Ultrawideband Antenna Systems Embedded into a Load Bearing Wall for Connected Buildings

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Abstract—The importance of indoor mobile connectivity has increased during the last years, especially during the Covid-19 pandemic. In contrast, new energy-efficient buildings contain structures like low-emissive windows and multi-layered thermal insulations which all block radio signals effectively. To solve this problem with indoor connectivity, we study passive antenna systems embedded in walls of low-energy buildings. We provide analytical models of a load bearing wall along with numerical and empirical evaluations of ultrawideband back-to-back antenna systems. We embedded an ultrawideband antenna system in terms of electromagnetic- and thermal insulation. The antenna systems are optimized to operate well when embedded into load bearing walls. Unit cell models of the antenna embedded load bearing wall, which are called signal-transmissive walls in this paper, are developed to analyze their electromagnetic and thermal insulation properties. We show that our signal-transmissive wall improves the electromagnetic transmission compared to a raw load bearing wall over a wide bandwidth of 3–8 GHz, covering most of the new radio frequency range 1 (FR1), without compromising the thermal insulation capability of the wall demanded by the building regulation.

Index Terms—Antenna systems, energy efficient buildings, radio transparency, thermal transmittance.

I. INTRODUCTION

The fifth-generation cellular networks, which have been rolled out during the last couple of years, promise higher data rates compared to legacy systems. With new radio (NR) frequency range 1 (FR1), where the frequencies are below 6 GHz, the capacity can be increased up to 20 times higher than the fourth generation systems [1]. At the same time providing sufficient indoor coverage has become more challenging [2]. During Covid-19 pandemic the use of mobile internet has risen drastically all over Europe [3] and in the world. The problems with the indoor coverage become increasingly serious in energy-efficient buildings which have e.g. multilayered thermal insulating layers, low-emission airtight windows, and other signal barriers which block the RF signals to propagate into a low-energy building with lower penetration loss compared to load bearing wall. The antenna system is also designed to keep the thermal insulation of the wall to the level stated by the nation-building code of Finland [16].

In summary, the novel contributions of the present paper are summarized in three-fold as

1) We developed an ultrawideband back-to-back spiral antenna system embedded onto the wall called signal-transmissive wall operating over a large portion of NR FR1 band i.e. between 2.6 and 8 GHz;
2) We perform an analytical, numerical and empirical evaluation of the electromagnetic- and thermal insulation of the wall to evaluate the efficacy of the signal-transmissive wall; and finally,
3) We perform a numerical study showing the effect of antenna system installation on realized reduction of electromagnetic transmission losses and maintained thermal insulation.

The rest of the paper is organized as follows: Section II defines the load bearing wall of modern buildings and their construction materials, thereby setting our goal to make the load bearing wall as the signal-transmissive wall. Analytical and numerical approaches to estimating the electromagnetic and thermal insulation of a load bearing wall are reviewed. Section III introduces the design of an ultrawideband antenna system embedded into the load bearing wall and reports their evaluation in free space, i.e., without being embedded into a...
wall. A comparison between simulated and measured realized gains of the antenna system shows adequate ultrawideband characteristics and efficacy of the antenna system design. Section IV covers the fabrication of the signal-transmissive wall, i.e., our antenna system embedded into a load bearing wall sample. The efficacy of the simulation model of the signal-transmissive wall is verified by seeing agreements between simulated and measured transmission losses of the wall sample enclosed into a waveguide. The electromagnetic and thermal insulation property of the wall was finally evaluated through numerical simulations to reveal the possible densest installation of the antenna systems while respecting the regulation of thermal insulation. Section V concludes the work and gives some insights for future works.

II. ELECTROMAGNETIC AND THERMAL INSULATION OF A LOAD BEARING WALL

A general structure of the load bearing wall that we study as an example in this paper is illustrated in Fig. 1. The wall is made from 220 mm thick rock wool layer for thermal insulation, which is sandwiched between 70 and 150 mm thick concrete layers. The following summarizes analytical models of the electromagnetic and thermal transmission properties of the wall, along with its comparison with numerical simulations to cross-validate the two approaches.

