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Chapter 3. Analysis of the impact of an energy-efficient brick wall and its structure on wireless communication

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Streszczenie. Cegła (zwłaszcza cegła pełna) ma wysoką pojemność cieplną, co oznacza, że nagrzewa się powoli i oddaje ciepło do otoczenia, co może przyczyniać się do wzrostu efektywności energetycznej budynku. Nowoczesne, porowate cegły lub ściany wielowarstwowe z dodatkową izolacją są bardziej energooszczędne. Ważne jest, aby zweryfikować, czy komunikacja bezprzewodowa w tego typu konstrukcjach spełnia oczekiwania użytkowników. Rozdział przedstawia analizę wpływu ściany z cegły perforowanej na propagację fal. Analiza objęła obszar zawierający ścianę z cegły perforowanej. Zbadano, jak rozmiar otworów wpływa na wartości natężenia pola za ścianą. Rozważono dwa warianty ściany różniące się rozmiarem otworów. Dodatkowo przeprowadzono analizę wielowariantową, uwzględniając zmienność przewodności dla każdego modelu ściany. Analizę przeprowadzono z wykorzystaniem metody różnicowej w dziedzinie czasu (FDTD). Wszystkie obliczenia przeprowadzono przy częstotliwości 5 GHz, która jest wykorzystywana np. w Wi-Fi. Zmiany wielkości pustych przestrzeni powodują zmianę procentowej zawartości masy ceramicznej w cegle. Różnice te nie są jednak tak znaczące w przypadku zmniejszania lub zwiększania długości pustych przestrzeni. Rozkład pola zależy przede wszystkim od złożonych zjawisk fizycznych zachodzących w cegłach (np. wielokrotnych odbić). Na podstawie przedstawionych danych można lepiej zrozumieć zjawiska fizyczne i precyzyjniej zaplanować rozmieszczenie nadajników.

Abstract. Brick (especially solid brick) has a thermal storage capacity, meaning it heats up slowly and releases heat to the surroundings, which can contribute to a building's energy efficiency. Modern, porous bricks or multi-layer walls with additional insulation are more energy-efficient. It's important to verify whether wireless communication in these types of structures meets user expectations. The chapter presents an analysis of the influence of a wall made of perforated bricks on wave propagation. The analysis involved an area containing a perforated brick wall. The analysis examined how the size of the holes affected the field intensity values behind the wall. Two wall variants differing in hole size were considered. Additionally, a multivariate analysis was carried out, taking into account the variation in conductivity for each wall model. The analysis was carried out using the Fine Difference Time Domain method (FDTD). All calculations were carried out at a frequency of 5 GHz that is used in e.g. Wi-Fi. Changes in the size of hollows result in a change in the percentage of ceramic mass in the brick. However, the differences are not so significant in the case of reducing or increasing the length of hollows. The field distribution depends primarily on complex physical phenomena occurring within the bricks (e.g., multiple reflections). Based on the data presented, we can better understand the physical phenomena and more precisely plan the transmitter placement.

Słowa kluczowe: efektywność energetyczna, systemy komunikacji bezprzewodowej, materiały budowlane, metoda różnic skończonych w dziedzinie czasu

Keywords: energy efficiency, wireless communication systems, building materials, Finite Difference Time Domain method (FDTD)

Introduction

Ceramic bricks insulate very well and have a high heat retention capacity. The heated material gradually releases heat to the surroundings and does not cool down dramatically. Advantages of bricks in terms of energy efficiency:

- Heat storage: brick stores heat, allowing one to maintain a more stable temperature in your home, reducing the need for heating in winter and cooling in summer.
- Thermal insulation properties: when combined with appropriate insulating materials, brick walls can significantly reduce heat loss.
- Acoustic insulation: bricks effectively muffle sounds, which increases the comfort of residents.
- Naturalness: brick is a natural material, which affects the healthy microclimate in the building and is environmentally friendly.

