# Radio signal attenuation measurements for modern residential buildings

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***Abstract*—This paper outlines the problems that cellular network operators will face as energy-efficient housing[1] becomes more popular. We report measurement results from houses made of modern construction materials that are required to achieve sufficient level of energy-efficiency. Energy-efficiency is especially important northern countries, where houses need to be properly isolated as heating generates a big share of the total energy consumption of households. However, the energy-efficiency trend will also reach rest of the Europe and other warmer countries as the tightening energy-efficiency requirements concern also cooling the houses. The measurement results indicate severe problems originating from radio signal attenuation as it increases up to 35 dB for individual construction materials for cellular frequencies around 2 GHz. From the perspective of actual building penetration losses in modern, energy-efficient houses, average attenuation values even up to 30 dB have been measured, which is in general However, such huge attenuations are sensitive to buildings materials. The observations here clearly indicate increasing level of problem in terms of cellular network coverage in modern, energy-efficient residential houses.**

***Keywords-radio signal measurements, electromagnetic wave propagation, energy-efficient buildings, cellular networks, radio network planning.***

## I. INTRODUCTION

Among all the other things, climate change possibly as a result of human activies and lack of oil as means of producing energy has driven the society to decrease the level of carbon dioxide and other fossil fuels as a source of energy. Housing, as one of the main necessities for humans, creates all together lots of needs for consumption of natural resources already in the construction phase, but requires energy also later on for several purposes as heating and cooling. From natural resource efficiency point of view, having houses thermally as isolated as possible is extremely beneficial, and would mean savings in the natural resources. Especially, in the northern countries (Northern Europe, Northern America, Russia, etc.) where winters tend to be rather long and cold, heating of houses is one of the main shares of energy consumption for households. Given the pressures in energy-efficiency it has been a natural demand for governments and authorities to increase the energy-efficiency of buildings. In more southern parts of the world (as central and southern Europe, etc.), heating as such does not play such an important role as in the north, but the overall energy consumption of houses for heating and cooling naturally reduces if buildings were well thermally isolated. The trend of using more and more energy-efficient construction material is expected to increase in the future as for example EU mandates that all new constructed buildings by 2021 need to achieve so called zero-energy level [1].

Metal has very good properties as means of achieving proper level of thermal isolation, and this helps with achieving the energy-efficiency requirements. Hence, this has been most obvious solution for window manufacturers to achieve higher level thermal isolation. Using metal is insulator generated issues with radio frequency (RF) signals, which are the basis of modern mobile communication networks, as they cannot propagate well through a metal shielding. This has been observed for example in urban high-rises and skyscrapers that have been deployed with energy-efficient windows [2]. Due to increasing energy-efficiency needs, trend using of energy-efficient windows is also reaching residential housing. Measurements have shown that, e.g., double-glazed, energy-efficient windows can attenuate the signal by 20 dB in the 2 GHz frequency range [3].

The radio signal penetration losses through different construction materials are rather widely known [4] and can be easily modeled with different material parameters [5]-[10]. The individual material losses naturally have an impact on average attenuations for residential houses. In addition to construction materials, the actual average building penetration losses (BPL) depend also on the height of the base station antenna, on the dominating angle of arrival and frequency of the signal. They are typically known locally by the network operators and some of them reported publicly [11], [12]. These losses are then taken into account by cellular operators in the radio network dimensioning and planning phases based on dominant building types and their average building penetration losses [13], [14]. Typical BPL values depend on the planning area, but are in general at the level of 5-15 dB for residential houses. However, utilization of metals in windows and possibly also in wall building materials is expected to increase the level of average attenuation, hence creating coverage problems for mobile users. In general, the lack of construction industry not taking into account the requirements of wireless signals has fortunately generated some attention [15]. Building regulations need to take into account several other boarder conditions as thermal and sound isolations, and wireless signal propagation is not the most

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[1] The variety of definitions for energy-efficient houses is very large. In the context of this publication the term ‘energy-efficient’ refers in general to houses which are constructed or renovated to improve their energy efficiency in terms of thermal isolation properties. Commonly used terms are e.g., low-energy houses, passive-energy houses, and zero-energy houses.

important one. However, additional attenuations are, for the sake of energy-efficiency, converted in to a need of having more wireless infrastructure, and ultimately mean more costs for wireless operators.