A. Electromagnetic insulation of the wall

1) Analytical model: The electrical parameters of concrete and rock wool are derived from 1 to 100 GHz in ITU-R P.2040 [17]. The permittivities of different building materials are defined as [17]

\[ \epsilon_r(f) = \epsilon' - j\epsilon'' = a f^b - j \frac{c f^d}{\epsilon_0 \omega}, \]  

where the \( a, b, c \) and \( d \) are summarized in Table I that determine the frequency dependent permittivity while \( f \) is the RF in GHz. We model the wall as a three-layered dielectric structure that is infinitely long in \( x \) and \( y \) directions as defined by the coordinate system in Fig. 1.

2) Numerical study: Electromagnetic insulation of the load bearing wall was numerically simulated using the CST Studio Suite [18]. An infinitesimally large load bearing wall is considered along with a plane electromagnetic wave incidence. The infinitely large wall can be simulated using unit cell boundary conditions with two Floquet ports [19] which are placed quarter wavelength distance away from the outdoor and indoor facing sides of the wall which is calculated from the smallest frequency in the simulation. Thereby the small unit cell is copied around itself in \( \pm x \) and \( \pm y \) directions, making it virtually infinitely large. This means that if an antenna system is placed on a unit cell, it is repeated with the rest of the unit cell and antenna separation will be the same as the \( x \) and \( y \) dimensions of the unit cell.

According to [19], the electromagnetic field at any point in the unit cell can be considered as Fourier series whose basis functions are the Floquet modes. Unlike in waveguides, the group velocities of Floquet modes are constant but the phase velocities are not. The total field at any point in the unit cell is obtained by summing up coefficients of all the Floquet modes. In order for the solved total field to satisfy the Maxwell equations and boundary conditions, all the propagating Floquet modes must be considered.

Floquet ports are plane wave ports if the unit cell is smaller than the wavelength, where only fundamental modes can propagate. If the unit cell is larger than the wavelength the Floquet ports can transmit and receive higher-order modes. If the RF is increased and unit cell size is kept constant the higher-order modes can propagate in the unit cell. The cut-off frequency of Floquet modes can be calculated with similar formula as in the case of waveguides as

\[ f_{c_{mn}} = \frac{c_0}{2} \sqrt{\left( \frac{m}{w} \right)^2 + \left( \frac{n}{h} \right)^2}, \]  

where \( c_0 \) is the speed of light in vacuum, \( m, n = 0, 1, 2 \ldots \) are the mode indices, \( w \) and \( h \) are the side dimensions of the unit cell; in a case of squared unit cell \( w = h \). The modes are defined as TE_{\pm m, \pm n} and TM_{\pm m, \pm n} for electric- and magnetic field respectively. This leads to a large number of modes even with small values of \( m \) and \( n \).

We assume a right-handed circularly polarized incoming plane wave. Since the unit cell is larger than the wavelength, the higher-order modes must be considered on the receiving side to ensure that all the power coming from the wall is captured. In the simulations, the entire RF band of interests is split into 1 GHz sub-bands to ensure the feasible simulation time. More modes need to be considered on the receiving side at the higher RF. In this study the number of Floquet modes \( N_F = 50 \) to \( 100 \) is enough to model all the power leaving the wall. The total transmission of the electromagnetic fields through the wall can be calculated by integrating all the mode coefficients in the receiving port as \( T = \sqrt{\sum |T_i|^2}, \) \( i = 1 \ldots N_F \), given by numerical simulations in the CST Studio.

The transmission coefficients of the load bearing wall derived from the analytical model and numerical simulations are compared to cross-validate both approaches. As we see from
B. Thermal insulation of the wall

1) Analytical Study: Thermal insulation of the wall is often described by conductive heat flux. In the case of steady-state, the heat flux density can be evaluated by using a sample wall, whose dimensions in $x$ and $y$ directions are much larger than in the $z$ direction, so that one dimensional steady state heat conduction can be assumed. The heat flux depends on the types of materials and the number of wall layers as well as the temperature difference between different sides of the wall sample. Therefore we use a heat transfer rate per temperature, also called a $U$-value and thermal transmittance, as an evaluation metric. Walls with smaller $U$-values are preferred for energy-efficient buildings. The thermal transmittance is defined as the inverse of the thermal resistance as

$$U = \frac{1}{R_{\text{tot}}} = \frac{1}{R_{\text{in}} + R_{\text{out}} + R_{\text{se}}}, \quad (3)$$

where $R_{\text{in}}$ and $R_{\text{se}}$ are indoor-facing and outdoor-facing thermal surface resistances. The thermal resistance of a wall is affected by radiation from heat sources influencing the wall, e.g., the sun and electrical equipment. Also, air convection affects the thermal surface resistances on both indoor- and outdoor-facing sides of the wall. The ISO6946 standard [20] for building components and elements recommends that evaluation of thermal transmittance of walls is made with $R_{\text{in}} = 0.13$ and

