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Article

Measuring Electromagnetic Wave Propagation Transmission Parameters Through Traditionally Constructed Buildings

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Abstract: This paper examines the potential for shielding against electromagnetic (EM) radiation in traditional buildings. The primary objective is to evaluate how effectively these buildings can reduce the intensity of the electric field from external sources, while also identifying the factors that influence this reduction, such as geometry, structure, and the characteristics of EM waves. Measurements were conducted on the transmission parameter S_{21}, which indicates how EM waves propagate through the walls of residential buildings constructed using traditional methods. The buildings analyzed were made from wood, rammed earth, raw bricks blended with straw (known in Croatian as ćerpič), and baked bricks, which served as the reference material. During the measurements, conditions such as the thickness, humidity, and temperature of both the walls and the surrounding environment were carefully controlled. The buildings represented traditional construction styles typical of Croatia and most of Central and Eastern Europe. The results indicate that structures made from rammed earth and raw bricks with added straw significantly decrease the transmission of EM wave energy compared to those made from wood and baked bricks. It is important to note that the walls of wood buildings were considerably thinner than those made from the other materials tested. Additionally, both the moisture content and thickness of the walls contributed significantly to reducing transmission parameters. These findings support the use of these traditional materials for constructing environmentally friendly buildings, while also suggesting the need for further architectural design and testing. Since this research does not cover all types of traditionally constructed buildings—such as stone houses, wicker structures, and dugouts—future studies will aim to expand this investigation to include a broader variety of traditional building styles.

Keywords: electromagnetic shielding; rammed earth; raw brick; reflection parameter; transmission parameter; traditional building

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1. Introduction

The traditional residential buildings still standing on the Croatian mainland today were constructed during the 18th, 19th, and 20th centuries. Older residential and farm structures were made from materials such as wood, rammed earth (batten), wattle (woven wood), and unbaked bricks (fresh bricks made from clay), which were often covered with straw or reeds. By the mid-19th century, newer houses began to be built using baked bricks and tiled roofs. In regions where wood was plentiful, homes were constructed from wood and wattle with an earth covering. Wooden structures represent the oldest method of building residential homes. Rammed earth construction, one of the earliest forms of architecture utilizes earth as a building material. This material does not require special processing and can be found in its natural, unbaked state directly at the construction site. These objects possess excellent thermal properties, a long lifespan, high strength, and the ability to bear loads. Raw brick, which may contain additives like straw, is a type of clay brick that has not been baked. Constructing buildings with these bricks is generally simpler than using rammed earth, although it requires prior manufacturing of the bricks. Buildings made from raw bricks share many characteristics with rammed earth structures.

This paper examines the electromagnetic (EM) potential of traditional buildings regarding their ability to protect against EM radiation. The most effective method for shielding against EM radiation involves using materials that reduce the transmission of EM waves. This can be achieved by reflecting, attenuating, or absorbing the energy from these waves.

Once a traditionally built object is no longer useful, it is fully recycled by returning its remaining materials to nature. This process minimizes pollution, as the materials are returned to nature in the same condition they were originally taken from it, without any additives or processing.

A group of authors provided a detailed description of the traditional wooden construction characteristics found in the Posavina region of Croatia. They offered fundamental instructions and guidelines for renovation, along with technical advice for refurbishing the building elements of the house and its interior [1]. In another work by a group of authors, it was analyzed how various building materials (brick, concrete, plastic, wood, etc.) affect the propagation of EM waves to enhance wireless communication quality [2]. In another study, the concept of traditional houses was explored based on historical settlement forms and the organization of village economies. This study provided a detailed presentation of various elements of traditional houses in the Slavonia and Baranja regions of Croatia, including foundations, walls, porches, roofs, coverings, windows, and doors. Particular attention was given to houses constructed from raw bricks, rammed earth, and baked bricks [3]. In 2013, the Ministry of Culture published the book *Croatian Traditional Architecture*, which explores houses constructed in traditional styles across four regions of Croatia: the Pannonian, Alpine, Dinaric, and Adriatic regions. The book covers various types of houses made from materials such as wood, wattle and daub, compacted earth, and raw brick, as well as stone. The author examines construction methods, solutions, and techniques, along with the utilization of space and building materials. Additionally, the book highlights the unique details and characteristics of each traditional construction method [4].

Various studies have been conducted on measuring EM wave radiation. For example, Honggang et al. [5] performed numerical calculations and measurements related to brick walls. Their research focused on how EM waves are attenuated while passing through multi-layered structures similar to contemporary brick walls. These analyses were conducted within the frequency range of 2 to 8 GHz, with the results indicating maximum attenuations of up to 25 dB. In their research, De Jeu et al. [6] investigated how moisture affects various soil parameters. They determined the dielectric constant of typical sand, loam, and clay soils using the dielectric mixing model developed by Wang and Schmugge [7]. This analysis was conducted at a uniform soil temperature of 290 K and a frequency of 6.9 GHz. An equation was provided to represent the ratio of wet volume density (w) to dry volume density (d) of a powdered material mixture. It was noted that the bulk density of the material increases as the moisture content rises.