The target of this paper is to increase the level of awareness of expected radio signal coverage problems in modern residential buildings. The main emphasis on the residential buildings as it is anticipated that dedicated indoor networks are reaching more rapidly urban residential high-rises. To support our discussion and arguments, first material attenuation measurements are provided for different isolation materials and for a four-layered window. Secondly, radio signal attenuation measurements from modern energy-efficient residential buildings are presented.

## II. ON THE WIRELESS COVERAGE IN RESIDENTIAL BUILDINGS

### *A. Materials for residential buildings*

In residential buildings windows typically provide the easiest entry for radio signals as they are not cause more than a few dB of attenuation [4]. However, if windows are replaced with energy-efficient windows the resulting building penetration losses obviously increase as reported in [3]. Lately, the trend for example in Finland has been to deploy window frames out of an aluminum profile to facilitate lower costs for the annual maintenance. This increases the overall building penetration loss, especially if windows are energy-efficient. One extreme of energy-efficient windows has been observed in Finland that some window manufacturers have adopted four-layered windows to even further increase the energy-efficiency. This has occurred so far only in Finland due to highly strict and important thermal isolation requirements directed by the local government and building construction authorities.

In addition to windows, the wall construction materials used for residential buildings consist of brick, wood, masonry block, rock, or reinforced concrete structures. Brick and wood as building materials do not generally cause huge attenuation for the signals, but masonry blocks, rocks and especially reinforced concrete attenuate signals on cellular frequencies around 2 GHz between 20 and 40 dB [4]. However, the attenuation of walls increases if brick and wood is combined with masonry block or reinforced concrete, or with some metal-based material. Isolation properties of buildings can be further improved with isolation boards (typically glass or rock wool, urethane plate, and lately polyurethane plate) between the outer and interior lining. Glass and rock wools or different urethane materials are not as such causing any significant attenuation for the signal. However, thermal properties of polyurethane are in general better, and in order to reduce the thickness of traditional glass/rock wool insulations in the walls, some manufacturers have adopted a new polyurethane boards that unfortunately use metal shielding to improve the thermal radiation and moisture properties. Hence, the use of energy-efficient windows and the use of masonry block, rock or reinforced concrete as the main construction material or metal based isolation boards has resulted in a phenomenon that new highly energy-efficient residential buildings have become almost Faraday gages. Note also that in some residential houses metal shielding could be also intentional as reported in [3G4G-blog].

### *B. Cellular network evolution*

Additional loss due to energy-efficient building materials reduces the coverage probability, or requires cellular operators to densify their networks [15]. Cellular operators have faced several problems in deploying denser network due to planning restrictions (e.g., radiation limitations and suspicions). This combined with increased carrier frequencies (higher frequencies provide more bandwidth and hence capacity) have inevitably resulted in a degradation of signal coverage probability. The problem becomes even more important in the future as the share of UMTS and LTE data services is increases. With these technologies, the average signal-to-noise-and-interference (SINR) levels define the achievable data throughputs, and hence affect also the average network capacity. Moreover, majority of the data traffic increase estimate is expected to originate from indoors [16]. An extremely unfortunate result of reduced coverage can be also the unavailability of cellular emergency calls as they might be prevented due to lack of coverage as concluded in [15].

The evolution of network configuration is also playing a role here. Due to increasing amount of indoor data traffic there will be a natural need for additional sites in the future. Macrocellular network densification is one methodology to provide more network capacity. In order to satisfy these capacity requirements, more sites need to be deployed, and as a side-effect also the coverage is improved. Due to higher frequencies and increased capacity demands, operators have been deploying denser networks that is general are also improving the level of indoor coverage. Microcellular networks (also called small cells) are in general providing localized coverage due to lower antenna placement, but they have also tendency to improve the coverage levels indoors. On the other hand, as small cell solutions are seen as one solution for the predicted exponential capacity demand of cellular services, their level of deployment is predicted to increase significantly in the coming years. This would and most probably will mean that future network configurations will be denser heterogeneous in nature, and hence, e.g. 3GPP has adopted this as a part of standardization.