TABLE I

| Layer # / Material | Thickness [mm] | Relative permittivity model $\epsilon_r$ in (1) [17] |
|--------------------|----------------|----------------------------------------------------|
| #1 Concrete        | 70             | $a = 5.24, b = 0, c = 4.6 \times 10^{-2}, d = 0.7822$ |
| #2 Rock wool       | 220            | $a = 1.48, b = 0, c = 1.1 \times 10^{-2}, d = 1.0750$ |
| #3 Concrete        | 150            | $a = 5.24, b = 0, c = 4.6 \times 10^{-2}, d = 0.7822$ |

TABLE II

| Material        | Thermal conductivity at 20°C $\lambda$ [W/(m·K)] |
|-----------------|-----------------------------------------------|
| Rogers RT/duroid 5880 | 0.2                                    |
| Styrofoam (EPS)    | $5 \times 10^{-2}$                        |
| Stainless steel   | 15                                         |
| Copper            | 400                                        |
| Teflon (PTFE)      | 0.24                                       |
| Rockwool          | $3.5 \times 10^{-2}$                      |

$R_{\text{se}} = 0.04$ m$^2$. K/W. Thermal resistance $R_n$ of the multi-layered wall can analytically be derived for a simple wall made of layers of $N$ slabs by

$$R_n = \sum_{n=1}^{N} \frac{d_n}{\lambda_n}, \quad (4)$$

where $d_n$ is the thickness of layer $n$ and $\lambda_n$ is a thermal conductivity [W/(m·K)] of layer $n$.

2) Numerical Study: To simulate the thermal transmittance of the wall, Comsol Multiphysics heat transfer module [21] was used. The same unit cell model was used as in the electromagnetic simulations. The values of thermal conductivity can be found in Table I for each layer of the load bearing wall shown in Fig. 1. Convective heat fluxes $q_{si} = T_{si}/R_{si}$ and $q_{se} = T_{se}/R_{se}$ as a boundary condition were assigned for indoor and outdoor facing sides of the wall, where $T_{si} = 293$ K and $T_{se} = 271$ K are the indoor and outdoor facing surface temperature, respectively. These convective heat fluxes work as a source of our thermal simulation. For the four sides of the unit cell facing towards $\pm x$- and $\pm y$-directions in Fig. 1 thermal insulation boundaries were assigned so that the wall was virtually infinitely large along with those directions. The thermal insulation boundary ensures that the normal component of conductive heat flux on the boundary is zero, i.e., no heat is dissipating on those four sides. To verify the simulation model we compared the simulated thermal transmittance to the analytically calculated one. For the comparison, we used thermal conductivity of 1.3 W/(m·K) which corresponds to a medium-density concrete [22]. Both simulation and analytical calculation give thermal transmittance of 0.15 W/(m$^2$·K) validating our model.

A symbol for thermal conductivity $\lambda$ should not be confused with the wavelength of electromagnetic waves in this paper. We follow the notation of ISO6046 [20] for the symbol $\lambda$. 

Fig. 2 the electromagnetic transmission coefficients from the two approaches agree perfectly.
III. ANTENNA SYSTEM

A. Design of a ultrawideband antenna system

Our antenna system contains two antenna elements located on different sides of the wall connected back-to-back with coaxial cables, similarly to the earlier work of ours [15]. However, the earlier work uses patch antennas that cover only 1.3% of the relative bandwidth. Ultrawideband antennas are preferable over narrow since those can cover a wide variety of cellular services. The ultrawideband antenna systems embedded into the load bearing wall is shown in Fig.3 where the Archimedean spiral antennas are designed and installed instead of the patch antennas. As the spiral antennas are electrically balanced, a dual-coaxial cable is introduced to connect two antennas on different sides of the wall. The outer conductors of two coaxial cables are galvanically connected, thereby omitting the need for a matching network or balun. Each coaxial cable has a center pin and the dual-coaxial cable, thereby omitting the need for a characteristic impedance. As reported in [15], the thermal transmittance of the wall is too high if copper coaxial cables are going through the whole wall. The thermal conductivity of stainless steel is about 27 times smaller than copper, as shown in Table II. This makes it a suitable conductor material for coaxial cables going through the wall. Because the thermal conductivity of stainless is low, the cables cannot be soldered together so we decided to place them inside of a heat shrink tubing.