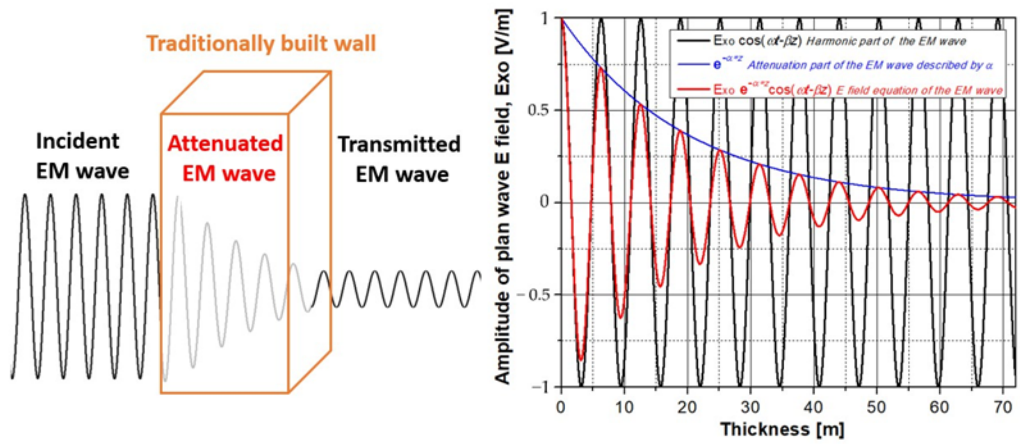
In a study conducted by Hollenbach et al., six equations for dielectric mixtures were introduced, and their effectiveness in calculating the dielectric properties (specifically, the relative complex permittivity) of solids was assessed. One of these equations is used to calculate the complex refractive index, which is considered one of the most accurate methods for estimating the dielectric constant of soil materials [8].

Another study measured the penetration of EM waves through commercially available building materials, specifically focusing on the frequencies used by mobile network operators. The electric field (E) and magnetic field (H), which are the components of the EM wave, were measured as they passed through brick walls, including walls that were painted with a magnetic coating. Subsequently, the results of the shielding effectiveness (SE) calculations for each measurement case were presented. The frequency range for the measurements was between 1 GHz and 9 GHz, with the maximum SE being recorded at 22 dB for the brick wall and 35 dB for the brick wall with coating, both at a frequency of 9 GHz [9]. In 2019, a group of researchers assessed the SE of a concrete building's armor within the frequency range of 1 to 9 GHz. The wall thickness was measured at 120 mm. The highest recorded SE value, which was 20 dB, was achieved at a frequency of 9 GHz [10]. A 2020 study elaborated on energy-saving methods through ecological architecture and the use of sustainable building materials, emphasizing that energy conservation via building materials is a crucial step towards sustainable development [11]. Lee et al. conducted measurements to assess the effectiveness of SE in concrete blocks of various structures and thicknesses within the frequency range of 400 to 1400 MHz. They found that the highest SE was recorded at 850 MHz, reaching a value of 58 dB [12]. Another group of authors conducted an empirical analysis of EM wave propagation through concrete-based composite building materials reinforced with iron oxide (Fe_2O_3). This analysis focused on the frequency bands used in 4G and 5G mobile communication systems [13]. Furthermore, a simulation was conducted to calculate the propagation parameter S_{21} through clay-based materials within the frequency range of 1.5 to 6 GHz. Measurements of this parameter (S_{21}) were also taken for concrete composites reinforced with steel (SF43) and carbon fibers (CF1.5) in the same frequency range, as documented in [14,15]. Pavlík et al. [16] evaluated the protective effect of the EM field, known as SE, for various building materials within the frequency range of 1 GHz to 9 GHz. They conducted measurements of the SE, reflection (R), and calculated absorption (A) to assess the shielding properties of several materials, including mineral wool, toughened polystyrene, extruded polystyrene, polyurethane panels, a brick wall, a brick wall filled with mineral wool, and a concrete wall.

An analysis of the available literature indicates that different building materials significantly affect the propagation of EM waves. These materials can attenuate the amplitude of the electric (E) and magnetic (H) fields of the waves, with attenuations reaching as high as 58 dB in concrete. Most studies focus on modern building materials, such as concrete, fired bricks, and concrete–brick composites. However, traditional materials like wood, soil, clay, and clay–soil composites are often overlooked in these investigations. Furthermore, all previous investigations were conducted within a limited frequency range and did not encompass all known fixed sources of EM fields. As a result, the attenuation (transmission) of EM waves in significant portions of the spectrum—specifically below 400 MHz and above 9 GHz—remains unexplored and unknown. This paper aims to address this gap. Concerning the findings reported in the existing literature, the frequency range examined in this study has been expanded to include frequencies ranging from 30 MHz to 18 GHz. Today, there are residential buildings constructed using traditional methods, and recently, more individuals have chosen these materials to promote eco-friendly construction. This paper aims to evaluate the protective capabilities of these traditional materials against EM radiation in modern buildings made of baked brick. The evaluation was based on measurements taken from existing residential buildings constructed with traditional materials such as earth, straw, and wood. The measurements were conducted by assessing the transmission parameter. The tested objects represent a specific construction method. Further research is needed to gain a more detailed understanding of the particular performance characteristics by examining the composition, structure, and types of individual materials. This includes analyzing the composition and type of soil and wood, as well as the methods used to connect the structures. Additionally, it is important to consider the field levels transmitted through these materials.

2. Propagation of EM Waves Through Materials (Non-Ionizing Radiation)

EM waves come from various sources, including both natural and man-made origins. Regardless of where they originate, EM waves travel through space. When these waves encounter the boundary of a material, they can be reflected, transmitted, or absorbed, affecting the energy of the EM waves in or on that material (Figures 1 and 2).



(a) (b)

Figure 1. The transmission and attenuation of a plane EM wave in a lossy medium: (**a**) a sketch of EM wave propagation through a traditional building wall; (**b**) the amplitude of the E field versus the thickness of the traditional wall.

