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Radio Propagation into Modern Buildings: Attenuation Measurements in the Range from 800 MHz to 18 GHz

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Abstract—Energy-efficient buildings are gaining momentum in order to comply with the new energy regulations. Especially in northern cold countries, thick reinforced walls and energy-efficient windows composed of several layers of glass plus metal coating are becoming the de facto elements in modern building constructions, and it has been noticed that they can impact heavily on radio signal propagation. This paper presents a measurement-based analysis of the outdoor-to-indoor attenuation experienced in several modern constructions compared to an old building. The measurements are performed for frequencies from 800 MHz to 18 GHz with the aim of identifying the frequency dependence and the impact of the new materials on not only the cellular frequency bands used today (mainly below 3 GHz), but also the potential future bands (above 3 GHz). The results show a material dependent and a frequency dependent attenuation, with an average increase of 20-25 dB in modern constructions compared to the old construction, which presents a low and almost constant attenuation below 10 dB. The different measurement results and observations presented along the paper are useful for future radio network planning considerations.

I. INTRODUCTION

Due to new energy-efficiency regulations [1, 2] aiming at achieving the so called zero-energy level in buildings, new construction principles and materials are being used in order to provide a proper level of thermal isolation. While in old building constructions the most common wall materials used are brick, wood or light concrete, in modern building constructions, masonry blocks, reinforced concrete or metal-insulated materials such as polyurethane with aluminum are becoming the most prevalent. Unlike the old walls, due to new constructions principles, modern walls tend to be multi-layer and thicker than in the past. Similarly, windows also make a difference between old and modern constructions, especially in cold northern countries. Old windows are often composed of a thin single layer of glass surrounded by wooden frames, while modern windows typically consist of several layers of glass with metal coating. Modern windows contribute to achieve the energy-efficiency requirements and are commonly known as energy-efficient windows [3].

When considering radio propagation into buildings, the signal penetrates into the building through the areas on the external facade which present the lowest attenuation (e.g. windows). It is clear that the different properties of the

construction materials have an impact on the attenuation experienced by the radio signals. This attenuation has been carefully studied and modeled for some representative construction materials of old buildings through controlled experiments [4]. However, when addressing a practical scenario, where a combination of materials is present, the experienced attenuation may vary. Radio propagation into buildings has been previously addressed in the literature mainly through penetration loss studies, which typically report average values. Such average values for the dominating types of buildings are considered by network operators in their radio planning tasks. In general, the literature does not agree on the frequency dependence of the penetration loss. For example, [5] and [6] reported a constant low penetration loss for frequencies in the range from 450 MHz to 15.5 GHz and 800 MHz to 8 GHz, respectively. On the other hand, [7] elaborated on the increasing behavior of the penetration loss with frequency in the range from 900 MHz to 5.9 GHz. However, besides from the frequency dependence, these studies report very similar overall average penetration loss values in line with the 20 dB typically used as a reference for residential areas [8].

With focus on material dependence, [9] reported an increased attenuation of 25-50 dB for glass walls with metalized coating to reduce ultraviolet and infrared radiation. Similarly, recent studies have pointed to a considerable increase of the building penetration loss due to the use of modern construction materials. According to [10], the modern 4-layered metal-coated windows can attenuate the outdoor-to-indoor signals by 20-45 dB in the frequency range from 800 MHz to 5 GHz. In our previous work [11], a 10 dB increased penetration loss was detected in modern buildings compared to old buildings at both 1.9 GHz and 3.5 GHz. Recently, [12] reported a 13-14 dB penetration loss increment in modern buildings compared to old buildings, based on measurements at 900 MHz and 2.1 GHz. From the literature review and the personal experience of the authors, it has been detected that construction industry does not take into account the requirements of wireless signals, as they consider thermal and sound isolation as more important. The lack of attention to the increased attenuation of the modern materials could present a problem for cellular indoor coverage in the future.

While previous studies have typically focused on frequencies below 5 GHz, this paper complements the previous work by presenting the analysis of several attenuation measurements performed in practical scenarios for an extended frequency range up to 18 GHz. The aim is to get a better understanding of the frequency dependence and the impact of modern buildings on the potential future frequency bands used by cellular technologies - above 3 GHz. The main focus is on modern constructions, but a similar measurement was done in an old building and is presented as a reference.

The rest of the paper is organized as follows: Section II describes the different aspects of the measurement campaign such as the setup used, the scenarios considered and the measurement procedures. Section III presents the results and the discussion and, finally, Section IV concludes the paper.