Energy demand depends primarily on the heating and ventilation method. Energy consumption differences between individual systems can be even severalfold. The lowest energy demand is observed for an electrically powered heat pump heating system – an average of 21.6 kWh/(m²·year). Much higher demand is observed for gas heating (an average of 74.4 kWh/m²·year) and biomass heating (an average of 107.2 kWh/m²·year). The impact of walls on energy demand is much smaller, although not negligible.

Differences in energy demand between wall variants can be as high as 15%. Single-layer walls are just as good a solution as insulated walls. The lowest energy demand was observed for single-layer walls made of 36.5 cm thick YTONG ENERGO blocks. It's worth noting that walls made of 36.5 cm thick YTONG ENERGO PP2/0.35 blocks have a U-value of 0.25 W/m²K, while walls made of 25 cm thick ceramic blocks with a 12 cm layer of polystyrene have a U-value of 0.24 W/m²K. Despite the slight difference in favor of the double-layer wall, the building made of YTONG ENERGO blocks demonstrated a better energy demand indicator.

An undeniable advantage of single-layer partitions is their precise installation technology, which eliminates linear thermal bridges at joints, positively influencing internal gains. Depending on the construction team, these gains can actually be even higher compared to the relatively imprecise masonry techniques using standard mortar. Furthermore, the practice of installing insulation systems sometimes involves the use of certain simplifications that negatively influence the thermal insulation of the partition. Examples include only partial insulation of thermal bridges or reducing insulation thickness by smoothing the surface of the external partitions.

While ensuring energy efficiency, it is also important to consider the functionality of such a home. Nowadays, more and more devices operate wirelessly. This is due, among other things, to the trend toward SMART homes, and the elimination of wiring, which often makes it difficult to conceal while maintaining a room's aesthetic. Thanks to the use of standard devices, the installation of wireless data transmission systems is in many cases easier and faster than the installation of cable networks. Technologies of this type constitute an important supplement to wired networks. They can be used where technical considerations make it difficult to lay wired networks. Wireless data transmission networks allow for uncomplicated and fast connection of many devices, while maintaining the probability of dynamic configuration of the set of communicating components [1–3].

The effects occurring during the propagation of electromagnetic waves inside buildings do not always allow for maintaining good communication. The biggest problem is the geometry and material from which the construction elements are made. Checking the quality of the network involves conducting many tests in real conditions, which is expensive and laborious. Numerical analysis allows for quick and accurate performance of a multi-variant analysis of the quality of the wireless connection. The use of numerical modeling algorithms enables the determination of electromagnetic field distributions in small and large-scale systems. Despite the inevitable approximations in the constructed models, the use of numerical analysis allows obtaining solutions to complex constructions. The propagation of electromagnetic waves in discussed constructions belongs to a group of issues in which numerical algorithms can be an important, useful tool for assessing field phenomena and provide assistance in designing a wireless network.

Due to the complex nature of the occurring physical phenomena and the significant diversity of geometry and material structures in building structures, the results presented in the available literature are often fragmentary. In selected cases, they concern systems that are largely theoretical in terms of geometry and materials used. This is partly due to the choice of method for calculating field phenomena.

Correct determination of electrical properties of materials is an essential condition for accurate representation of field phenomena in modeled construction. The evaluation of wave propagation in the high frequency range involves the need to analyse the influence of the structure itself and building materials with different values, especially in terms of electric permittivity ($\varepsilon = \varepsilon_0 \varepsilon_r$) and conductivity ($\sigma$) [4]. Basic building materials are normally imperfect dielectrics. For this cause, the chapter additionally presents a summary of the values used for electrical parameters of building materials.

A review of publications and a discussion on the influence of various factors on the electrical parameters of brick, concrete, glass and wood are presented in [5]. According to the chapter, the authors observed that it is practically impossible to know the exact values of the parameters for all environments. They state that measurements should be made for specific variants of models, taking into account the frequency or conditions of the surrounding environment, which affect the composition of the material. Many publications do not take into account the above factors and, for example, concrete is treated as a material for which the authors do not take into account the diversity of components, which depend on the expected mechanical properties of concrete, the type of construction or the construction technology used.