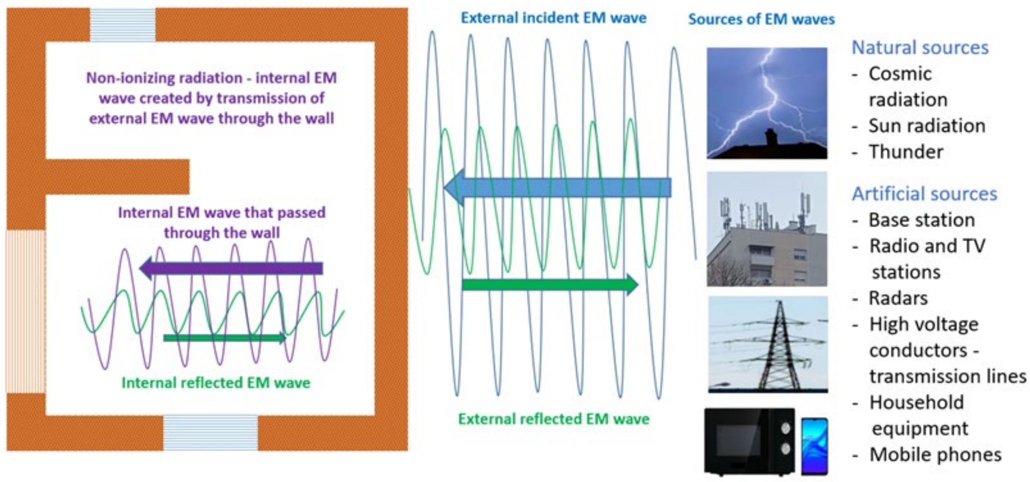


Figure 2. The floor plan of the house with marked possible sources of EM waves and their components when they encounter an obstacle such as a wall. The external incident and reflected wave on the outer surface of the wall are shown, as well as the wave that passes through the wall and the reflected wave of the inner surfaces of the wall inside the house.

EM waves are physical phenomena that occur when a dynamic charge is accelerated, causing changes in the surrounding space. This dynamic change in the EM field propagates outward from the source. If there is a material present in that space, EM waves can travel through it. The characteristics of EM waves, such as amplitude, phase, and frequency, may change—especially in nonlinear materials—depending on the EM properties of the medium. Additionally, EM waves of different frequencies (or wavelengths) exhibit distinct behaviors as they propagate through various materials or structures. The E and H field strengths of an EM wave traveling through a linear material can be expressed as follows: if the plane wave travels in the +z direction and only the *Ex* component (electric field) and *Hy* component (magnetic field) are present, the in-phase surfaces are planes [17].

$$E_x(z,\ t) = E_{x0}e^{-\alpha z}\cos(\omega t - \beta z), \quad (1)$$

$$H_y(z,\ t) = H_{y0}e^{-\alpha z}\cos(\omega t - \beta z), \quad (2)$$

where E_{x0} is an amplitude of the electric field strength; H_{y0} is an amplitude of the magnetic field strength; $\omega = 2\pi f$ is the angular frequency; α is the attenuation constant, and β is the phase constant. These two constants are determined through the following relations [17]:

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right)}, \quad (3)$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right)}. \quad (4)$$

It is clear from relations (3) and (4) that both constants also rise as the frequency increases. This indicates an increase in the attenuation of the amplitude and phase of the E and H fields of the EM wave. Additionally, it is important to note that the expression under the square root allows the quotient ($\sigma/w\varepsilon$) to take on various values across various frequencies. Since the transmission of EM wave energy also depends on the electrical parameters of the material—namely electrical conductivity (σ) and permittivity (ε)—through which the wave travels, it becomes evident that this transmission will be frequency-selective. It is widely understood that as the frequency increases, the attenuation of electromagnetic (EM) waves passing through a material also increases. This relationship is evident in expressions (2) and (3). When the electrical conductivity of a material increases while the frequency and permittivity remain constant, the ratio of conductivity to the product of frequency and permittivity ($\sigma/w\varepsilon$) can become dominant, significantly impacting the final values of both constants. Additionally, the values of permittivity and permeability for certain materials (based on their electrical conductivity) can influence these constants at specific frequencies. The variations in the electrical conductivity and permittivity of the materials discussed in this work depend largely on the material type used in constructing buildings. However, in the case of natural materials such as wood, clay, and earth, these properties are primarily affected by moisture content and material density. The moisture level in a material significantly influences its real permittivity (for example, in soil). This is supported by the data presented in Table 1, which show that the real permittivity increases with a greater moisture content for various types of typical soils. As a result, the damping constant of the EM wave also increases as it passes through these materials.

Table 1. The real part of the dielectric constant ε for a typical sand, loam, and clay soil (soil temperature of 290 K; frequency of 6.9 GHz) as derived by Wang and Schmugge (1978) dielectric mixing model [7].

Soil Moisture [m^3m^{-3}]	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Clay	2.7	3.3	6.1	10.0	17.1	23.8	31.9
Loam	2.7	3.8	8.2	15.7	22.2	30.0	36.9
Sand	2.7	4.4	10.4	17.2	25.0	32.2	39.5

There are several mathematical models for calculating the density of materials based on their moisture content. The simplest of these models is $\rho_b = \rho_d(1 + M_w)$ [1], where ρ_b is the bulk density of samples on a wet basis (kg/m^3) at a moisture content of M_w, and ρ_d is the bulk density on a dry basis (kg/m^3) when the sample is bone dry. In addition to the increase in permittivity, higher moisture levels lead to an increase in the electrical conductivity of the soil. As a result, the attenuation constant increases due to both the rise in permittivity and the increase in electrical conductivity. The materials used in the construction of traditional houses are not uniform. However, when constructing walls, materials such as straw, hay, and wood are added to the primary building materials like clay, loam, and soil to enhance the structural strength of the walls. This alters the material's parameters (dielectric constant, electrical conductivity, density, etc.), which affects how the EM wave propagates through these materials.

