Impact of modern construction materials on radio signal propagation: Practical measurements and network planning aspects

Impact of Modern Construction Materials on Radio Signal Propagation: Practical Measurements and Network Planning Aspects

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Abstract—**Use of energy efficient construction materials is increasing all the time due to more and more tightened building regulations, which aim is to reduce overall energy consumption and thereon e.g. mitigate climate change. Energy efficient building materials and structures improve heat insulation but also change the propagation characteristics of radio signals between outdoor and indoors. This paper examines in details such propagation effects and increased levels of outdoor-indoor attenuation in modern apartment buildings, and their impact on mobile cellular networks. In particular, the aim is to compare external wall attenuations for the modern and older apartment buildings and to assess the impact of increased attenuations for the density and planning of cell sites of mobile cellular macro networks. We also demonstrate and evaluate the opportunities for increased indoor signal coverage by using a dedicated aperture installed in building materials.**

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

I. Introduction

Energy efficiency becomes more and more important in all fields of everyday life. The main reasons for this are increasing energy prices and decrease of fossil fuel resources globally. During the last two decades, also the global warming effect has become a burning topic of both scientific and political discussions and decision-making. A significant part of the total energy consumption is related to heating of the buildings, especially in northern regions like in Northern Europe and North America. For example, in Finland heating of the buildings is estimated to be approximately 23 % of the total energy consumption [1]. In warmer areas, in turn, also cooling and air conditioning of buildings is a remarkable source of energy consumption. Thus, new regulations are obligating to decrease energy consumption and greenhouse emissions considerably by 2020 on European Union (EU) -level [2].

The requirements to lower the energy consumption related to building heating and cooling can be reached by using more efficient thermal insulation materials. The decreasing of external wall structure energy losses is one of the essential parts of the energy efficiency improvement. In principle, buildings' external wall structure heat losses can be divided in two main categories which are losses due walls and windows. The energy efficiency improvement for walls is pretty straightforward, because it is possible to increase insulators thickness or using even better insulation materials. Especially, when it is necessary to keep insulators as thin as possible, the polyurethane insulating plates can be used. Usually both sides of these plates are covered with aluminum foil. This, on the other hand, has already massive impact on radio frequency (RF) signal propagation. This fact, and the resulting impact on mobile cellular network coverage and capacity, is indeed the central theme of this article. We also wish to emphasize that since the building construction industry and mobile network industry have been fairly isolated entities, so far, we provide fairly detailed discussions in this article, with details from both communities, to hopefully catalyze the dialogue and mutual understanding in the future. This is perhaps one of the biggest merits of this article, overall.

Compared to walls, the relative heat losses in windows are typically even bigger. That is why recently the energy efficiency of windows has been paid more and more attention to. Today, the numerical values of thermal transmittance through conduction, convection and radiation, i.e., the thermal transmittance or U-value, is the most important selection criteria for new windows in Northern Europe [3]. Usually in energy efficient windows, this U-value is below 1 which is in practice achieved using spectrally selective coatings on glass surfaces and is many times called low-emittance coating [3]. Such selective coating is very thin (about100nm) metal- or metal oxide layer, which is produced on the surface of the glass surface. It is manufactured typically of tin oxide or silver, but it can also be chromium, nickel, cobalt or another metal. Again, metal based foil is a very efficient way of improving the building material energy efficiency, but at the same time RF propagation is also heavily impeded. The theoretical attenuation for example for Optitherm glass is 33 dB in mobile phones band 900–2100 MHz [4] that is also confirmed in other sources [5]. Similar attenuation levels of 20–35 dB have been reported also in earlier measurement campaigns [6].

In this article, the impact of above-type modern wall and window structures on the radio signal propagation in mobile networks is addressed through realistic measurements of commercial 2G and 3G cellular network signals. Both apartment house and townhouse scenarios are measured and comparisons between modern and older buildings are made. Also the impact of the increased attenuation levels on the cellular network coverage is analyzed, through link budgets, and further insight on cellular network planning is extracted. We also investigate and demonstrate the possibility of using dedicated apertures in the building materials, both through frequency selective surface (FSS) theory and practical measurements, in relaxing the increase attenuations without essentially compromising the heat insulation.

