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Building materials and electromagnetic radiation: The role of material and shape

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ABSTRACT

The electromagnetic shielding effect of common building materials is reviewed in order to provide baseline data for computer simulations. The first part of this paper presents the "raw" electromagnetic properties of these materials, like brick, concrete, wood, glass, and a complex material like reinforced concrete with different reinforcement square grid sizes. The second part of the paper presents the effect of the shape of a room made from these materials and the effect of the rounding of corners and window edges on the in-house electromagnetic fields. Simulations are performed with a state-of-the-art computational tool: CST Microwave Studio. It is demonstrated that, apart from slightly focusing the electromagnetic waves to the centre of the room, rounding has a very small effect on the electric and magnetic fields. The last part presents comparative data about different building materials regarding their attenuation and electromagnetic penetration. At the end a carbon foil based shielding technique is described, and the importance of and solutions for window shielding are presented.

1. Introduction

Nowadays people are more frequently talking about the possibly hazardous effects of in-house electromagnetic fields, because the general public is currently exposed to a wide range of artificially generated electromagnetic radiation caused by systems such as GSM, UMTS, wireless internet through WLAN, to name the most well known applications. These electromagnetic fields are often suggested to be possibly harmful to health, but researchers still have not come up with a final proof. Also, there is no generally accepted scientific consensus on these health issues. A few effects that have been suggested are the possible interference with the brain's normal functioning [1] by inhibiting the release of melatonin and other endocrine secretions needed to replenish the immune system [2], changed glucose metabolism in the brain [3], adverse effect on the memory of rats [4], change in orientation by ants [5], impacts on biosystems and ecosystems [6], and the fact that careless building design may contribute to the so-called sick building syndrome (SBS) [7].

The word "electrosmog" refers to those electromagnetic fields coming from high- and low-voltage electric wires in homes and normal appliances which are the by-product of usage. Non-useful electromagnetic fields from the antennas of different wireless telecommunication systems can be refered to as electrosmog. More specifically, the term is especially used from the viewpoint of the subject that is not using the application: electrosmog is generated by the neighbour's Wi-Fi, the nearby GSM base station, etc. The level of the electromagnetic fields depends on many factors, like the structure and topology of the house (for example the proportion of used area and wall structure), the environment, the building structure which surrounds us, the placement of electrical wires in the walls, the distance from the transmission tower in case of mobile communication, etc.

In a societal environment, the electromagnetic fields have been mainly studied related to propagation loss, this with the target in mind to obtain a sufficient coverage of the wireless application considered. In and around residential areas the calculation of indoor coverage probability for wireless networks already has been addressed [8,9]. By far most of these studies work with existing situations. In this paper the factors of building structure and building materials will be discussed from an architectural view point. We have to know the electromagnetic properties of building materials in order to evaluate the reflection and transmission coefficients, which quantitate the RF reflection and transmission loss. Being aware of these values we can take steps to effectively calculate and simulate how to shield our room or building, so that external electromagnetic fields will be reduced inside to a required level.

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2. Review of the electromagnetic properties of building materials

Every (building) material has its own electromagnetic properties, just as it has for example mechanical and thermal conductivity properties. The electromagnetic properties to be considered are the permittivity (or dielectric constant), electric conductivity, and magnetic permeability. These constitutive characteristics are needed for example to determine reflection and transmission loss through a wall. In general they are frequency dependent. Measurement of these values usually takes place with dedicated measurement set-ups, in anechoic chambers. Although most parameters are characterized in open literature, this information might be hard to find for architects because this literature is usually not accessible by them. For this reason a brief review is given here. In the rest of the paper, the term "permittivity" is actually referring to "relative permittivity". However, confusion is not possible, given the context and the values reported.

Brick is the oldest and most commonly used building material. Measurements show [10] an electrical relative permittivity range between 4.62 (1.7 GHz) and 4.11 (18 GHz). Note that the electrical permittivity does not necessarily vary linearly. Conductivity was found to vary between 0.0174 and 0.0364 S/m in the same frequency range [10]. Other measurements [11] were performed at 3 and 9 GHz on walls made of small sized solid bricks, and the electrical permittivity was found to be almost constant between 3.7 and 4.

Concrete was already known in ancient Rome but it was only after its rediscovery in 1824 by Joseph Aspdin that it spread worldwide. Since it is a mixture of water, cement and sandy gravel, and can be mixed in different ratios, the question can be raised whether different mixing ratios yield different dielectric properties. Many different mixtures have been investigated [12,13] between 900 MHz and 24 GHz. They all tend to show that the real part of the permittivity varies between 5 and 7 and that the imaginary part varies between 0.1 and 0.7. Note that there is a one-to-one relation between the imaginary part of the permittivity and the conductivity. They both express the same intrinsic material property and can be calculated from one another using Maxwell's equations [14].

For example, if the imaginary part is 0.3, the conductivity is 0.001667 S/m at 1 GHz. Results given by these authors show that in this case the permittivity does not vary significantly with frequency or with different mixing ratio of the constituents in concrete samples. The biggest difference was observed between concrete and lightweight concrete, which has a permittivity with a real part of 2–2.5 and with an imaginary part of 0.12–0.5. [12].