Additionally, operators have used to some extent repeaters to combat coverage problems; both for indoor coverage and outdoor coverage (e.g., valleys). An analog repeater receives the signal through its donor antenna, amplifies the signal, and forwards it through serving antenna (amplify-and-forward principle). Nevertheless, we have not seen any massive deployments of repeaters as they are posed to certain network management challenges. For LTE-A technology relays (digital repeaters, decode-and-forward) have been standardized, and they will most probably be inherent part of network configuration in LTE-A.

Also dedicated indoor solutions play a role as a partial solution. Traditionally, wireless operators have been deploying dedicated indoor solutions for commercial and business buildings as they have better financial incentives for it. However, this has rarely realized for residential buildings, and operator's services and base stations have not been available for residential houses own by private persons. Moreover, the problem will be more significant if the energy-efficiency requirements are satisfied with materials that include metals. Nowadays small base stations called femtocells (also called home base stations) [17] are been provided by some operators to provide indoor coverage. Unfortunately, this solves the problem locally (i.e. for one building possible even with closed subscriber group) and typically only for one operator.

Implications of the metal shielding in the construction materials are harmful in the case that signal is transmitted from outdoors. Cellular operators use outdoor base stations (BS) to provide wireless services for their customers. In the commercial buildings and different business parks operators have financial incentives to achieve as good indoor coverage and capacity as possible, and hence they have been and are deploying dedicated indoor base stations and networks. In cases where the signal is provided from indoors to serve indoor users, the outdoor network benefits from energy-efficient construction materials in the buildings as they provide isolation between outdoor and indoor networks; this reduces the amount of inter-cell interference and hence increases also the network capacity.

### *C. Embedded improvements for RF penetration*

The coverage can be also improved in a passive sense without adding network configuration by using frequency selective structures (FSS) in the construction materials [18]-[23]. The underlying theory of FSS is well-known, and the solutions have been studied in the frame of energy-efficient windows and other materials. FSS can be arranged in the metal shielding of windows with a special grid structure. This, however, has not realized as window manufacturers do not easily adopt new manufacturing mechanisms without regulations [15]. Other passive methods to improve the radio signal propagation into buildings can be arranged by introducing different kind of 'RF holes' to couple RF energy into buildings with some conductive material or element that can conduct signals on intended frequencies. In practice, this might mean drilling holes with metal probes, or in a more sophisticated case, a passive antenna arrangement with cabling through the wall or floor.

## III. MODERN CONSTRUCTION MATERIAL MEASUREMENTS

In order to complement and assess the attenuation values for new construction materials, measurements were performed with selected isolation plates and four-layered, energy-efficient window. The materials measurements were conducted with traditional isolation plates made of glass wool, traditional paper polyurethane and metal-based polyurethane. The measurement arrangement is shown in Fig. 1. The measurement equipment consisted of two horn antennas (A-INFO JXTXLB-880-NF), RF cables, (RG213), signal generator (Rohde & Schwarz SMJ100A) and spectrum analyzer (Rohde & Schwarz FSG). The frequency range for the measurements was from 800 MHz to 5000 MHz with a 50 MHz resolution. On every point frequency, several measurements were conducted and the results were averaged. The antennas were placed to the far-field in all frequencies. The reception antenna was additionally covered with a metal box that prevented local scattering components not to produce error in the measurements. The free-space propagation measurement was taken as reference and attenuation levels for different materials were evaluated by subtracting reference measurement values from the measurement values with different materials. The tested isolation materials were a 100 mm thick glass wool (manufactured by Isover), polyurethane isolation board without aluminum and polyurethane isolation board with aluminum (both manufactured by SPU-eristeet). The four-layered window that had a double double-glazing glass (both with metal shielding layers) was from Fenestra.