II. MEASUREMENT CAMPAIGN

A. Measurement Setup

The measurement setup, depicted in Fig. 1, consisted of two ultra-broadband horn antennas (ETS Lindgren EMC 3115), RF cables, a signal generator (Rohde & Schwarz SMR20) as transmitter (TX), and a spectrum analyzer (Agilent E4440A) as receiver (RX).

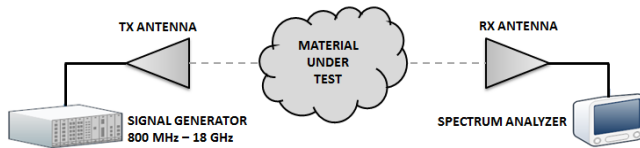


Fig. 1. Overview of the measurement setup.

B. Measurement Scenarios

The outdoor-to-indoor attenuation was measured in the 4 different practical scenarios illustrated in Fig. 2. The locations selected are placed in Aalborg, Denmark, and they are representative of the constructions used in northern countries. According to the different locations, the scenarios are classified as follows:

- 1) Modern Office Building (MOB).
- 2) Modern Glass Building (MGB).
- 3) Modern Test Facility (MTF).
- 4) Old Office Building (OOB).

Each of the scenarios presents a different composition. MOB is composed of 45 cm thick multi-layer walls made of reinforced-concrete and brick, combined with 2-layered energy-efficient windows with metal frames. MGB is totally composed by 3-layered glass panels and doors with metal frames. MTF is a lab facility from the Department of Civil Engineer, Aalborg University, with a 50 cm external wall composed of 7 different high-isolation materials and a 2-layered energy-efficient window with a wooden frame. OOB is an old building used as a reference which is composed by 10 cm walls made of light concrete combined with 1-layered glass windows with wooden frames. For clarification, Fig. 3 presents a detailed overview the different materials measured in each scenario.



Fig. 2. Overview of the measurement scenarios.

C. Measurement Procedures and Calibration

The measurement aimed at being something in-between a controlled measurement (similar to the typical construction materials attenuation measurements), but in a practical scenario (similar to the penetration loss measurements reported in the literature). For each measurement, the TX and RX antennas were aligned in height and azimuth so that the boresight of the TX and RX antennas were pointing to each other. The material under test (MUT) was located perpendicularly to the TX-RX boresight, aiming for an orthogonal incidence of the radio signal on the material. Under these conditions, with vertical polarization and E-field normal to the plane of incidence, the attenuation measured includes a reflected part. As a simple example, assuming free space propagation incident on a glass with a relative permittivity $\epsilon_r = 4$, normal incidence gives the minimum reflection coefficient of 0.33 [8]. Correspondingly, 89% of the incident power goes through and 11% is reflected to the outside. Practically, this set of measurements should serve as a lower bound on the expected attenuation in real scenarios. For smaller grazing angles, the reflected part will be higher, leading also to a higher attenuation experienced [13].

The measurements were done by sweeping a continuous-wave (CW) signal in the frequency range from 800 MHz to 18 GHz. A initial sample was taken at 800 MHz, and the rest were taken from 2 GHz to 18 GHz with a resolution of 1 GHz. For each scenario, the measurement was repeated for different sets of TX-MUT and MUT-RX distances (d) in order to check whether they lead to different results as a consequence of the different illuminated areas and different near-field (NF) and far-field (FF) radiation zones. The three different pairs of distances measured were $(d_{TX-MUT} / d_{MUT-RX}) = \{ (1.8 \text{ m} / 1.8 \text{ m}), (3.6 \text{ m} / 1.8 \text{ m}), (10 \text{ m} / 3 \text{ m}) \}$. The first set of distances corresponds allows a direct comparison of the measurement results with previous studies (i.e. [10]).