The review of the source materials shows that the issues discussed in this work constitute an important, still unexplored issue. The aim of this study is to design and assess the operating conditions of wireless communication systems. Most studies focus on the analysis of the impact of the arrangement of walls and other construction elements on the propagation of electromagnetic waves [6]. The following issues are considered to a lesser extent: complex structure of wall materials and the variety of building materials used (i.e. types of bricks).

In the literature, walls made of basic building materials are analyzed, which are often treated as uniform homogeneous structures. Despite the diverse composition and properties of individual components, the particle sizes, e.g. aggregate; meet the conditions of quasi-stationarity. The dimensions of the model remain relatively large compared to the unordered components, e.g. concrete [7]. The second reason for the homogenization of the properties of a given material is related to the limited possibilities of mapping a complex structure due to the capabilities of the computer or software.

In this chapter, the author wanted to demonstrate the change in conductivity in various wall models.Different building materials (e.g. concrete, solid and hollow bricks, aerated concrete) have a significant effect on the electric field values. The main reason for the analysis was the use by other authors [8, 9] of different electrical parameters of bricks, concrete or aerated concrete. For example, the variety of conductivity of the brick is very wide 0.0174–0.12 S/m. The same applies to other electrical parameters describing building materials.

This chapter presents an analysis of the effect of varying the width of the brick holes on electromagnetic wave propagation and the electric field intensity. The multivariate calculations also took into account the variation in the brick conductivity, which depends on humidity, environmental conditions, and the local climate. Commonly used bricks containing 18 holes each were considered. The analysis utilized the FDTD differential method, which allowed for the observation of instantaneous field distributions and phenomena occurring within the bricks. Numerous assumptions were made when developing the numerical model.

Building materials

In the literature, walls made of basic building materials are often treated as uniform homogeneous structures. Despite the diverse composition and properties of individual components, the particle sizes, e.g. aggregate; meet the conditions of quasi-stationarity. The dimensions of the model remain relatively large compared to the unordered components, including concrete [10]. The second reason for the homogenization of the properties of a given material is related to the limited possibilities of mapping a complex structure due to the capabilities of the computer or software.

For the reasons given, the analyzed walls are described as homogeneous plates of various sizes, whose properties are uniform, isotropic and expressed by three parameters: relative electric permittivity, relative magnetic permittivity and conductivity. Building structures are created based on basic building materials whose complex and variable internal structure affectsmaterial parameters, impacting building and electrical properties. The discussion of these types of materials allows for taking into account the building technologies used in a given country.

Lime-sand (silicate) products and aerated concrete are produced from almost identical raw materials, but different production technologies mean that the resulting materials have different properties. In both cases, the basic ingredients are lime, sand and water. Silicate materials, like building ceramics, are characterized by high volumetric density resulting from the small amount of free space in the material.

Bricks are a type of building material typically made of sand, lime, or clay. They are generally used to construct walls, pavements, and other types of architecture. The geometry of bricks is very diverse and based on the proportion of height (*h*) to width (*b*) and length (*l*) of 1:2:4 (Fig. 1).

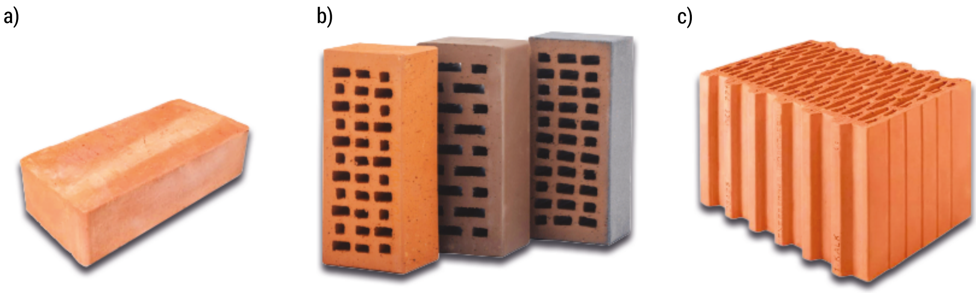

FIGURE 1. Examples of masonry elements: (a) full brick; (b) hollow brick; (c) hollow block