A more advanced building material is reinforced concrete where steel and concrete are combined in a way that the useful properties of both materials are best utilised. In this case the steel bars are influencing the transmission characteristics of the wall depending on the grid size and the diameter of the reinforcement. The dielectric properties of concrete do not differ from the values mentioned above, and are thus used by many authors in literature, e.g. Antonini [15]. He calculates the transmission and reflection of reinforced concrete using 0.004 S/m for the conductivity and 5 for the electric permittivity of the concrete itself and 2.3×10^{-6} S/m for the electric conductivity of the steel reinforcement.

Glass is gaining popularity in architecture, as huge sliding terrace doors of luxury houses and whole glass facades of business buildings are made of it. Unlike in the case of concrete, composition makes a difference in the electrical permittivity of glass. For example adding PbO can increase attenuation values, and therefore special windows can be constructed. Normally, commercial glasses have an electrical permittivity between 4 and 9 in the lower VHF to microwave range, and a tangent delta (delta is the angle of the permittivity in the complex plane and thus describes the losses in the material) between 0.00005 and 0.0350 [16]. Simulations and measurements confirm that a regular glass window is fully permeable for electromagnetic waves at microwave frequencies, as if the glass was not even there.

However, low-emissivity (low-E) glass has a special surface coating consisting of microscopically thin, optically transparent layers of silver sandwiched between layers of antireflective metal oxide coatings. Low-E glass is broadly used in residential and commercial architectural applications. Most low-E coated glass will significantly reduce the loss of generated heat. The most common low-E products also minimise undesirable solar heat gain through a window without the loss of colour neutrality and visible light transmission. It is also proved that the electromagnetic radiation in the microwave region is considerably shielded by the coating. This shielding increases as the frequency increases. For a commercial low-emittance window, the coatings provide a 20–35 dB of transmission damping in the frequency range 1–2 GHz [17], which is used for radio communication.

Wood is also used for constructing family houses, and it is the most frequently used material for attics. Relative permittivity depends on the type of wood, which is in close connection with the density of the wood, its water content, and the type of chemical treatment (if any). In literature [18] the relative permittivity was found to vary from 1.2 to 4.5, the loss tangent from 0.007 to 0.061 in the frequency range of 100 MHz–10 GHz for oven dry wood with density 0.13–1.53 g/cm^3. These results refer to the case where the electric field is applied across the grain. The electric field orientation in relation to the direction of the grain has been found to be important in connection to the dielectric properties of the material.

Other important wood based materials used in buildings are fibreboards and particleboards. Fibreboards are composed of wood chips or plant fibres bonded together and compressed into rigid sheets. During the production of fibreboards the wood is also subjected to thermal and moisture treatment. The dielectric properties of fibreboards will also vary depending on their density, moisture content, wood type, temperature, frequency and orientation of the incident electromagnetic field. The relation between the dielectric properties of oven-dry fibreboards and oven-dry wood can be estimated by comparing their properties at different frequencies and assuming that the fibres in the fibreboard are parallel to the sheet plane. This allows the direct comparison of dielectric parameters of wood and fibreboards in tables presented in literature, where the electrical field is applied perpendicular to the longitudinal axis of the wood under investigation [19].

Table 1 contains a summary of the electromagnetic properties of the discussed building materials. It is important to stress that all materials discussed are magnetically inactive, which means that their relative magnetic permeability is 1. Even the magnetic permeability of the steel reinforcement in reinforced concrete does not have any noticeable effect. The fact that it is used in bar form makes the conductivity the governing factor.

3. Numerical simulations

Knowing the electromagnetic characteristics of building materials, attenuation through walls and electromagnetic fields inside entire buildings can be simulated using computer programs. The software used here is CST Microwave Studio. In this software a 5 m × 3.6 m × 3.3 m outer sized reference building was emulated. This is actually just one room. The building was kept small on purpose since we want to establish a reference case, without being compromised by huge calculation times. The walls, the roof, and the floor consist of 30 cm thick slabs/panels. Unless otherwise

Table 1
Electromagnetic properties of building materials.

Material	Frequency	Permittivity	Conductivity (S/m)	Imaginary part of permittivity	Tangent delta	References
Brick	1.7–18 GHz	3.70–4.11	0.0174–0.0364			[10,11]
Concrete	0.9–24 GHz	5-7		0.1–0.7		[12,13]
LW concrete	0.9–24 GHz	2–2.5		0.12–0.5		[12]
RF concrete(+steel)	948, 1865, 2140 MHz	5	0.004 2.3×10^{-6}			[15]
Glass	0.003–300 GHz	4–9	10^{-12}		0.0005–0.0350	[16,17]
Wood	0.1–10 GHz	1.2–4.5			0.007–0.061	[18]

mentioned, the built in “one year old concrete” was chosen from the material library of CST for the walls and slabs with a permittivity of 5.61 and a tangent delta of 0.039 at 1 GHz. This building was irradiated with a plane wave at frequency 1 GHz of 1 V/m. The electric field of the wave was vertical with the propagation direction perpendicular to the longer side of the building. In the simulations performed the electromagnetic field inside the small building was investigated. We used standard “Open Boundary” settings for the boundary conditions in CST. The resulting minimum distance between the structure and the faces of the simulation box are 1/8 of a wavelength The observation height was chosen to be the sitting height of a regular man, namely 1.40 m, because people sit in the same position while working/studying for a longer period. This means that the figures given below depict