Several mathematical models describe these mixtures, with one of the most widely used being the equation for the complex refractive index of the mixture [8]:

$$\varepsilon^{1/2} = v_1\varepsilon_1^{1/2} + v_2\varepsilon_2^{1/2} \tag{5}$$

where ε is the complex permittivity of the mixture; ε_1 is the complex permittivity of the basic material (medium); ε_2 is the complex permittivity of added material; v_1 is the volume fraction of the basic material; and v_2 is the volume fraction of added material where $v_1 + v_2 = 1$.

To apply this equation, it is essential to understand the dielectric properties (permittivity) of the primary material (such as clay or loam) and the additional material (for example, straw). Additionally, one needs to know the bulk density of the mixture and the specific density of the added material. The volume fraction of added material v_2 in the mixture is determined by the following equation: $v_2 = \frac{\rho}{\rho_2}$.

The influence of temperature on the relative dielectric constant and loss tangent is observed; however, in practical scenarios, temperature variations do not significantly affect the propagation of EM waves through clay- and earth-based materials.

3. Materials and Methods

Traditional construction utilizes materials that are readily available in the local area. In regions with abundant stone, wood, or earth, houses are built using these materials for their walls and roofs. In agricultural areas, where the local population primarily grows crops, builders often incorporate crop residues, such as straw, into the structure of the houses.

This paper presents measurements taken as part of studies on four types of traditional buildings: houses constructed from wood (specifically oak), houses made of fresh bricks reinforced with straw, houses built using rammed earth, and houses created with baked bricks.

3.1. Houses Built from Wood

Traditional residential houses in central Croatia, specifically in Posavina and Gorski kotar, are typically one-story wooden structures (Figure 3). These homes are constructed by horizontally stacking oak planks that are joined together using wooden wedges or cuts (joints). Originally, these houses were elevated from the ground on wooden or stone pillars, though later versions featured lower parts built from bricks. Ground-floor buildings were typically designed with two or three rooms, while multi-story versions came in various designs. The oldest wooden houses were traditionally covered with straw or wooden boards, while more modern constructions used tiles. Auxiliary structures and outbuildings, such as stables and garden sheds, were built similarly.

(**a**) (**b**) (**c**)

Figure 3. Photos of a wooden house: (**a**) details of the wall; (**b**) details of the column; (**c**) facade view.

3.2. Houses Built from Rammed Earth

Houses made of rammed earth (Figure 4) were constructed in continental areas and at higher altitudes where moisture and flooding were uncommon. The walls are built in segments by compressing a mixture of earth, chopped straw or sawdust, and water into double-sided plank formwork. The next layer of the wall is applied only after the previous section has dried. Often, the wall is reinforced with wickerwork of vines and willows, with additional support in the corners. The complete drying of the walls depends on their thickness and composition and can take a significant amount of time, sometimes up to two years. Walls built using this method create a high density that limits the propagation of EM waves through them. Specifically, as the material's density increases, the relative dielectric constant also rises, leading to a decrease in the transmission parameter S_{21} (or S_{12}) of the EM wave. During the construction phase, openings for windows and doors are created by cutting into the walls or adding wooden formwork [3].

3.3. Houses Built from Raw Bricks

A brick is a dried, raw (unfired) block made of clay, loam, and loess. In contrast to houses built from rammed earth, construction with bricks involves using prefabricated elements, eliminating the need for formwork. The dimensions of bricks can vary significantly, but three standard sizes are commonly used: 28 × 14 × 7 cm, 30 × 15 × 8 cm, and 40 × 15 × 10 cm. The mixture used to make clay bricks is prepared similarly to the mixture for constructing rammed earth walls. The thickness of the walls ranges from 30 to 45 cm (Figure 5). The roofs of the oldest houses are made of straw, while newer houses have roofs made of bricks [3].

(**a**) (**b**) (**c**)

Figure 4. Photos of a house constructed from rammed earth. (**a**) A close-up of a rammed earth wall; (**b**) a close-up of the ceiling featuring wooden beams; (**c**) an image showcasing the facade of the rammed earth house.

(**a**) (**b**) (**c**)

Figure 5. Photos of a house constructed from raw brick. (**a**) Details of a wall made of raw brick; (**b**) details of the ceiling in a room made of raw brick; (**c**) the facade of the house made of raw brick.

In addition to constructing houses from rammed earth and raw bricks, these materials were frequently used to build homes with small wooden extensions, which are wooden reinforcements in the walls. Such constructions are called bondruk or kanat constructions (Eng. timber framing; Germ. fachwerkbau, holzskelett) (Figure 6). The construction of these walls involves a wooden frame made of oak beams that rest on a masonry foundation. Vertical columns are supported at distances of up to 100 cm apart. The space between the columns can be filled with a mixture of compacted earth, clay, baked bricks, or woven wicker coated with mud. The thickness of these walls ranges from 20 to 40 cm. The beams that are driven into the ground were partially burned beforehand, as this treatment helps prevent the wood from rotting [3].