The authors of the publication [11] measured the electrical parameters for three types of solid bricks (red, brown and grooved), with water content close to zero. The analysis concluded that:

- at frequencies {3, 9, 24} GHz the value of ε_r' is similar and is within the limits of 3.7–4;

- regardless of the brick type, displacement current losses are comparable at two frequencies (3 GHz and 9 GHz);
- whereas for $f = 24$ GHz the value of ε_r' is convergent to the ε_r' obtained at $f = 3$ GHz and 9 GHz, and the value of ε_r'' is five times higher in comparison with the two analyzed frequencies, i.e. for 3 GHz and 9 GHz ε_r'' is 0.12 and for 24 GHz $\varepsilon_r'' = 0.6$.

Depending on the frequency, the available literature reports relative permittivity values in the range of 2.82–19, while conductivity values range from 0.00278 to 0.2 S/m.

In an era of growing environmental awareness and rising energy prices, building energy efficiency is becoming a key issue not only among investors and architects but also among everyday property users. One of the most important aspects that affect energy savings is adequate thermal insulation. Brick buildings have traditionally dominated in Poland, and their thermal insulation properties raise many questions and concerns. The right techniques and materials can help us strive for warmer, more economical, and environmentally friendly interiors

In the context of brick construction, thermal insulation plays a particularly crucial role. Brick, although extremely durable and aesthetically pleasing, lacks high insulating efficiency. Therefore, to eliminate this drawback, it is worth using modern insulating materials that are adapted to the specific characteristics of brick buildings.

Numerical analysis method

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 choice of a computational algorithm requires consideration of the needs and constraints related to the specificity of the analysis of field phenomena in wireless transmission systems. The fundamental factors determining the use of numerical simulation methods remain interdependent and are largely opposed in nature. A classic example is the contradiction between increasing the size of the model while maintaining the expected precision of the material structure mapping and the accuracy of modeling real systems. The contradictions of the indicated factors are emphasized when striving to analyze larger and larger systems. The factor related to the numerical cost of calculations also becomes important.

The considered issues of electromagnetic wave propagation belong to the group of open problems. Despite the relatively small range of operation of local wireless communication systems (e.g. within buildings), the mapping of field phenomena is associated with the reproduction of wave propagation phenomena in an open, theoretically infinite area. In local wireless communication systems, the boundaries of wave propagation are not limited to the building area; hence, the complexity and size of the considered area must be taken into account, as well as the adoption of such boundary conditions that will accurately reflect the modeled system.

The geometry of the modeled building structures is at least comparable to or greater than the length of electromagnetic waves in the analyzed microwave frequency band. Due to the failure to meet the quasi-stationarity condition, the considered task comes down to solving the boundary-initial problem described by differential equations [12]. The component materials occurring in the studied systems are treated as continuous media, characterized by means of homogenized electrical parameters *ε*r, *m*r *s*.

The FDTD method was used to determine the electromagnetic field distribution in the analysed model [4, 6]. It is useful for calculating time-varying electromagnetic fields for high frequency and broadband signals. Maxwell's curl equations in time and space are the basis of the FDTD method [12]:

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

$$\nabla \cdot \mathbf{H} = \mathbf{J}_p + \mathbf{J}_D + \mathbf{J}_I \tag{2}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{4}$$

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \tag{5}$$

where: **E** means the electric field (vector), **H** is the magnetic field (vector). Electric charges and electric currents are the sources of these fields, which are indicating as local densities, namely the charge density ρ and the current density **J,** $\mathbf{J}_P$. – the density of displacement current is and the density of conduction current ($\mathbf{J}_D$), while $\mathbf{J}_I$ denotes the current density vector that forces the field.