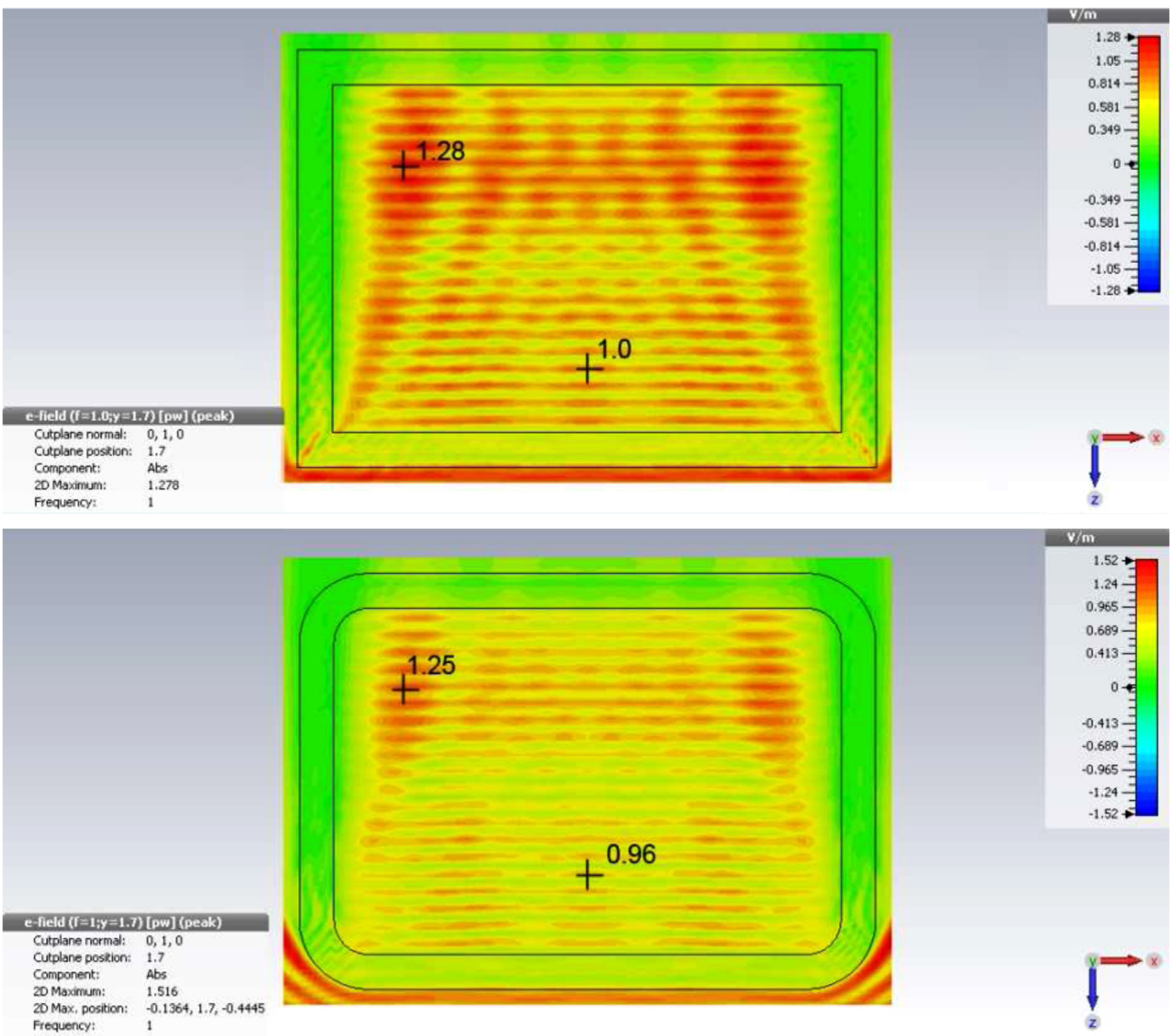

Fig. 1. Original (top) and rounded corner version (bottom) of the building.