3.4. Houses Made of Baked Bricks

Burnt bricks have been traditional building materials in continental Croatia, particularly in Slavonia and Baranja, since the late 19th and early 20th centuries (Figure 7). Walls were constructed using baked bricks, often combined with rammed earth and clay. To create these bricks, crushed clay was mixed evenly and pressed into molds, which were then air-dried to remove about 10–20% of their moisture content. After drying, the bricks were "fired" in tunnel kilns at temperatures ranging from 900 to 1000 °C. Initially, the dimensions of the solid bricks were 30 × 14 × 6.5 cm. However, later versions measured

25 × 12 × 6.5 cm. The thickness of the load-bearing walls ranged from 30 to 45 cm, while the partition walls had a thickness of 15 cm.

Figure 6. House walls constructed from wood and rammed earth or bricks, reinforced with wooden rope (bondruk). Reprinted with permission from ref. [3]. Copyright 2011 Lončar-Vicković, Stober.

(**a**) (**b**) (**c**)

Figure 7. Photos of a house made of baked bricks: (**a**) details of a brick house wall; (**b**) details of a brick house pillar at the entrance door; (**c**) the facade of a house made of baked bricks.

3.5. Measurement

Transmission parameters are defined by the ratio of the amplitude of the electric field strength received by antenna 2 to the amplitude of the electric field strength transmitted by antenna 1 (S_{21}), or vice versa (S_{12}). These parameters represent the portion of EM wave energy that successfully passes through the measured medium (the wall) from antenna 1 to antenna 2, or in the opposite direction. The transmission parameters of S_{21} were measured using the free-space method. An MS2038C Vector Network Analyzer (VNA) from Anritsu was employed for these measurements. Two sets of antennas were utilized, with each set containing two antennas: (a) The first set consisted of two Hyperlog 30200 AARONIA antennas, which operate within the frequency range of 380 MHz to 18 GHz. (b) The second set comprised two Bicolog 30100 AARONIA antennas, covering a frequency range of 30 MHz to 1 GHz. The measurements were conducted over two frequency ranges: the first from 30 MHz to 1 GHz, and the second from 1 GHz to 18 GHz. This frequency range encompasses most modern communication and broadcasting systems, including 2G to 5G mobile telephony, FM radio, Wi-Fi, WLAN, DVBT2, and radar systems. The S_{21} transmission parameters were measured by positioning two antennas on opposite sides of a wall in a house. One antenna was placed outside the house at a distance, d1, from the wall, while the other was inside at another distance, d2, at a height of 1.5 m from the ground. The transmission parameters represent the ratio of the received field amplitude at antenna 1 to the transmitted field amplitude from antenna 2, and vice versa. Before conducting these measurements, a thermo/hygrometer (FLIR MR 277) was used to assess the wall's temperature, relative humidity, and thickness at a height of 1.5 m. Since the measurements were taken in existing homes, only those with approximately the same wall thickness were selected, excluding houses built from wood. Figure 8 illustrates the floor plans of two typical traditional houses, each equipped with a designated measuring system. The first part of the figure (Figure 8a) presents the floor plan of a traditional one-room wooden house. In contrast, the second part (Figure 8b) depicts the floor plan of a typical three-room house constructed from rammed earth or bricks, both raw and baked.

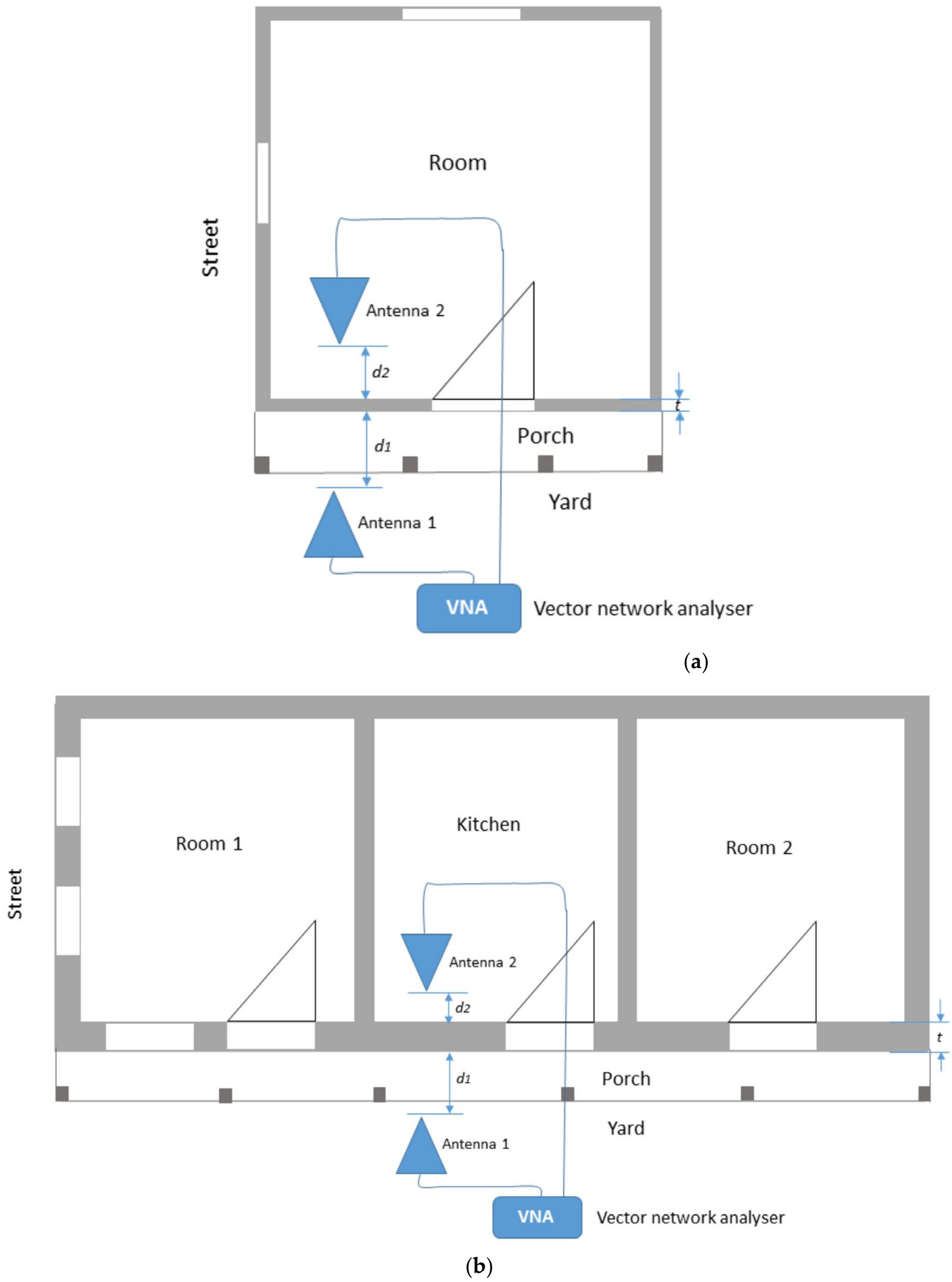
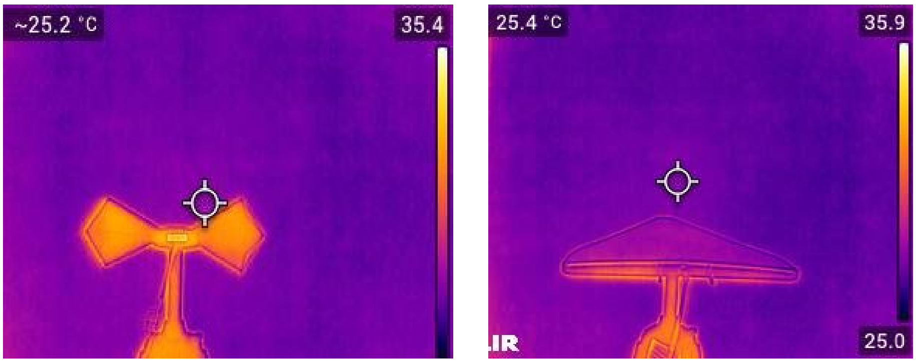


