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Analysis of the influence of the location of holes in bricks on the electric field intensity

Abstract. *The article contains the results of the analysis of the influence of the conductivity of the building material (brick) on the values of the electric field intensity inside the analyzed area. The analysis also took into account the variation of the drill length, which also causes variable drill location, and the two frequencies (2.4 GHz and 5 GHz) used in wireless communication like Wi-Fi. The change in the length of the drills also results in a change in the percentage of the ceramic mass in the brick, which affects the values of the field intensity in the analyzed area. In order to perform the multivariate analysis, the Finite Differences Time Domain (FDTD) method was used.*

Streszczenie. *Artykuł zawiera wyniki analizy wpływu konduktywności materiału budowlanego (cegła) na wartości natężenia pola elektrycznego wewnątrz analizowanego obszaru. W analizie uwzględniono także zmienność długości drążeń, co także powoduje zmienną lokalizację drążeń oraz dwie częstotliwości (2.4 GHz i 5 GHz) stosowane w komunikacji bezprzewodowej Wi-Fi. Zmiana długości drążeń także skutkuje zmianą udziału procentowego masy ceramicznej w cegle, co ma wpływ na wartości natężenia pola w analizowanym obszarze. W celu wykonania wielowariantowej analizy zastosowano metodą różnic skończonych w dziedzinie czasu (Finite Differences Time Domain, FDTD). (**Analiza wpływu rozmieszczenia drążeń w cegłach na natężenie pola elektrycznego**).*

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

Introduction

Modern day building technology is based mainly on ceramic materials and layered construction of walls depending on used material and function of the whole construct. Single family units, contain single-layered and multi-layered walls consisting mainly of ceramic elements, i.e. bricks and hollow bricks. They are formed chiefly of clay, lime, sand or other mineral substance. The mechanical durability and resistance to weather effects is acquired in the process of drying and firing (or alternatively, steaming). Depending on the used materials, these bricks may be used to build walls, pillars, posts, also foundations or be the filling material of ceilings (Klein's ceiling). The division of ready elements is based on their geometric qualities, firing degree and materials used [1]. The dimensions of bricks are varied but based on the height (h) to width (b) to length (l) ratio which is 1:2:4 [1-3].

The location of wireless communication systems (Wi-Fi) inside such buildings requires a detailed analysis of the electromagnetic field distribution. The analysis of wave propagation in the high-frequency range involves the need to examine the influence of the structure itself and building materials. The use of modern wireless communication systems requires taking into account the effects that may reduce the assumed quality of data transmission. The analysis of fields in wireless communication systems requires a discussion of the effects related to: multiple reflections, refractions, interference and attenuation of waves caused by the geometry and complexity of the structure. The factors listed above are the subject of many research works aimed at determining the field distribution in the discussed systems in the most precise way [2-8].

The phenomena listed are a direct result of wave propagation in structures made of non-ideal dielectrics or complex elements containing holes, such as bricks. Some factors are random in nature, related to changes in wave propagation conditions. However, building resilient communication networks requires taking into account elements influencing the field distribution (including building geometry, complex material structures on the path between the transmitter and receiver) at the system design stage. The problems listed are particularly visible in low-range wireless networks (Wi-Fi) used in buildings. Taking into account new and existing structures is crucial when selecting the location of network transmitters.

Another important issue is the appropriate choice of materials' parameters for the analysed construction structures. Basing on the available literature, significant discrepancies may be seen in the values of electrical parameters of the analysed materials, resulting from [9-13]:

1) large range of values and various methods of their representation,
2) assuming constant parameters without taking into account the changes frequency,
3) homogenisation of parameters while analysing different building materials,
4) assuming a constant conductivity value without taking into account the absorption ratio of the material.

Authors [9] have proven that in the case of building materials one cannot use the same trends of constant dielectric dependency (ε_r) on frequency (f). While conducting an analysis of a wall made of full brick, they have proven that ε_r decreases along with an increase in frequency. At the same time, in case of plaster, the dielectric constant rises. A similar situation happens with conductivity (σ), where one cannot assume uniform dependencies for all materials. For example, the range of conductivity of a clay (brick material) is significantly wide (σ=0.00278÷0.244 S/m) [9-11]. For this reason this analysis of a building construction includes changes in conductivity.

In this article the distribution of electromagnetic field behind the brick wall is analysed. Two kinds of brick were taken into account: full and with 18 vertical holes. The presented results may serve as a source of knowledge for distribution of electromagnetic field in an area containing non-ideal, absorbing dielectrics.