The remainder of the paper is organized as follows: In Section II, a short overview of modern wall and window structures and their connection to RF propagation is given. Section III describes the actual measurement scenarios and obtained signal level measurement results. In Section IV, the observed extra attenuation in the measurements is taken into link budget analysis and the impacts of increased material attenuations of cellular coverage and needed macro cell density are analyzed. Specific material aperture issues, as possible solution to lower the RF signal attenuation, are then examined in Section V while conclusions are drawn in Section VI.

II. Overview of Wall and Window Structures of Typical Modern Apartment Buildings and Associated RF Signal Attenuations

Here we elaborate further the current trends in energy efficient building materials and structures, with special focus on issues that have impact of the RF signal propagation. We also focus mostly on block of flats type apartment house accommodation scenarios, as the population density and hence the needed indoor traffic capacity and coverage requirements, are in these scenarios typically most challenging.

As shortly mentioned already earlier, the external wall structure's impact on RF signal attenuation and propagation depends mostly on two factors - external wall and windows attenuation. External wall's concrete elements, and especially the so-called sandwich structures shown in Figure 1, include typically two separate concrete layers. Reinforced concrete attenuation for RF signals is fairly well known and studied, if looked from plain material measurement perspective. As an example, according to NIST's report, 200 mm thick concrete element attenuation is about 26–35dB in 900–2100 MHz frequency range, which means that the attenuation can be comparable with energy efficient windows [7]. Therefore, the attenuation of the external wall structure including wall elements and energy efficient windows for 900–2100 MHz frequency range is about 25 dB. The attenuation of selected building materials have been studied also by material parameters based modeling [8]-[13].

Typical wall of new concrete element building is approximately 420 mm thick, which includes about 220 mm of reinforced concrete, as shown in Figure 1. In real scenarios, estimating the attenuation of the external wall is not feasible, if only material knowledge is deployed. Separate material attenuations are usually measured in the laboratory conditions where signals are transmitted orthogonally towards the surface with highly directional antennas. This, however, does not correspond to practical real-life signal propagation situations where the incoming radio waves are arriving simultaneously from many different directions [12], [13]. Furthermore, in real buildings, there are special gaps between different elements where the RF signal is going through more easily. One of such gaps is window frames. These used to be wooden, but they are more recently covered by aluminum profile, which requires less maintenance. This can also be problematic to radio signal propagation because aluminum is attenuating the RF signal penetration heavily.

All these are reasons why we in this paper finally deploy actual onsite mobile network measurements in actual buildings, to be discussed and reported in Section III. It is also interesting and important to note that in many classical works, like [14], [15], the basic cellular network planning is building on the assumption of only 5-10dB of total building penetration losses. This is indeed very close to what has been measured earlier, with concrete external wall structures and standard windows, but with improved thermal insulation levels, and especially with low-emission glasses in windows, realistic attenuations are much bigger as shown in this article. Hence also the network planning guidelines deployed by operators and cellular network vendors should be updated accordingly, or otherwise providing the indoor mobile broadband experience through outdoor macro cell networks does not work as planned.

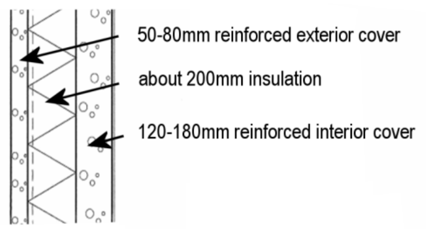

Figure 1. Typical wall sandwich element.

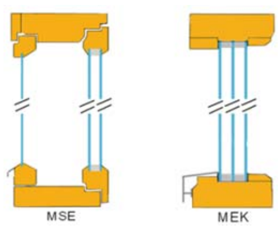

Figure 2. General structures of windows.

III. MOBILE NETWORK MEASUREMENTS IN MODERN AND OLDER APARTMENT BUILDINGS

The focus of the measurement campaign is to study and find out the realistic average signal level difference between outdoors and indoors, in different building scenarios, and also elaborate how much this has changed during last years through the introduction of more energy-efficient construction materials. As already shortly discussed, separate laboratory-scale material measurements do not provide reliable answers to the observable indoor field strengths of practical mobile networks and real-world buildings, even if outdoor signal levels are accurately measured. This is because RF signals are generally arriving from several different directions simultaneously, due to multipath propagation, reflections and scattering, having different penetration losses in various materials. Thus the signal strength detected by an indoor receiver is a complex sum of various propagating signal components, which cannot be easily predicted by laboratory material measurements alone. Hence, we deploy a practical approach and evaluate the true total penetration loss by measuring both the average indoor and outdoor signal levels and compare them to obtain realistic figures in true buildings.