Figure 8. Floor plans of traditionally constructed houses: (**a**) a single-room wooden house; (**b**) a three-room house made of raw and baked bricks and rammed earth, including a measuring system.

The houses used for measurements in this study are not entirely uniform in terms of geometric (wall thickness and construction) and structural parameters (such as the type of finishing layer, soil density, and type—specifically clay). As a result, the key EM parameters—the relative dielectric constant, loss tangent, and electrical conductivity—vary among the houses. This variation partially undermines the final comparative conclusions and opens the door for further detailed research. Additionally, it is important to note that EM parameters are frequency-dependent, given the wide frequency range over which the measurements were conducted. Consequently, the measured values of the transmission parameters are also significantly influenced by frequency. The temperature and humidity of the air and wall (Table 2) were controlled during the measurement (Figure 9). Humidity and temperature control were conducted using a FLIR-type infrared (IR) camera, referenced as MR277. The camera has the following specifications: a relative humidity measurement range of 10% to 90% with a basic accuracy of ±2.5% RH. The relative humidity measurement was conducted with a pin range of 7% to 30% with a basic accuracy of ±1.5% MC. The air temperature measurement range is 0 °C to 50 °C with a basic accuracy of ±0.6 °C. A total of 11 material groups were used for the humidity measurement using a pin.



(**a**) (**b**)

Figure 9. Thermal imaging technology for measuring temperature and humidity in the walls of traditional houses: (**a**) measurement using a BICOLOG30100 antenna; (**b**) measurement using a HYPER LOG 30200 antenna.

Table 2. The measurement of moisture levels in the walls of traditional houses.

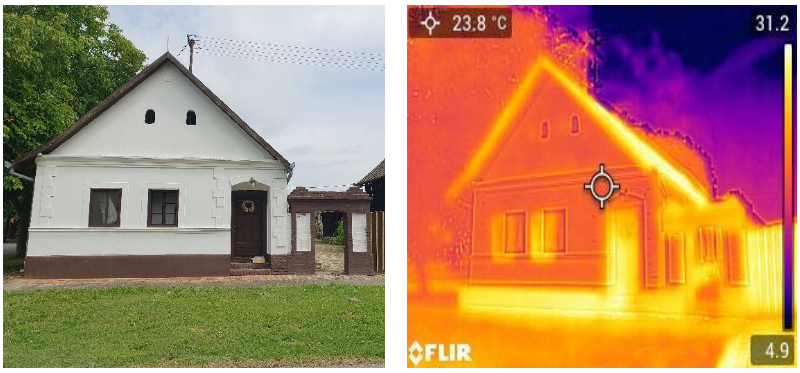
Type of House Walls/Thickness	Settlement/City	Measured Height [m]	Measured Moisture, Outdoor [%]	Measured Moisture, Indoor [%]	Pin Moisture Group [18]	Comment (Date/Time)
Wooden wall/2.8 cm	Karanac	1.5	1.0–1.2	1.3–1.4	1st and 4th	21 May 2024 12:00–14:00
Baked brick wall/45 cm	Beli Manastir	1.5	1.1–1.2	1.2–1.4	10th and 11th	23 May 2024 10:00–11:45
Raw brick wall/52 cm	Kopačevo	1.5	2.1–3.1	12.1–14.8	10th and 11th	6 June 2024 14:15–15:20
Rammed brick wall/52 cm	Bijelo Brdo	1.5	0.9–1.2	8.2–9.1	10th and 11th	7 July 2024 11:30–12:30