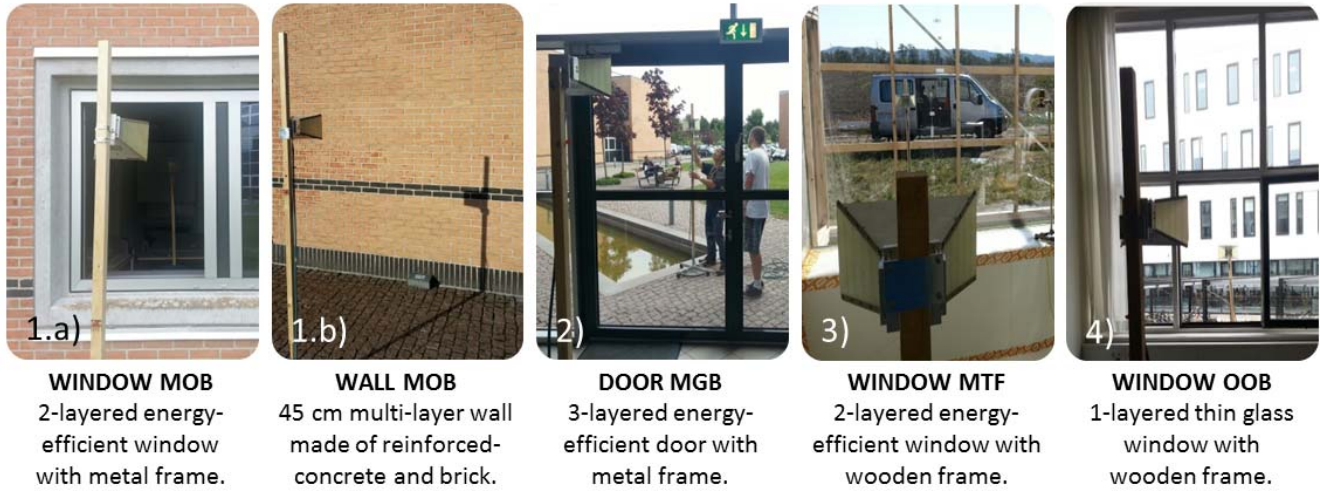


Fig. 3. Detailed overview of the different materials measured.

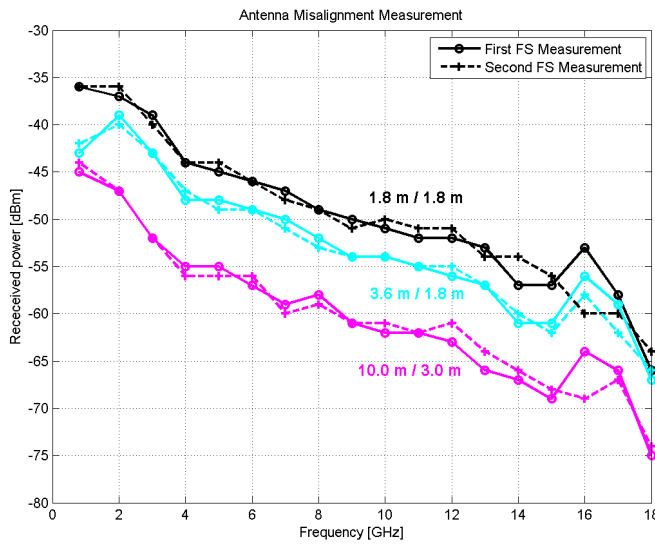


Fig. 4. Quantification of the impact of a potential antenna misalignment.

As indicated in (1), the attenuation of the different materials is computed as the difference between the power measured with the MUT in-between the TX and RX (P_{MUT}) and a reference considered without the material (P_{REF}). There is no need to apply any further calibration to this equation, since the link budget parameters are constant for both measurements, so the only difference is the attenuation introduced by the MUT.

$$Attenuation[\text{dB}] = P_{MUT}[\text{dBm}] - P_{REF}[\text{dBm}] \quad (1)$$

From Fig. 3, and under the constraint of the practical scenario, the reader can understand that the P_{REF} measurements in MOB, OOB and MGB were done with the windows and door open, while the P_{MUT} measurements were done with the windows and door closed. The wall in MOB and the window in MTF are fixed elements, so only P_{MUT} measurements were possible.

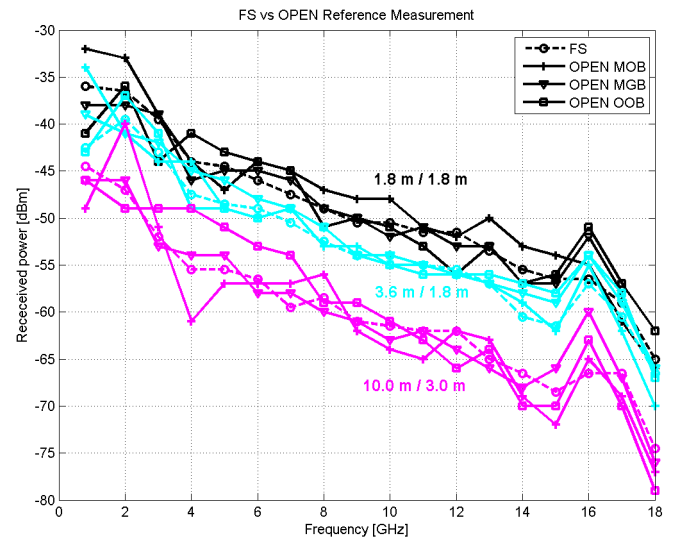


Fig. 5. Comparison of the different reference measurements.