A. Measurement Frequencies and Deployed Mobile Networks

The practical mobile network measurements were done at two frequency bands and mobile network technologies, namely 2G GSM 900 MHz and 3G UMTS 2100 MHz. Signal levels were measured by NEMO Handy-software for three different Finnish mobile operators. At GSM band, the measurements were based on GSM BCCH (broadcast control channel) signal level (later Rx level) while the 3G-measurements are based on P-CPICH (primary common pilot channel) signal level, in particular received signal code power (RSCP). Outdoor measurements were conducted while walking in parallel to the external wall, and the corresponding indoor measurements at about 1-2 meters away from corresponding external wall. This distance was chosen because the mobile phones are usually used in that kind of distances from the walls due to apartment planning (placing of furniture, free space etc.).

During one measurement sequence, several meters route was passed along the wall and the captured signal level samples were stored in the measuring mobile phone. All the collected data were then converted into required data vectors using NEMO Outdoor and analyzed using MATLAB-software. A typical measurement route is described in Figure 3 as an example. Each individual measurement route was walked through six consecutive times, once for measuring the signal level of each three operators' networks and separately for GSM and UMTS cases, respectively. Measurement data from each operator was collected and differences between outdoor and indoor signal levels were then calculated from every outdoor and indoor measurement pair. After that, the cumulative distribution functions (CDFs) of the measurement scenarios were analyzed. These are illustrated and discussed in details in Subsections III.C and III.D, for apartment home and townhome scenarios, respectively, and separately for the two considered cellular technologies.

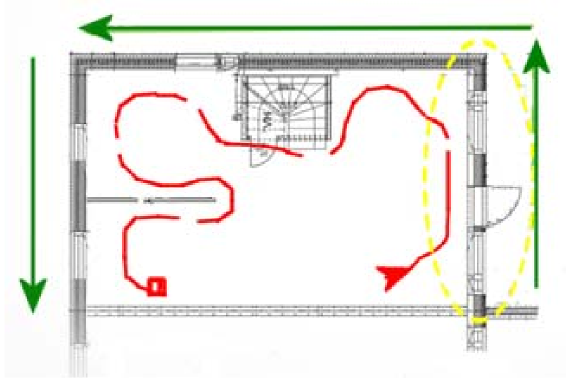

Figure 3. Example outdoor and indoor measurement routes along the building walls.

B. Measurement Objects

Measurement results were collected by measuring various different types of real-world buildings. Most of the measured buildings were just recently built or in the final phase of the building process, hence representing modern construction scenarios. Among the measured buildings, there were 11 apartment houses within which measurements were done in 27 different apartment complexes. Furthermore, 4 new townhouses were measured with 5 measurement premises. Also some business premises and one new school building were measured. In these new building apartments and townhouses, concrete-based wall elements have been installed with the structure described in Section II and illustrated in Figure 1. The windows, in turn, in these new buildings are like illustrated in Figure 2, either of type MSE or MEK. Both types have one or two selective surfaces [3], as illustrated in Figure 2.

In addition to above buildings, in order to obtain realistic reference levels from older construction materials and buildings, 8 old apartment houses were also measured, where measurements were performed in 15 different apartment complexes, as well as 2 old townhouses. Here, in order to categorize a building into the "old building" group, it should be at least 20 years old and should not contain any selective glasses in windows.