4. Results and Discussion

After conducting multiple systematic measurements on specific objects (Figures 10 and 11), some conclusions can be drawn. In the frequency range of up to 1 GHz (Figure 12a), buildings constructed from raw brick exhibit the lowest values of the transmission parameter S_{21}. The lowest measured value recorded is −50.99 dB at a frequency of 993.45 MHz. When compared to reference buildings made of baked brick, the transmission parameter for raw brick structures is lower by a maximum of −19.73 dB at a frequency of 650.50 MHz.

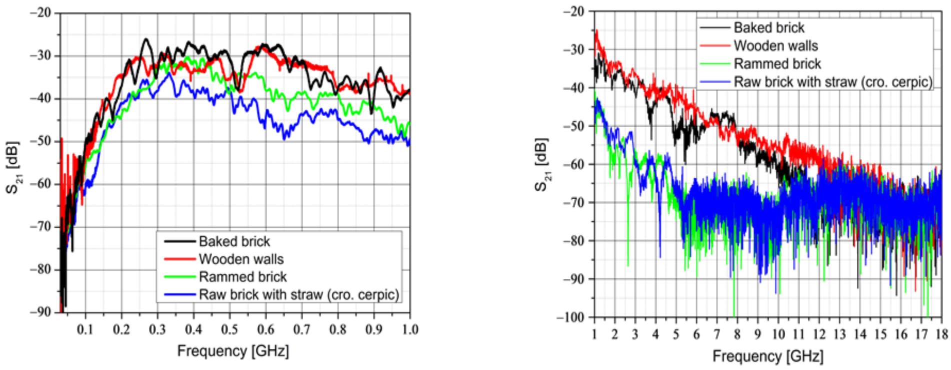
(**a**) (**b**)

Figure 10. Measurement of parameter S_{21} in a rammed earth house in Bijelo Brdo was conducted using (**a**) HYPERLOG 30200 antenna and (**b**) BICOLOG 30100 antenna.



(**a**) (**b**)

Figure 11. A traditional house in Bijelo Brdo, constructed from rammed earth. (**a**) A photo of the front elevation of the house; (**b**) a thermovision image of the house facade.



(**a**) (**b**)

Figure 12. The S_{21} parameters of traditionally constructed buildings were measured in two frequency ranges: (**a**) from 30 MHz to 1 GHz and (**b**) from 1 to 18 GHz. The wall thicknesses measured were as follows: wooden wall: 2.8 cm; raw brick: 52 cm; rammed earth and baked brick: 45 cm. Additionally, the temperature ranged from 23.8 °C to 28.1 °C, and the indoor humidity of the walls varied from 1.2% to 14.8%.

Therefore, the transmission of EM wave energy through raw brick walls exhibits the lowest values within the frequency range of 0.03 to 1000 MHz. Among the materials tested, houses made of raw brick demonstrate the lowest transmission values, followed by rammed earth houses, and then wooden houses. The S_{21} parameters for rammed earth houses fall between those of wooden houses, representing higher values, and raw brick houses, representing lower values. Measurement data of the S_{21} parameter for traditionally built houses within the frequency range of 30 MHz to 1 GHz can be found in Table 3.

Table 3. Measurement data of parameter S_{21} from traditionally built houses in the frequency range of 30 MHz to 1 GHz.

Type of Walls	$S_{21,\,min}$ [dB]	$fS_{21,\,min}$ [MHz]	* $DELTAS_{21}$ [dB]	$S_{21,\,max\,\Delta}$ [dB]	$fS_{21,\,max\,\Delta}$ [MHz]	* $DELTAS_{21}$ [dB]	Comment
Baked bricks	−49.50	650.80	0	-	-	-	Ref. type
Wooden walls	−37.05	891.68	−6.85	−37.05	891.68	−6.85	-
Rammed earth walls	−48.93	984.48	−9.94	−42.85	660.74	−10.58	-
Raw brick with straw	−50.99	993.45	−7.64	−49.50	650.50	−19.73	-

* $DELTAS_{21}$ represents the difference from the reference house type made of baked brick at the same frequency. $S_{21,\,max\,\Delta}$ represents the maximum transmission parameter compared to baked bricks, while f $S_{21,\,max\,\Delta}$ is the frequency at which this difference occurs.

In the frequency range above 1 GHz (Figure 12b), buildings constructed from rammed earth exhibit the lowest values for the transmission parameter S_{21}. The lowest measured value was −100.18 dB at a frequency of 7.85 GHz. When compared to the reference buildings made of baked brick, the transmission parameter shows a maximum difference of −48.64 dB at a frequency of 100.18 MHz. Consequently, the transmission of EM waves through walls made of compacted earth is the lowest within the frequency range of 1 GHz to 18 GHz. Additionally, it is noteworthy that buildings made from raw bricks display transmission parameter S_{21} values like those of rammed earth structures. Measurement data for the parameter S_{21} of traditionally built houses in the frequency range of 1 to 18 GHz can be found in Table 4.

Table 4. Measurement data for the S_{21} parameter of traditionally constructed houses within the frequency range of 1 to 18 GHz.