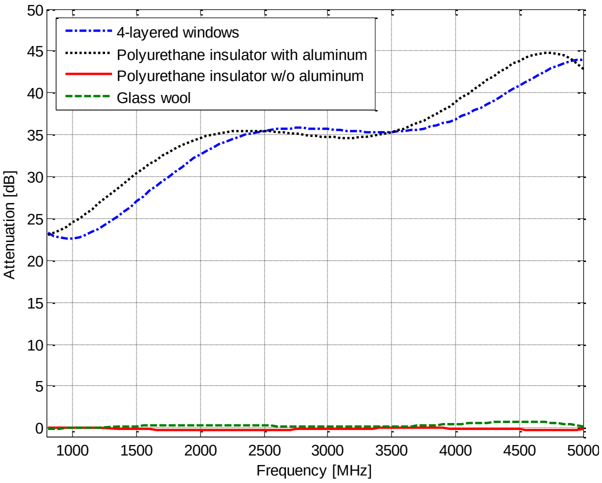

Figure 2. Attenuation measurement for with different materials over 800 to 5000 MHz.

The attenuation values for all material are shown in Fig. 2. The measurement results are all fitted to fifth-order polynomial in order to average the ripple. As can be seen from the results, glass wool and polyurethane isolation board are not causing practically any attenuation for the RF signal, where as the polyurethane isolation board and the 4-layered window have already over 20 dB attenuation on 800 MHz frequency. Furthermore, the attenuation increases to the level of 35 dB for 2000 MHz frequency and reaches even 45 dB on the higher end off the frequency range. Hence, the attenuation values are at the level of reinforced concrete, and clearly indicate RF signal coverage problems for residential houses that use energy-efficient windows and metal-based isolation boards as construction material.

## IV. SIGNAL LEVEL MEASUREMENTS IN MODERN RESIDENTIAL HOUSES

The material measurements do not provide the building penetration losses as the radio signal propagates to buildings from different directions in mobile environment. The signal strength indoors is a sum of all the multipath components in the buildings: including the ones propagated through different holes in the structures (including window frames and smokestack). Hence, in order to complement the assessment, different modern houses were measured. The measurement approach took advantage of cellular networks, and the aim was to acquire the average level difference between the signal levels outdoor and indoor. The measurements were conducted on two point frequencies: 900 MHz and 2100 MHz. For the measurements at 900 MHz frequency, GSM BCCH (broadcast channel) signal levels (called here RX LEVEL), and for 2100 MHz frequency, UMTS P-CPICH (primary common pilot channel) levels (called here RSCP, received signal code power) were measured. The measurement samples were gathered with radio interface protocol analyzer from Anite (Nemo outdoor and Handy). Altogether the attenuation values for 15 different houses were assessed, and the measurement was taken from all three Finnish cellular operators (if coverage indoors was available), analyzed and averaged per building basis. For every measurement, more than 500 signal level samples were gathered from each the operators on both frequencies.

The measurement results are shown in Table 1 together with some information related to houses. They have been constructed from different materials (as bricks, wood, rock, masonry block), they had variety of isolation materials and they all used energy-efficient windows (either three-layered or four-layered windows) from different manufacturers. All the buildings were considered as energy-efficient by the local regulations.

The measurement results are given as 5%-tile, average and 95%-tile differences between the measurement samples from outdoor and indoor locations, respectively, for 900 MHz and 2100 MHz frequencies. The average signal level differences are expectedly all larger for 2100 MHz than 900 MHz. Signal level differences for houses 2, 5-8 and 15 for both frequencies below 10 dB or barely above. The common nominator for these buildings is that they are manufactured out of wood and are not using aluminum polyurethane (except house 5 that had temporary windows out of wood panels during the measurements). The average level differences are 4.7 dB and 9.7 dB for 900 MHz and 2100 MHz frequencies, respectively. On the contrary, houses 1, 3, 4 and 9-14 have on average 15.3 dB and 21.0 dB level differences on 900 MHz and 2100 MHz frequencies, respectively. They have been made out of brick, masonry block or rock, or alternatively out of wood but using metal-based isolation broad. These values are on the level of building penetration losses of high-rises and other commercial buildings and hence are definitely causing problems for wireless operators to provide coverage within the residential houses.