C. Measurement Results for Apartment Houses

Here the results for apartment house measurements are presented and analyzed, through cumulative distribution functions of the measured signal level differences between outdoors and indoors. Figure 4 below presents the average attenuation of external walls in GSM 900 MHz and UMTS 2100 MHz bands, and separately for old and new apartment houses. Based on the results, especially for modern buildings, the CDF shape resembles closely the Gaussian CDF. The measured average differences for modern buildings are 19.4 dB and 21.5 dB for GSM 900MHz and UMTS 2100 MHz, respectively, while the corresponding standard deviations are 7 dB and 6.4dB. Such average level differences are substantial compared to earlier knowledge and conventions in classical radio network planning. The corresponding CDF plots for signal level differences in old apartment houses show somewhat different CDF shape, compared to modern houses, and most importantly the measured average differences between outdoor and indoors are only 7 dB and 8.2 dB for GSM 900MHz and UMTS 2100 MHz, respectively, while the corresponding standard deviations are 3.8 dB and 3.4 dB. This indicates that there is, indeed, substantial difference in the outdoor-indoor propagation between older and modern apartment buildings, which when interpreted for the 50% CDF point is in the order of 13dB. This is very substantial additional building penetration loss for any typical macro network.

It is also interesting to notice that the measured standard deviations in the new buildings are substantially higher, and especially that the worst-case penetration losses can be peaking even up to 35dB range, compared to 15dB range in the older buildings. This emphasizes the importance of propagation differences and their understanding in the future radio network planning even further.

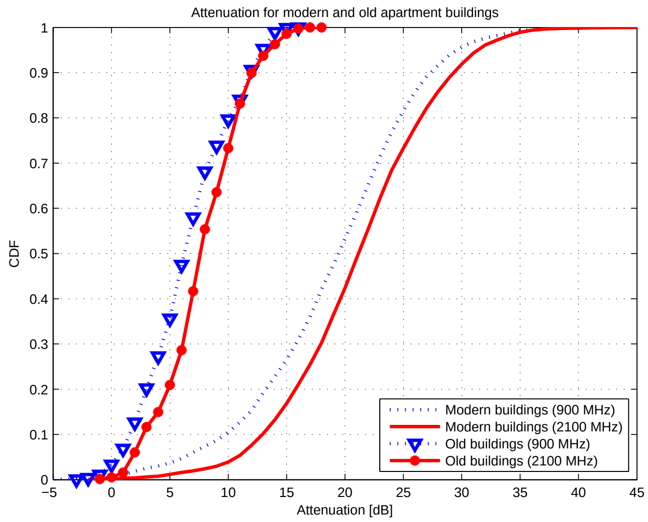

Figure 4. CDF plot for distribution of outdoor-indoor signal level differences for both older and modern apartment buildings.

The obtained measurement results are also in good correspondence with the earlier measurements, reported and analyzed in [6], related to modern single-family residential houses. It is also interesting to notice that while individual material attenuation measurements are typically clearly frequency dependent, the actual total observable signal level attenuation measurements are fairly close to each other at the two measured cellular bands. This is mostly stemming from the rich scattering and multipath propagation in the realistic building measurements compared to isolated laboratory studies where directional antennas and possibly also anechoic chamber are typically used. The measured average difference in modern apartment houses, between GSM 900MHz and UMTS 2100 MHz, is only around 2dB.

D. Measurment Results for Townhouses

Similar result analysis and comparisons are next made for the townhouse measurements. All townhouse measurements were performed on the first floor of two-storey townhouses, such that the impacts of possible differences in roof constructions are minimized. The results, in terms of measured CFDs, are shown in Fig. 5 and are fairly similar to earlier apartment house measurement results. In short, the measured average differences for modern townhouses are 19.8 dB and 22.9 dB for GSM 900MHz and UMTS 2100 MHz, respectively, while the corresponding average differences for older townhouses are 5.2 dB and 6.8 dB. Thus, again a substantial difference in the outdoor-indoor propagation between older and modern construction are observed, which when interpreted for the 50% CDF point is now approximately 14dB. This is very close to the corresponding number of 13dB observed in the earlier apartment house measurements, which makes sense also intuitively since the construction structures of two-storey townhouses are in practice fairly similar to apartment buildings especially in street levels.