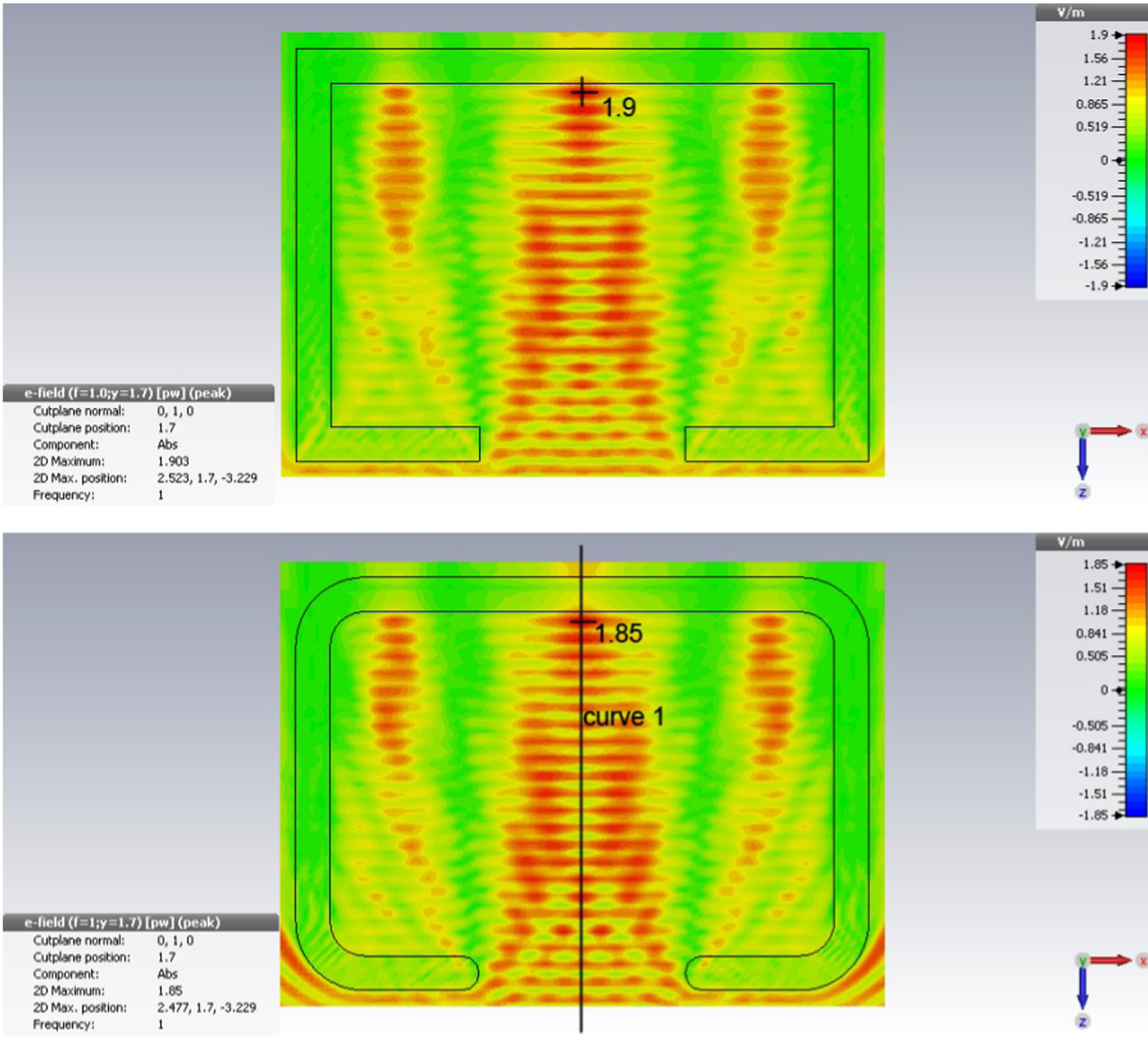

Fig. 2. Building with window (top) and with rounded corners and window edge (bottom).

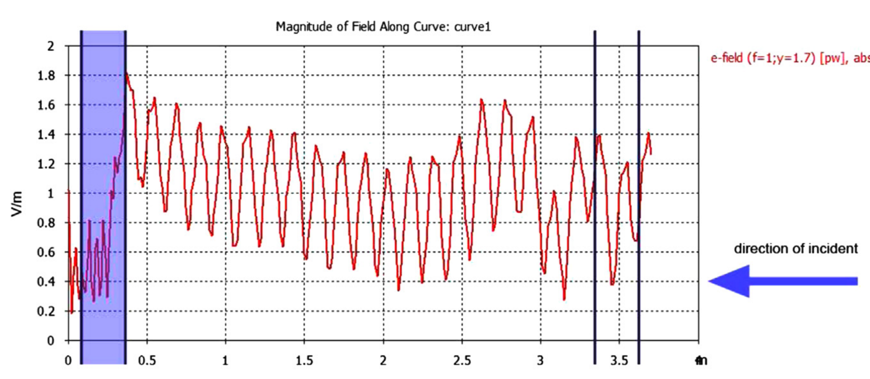

Fig. 3. Graph of electric field on curve 1 marked in Fig. 2.

the electric field levels at this height. Normal corners and rounded corners are considered. The inner radius of the rounded corners is 30 cm. The radius used for rounding the window edges is 15 cm.

3.1. Effect of shape

It is known in electromagnetism that edges cause the diffraction of waves. It can indeed be observed in Fig. 1 top that corners have an effect. However, the idea of rounding corners to reduce levels does not work, as can be seen in Fig. 1 bottom. The maximum levels are quasi the same.