In order to calculate the attenuation of these two scenarios, a P_{REF} measurement was necessary so a free space (FS) reference was considered. The FS reference for each different pair of distances was computed as the average result of different measurements performed in an open space without nearby buildings in order to avoid strong reflections. Across the FS measurements, it was possible to verify the accuracy and repeatability of the empirical procedure. It was found that a small variation of 1-2 dB in received power by repeated measurements, and that a potential misalignment of $\pm 5^\circ$ in azimuth between the TX and RX antennas would result in a small variation of ± 0.5 dB in average. Fig. 4 shows the result of the FS antenna misalignment test. As it can be verified, the scaling between the measurements at different distances follows nicely a factor $20 \cdot \log_{10}(1/d)$ which indicates that the measurements were not affected by ground reflections.

In order to see the validity of the FS reference, it was compared to the open window/door reference measurements. This was done in Fig. 5, and as it can be seen, the FS reference measurements have an overall good agreement with the open window/door reference measurements with a mean error of 0.4 dB, which supports the use the FS measurement as P_{REF} measurement to calculate the attenuation of the wall in MOB and the window in MTF. This same agreement also suggest that the impact of reflection and diffraction of surrounding materials, such as frames or wall elements, is minimal. This can be explained by the high directivity of the TX and RX antennas. Another interesting aspect of the match between reference measurements, is the correlation between the measurements at different distances, especially for higher frequencies, which suggest that the potential NF/FF effects are negligible using this measurement procedure.

III. RESULTS AND DISCUSSION

The measurement results for the 4 scenarios are shown in Fig. 6. They are presented as the average attenuation value from the measurements performed at the 3 different pairs of TX-MUT and MUT-RX distances. The calculated attenuation was very similar for the different distances, with an average standard deviation of 2.9 dB, which gives an indication of the small dispersion of the measurement results. This fact confirms again the validity of the measurement procedure and the observations given at the end of the previous section.

In the first scenario (MOB), the reinforced concrete wall presents an increasing attenuation with frequency. This behavior was already reported in [14] with slightly lower values of attenuation due to the different thickness of the wall. As it can be seen in the figure, the window in the same scenario presents a lower attenuation compared to the wall, which verifies that the radio propagation into this type of modern buildings with thick reinforced walls occurs through windows, even tough the window itself present a high attenuation value. In this case, it is shown that the attenuation for this type of window behaves irregularly, varying quite a lot depending on the actual frequency. The low attenuation experienced of approximately 15 dB at 800 MHz and 9 GHz is remarkable. This fact suggests a behavior similar to the one from frequency selective surfaces (FSS), which are one of the possible solutions to overcome the potential problems derived from high attenuation as for example, the lack of outdoor-to-indoor coverage [15].

In the second scenario (MGB), where the whole facade is composed of energy-efficient glass, an almost constant attenuation slightly higher than 30 dB is experienced for the entire frequency range.

The third scenario (MTF), as previously mentioned, was a test facility from the Department of Civil Engineering at Aalborg University. The composition of the external wall in this scenario ensures that the radio signal penetrates into the lab through the window. The attenuation measured presents a irregular frequency dependence with increasing attenuation from approximately 15 dB at 800 MHz to 30 dB at 5 GHz,

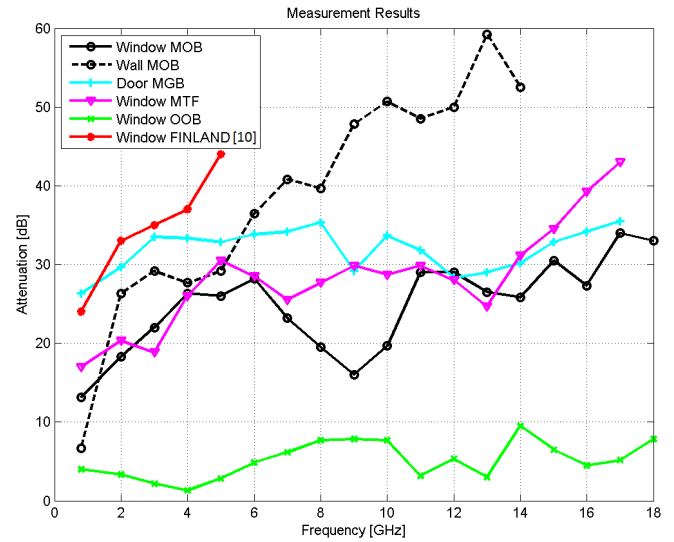


Fig. 6. Measured attenuation for the different scenarios in the range from 800 MHz to 18 GHz.

approximately constant attenuation of 30 dB from 5 GHz to 13 GHz, and again increasing attenuation from approximately 30 dB at 13 GHz to almost 45 dB at 17 GHz.