The description of the problems using equations (1)–(5) permits us to determine the field distribution in the unsteady state, as well as in the steady state. After applying the decomposition, equations (1)–(2) are introduced as 6 coupled first-order differential equations that describe the components of the electric and magnetic fields [12]:

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x\right) \tag{6}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y\right) \tag{7}$$

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

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) \tag{9}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right) \tag{10}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) \tag{11}$$

The field changes in the model area are determined assuming appropriately defined locations of the E and H vector components. In the time-domain differential method formulation, a shifted mesh design is considered for the electric and magnetic field components. The grid shape reflects the physical interpretation of EM phenomena.

Yee cell contains six suitably arranged field intensity component vectors: electric and magnetic. All analysed models aredivided of into an appropriate number of cells. Appropriately, distributing the components of vectors describing the intensity of the electric field **E** and magnetic field **H** within each cell realize the FDTD scheme in this area. The determined distributions of physical quantities are assigned at certain points of the area (x, y, z). Discrete, finite integration step size of the field is presented by Δ_x, Δ_y, Δ_z.

The components of the electromagnetic field are calculated at different points in space. Iterative integration of Maxwell's equations is based on the use of a two-step scheme. In choosen step n, the electric field distribution is determined, while the values of the components of the magnetic field intensity vector are calculated from the displacement at the moment Δ_t. Applying Euler's scheme of central differences to the approximation of partial derivatives in the area and after time, the equations (6)–(11) take the structure, e.g.:

$$\frac{{}^{n+1}_{i,j,k}E_z - {}^{n}_{i,j,k}E_z}{\Delta_t} = \frac{1}{\varepsilon_{i,j,k}}\left(\frac{{}^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}H_y - {}^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}H_y}{\Delta_x} - \frac{{}^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}H_x - {}^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}H_x}{\Delta_y} - \sigma_{i,j,k}\,{}^{n+\frac{1}{2}}_{i,j,k}E_z\right) \tag{12}$$

The geometry of the analyzed models

The adopted classification of materials results from the relationship between the sizes of the components of the materials in relation to the length of the propagating electromagnetic wave. The work carried out was aimed at assessing the phenomena occurring inside the structure. The influence of electrical parameters of the material and the construction on the field distribution at frequencies used in WiFi wireless networks defined by standards created for the construction of wireless networks based on communication in the 5 GHz bands, was presented.

The focus of the analysis was an area consisting of a wall (0.12 m) made of a selected building material. On both sides of the wall, there was air. The geometry of the wall in the direction perpendicular to the direction of wave propagation were much larger than the wavelength in air ($\lambda_p = 0.125$ m). It was possible to reduce the length of the model by applying the appropriate boundary conditions (perfectly match layer, PML), in particular periodic boundary conditions (PBC) [12].

The adopted assumptions allow, in accordance with the goal, to determine the impact of the materials considered on the field intensity values, in an isolated system, omitting other factors. Additionally, an analysis of the impact of the variation of the length of the hollows in the brick was carried out. The model of the brick and parameters which were changed were shown in Fig. 2.