Adding a 1.5 m by 1.5 m sized window at 90 cm sill height to the reference building totally changes the in house field behaviour of the waves. As discussed in the first part of this paper, regular glass has zero shielding effect, meaning that the electromagnetic waves can simply pass through as if there was an opening. This can be clearly seen in the Fig. 2 top. Rounding the corners and window edges does not make any significant change, as can be seen in Fig. 2 bottom.

Looking at Fig. 3, which shows inner field values along the black line in Fig. 2, the problem with this window opening becomes even more interesting. The value of the incident field is 1 V/m. The maximum resulting field value inside is 1.9 V/m close to the back wall opposite to the window. This quasi double value can be explained by the effect of positive interference between the wave transmitted through the window and its reflection against the back wall.

A real life example was considered where the effect of a window is illustrated in practice. The first author of this paper has taken measurements in a situation where a mobile base station was placed on top of a building about 100–150 m away from the building that was measured. The room considered had a corner window on one side facing the base station, and a child's bed was one metre away from the window as in Fig. 4. Using a Gigahertz solutions' HF 59B high frequency analyser facing the base station the electromagnetic power level was measured to be 0.4 mW/m^2 near the wall, and 1.3 mW/m^2 at 30 cm away from the window. This clearly illustrates that in this case, this window behaves as predicted in our simulations. As a result of the measurements, the author suggested to move the bed of the child next to the bathroom close to the wall where the electromagnetic field was lower.

Rounding the edges of the back walls to maintain symmetry causes another phenomenon. The reflected electromagnetic waves start to show a concentration effect in the centre of the room. This is presented in an extreme situation, namely a round room with an outer radius of 2.5 m in Fig. 5 top left.

It can be observed that the waves are somewhat focused towards a region around one point, where the inner E-field reaches its maximum value of about 1.4 V/m (which is higher again than the incident field, i.e. 1 V/m). In the octagonal building the highest value is inside, next to the wall, see Fig. 5 bottom left. There does not seem to be a similar concentration effect. This can be explained based on the effect that is used in a parabolic dish antenna, where this focusing phenomenon is very useful. Note also the clear interference pattern outside in front of the building in Fig. 5. The incident plane wave interferes with the reflected wave to form a wave pattern following the shape of the front wall, in this way reaching an electric field as high as 1.54 V/m.

With an opening like a window, again the wave transmitted through this window can be clearly observed, see Fig. 5 right. The inner field rises to an around two times higher value. Notice that in this case the width of the region of high field values is different from the width of the window.

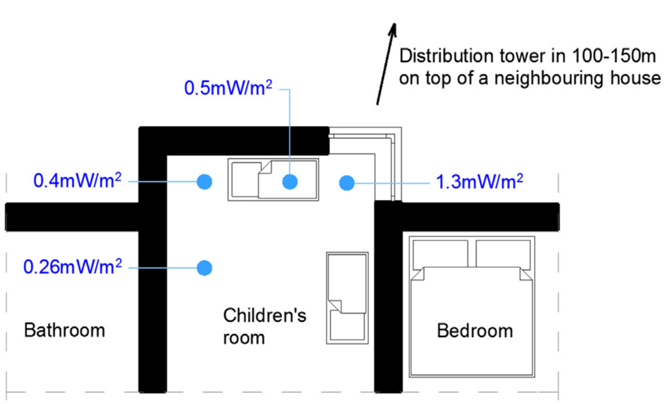

Fig. 4. A real building, Budapest, measured on 27/06/2013.

3.2. Comparative data

In this section several building materials of Table 1 are used within the same reference building as in the previous section. Brick, concrete, and reinforced concrete with different reinforcement grid sizes are considered. The incident wave is the same as before. The logical assumption is that brick and concrete yield minimal shielding, and that reinforced concrete is able to shield considerably. The shielding efficiency (SE) in decibels (dB) is defined as the ratio of the excitation incident field (1 V/m) to the internal field (RMS):

$$SE = 20\log\frac{|E_{exc}|}{|E_{int}|} \tag{1}$$

where

SE – is the shielding effectiveness;
E_{exc} – is the excitation electric field;
E_{int} – is the electric field inside.

A single observation point is chosen in order to perform the comparison between the different building materials. This point is the point where the highest value was found along the observation line (the black line in the middle as in Fig. 2) as defined before. This place is 1.95 m away from the front wall. Two main setups were considered: one with the reference building as a closed box, and one without the back wall in order to avoid reflection, as depicted in Fig. 6. Values observed here were compared to incident field strength which was 1 V/m in every case.

Brick comes in many different types, but for this simulation solid brick was chosen. The effect of composite periodic block walls or cavity walls was examined already by other authors [19]. The brick wall considered here is the front wall of the reference building, a 30 cm thick wall with a height of 2.7 m and a width of 5 m. A control simulation was made with a 50 cm thick wall. The permittivity is 4.62, the conductivity 0.02 S/m, and the density 1600 kg/m^3. Results can be found in Table 2.