The last scenario (OOB), is presented as a reference of the attenuation experienced in an old construction. As it can be seen, the attenuation is much lower than in the modern scenarios previously described. In this case, the attenuation measured is almost constant and lower than 10 dB for the entire frequency range.

From the previous observations, it can be concluded that the attenuation experienced by the radio signals when propagating into a modern building is very dependent on the composition of the outer walls and windows. Due to the increased attenuation of modern external walls, radio signals penetrate into the building through windows and their composition is proven to be a very relevant factor for radio propagation. From the measurement presented in this paper, it can be seen how the 2 and 3-layered energy-efficient glass elements present a much higher attenuation than the single-layer glass. In order to complete Fig. 6, the measurement results for 4-layered energy-efficient windows done in Finland [10] have been included. The attenuation is reported for the frequency range from 800 MHz to 5 GHz and, as one could expected, is higher than in all the previous scenarios, due to the increased number of layers. Considering the above, in future studies, it could be interesting to find a correlation between attenuation and number of glass layers, coating materials, number of coated layers, thickness of the glass; or, even with standard glass parameters such as g and u values, that are related to heat losses and solar radiation gains, respectively.

From the measurement results reported in this paper, one can also understand the different trends of the penetration loss with frequency previously reported in the literature. For example, the low and constant behavior of the penetration loss described in studies such as [5] and [6] could be related to

measurements done in constructions with glass windows closer to the old type presented in this paper. Similarly, the increasing penetration loss with frequency reported in [7] could be related to measurements done in modern constructions similar to the ones presented in this paper. As it can be seen in Fig. 6, all the attenuation measurements in the modern scenarios present an increasing behavior with frequency in the range from 800 MHz to 5 GHz. The fact that attenuation varies a lot around the trend and between different building types supports that the literature is inconclusive in this respect, and all the previous studies are very dependent on the type of scenario and the range of frequencies explored.

By considering the windows or doors as the main contributors to the attenuation experienced, and neglecting the irregular frequency dependence, the attenuation in each of the scenarios can be seen as a constant with a certain standard deviation over the frequency range from 800 MHz to 18 GHz. These results are gathered in Table I. According to this analysis, the set of attenuations experienced in scenarios with energy-efficient modern materials ranges from 24.86 dB to 31.98 dB, meanwhile the one experienced in the old building scenario is much lower (only 5.16 dB).

TABLE I
AVERAGE ATTENUATION OVER THE FREQUENCY RANGE 0.8-18 GHz.

SCENARIO	AVERAGE ATTENUATION	STD
1) MOB	24.86 dB	5.60 dB
2) MGB	31.98 dB	2.61 dB
3) MTF	28.43 dB	6.42 dB
4) OOB	5.16 dB	2.03 dB

The high attenuation in modern constructions must be carefully considered by network operators in future radio planning tasks. However, this fact can be seen as both a disadvantage or advantage by network operators. It can be seen as a problem when addressing outdoor-to-indoor coverage, but also an advantage for future frequency reuse in heterogeneous networks, since the modern constructions will provide a natural isolation between macro and indoor small cells in co-channel deployments.

IV. CONCLUSION

This paper presented a measurement-based study of the outdoor-to-indoor attenuation experienced in practical scenarios. The analysis focused on modern building constructions composed of thick reinforced walls and energy-efficient windows/doors compared to an old building with thin walls and single-layered glass windows. The attenuation measurement results were reported for the frequency range from 800 MHz to 18 GHz, presenting a material-dependent behavior and irregular frequency dependence. The measurement results confirmed that radio signals penetrate into modern buildings through windows, which present lower attenuation than external walls. According to average results, the attenuation experienced in a modern construction is approximately 20-25 dB higher than the attenuation experienced in the old building reference case, which

presents an almost constant attenuation lower than 10 dB. This difference is due to the increased use of metal-shielded materials in modern constructions oriented to provide thermal isolation and comply with the new energy-regulations. Networks operators must consider this fact carefully in order to overcome it when indoor coverage is provided by outdoor cells, or exploit it as isolation between indoor and outdoor cells in future heterogeneous deployments. For future work, an extension of the analysis to higher frequencies (i.e. millimeter-wave bands) is proposed, together with a detailed analysis of the attenuation for different types of glass.

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