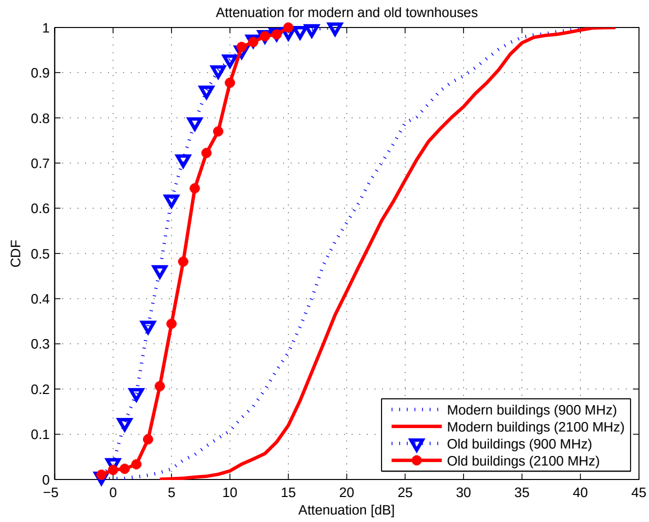

Figure 5. CDF plot for distribution of outdoor-indoor signal level differences for both older and modern townhouses.

E. Measurement Reliability

One possible error source in the measurements is the accuracy of the used measurement mobile device. However, since the aim is to study primarily the outdoor-indoor attenuations and attenuation differences between older and modern buildings, instead of absolute signal levels, such possible effects should not be considerable. Furthermore, a lot of measurements were collected, from the networks of all three major Finnish cellular operators, which adds the credibility of the measurement campaign. For example, in case of apartment building measurements, more than 250 measurements for both older and modern building types were done, which reflects high reliability.

IV. Link Budget Analysis and Impact on Cellular Coverage

A. Trends in Cellular Networks

Based on the measurement results, it can be clearly concluded that new building materials create higher building penetration losses than older ones. For mobile operators it is difficult to meet the challenge of the increased attenuations. Straightforward solutions can be increasing the transmit power of mobile terminals and base stations, or deploying more base stations (i.e. base station densification). The increasing power limit is difficult in mobile equipment due to radiation restrictions and limited battery lifetime. On the other hand, especially growing macrocellular network densification is facing objection from different sides – the deployment and operational costs of new base stations are remarkable. Furthermore, it is challenging to find suitable places for macro base stations due to people and building owners suspicions on increasing amount of radiation from base stations. Merely from technical perspective, macrocell network densification has been observed to loose its' efficiency [16]. As the cellular industry is currently looking solutions for growing capacity demands from small cells, it should be noted that the increased attenuation is not a problem only for macrocells but also for small cells if base station antennas are located outside of buildings.

Indoor usage of mobile equipment is growing up with new applications which use developed mobile networks. Different applications increase the requirements for data transfer capacity which means even better signal-to-interference-and-noise ratios (or SINRs) and wider bandwidth. Due to these requirements, operators have to provide better capacity also indoors. This anticipates a trend where operators deploy also more indoor-only base stations. On the other hand, modern radio network technologies which are developed especially for data transmission utilize higher frequencies than before. The reason for that is there are no more enough frequency resources available in lower frequency bands. Hence, higher building penetration losses are harmful for outdoor small cells also. Hence, solutions for better RF penetration into buildings are definitely needed in the future.

B. Link Budget Analysis with Measured Attenuations

Here, the impact of additional attenuation is illustrated with the help of link budget analysis. Table I illustrates a very simple link budget for high-speed packet access (HSPA) for 900 and 2100 MHz frequencies, and covering both uplink and downlink. The other values are in general inline with other HSPA link budgets and further information can be found e.g., from [17]. The obtained cell ranges and coverage areas are based on Okumura-Hata model, in which BTS antenna heights were 50 m for 900 MHz and 25 m for 2100 MHz. Mobile station antenna height was 1.5m for both systems. Stemming from the measurements, calculations below use a value of 7 dB for old buildings at 900 MHz frequency and 8.2 dB for 2100 MHz frequency, and correspondingly for new buildings 19.4 dB for 900 MHz and 21.5 dB for 2100 MHz frequency.

Table I. Example link budgets for 900 and 2100 MHz HSPA systems with approximated cell ranges and coverage areas.