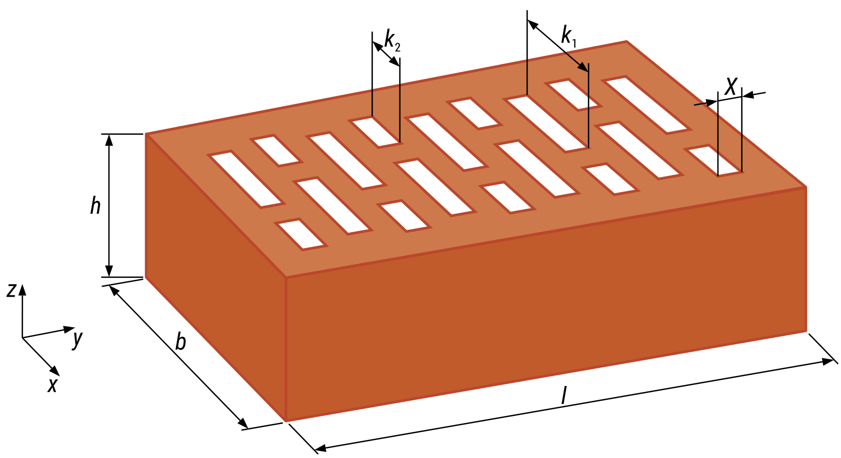

FIGURE 2. **Analyzed perforated brick**

The model length assumed in the calculations ensured the observation of the field intensity distribution in front of the wall and behind the wall in the area with the longitudinal dimension (in line with the propagation vector of the plane wave). The analysis of the electric field distributions and the quantitative assessment in the individual variants were carried out based on the observation of the electric field component max(E_z) in the area behind the wall. The assumed analysis area allowed for the consideration of possible deformations in the field distribution, related to the non-uniform structure of the materials considered and changes in the field at a certain distance from the wall. The field forcing in the system was a harmonic plane wave polarized linearly, propagating in the direction consistent with the Oy axis.

The wall was treated as a non-homogeneous material in terms of its internal structure and assumed material properties. The height (*h*), width (*b*) and length (*l*) of all analyzed bricks were 0.065×0.12×0.25 m, respectively (Fig. 2). Due to the homogeneity of the material structure, the width of the entire model area measured along the Ox axis could take any values. The area of the models considered was subject to discretization by entering a uniform grid of Yee cells ($\Delta_x = \Delta_y = 0.05$ mm).

Due to the fact that various values of electrical parameters of building materials are found in the literature, the analysis also takes into account the variability of the conductivity value $\sigma = 0 \div 0.2$ S/m [25]. The average length of air holes in a brick is 0.011 m (x), with different widths (k_1 and k_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 ($V_{\%}$) on the electric field values was analyzed. This factor was modified by changing the size of the ventilation holes (Table 1). The *vp* model is a reference model with actual dimensions of the holes. The percentage of the total brick volume inside the brick with different size of the holes was marked by $V_{\%}$.

TABLE 1. Relative volume of the clay mass in the perforated brick

Model	Figure of brick	(k_1) [m]	(k_2) [m]	$V_{\%}$
v1 (from *vp* less 0.012 m)		0.031	0.009	86.80%
vp		0.043	0.021	78.88%

Results of the analysis of the influence of wall material on the field intensity values

Fig. 3 presents characteristics depending on the conductivity and type of building material (solid brick and perforated brick). These are field values obtained after a plane wave passed through the wall at a distance of 2 m from the wall. It can be seen that although the hollow brick contains air holes, the field values are higher for solid brick, but at low conductivity values, i.e., up to 0.04 S/m. At higher conductivities, the field values are higher for perforated bricks. Additionally, Fig. 3 shows a comparison of the values obtained numerically and analytically for solid brick.

This section presents an analysis of the influence of the variation of the width of the hollows (k_1, k_2) in bricks on the values of the electric field intensity. The analysis also takes into account the changes of the conductivity 0–0.2 S/m.

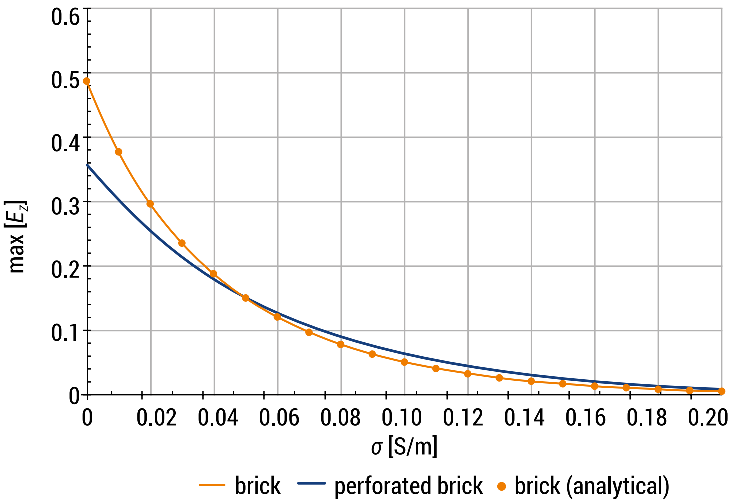

FIGURE 3. Maximum values of the E_z component behind a wall made of typical bricks

The analyzed differences in field values can be explained in macroscopic terms, by taking into account the share of ceramic mass in the volume of the brick. A higher value of $V_{\%}$ causes less wave front distortion in the area behind the wall. This results from the greater resultant homogeneity of the material. However, due to attenuation, this negatively affects the maximum field values. Fig. 4 presents a comparison of field intensity values for the analyzed wall variants for different conductivity values.