## V. CONCLUSIONS AND DISCUSSION

The increasing energy-efficiency requirements have turned the construction industry to use metal layers in the materials in order to provide sufficient isolation for the buildings. In the windows this has meant utilization of frequency selective glasses or layers to keep the thermal radiation in the preferred side of the building. The metal shielding provides considerable and additional attenuation for radio frequency signals, which produces problems for wireless network operators to provide indoor coverage. The problems have been widely observed in the wireless RF engineering community for some commercial high-rise buildings equipped with frequency selective windows. However, lately the residential houses have been constructed with the same philosophy creating substantial coverage problems for residential housing as well. For individual construction materials as 4-layered windows and metal-based isolation board attenuations of 20 and 35 dB were measured around 900 and 2100 MHz frequencies, respectively. This attenuation converts to additional building penetration loss of 10-15 dB (typical in Finland) compared to common understanding of the building penetration losses in residential houses built with older standards. Hence, there is a clear need for having a solution for the problem.

As there are several solutions for delivering and improving the radio signal levels indoors, part of the future work is related to assessment of different solutions and their applicability as whole. The future work will also consist of looking for possible solutions from the passive antenna arrangements point of view as proposed in [24].

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| | Main construction material | Isolation material | Windows | 900 MHz | | | 2100 MHz | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5% | Average | 95% | 5% | Average | 95% |
| **House 1** | Wood | Polyurethane (aluminum) | 3-layered | 12.0 | 13.3 | 18.8 | 22.0 | 24.0 | 28.0 |
| **House 2** | Wood | Mineral wool | 3-layered | 4.7 | 5.2 | 6.8 | 7.0 | 8.9 | 9.5 |
| **House 3** | Rock | Styrofoam | 3-layered | 14.0 | 14.3 | 15.8 | 16.8 | 20.5 | 21.4 |
| **House 4** | Wood | Polyurethane (aluminum) (x2) | 4-layered | 16.3 | 17.6 | 18.0 | 22.3 | 23.8 | 26.6 |
| **House 5** | Wood | Polyurethane (aluminum) | Wood panel | 7.0 | 7.8 | 11.0 | 4.9 | 9.9 | 15.0 |
| **House 6** | Wood | Mineral wool | 3-layered | 0.0 | 1.3 | 4.4 | 12.0 | 11.4 | 10.2 |
| **House 7** | Wood | Glass wool | 4-layered | 1.0 | 3.2 | 5.5 | 4.7 | 9.1 | 8.3 |
| **House 8** | Wood | Glass wool | 3-layered | 2.5 | 2.7 | 6.0 | 8.0 | 10.2 | 11.4 |
| **House 9** | Masonry block | Styrofoam | 3-layered | 15.2 | 15.5 | 15.0 | 18.7 | 19.5 | 21.2 |
| **House 10** | Brick | Polyurethane (aluminum) | 3-layered | 19.2 | 21.4 | 23.0 | 25.3 | 24.9 | 26.1 |
| **House 11** | Brick | Styrofoam | 3-layered | 18.8 | 17.9 | 16.8 | 22.9 | 19.0 | 16.7 |
| **House 12** | Wood | Polyurethane (aluminum) | 3-layered | 11.0 | 12.9 | 16.0 | 18.9 | 20.9 | 21.1 |
| **House 13** | Wood | Polyurethane (aluminum) | 3-layered | 8.5 | 9.2 | 11.0 | 16.6 | 12.5 | 9.3 |
| **House 14** | Rock | Styrofoam | 3-layered | 16.0 | 15.9 | 16.2 | 24.8 | 23.5 | 21.4 |
| **House 15** | Wood | Mineral wool | 3-layered | 5.7 | 6.6 | 7.5 | 5.4 | 8.6 | 11.0 |

Table 1. The measurement results.

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