temporary and quite strong decreases in the electric field value, which may reduce the signal value and the quality of data transmission. For this reason, it is very important to consider whether introducing additional field sources to amplify the signal is really justified. On the one hand, there are higher values of the electric field, but on the other hand, interference in places can unpredictably reduce the values to almost zero, which results in signal loss and lack of communication.

Conclusions

Wireless technology introduces an increasing number of transmitters and receivers, which in turn affects the appearance of many physical phenomena related to the propagation of EM waves. The consequences that may arise, as a result of these phenomena, are often unpredictable, which results in, among others, temporary signal loss. The variety of materials and building structures, or the internal complexities of materials (e.g. hollow bricks) are of great importance for the propagation of EM waves. In this type of structures, it is impossible to perform analytical calculations. The only solution is to use numerical analysis, and in specific in individual cases, also to perform experimental research.

Based on the performed analysis, there is a problem with the overlapping of EM waves from different sources, which work at the same frequency. Interference phenomena are still a problem that is being studied and solved in various ways. However, there is no perfect solution, and a trade-off between expectations and results should always be used. The best solution is experimental verification of a single case or room, taking into account all data related to the construction of the room, other sources of the field (permanent as well as temporary, such as Bluetooth). Only the distribution of the field in the entire area, obtained in this way can show the actual quality of wireless communication.

The aim for devices operating on the same frequency, e.g. Bluetooth and Wi-Fi, is to maintain the signal intensity at the lowest possible level, allowing for proper data transfer. If the transmitted signal power is too high for a given frequency, the risk of interference increases. However, in most cases, the distance between devices on a network does not change dramatically, so it is possible to maintain minimum signal intensity without compromising network performance. The problem mainly concerns devices between which the distance changes rapidly. This topic is still being analyzed in order to find a solution to eliminate the effects of interference.

If there is only one source of the field (e.g. Wi-Fi transmitter), some solutions improve the transmission quality. Major locations provide the best signal coverage throughout the building. For two floors, the transmitter should be on the first floor and preferably on a shelf to provide a stronger signal for devices on the second floor. Particular attention should be paid to the fact, that metal objects can attenuate the EM field values, so locations containing such elements should be avoided.

Further research will focus on the analysis of different locations of EM field sources, and configuration of rooms using the latest technologies in construction, and changes in the electrical properties of the used materials.

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