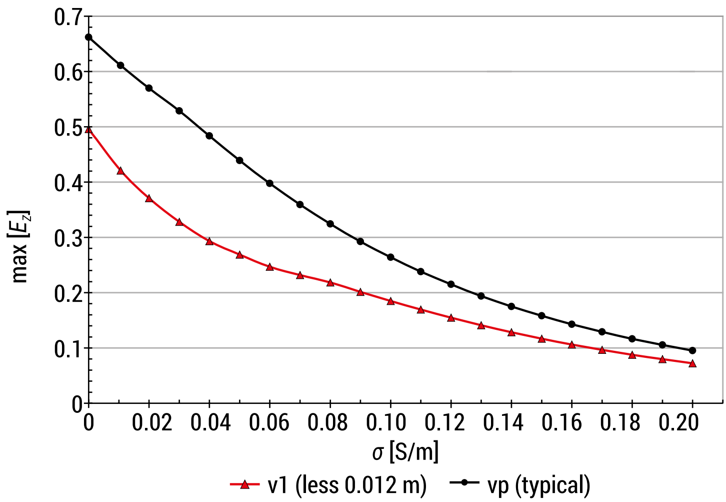

FIGURE 4. Maximum values of the E_z component behind a wall made of perforated bricks

When analyzing the model containing the smallest holes (*v1*) it was found that an almost 8% difference in *V%* compared to the reference model (*vp*) results in a large decrease in the field value by up to 35%. This result is caused by a porous material made of air holes. When passing through different areas of bricks, local changes in the wave velocity cause the appearance of momentary field images, which can increase the E_z values.

Table 2 presents numerically calculated values of the observed electric field component E_z for models with a wall made with different lengths of hollows. With the same values of electrical parameters of bricks (ε_r' = 4.44 and σ = 0.01 S/m), which were also selected for the analysis of the variant with a non-uniform wall, the results are for σ = 0.01 S/m. As can be seen, the greatest discrepancies in the results are precisely for small values of conductivity.

Table 2. Max(E_z) component behind a wall made of different length of perforated bricks

Model	Brick	$V_{\%}$	max(E_z) [–]
v1 (less 0.012 m)		86.80%	0.42
vp		78.88%	0.61

Assuming the same conductivity value (0.01 S/m), it was observed that the lowest electric field values were obtained for the model with the smallest holes (*v1*).

Conclusions

Bricks are one of the most popular building materials, significantly affecting a building's insulating properties. Choosing the right type of brick is crucial for the energy efficiency of buildings. Different types of bricks differ not only in appearance but also, above all, in their thermal properties. Here are some of the basic types:

- Solid brick – characterized by high density and strength, but its insulating properties may be limited.
- Perforated brick – known for its lightness and porosity, it improves thermal insulation by allowing more air to enter the building. Ideal for building exterior walls.
- Ceramic brick – has the best insulating properties, retains heat perfectly and regulates humidity inside the building.

- Silicate brick – although less effective in terms of insulation, it is characterized by high fire resistance and very good acoustics.

As one can see, the brick has many advantages and for this reason, it is also necessary to examine the quality of wireless communication. The chapter presents the FDTD method, which has proven to be indispensable in the analysis of non-homogeneous building materials, where analytical methods fail. The presented analysis results were aimed at determining the impact of the building material and the electrical parameters describing it on the field intensity values.

The results show that in the case of hollow bricks, the phenomena that occur inside the brick are very random and unpredictable. Based on the numerical analysis carried out and the results obtained, it can be stated that the phenomena occurring during wave propagation have an unpredictable nature, which, especially at low conductivity values, strengthens or weakens the field values.

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