B. Spiral antenna element and its measurements in free space

The spiral antenna is realized on top of 0.5 mm thick Rogers RT/duroid 5880 laminate ($\varepsilon_r = 2.2$, $\tan \delta = 9.0 \times 10^{-5}$) with the size of $40 \times 40$ mm. The legs of the spiral are realized with lines of 0.68 mm width. The number of turns in the spiral is 6 with internal and external radius of $r_{in} = 1.08$ mm and $r_{ex} = 17.4$ mm. Since the internal radius is the same as the radius of our coaxial cable, each leg of the spiral antenna can be connected to the center pins of the dual-coaxial cable to build the back-to-back antenna systems.

To be able to test the spiral antenna in free space, without the influence of wall, a balancing unit (balun) is needed. An experimentally tapered balun, similar to the one in [23], was designed. The balun is realized on top of 1.575 mm thick Rogers RT/duroid 5880 laminate with the size of $22 \times 46.5$ mm. The unbalanced end of the balun is a transmission line with 5.28 mm width to have 50 $\Omega$ input impedance. The tapering of the line and the ground plane leads to a parallel plate line of 1.595 mm width so that the input impedance at the balanced end is 164 $\Omega$ which is similar to the input impedance of the spiral antenna and the dual-coaxial cable. The ground plane printed on the backside of the balun is 19.75 mm wide on the unbalanced end and is tapered to the same width as the feed line. The top and bottom sides of the balun are shown in Fig.4.

Two vias were used to connect between each leg of the spiral antenna and the balun. Via dimensions are similar to the center connectors of the dual-coaxial cable to ensure a similar current transition with balun and dual-coaxial cable. Amphenol SV Microwave 2.92 mm connector (Mfr. No: 1521-60051) was used to connect the antenna to the VNA. To make sure that the connector does not touch the feed line, supporting legs on the top side of the connector are removed to ensure that the connector does not touch the feed line of the balun.

Fig. 3. Unit cell of load bearing wall with embedded back-to-back spiral antenna system

Fig. 4. Front and back view of experimentally tapered microstrip balun. Supporting legs on the top side of the connector are removed to ensure that the connector does not touch the feed line of the balun.

Fig. 5. The assembled antenna system for the free space measurements. Figure 6 shows the measured and simulated reflection coefficient of the balun attached to the spiral antenna between 2 and 8 GHz covering most of the NR
FR1. The analysis is limited below 8 GHz since we do not have the capability to simulate the infinitely large antenna embedded wall above 8 GHz. The simulated reflection coefficient is smaller than the measured one over the whole frequency band. This could be caused by the manufacturing tolerances since the balun is experimentally tapered and small changes in balun dimensions can improve the balun. Both simulated and measured curves show ripples over the frequency band. This is most likely caused by imperfect connector and soldering which can cause small changes to the matching level over the frequency range. Also, the matching between the antenna and balun can vary a little over the frequency. The black line corresponds to the simulation with a discrete port with 164 Ω is used as the normalization impedance, i.e., that of the dual-coaxial cable. All simulated and measured reflection coefficients agree well with each other.

The realized gain of the spiral antenna was measured in an anechoic chamber between 2 and 8 GHz. Figure 7 shows the maximum of realized gain of the spiral antenna over the frequency to broadside direction +z. The simulation with a discrete port has a much smoother gain pattern over the frequency, suggesting that the balun causes some losses and standing waves to the system. The standing waves can be caused by e.g., imperfect matching between the antenna, balun and VNA. Although the measured maximum gain fluctuates more than the simulated one, the overall trend of the realized gains agrees with each other, confirming the efficacy of the designed spiral antenna.