Reinforced concrete was simulated as a concrete wall with reinforcement bars with a diameter of 1 cm. Different grid sizes were used: 20 cm, 10 cm, and 5 cm. The correct properties of the steel are defined in CST's database and were used as such. Results can be found in Table 2, where the numbers after the “Reinf. concrete” indicate the size of the square shaped reinforcement grid (in cm × cm). Results are in close agreement with other author's experiences, where the attenuation of the reinforced concrete slabs was found to be around 3 dB [15].

From Fig. 6 it can be clearly seen that in the closed environment the reflection from the back wall slightly raises the levels of the E-field. Peculiar is also the effect at the front corners of the building. Electromagnetic waves seem to originate from these corners. The results from these simulations suggest that brick has a slightly higher attenuation than concrete. Simulations with

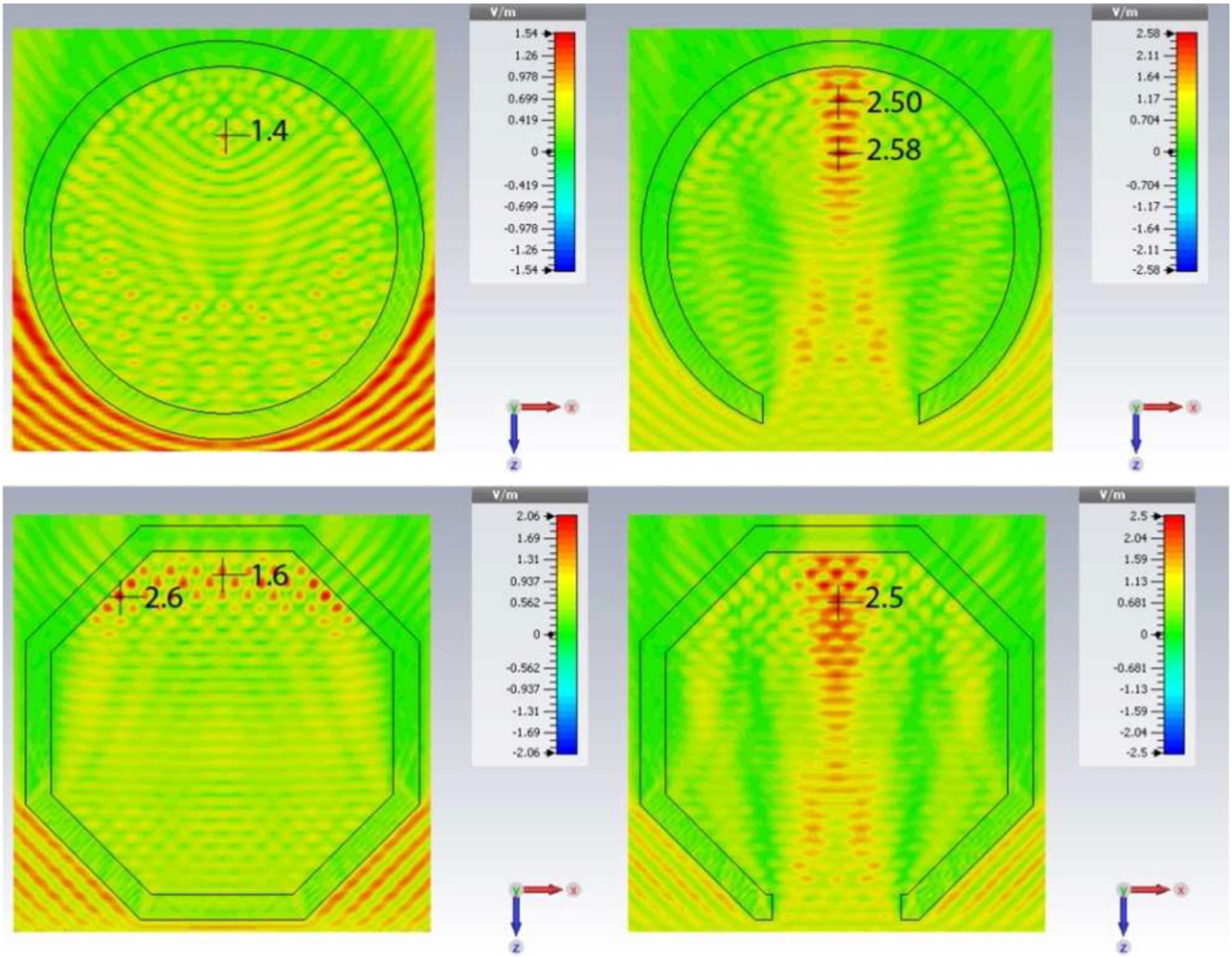

Fig. 5. Round and octagonal building with and without window.

50 cm thick walls showed that the highest levels were located not at the previously defined position. This means that thicker walls yield another maximum electric field level position inside the building. In addition, the previous maximum points became low value points, as shown in Fig. 7. Considering the reinforcement it can be observed that for a wave at 1 GHz a grid of 20 cm or 10 cm does not yield a considerable attenuation, while a grid of 5 cm yields a remarkable 6.1 dB attenuation.