In order to assess the effect of brick complexity (ceramic and hollow material) on the values of the electric field strength, the variants with different percentages of clay mass in the brick were analysed. The analysis of the electric field created as the result of EM wave propagation through a wall made of various types of bricks will let to understand the processes, which take place in environments with a non-homogenous dielectric.

Geometry of analysed models

From the point of view of modelling electromagnetic phenomena in these systems, the direct, relative measure of the size of the analyzed model should be the size of the linear dimensions of the system in relation to the length of the propagating electromagnetic wave. The choice of the calculation method is largely dictated by the relative size of the model and the resulting approximations in the representation of physical phenomena.

The work carried out was aimed at assessing the phenomena occurring in model systems. The influence of electrical parameters and the internal structure of building materials on the field distribution at frequencies used in WiFi wireless networks, which refer to a set of standards created for the construction of wireless networks based on communication in the 2.4 GHz and 5 GHz bands, was presented. The aim of the analysis was to assess the influence of walls made of clinker bricks on the values of electric field intensity. The conducting of such analysis was reasoned with the practical applications and popularity of such building material, both in putting up walls and facing without the need for plastering. A brick with 18 hollows was selected for analysis (Fig. 1). The height (*h*), width (*b*) and length (*l*) of all analyzed bricks were 0.065×0.12×0.25 m, respectively.

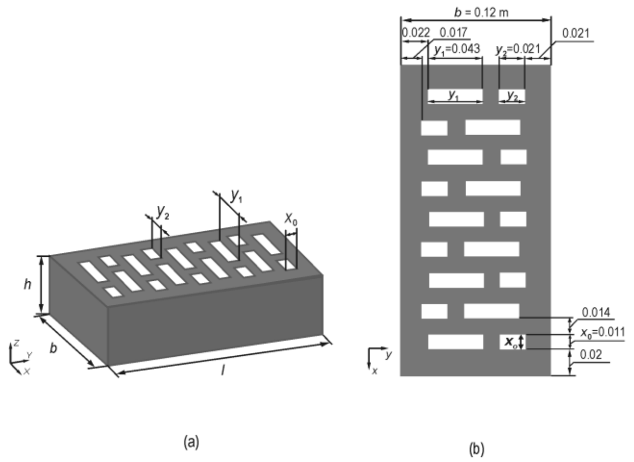

Fig. 1. Analyzed brick: (a) 3D brick with 18 holes; (b) dimensions of brick with 18 holes

The standard dimensions of bricks, as well as the width of the holes shown in them, are presented in Fig. 1b (model MW). The average size of air holes in a brick is x_0 =0.011 m. For the sake of the analysis, bricks of different widths (y_1 and y_2) along the width of the brick (b=0.12 m). After all the processes (drying and hardening), some parts of the brick may have an unusual size. For this reason, the influence of a different relative volume of the clay mass on the electric field values was analyzed ($V_{\%b}$). This factor was also modified by changing the size of the ventilation holes (y_1 and y_2) (Tab. 1).

Table 1. Percentage of the ceramic volume inside a brick in relation to the variable size of holes inside brick

Model	Analysed brick	x_0 [m]	y_1 [m]	y_2 [m]	$V_{\%b}$
M1 from model MW y_1 and y_2 less 0.005 m		0.011	0.038	0.016	82.18%
MW		0.011	0.043	0.021	78.88%

The analysis concerned the frequencies f=2.4 GHz and f=5 GHz. For the numerical analysis of the considered brick variants, the following methods were used: the relative electrical permittivity ε_r'=4.44 [5-13], whereas the conductivity was modified within the range σ=0÷0.2 S/m.

Numerical model

In order to analyze phenomena related to the propagation of electromagnetic waves, numerical methods: finite difference time domain method (FDTD) or finite element method (FEM) are used [14-19]. The use of numerical methods allows for multi-variant analysis, quick modification of the model and the adopted values. In described models the FDTD method was used for the analysis [14, 16]. This method is useful in the numerical analysis of high frequency time dependent electromagnetic fields. The method is based on the transformations of Maxwell's equations into a differential form [14]:

(1) $$\nabla \times \mathbf{H} = \mathbf{J}_P + \mathbf{J}_D + \mathbf{J}_I \, ,$$

(2) $$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \, ,$$

(3) $$\nabla \cdot \mathbf{D} = \rho \, ,$$

(4) $$\nabla \cdot \mathbf{B} = 0 \, ,$$

(5) $$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \, .$$

where: **E** – electric field (vector), **H** – magnetic field (vector). Electric charges and electric currents are the sources of these fields, which can be expressed as local densities, namely the charge density ρ and the current density **J**. The density of displacement current $\mathbf{J}_D$ and the density of conduction current $\mathbf{J}_P$ were described by dependences:

(6) $$\mathbf{J}_P = \sigma \mathbf{E} \, ,$$

(7) $$\mathbf{J}_D = \frac{\partial \mathbf{D}}{\partial t} \, .$$

while $\mathbf{J}_I$ denotes the current density vector that forces the field. The FDTD method allows the analysis of complex structures in which each material has its own electrical characteristics. The description of the problems using equations (1)-(5) allows us to determine the field distribution in the unsteady state, as well as in the steady state when time-varying field excitation appear.