IV. ANTENNA EMBEDDED WALL

A. Embedding antenna systems on the wall

The spiral antenna cannot be placed directly on top of concrete because concrete causes detuning and losses to the antenna. At the same time, in free space, a spiral antenna radiates the same way in ±z directions on Fig. 3. To improve the radiation efficiency of the antenna and direct more power to the +z-direction defined in Fig. 3, the antenna is backed with the Rohacell foam when integrated with a wall. The foam is placed inside of the concrete layer to create a small air gap between the antenna and concrete hence maintaining the high radiation efficiency of the antenna over the frequency. The thickness of the foam was optimized in simulations to maximize the radiation efficiency when the spiral antenna was placed on top of a 150 × 150 × 50 mm³ concrete slab. The antenna element was backed with a block of foam with the size of 50 × 50 mm². The thickness was varied from 0 to 10 mm. The antenna was fed by the dual-coaxial cable described in Section III-A. The radiation efficiency increases monotonically when the foam layer is thicker. Without the foam layer, the average radiation efficiency of the antenna between 2.5 and 8 GHz is −12 dB and a mean realized gain of −6.4 dBi towards +z-direction. When we add 10 mm thick foam to the backside of the antenna the average radiation efficiency is −3.1 dB and the mean realized gain of 4.6 dBi, thereby choosing 10 mm thick Rohacell in our back-to-back antenna system.

B. Electromagnetic transmission of the infinitely large antenna-embedded wall

The total electromagnetic transmission of the wall was simulated with and without an antenna system as explained in
If the measurements agree with simulations when the antenna embedded wall is enclosed by the metallic waveguide, the same should apply to other setups of the antenna embedded walls. The wall samples are cast inside of the waveguides to ensure that the samples are as close to the sizes of the waveguides as possible. The waveguide-enclosed antenna embedded wall being the device-under-test, the same spiral antenna with the balun that we used in free space measurements was used as a feed antenna. As a receiving antenna, we use a dual-polarized double ridge horn antenna. The setup using the waveguide allows measuring all the energy that is transmitted through the wall sample. The same setup was built in a simulation for comparison with measurements, where a waveguide port with a large enough amount of modes is used as a receiving antenna to ensure that all the transmitted power is detected.

The load bearing wall consists of a rockwool layer in addition to concrete. To ensure the correct thermal behavior of the wall, the Paroc COS 5gtt rockwool was used, which is widely used in concrete sandwich elements in Finland. The antenna system and rockwool were placed inside of the waveguide and concrete was cast in. Also, a wall without the antenna system was cast as a reference sample. The waveguide has 150 mm extra length at both ends of the wall sample, leading to the total length of the waveguides being 740 mm. The empty space created by the extra length of the waveguide is needed for placing the transmitting and receiving antennas. The curing time of concrete varies based on the temperature and humidity of the casting site. Concrete reaches its final strength roughly in 28 days [24] so any measurements were performed after that period.

D. Electromagnetic insulation of the antenna-embedded wall inside a waveguide

Prior to electromagnetic measurements of the antenna-embedded wall, a transmission coefficient of only the casted concrete block in the waveguide was measured to estimate the complex permittivity of the concrete. It turned out that the casted concrete had a moisture content that led to higher permittivity than the one in the ITU model. The permittivity was estimated by solving the analytical model of transmission coefficients for a slab explained in Section III. The estimated parameters for concrete to be used in equation II are $a = 5.84$, $b = 0$, $c = 0.205$, $d = 0.06$. We use this measured permittivity to compare the transmission through the reference and antenna embedded walls between the measurements and simulations.

Figure 10 shows the measurement setup used in the electromagnetic transmission measurements without the top-side waveguide wall. The feeding spiral antenna is mounted at the center of a piece of Styrofoam. The corners of the waveguide are strengthened with copper tape. During the measurements, the top-side of the waveguide wall is also used. Figure 11 shows the total transmission through the wall with and without the spiral antenna system. The losses caused by the measurement system, including the waveguide, are calibrated by normalizing the wall measurement coefficients with those with an empty waveguide of the same dimension. The measured and simulated transmission agrees well with each other. The
The measurement setup for the electromagnetic transmission measurements. Left side is the feeding spiral antenna and on the right side the dual-polarized horn antenna. The top-side metal is removed for the picture.