Measurements in an anechoic chamber are in agreement with this value at 1 GHz, as shown in Fig. 8. The setup involved a 30 cm

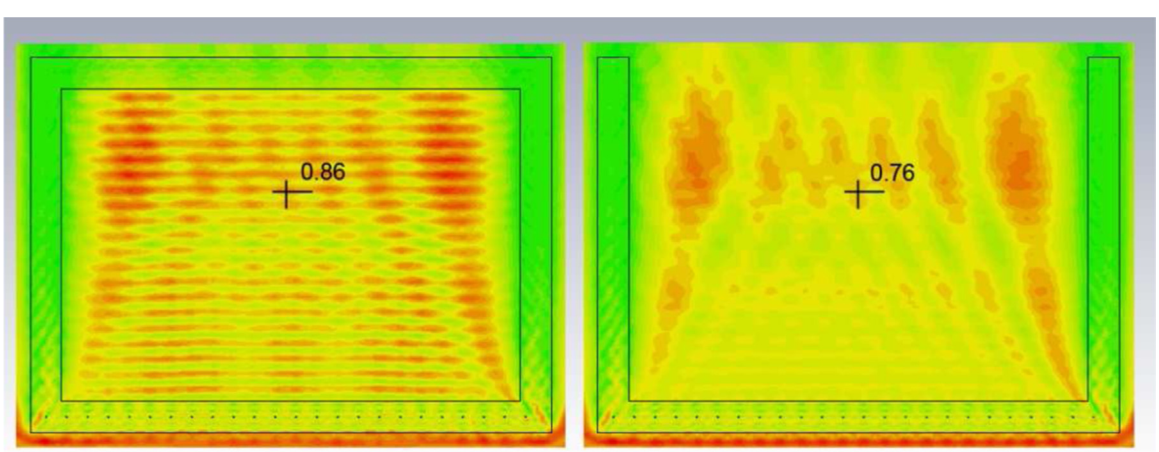

Fig. 6. Reference building and building with the back wall removed. Note that there is no perfect symmetry due to the fact that the reinforcement is not symmetrically placed. However, it is seen that this effect is small.

Table 2
Comparative data for a wall.

Building material	Wall thickness (cm)	In reference building		With open back	
		E-field	SE (dB)	E-field	SE (dB)
Brick	30	0.66	3.609	0.58	4.731
Brick	50	0.41	7.744	0.31	10.172
Concrete	30	0.903	0.886	0.788	2.069
Concrete	50	0.759	2.395	0.55	6.02
Reinf.concrete 20 × 20	30	0.86	1.310	0.76	2.383
Reinf.concrete 10 × 10	30	0.84	1.154	0.70	3.098
Reinf. concrete 5 × 5	30	0.495	6.107	0.39	8.706

thick brick wall of dimensions 100 cm × 75 cm. Later a 5 cm × 5 cm or 1.27 cm × 1.27 cm copper net was mounted at the back side. The transmitting Hyperlog antenna was put 140 cm from the receiving antenna which was 1 cm behind the wall. In order to extract the effect of unavoidable diffractions at the edges of the wall, a special technique was used to extract the shielding values from the raw measurements [20].

This has brought up the question of shielding. High frequency communication is designed with the purpose of penetrating walls. Therefore in normal circumstances building materials by themselves cannot provide enough attenuation in order to reach building biology standards [21]. Building thicker walls would help but this solution is not space efficient nor cost efficient. Based on the results of the simulations, a solution could be the use of metallic nets with a 5 cm to 1 cm grid, e.g. from copper. Results are shown in Figs. 9 and 10. Another solution could be the use of carbon based wall paints. The first author has performed shielding measurements on walls before and after applying paint of this kind. Giving details would go beyond the goal of this overview paper, but it can be mentioned that this brought at least about 10 dB extra attenuation to a room. As shown above, windows are penetrable structures. Increasing the attenuation ability of windows is not as simple as shielding walls. There are windows with built in metallic grids, which are designed to reduce electromagnetic wave penetration. The disadvantage of these windows is that the grid is visible, and thus not nice. Fortunately, thanks to modern technology there are other solutions, like electrically conductive transparent foils, which have an attenuation property of around 60 dB, and only decrease optical transparency to about 65% [22].

4. Conclusions

After the dielectric properties of several basic building materials were discussed, the effect of two possible topological measures to reduce field levels was studied through simulations. The first one concerned the rounding of corners. The second concerned the use of different building materials. The usage of reinforced steel nets with large grid sizes does not significantly improve attenuation. However, grid sizes of about 5 cm × 5 cm or lower give a relatively high shielding at a frequency of 1 GHz. The conclusion is that dense metallic meshes or fabrics with a grid size of about 1 cm × 1 cm applied on walls can effectively attenuate the inner electromagnetic fields, while windows can be shielded with