The field distribution in the analysed domain is calculated by direct integration method in time and space. Hence, for instance, the equation describing E_z component in the Cartesian coordinate system is determined from the following dependence:

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

After the approximation of partial derivatives Maxwell's equation in a differential form is obtained. For this case equation (8) takes the formula, which, after transformation, allow us to determine the value of E_z component of the electric field intensity at observation point (i, j, k) in time (n+1) basing on the components of the magnetic field in the previous moment t at suitable points of space.

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

The discretization in the space is performed by an appropriate location the vectors of both electric and magnetic field intensity within each cell. The vector components of the electromagnetic field are calculated for different points of space. The vector components of the electric field intensity assigned to Yee cell are placed in the middle of the respective edges whereas the components of the magnetic field intensity are placed in the middle points of the side walls.

The integration of Maxwell's equations in the time domain is based on the leap-frog scheme. The points of time at which the distribution of electric field vector **E** is determined, are displaced by $\Delta t/2$ with respect to the points where the component values of magnetic field intensity vector **H** is calculated. Every Yee cell is described by such material parameters, among others, as electric conductivity or magnetic permeability.

The stability of the time marching explicit scheme requires satisfying the Courant-Friedrichs-Lewy (CFL) condition [14-17]. The analysed area was composed of Yee cells (0.001 m).

The source of the field was a sinusoidal oscillating plane wave with f =2.4 GHz or f =5 GHz. The EM field is excited in a region far away of the wall. Omitting the phenomena occurring at the ends of the wall, near its edge or at the contact with another wall, it was possible to reduce the size of the model by applying the appropriate boundary conditions (perfectly match layer, PML), in particular periodic boundary conditions (PBC) [14]. PML condition were entered perpendicular to the equiphase surface. PBC conditions were assumed at the edges perpendicular to the Ox axis).

Results and discussion

The FDTD method used for calculations allows obtaining instantaneous images of the field. In order to obtain the maximum values of the observed E_z component (Figures 2-4), it was necessary to formulate and develop an additional algorithm written in C++. The aim of this program was to find and save the maximum values from any number of files containing instantaneous values of the electric field component. These files were saved at regular intervals to track wave propagation phenomena within one wavelength. Of course, the files were saved after reaching a steady state.

Figures 2-4 show the distribution of E_z component behind the wall. The results of calculation are shown at the time when the steady state of the EM field distribution had been achieved. In the case of walls with a homogeneous material structure, with a perpendicular incidence of a wave on the boundary of the media, the description of the phenomena occurring corresponds to the classical problem of propagation of a plane wave in open space and its interaction with a plate made of a dielectric [14, 20]. Before starting the analysis, tests were performed to check the correctness of the assumptions made. The results of the numerical analysis were compared with the results obtained by the analytical method [20], of course only for model containing a wall made of a homogeneous material, e.g. full brick (Fig. 2).

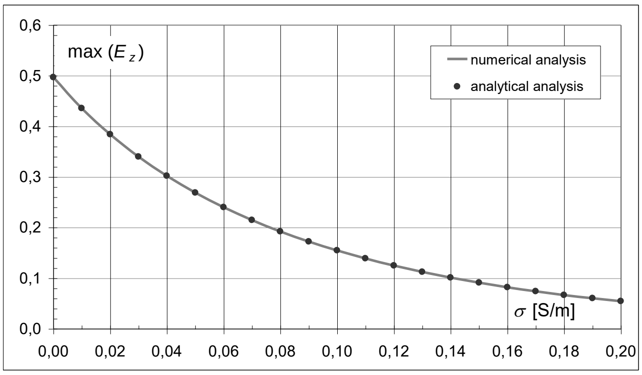

Fig. 2. The relative maximum values of the E_z component behind a wall made of full bricks

In Fig. 2, the results of the numerical analysis are presented as lines. The results obtained by the analytical method are presented as dots. Models containing a wall made of bricks with hollows were calculated using the presented FDTD algorithm. Based on the test results and the comparison of the results obtained by both methods, it could be stated that the correct size of the Yee cell (0.001 m) was assumed.