Type of Walls	$S_{21,\,min}$ [dB]	$f_{S21,\,min}$ [MHz]	* $DELTAS_{21}$ [dB]	$S_{21,\,max\,\Delta}$ [dB]	$f_{S21,\,max\,\Delta}$ [MHz]	* $DELTAS_{21}$ [dB]	Comment
Baked bricks	−93.36	9.89	0	−93.36	9.89	0	Ref. type
Wooden walls	−76.57	16.78	−0.80	−47.77	5.49	+11.92	-
Rammed earth walls	−100.18	7.85	−48.64	−100.18	7.85	−48.64	-
Raw brick with straw	−93.36	9.89	−32.35	−89.76	7.66	−41.99	-

* $DELTAS_{21}$ represents the difference from the reference house type made of baked brick at the same frequency. $S_{21,\,max\,\Delta}$ represents the maximum transmission parameter compared to baked bricks, while $f_{S21,\,max\,\Delta}$ is the frequency at which this difference occurs.

Transmission through walls made of raw brick (cro. ćerpič) and rammed earth is significantly lower than that of wooden buildings and those made of baked brick due to several factors: the wall thickness, material density, moisture content, and wall temperature. The wall thickness of raw brick buildings is the greatest, measuring 52 cm, closely followed by rammed earth walls at 45 cm. In contrast, wooden walls are much thinner, with a typical thickness of only 2.8 cm.

The outer portion of a raw brick wall, particularly its inner surface, has a higher humidity level compared to walls made of baked brick and wood. This increased moisture enhances electrical conductivity, permittivity, and the loss tangent, resulting in lower values of the transmission parameter S_{21}. This occurs because EM waves experience greater attenuation when passing through materials with higher conductivity and permittivity (as well as a higher loss tangent). While the density and temperature of the wall materials affect permittivity and the loss tangent, their impact is minimal compared to the significant influence of an increased moisture content in the wall material.

The sustainable construction of residential buildings encompasses several key aspects. It involves using eco-friendly building materials, effectively managing waste from construction and demolition, and ensuring buildings' energy efficiency. Furthermore, it considers the broader implications of building practices on environmental sustainability, structural integrity, and economic viability.

Natural materials like wood, straw, and clay, minimally processed from their original states, are ideal for sustainable construction. These materials can be easily returned to nature or reused after demolition, minimizing waste and environmental impact.

Using natural materials in traditional building methods reduces the construction industry's environmental footprint. This research further explores how these materials, compared to modern ones like brick and concrete, offer better protection against non-ionizing radiation, enhancing the sustainability of residential buildings.

While this research primarily focused on electromagnetic field measurements in traditional buildings made of natural materials, it also examined wall temperature and humidity. The findings reveal that raw brick and rammed earth walls maintain a humidity difference between interior and exterior surfaces ranging from 7.3% to 11.7%. This contrasts with modern baked brick, which exhibits a difference of only 0.1% to 0.2%. The larger humidity range in natural material walls contributes to optimal interior humidity levels, promoting comfortable living conditions and stable air quality.

Key techniques and strategies for sustainable architecture include energy-efficient buildings, energy production, renewable and sustainable materials, better waste management, ecological lifestyles, energy-efficient technologies, and building in harmony with nature. This paper focuses on at least four of these: renewable and sustainable materials, better waste management, encouraging ecological lifestyles, and building in harmony with nature.

Advances in science and technology offer significant potential for improving building construction. However, these advancements can also highlight the value of older, sustainable solutions, such as using natural materials and traditional construction methods. This paper focuses on such an approach, advocating for innovative design and construction that prioritizes sustainability.

5. Conclusions

This paper presents the measurement results of the S_{21} transmission parameters for EM wave propagation through the walls of residential buildings constructed using traditional methods. The frequency range studied spans from 30 MHz to 18 GHz. The measurements were conducted on houses made of various materials, including wood, rammed earth, raw bricks with straw (cro. ćerpič), and baked bricks. The results indicate that buildings constructed from rammed earth and raw bricks with straw exhibit the lowest S_{21} parameter values. The lowest recorded values were −89.76 dB for raw brick with straw at a frequency of 7.66 GHz and −100.18 dB for rammed earth at a frequency of 7.85 GHz. These materials showed significant transmission losses compared to the reference baked brick, with differences of −41.89 dB for raw brick and −48.64 dB for rammed earth. Buildings constructed from wood do not significantly reduce the EM wave transmission parameter S_{21} when compared to a reference building made of baked bricks. During the measurements, the thickness, humidity, and temperature of both the walls and the surrounding environment were carefully controlled. These findings can be attributed to the indoor humidity levels: raw brick walls have a humidity of 14.8%, while that of rammed earth walls is 9.1%. In contrast, the humidity levels for both baked brick and wooden buildings are at a maximum of 1.4%. An increased moisture content leads to greater electrical conductivity and permittivity of the wall materials, which in turn reduces the transmission of EM waves. Another reason for the differences in transmission parameters is the thickness of the walls: a raw brick wall measures 52 cm, a rammed earth wall measures 48 cm, and a wooden wall is only 2.8 cm thick. While the temperature affects the material's permittivity and is controlled within a limited range, the impact on transmission parameters is negligible. Additionally, other factors, such as the composition and structure of the wall material, the density of the material, and the permeability of the compacted material, may also play a role. Some influences, which were not examined in this study, can further affect transmission. Therefore, further research is necessary to investigate how these parameters influence the transmission of EM waves through walls constructed from traditional building materials. The data suggest that traditional houses constructed with raw brick, compacted earth, and straw have significant potential for protection against non-ionizing radiation (EM waves). This indicates that environmentally friendly materials hold promise for future use in buildings.

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