Improvement due to the inclusion of antenna systems is on average 16 dB between 2.5 and 8 GHz. The two dips in the transmission around 4.8 and 7.3 GHz are caused by feed antenna coupling to the embedded antenna system. These dips would be smaller if the distance between the feed antenna and embedded antenna would be larger. The impact of the antenna system in improving the electromagnetic transmission through the load bearing wall is clear.

E. Thermal insulation of the antenna-embedded wall

The thermal conductivities of most materials used in the signal-transmissive wall are given by manufacturers as listed in Table II. But the concrete was mixed in our lab and its thermal properties are unknown. ISO10456 [22] gives nominal thermal properties of most used construction materials. A sample of our concrete was measured with C-Therm TCI thermal conductivity measurement system [25] to characterize the thermal conductivity of our concrete. C-Therm TCI is based on a modified transient plane source technique, requiring only one probe. A single measurement of the thermal conductivity takes only a few seconds. The measurement was repeated a few times to make sure that the results are repeatable. The thermal conductivity estimate of our concrete was 1.3 \( W/(m \cdot K) \) which is similar to medium density concrete in [22]. The measured thermal conductivity of concrete is used for the following thermal simulations.

The thermal insulation of the wall was numerically simulated with the same structures as the electromagnetic unit cell simulations using the method described in Section II. The wall without the antenna system has a U-value of 0.15 \( W/(m^2 \cdot K) \), while that of the antenna embedded wall is 0.16 \( W/(m^2 \cdot K) \), showing a slight increase. The present U-value of the antenna embedded wall is better than the one in our previous work [15], where we reported a U-value of 0.51 \( W/(m^2 \cdot K) \), most likely because the stainless steel conductor was used in coaxial cables instead of copper. Also, the reduced size of the cables decreases the U-value. The presented antenna embedded wall has a lower U-value than 0.17 \( W/(m^2 \cdot K) \) limit given in the national building regulation [16].

F. Impacts of Antenna System Separation on Electromagnetic and Thermal Insulation

Now that the analysis methods of the signal-transmissive wall is verified through experiments, we are ready to study the effect of antenna separation on electromagnetic transmission and thermal transmittance. When antenna systems are placed more densely on the wall the U-value will increase. The national building code of Finland says that the U-value of the wall cannot be higher than 0.17 \( W/(m^2 \cdot K) \) [16], as mentioned in the previous section. The antenna separation is first studied in terms of thermal transmittance by changing the squared unit cell size \( w = h \) by varying their values from 70 to 200 mm to identify the smallest possible cell size that meets the 0.17 \( W/(m^2 \cdot K) \) limit. Figure 12 plots the results, showing that 90 mm antenna system separation satisfies the 0.17 \( W/(m^2 \cdot K) \) threshold.
efficiency of the antenna system while the signal-transmissive wall respects the U-value restrictions. It is also good to notice that even with 200 mm antenna system separation the transmission coefficient is improved at all the simulated RF.

V. CONCLUDING REMARKS

This paper introduces analytical, numerical and empirical evaluation of antenna embedded wall, which is called the signal-transmissive wall. Ultrawideband spiral antenna system was introduced, manufactured and its electromagnetic transmission characteristics was analyzed. Dual-coaxial cable assembly was introduced to connect two balanced spiral antennas back-to-back without the need of a separate balun or matching network. Penetration loss of load bearing wall was decreased down to 17 dB at 8 GHz when the antenna system is embedded to the wall every 150 mm, compared to 42.5 dB loss of the load bearing wall. The simulated and measured electromagnetic transmissions agrees well with each other the waveguide-enclosed signal-transmissive wall. The thermal insulation of the wall was analyzed with numerical simulations. The increase of the U-value was so slight that the signal-transmissive wall still achieves the demanded level of national building regulation. Finally, the impact of antenna separation on the electromagnetic and thermal insulation of the wall was studied numerically. Antenna systems could be placed as densely as to every 100 mm to the load bearing wall without exceeding the U-value threshold while improving the electromagnetic transmission at 8 GHz by 22 dB. The electromagnetic transmission is improved by more than 6 dB at RF above 4 GHz. Given the verified improvement of the electromagnetic transmission coefficient through the signal-transmissive wall, its impact on indoor cellular coverage inside low-energy buildings is a subject of a further study.

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