		HSPA 900		HSPA 2100	
	Units	UL	DL	UL	DL
Receiving end					
Thermal noise power	dBm	-174	-174	-174	-174
RX noise figure	dB	2,5	11	2,5	8
RX noise power	dBm	-105,6	-97,1	-105,6	-100,1
Required SNR	dB	-7	-2	-7	-2
Interference margin	dB	6	6	6	6
RX sensitivity	dBm	-105,6	-97,1	-105,6	-100,1
RX antenna gain	dBi	15	0	18	0
Cable loss	dB	0,5	0	0,5	0
Antenna diversity gain	dB	3	0	3	0
SHO diversity gain	dB	2	0	2	0
Required signal power	dBm	-123,1	-93	-126,1	-96,1
Transmitting end					
TX power connection	dBm	24	43	24	43
Cable loss	dB	0	0,5	0	0,5
TX antenna gain	dBi	0	15	0	18
Peak EIRP	dBm	24	47,5	24	60,5
Isotropic path loss	dB	147,1	150,6	150,1	156,6

		HSPA 900		HSPA 2100	
Cell densities for old buildings		UL	DL	UL	DL
MS antenna height	m	1,5		1,5	
BTS antenna height	m	50		25	
wall attenuation averag	dB	**7**		**8,2**	
Cell range	km	3	3,8	1,16	1,76
Coverage area	km^2	17,5	28	2,6	6,4
Cell densities for new buildings					
MS antenna height	m	1,5		1,5	
BTS antenna height	m	50		25	
wall attenuation averag	dB	**19,4**		**21,5**	
Cell range	km	1,2	1,6	0,49	0,75
Coverage area	km^2	2,8	5	0,46	1,1

As an example for 900 MHz frequency, path loss calculation has been performed as

$$Lp = 123{,}97 + 33{,}77 \cdot log10(r) + ewa \quad (1)$$

where Lp is the path loss [dB], r is the cell range [km] and ewa is the attenuation of external walls. The cell coverage for a 3-sector macro site has been estimated to be $1.95r^2$ as in [17]. According to link budget calculations, the coverage area of macrocellular site shrinks remarkably. For example for 2100 MHz system, the coverage area decreases from 2,6 down to 0,46 km^2, which converts to a 570% increase in the need for base stations, when increased building penetration losses are taken into account. Hence, it can be concluded that this kind of increase is not possible in practice. The solutions will likely be a combination of some additional macro sites, considerably amount of new outdoor small cells, dedicated indoor networks and base stations, and residential or corporate femtocells. In one potential network layout, macrocells can provide outdoor coverage and support high mobility cases. Majority of the capacity (and coverage) demand for indoor users is offered through dedicated indoor solutions. If outdoor and indoor network operate at different frequencies, outdoor networks can provide redundancy or additional capacity/coverage through, e.g., carrier aggregation (CA) functionalities. If outdoor and indoor networks operate at the same frequency, additional attenuation provided by buildings isolates these networks, and hence actually helps to cope with interference.

V. Dedicated Apertures for Building Materials

One seeming approach to solve the coverage problems of modern buildings is to examine whether there could be any kind of specific RF-apertures made into the external wall or window structures, to assist RF signal propagation without compromising thermal insulation. In general, RF signal attenuation studies for modern windows have been receiving growing interests in recent years, and promising results have been obtained by examining frequency selective surface (FSS) structures [18]-[22]. According to the knowledge of the authors of this paper, however, there are no commercial products with feasible production costs and price yet on the market.

Following the basic theory of wave propagation [23] and apertures, and to examine the possibility of using the 'aperture' solution to assist RF propagation, an experimental box with one isolated wall was next constructed in the laboratory environment. Size of the constructed box was approximately 3m x 2m with a 10cm thick gypsum plasterboard wall. Then front wall of the experimental box was isolated using modern insulation materials, namely 35 mm thick polyurethane plates with aluminum foil on both sides. A series of separate experiments was carried out to verify the resulting attenuation level, which was found to be approximately 30 dB. Then, the actual aperture was constructed into the wall isolation material and the size of the aperture was varied. The size of the aperture should be equal or bigger than the wavelength to obtain improvements in the signal propagation, while the exact effect depends in more details on the exact size of aperture compared to wavelength and from the incident wave direction. The direction of the incident wave was also varied in the actual measurements as illustrated in Figure 6, namely the experienced angles between the wall and the incoming signal direction were equal to 90, 60, 45 and 30 degrees with a constant distance from aperture to aperture. Series of experiments was then carried out for isolated wall without aperture, as a reference, and for aperture sizes of 15x15 cm, 30x15 cm, 60x15 cm, 30x23 cm, 23x30 cm, 30x30 cm, 60x23 cm, 60x30 cm. For the aperture sizes of 23x30 cm, 30x23 cm and 30x30 cm, the obtained results were almost identical, so only the results for 30x30 cm aperture were processed further.