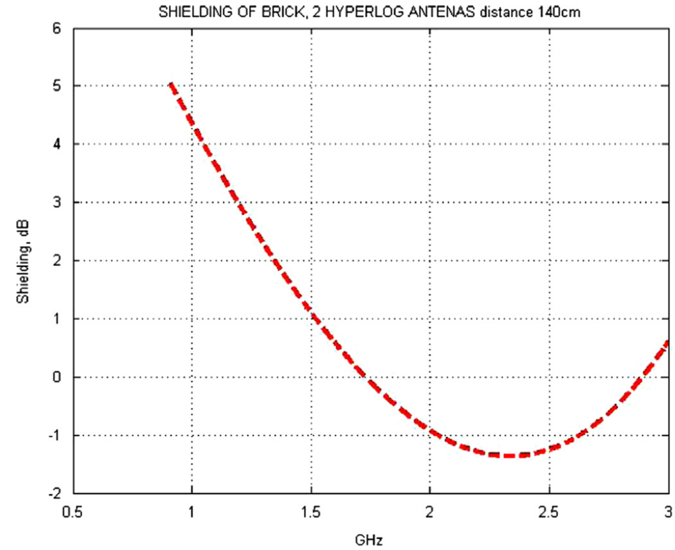

Fig. 8. Shielding performance of the brick wall.

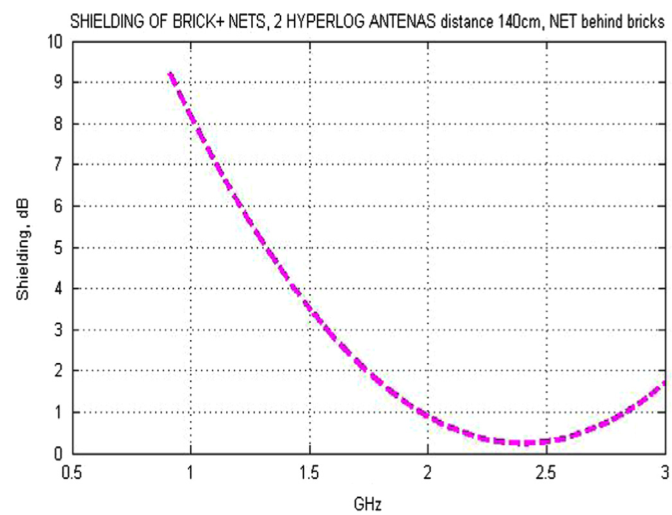

Fig. 9. Shielding performance of the 5 cm × 5 cm copper net located at the back of the wall.

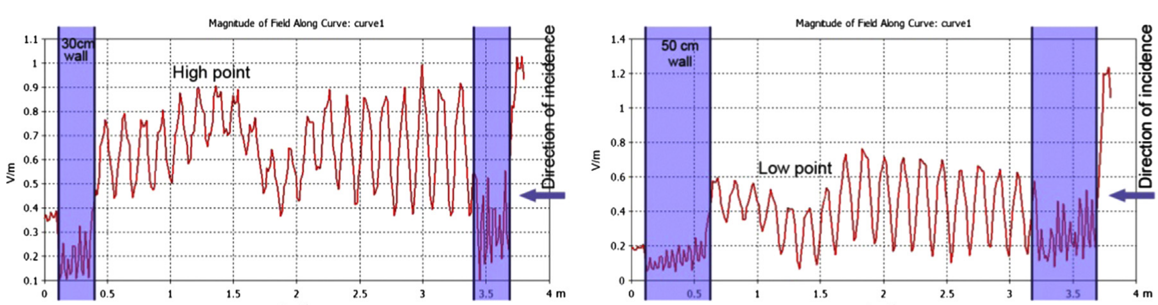

Fig. 7. Graphs of electric fields in the cases of 30 cm and 50 cm thick walls evaluated on the black line as in Fig. 2.

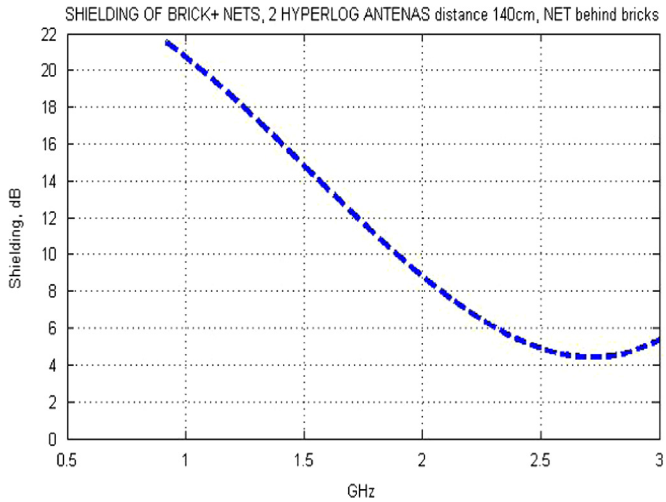

Fig. 10. Shielding performance of the 1.27 cm × 1.27 cm net located at the back of the wall.

electrically conductive transparent foils. It is evident of course that these simplified simulations are aiming at predicting an overview of trends, under "ideal" conditions. Buildings with more than one room, furnishing in a room, the presence of metallic objects like piping and radiators in real life have to be taken into consideration, yielding different results in different situations. In the simulations one perpendicular plane wave was used as exposure, but in real life multiple electromagnetic waves will appear from different incidence angles.

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