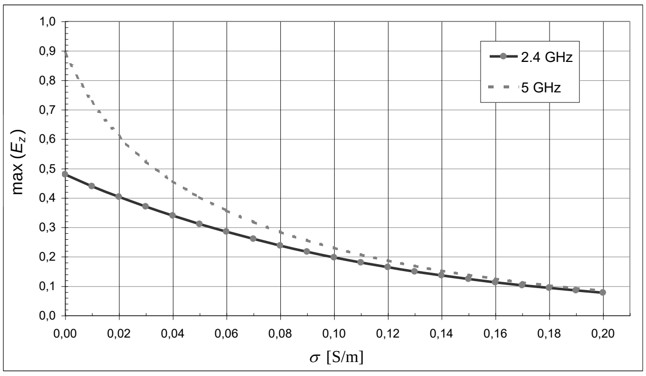

Fig. 3. The relative maximum values of the E_z component behind a wall made of bricks with typical size of holes (model MW)

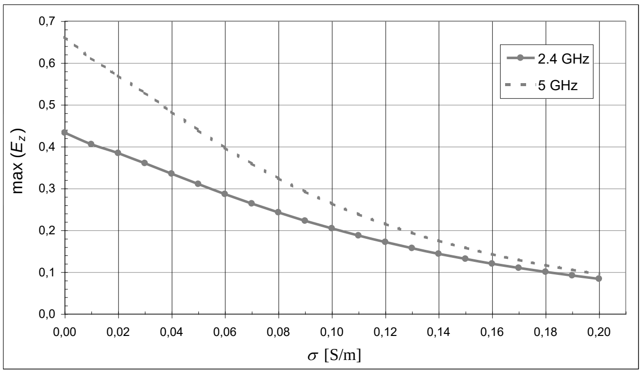

Fig. 4. The relative maximum values of the E_z component behind a wall made of bricks with holes (model M1)

As can be seen in Figs. 3,4, a higher value of the $V_{\%b}$ coefficient, i.e. a larger share of ceramics in the brick (model M1) causes lower values of the field intensity. The analysis shows that a wall composed of bricks with typical dimensions of hollows (model MW) causes higher values of the field intensity regardless of the frequency.

When analyzing the model made from typical drilling values (MW) and σ=0.1 S/m it can be seen that for the 2.4 GHz frequency the field strength values are higher than for the M1 model by about 4%. However, for a frequency almost twice as high (5 GHz) the difference is about 16%.

Regardless of the type of the analyzed walls with cavities, the electric field intensity decreases with the increase in conductivity. In the model with typical values of cavities (MW) already above the conductivity of 0.14 S/m, both characteristics have similar field values (i.e. 0.15 S/m).

The propagation of an electromagnetic wave in the brick area is complex. The porosity of the brick in the electromagnetic sense affects the appearance of multiple reflections at the air-ceramic mass boundary. The number and size of holes in the brick results in a change in the field image, in the area close to the wall. The local change in wave speed when passing through subsequent areas of air and ceramic mass is reflected in the field distributions and the occurrence of interference. Due to the large hollows and small boundary surfaces, the indicated effect is particularly visible when assessing the phenomena occurring behind the wall made in the m4 model. The range of field changes in this case takes on larger values. The effects of wave reflections from the wall, causing the formation of momentary minima and maxima, are particularly visible at a distance of 0.5 m behind the wall. The larger the area for drilling, the greater the number of maxima and minima.

The results prove the complex wave phenomena occurring during wave propagation through a complex material. Various wall structures or the variability of material parameters require individual analysis.

Conclusions

The article presents an analysis of the effect of the number of holes and conductivity on the values of the electric field intensity. A model of a wall made of clinker bricks with 18 holes was considered. Thanks to the FDTD method, it was possible to perform a multivariate analysis for different values of conductivity.

The propagation of the electromagnetic wave in the area of the brick is a complex process. The structure of brick with hollows affects the occurrence of multiple reflections at the air-ceramic interface. The number and size of openings in the brick cause temporary changes in the field image in the area just behind the wall. At higher frequency (5 GHz) higher values of field strength were observed regardless of the size of the drill holes. When analyzing lower frequency (2.4 GHz) and typical value of conductivity (0.1 S/m), reducing the ceramic in the brick by 4% also results in 4% increase of electric field value.

The presented graphs indicate complex wave phenomena that occur during wave propagation through an electrically porous material. Different wall structures or variability of material parameters require individual analysis. In the case of macroscopic analysis of buildings, it is necessary to homogenize and simplify the structure and homogenize the material properties. This approach is imposed by the limitations resulting from the computational capabilities of computers in numerical modelling of complex structures.

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