The measurement experiments were carried out using Rohde & Schwarz SMJ100A signal generator together with directional horn antenna A-INFOMW JXTXLB-880-NF, placed outside of the box, to facilitate deliberate directional measurements. Rohde & Schwarz FSG Spectrum analyzer together with omnidirectional antenna JXT-XDQ800/2500-3/5A were placed inside the box to experiment the signal levels. Measurements were performed at GSM 900MHz and UMTS 2100 MHz frequency bands. Distances from aperture of directional outdoor antenna and from aperture of omnidirectional indoor antenna to the wall were set to 145 cm such that the far field conditions are met, and the height of directional outdoor antenna was 160 cm while the height of the indoor antenna was 200 cm.

The obtained results, in terms of signal level increase relative to no aperture case, are presented in the Table II for various aperture sizes and incident angels. As can be observed from the results, higher signal level increases are achieved with bigger vertical sizes of the aperture. This is because the polarization of the generated signals of mobile networks is vertical and the used antennas are designed for the same polarization type. In general, the best results are achieved for the aperture size of 60x30 cm where e.g. at the UMTS2100 band, the achieved signal level increases are in the order of 6-13dB depending on the incident angle. Studying further, e.g., the impact of the wall structure thickness on the effective aperture size in true buildings, especially with small angles, is left for future work.

Table II. The measured effects of different aperture sizes on signal level increase, compared to isolated wall without aperture.

Hole size, cm (height*width)	Angle, deg	Average signal level increasing, dB	
		810-960 MHz	1.7-2.5 GHz
15x15	90	1,2	2,8
	60	0,7	1,9
	45	0,3	2,5
	30	0,2	0,6
30x15	90	1,3	6,3
	60	0,1	5
	45	0,4	4,7
	30	0,2	2
60x15	90	2,9	8,7
	60	0,7	6,7
	45	1	5,6
	30	0,9	2,8
30x30	90	3,7	10,8
	60	0,9	5
	45	0,9	4,3
	30	0,5	3,8
60x23	90	5,1	11,7
	60	1,5	6,6
	45	1,7	9,3
	30	0,7	7,4
60x30	90	6,5	13,5
	60	2,5	6,7
	45	1,9	7,2
	30	1	6,6

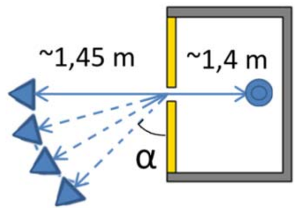

Figure 6. Principal illustration of the experiment setup related to aperture measurements.

In general, the results related to apertures are basically promising but will not most likely offer any complete solution for modern building coverage problems. Based on the measurements, one obvious limitation is that the size of the apertures needs to be fairly large, which may then already impact the thermal insulation. Another limitation is the area of influence, as the signal strength increases only in the vicinity of the aperture installation.

VI. Conclusions and Discussions

Energy saving demands and regulations are becoming increasingly tight and they are forcing building construction industry to find more energy efficient solutions. Nowadays a big amount of modern building materials includes metallic surfaces or foil, and modern windows also consist of low emission glasses, which all cause significant additional attenuation of radio signals compared to earlier building materials. This has started to cause mobile cellular network coverage problems in various modern buildings, and as the penetration of modern building materials keeps increasing, the propagation problems become more and more significant. In this article, these propagation and attenuation problems were studied in block of flats type apartment buildings and townhouses, using comprehensive measurements of commercial mobile networks covering both GSM 900MHz and UMTS 2100MHz bands. According to the measurement results, the average outdoor-indoor penetration losses in modern buildings are in the order of 19-23dB while the corresponding numbers for older buildings are around 6-9dB. Thus the additional average attenuation is around 13-14dB which is substantial. Furthermore, peak outdoor-indoor attenuations in measured modern buildings were around 35dB which is also substantially high number. Compensation of such massive extra attenuations is very challenging, and costly, though e.g. classical macro network densification. Hence alternative solutions, like dedicated indoor networks in form of e.g. small cells, are seen increasingly interesting and important. Also construction material innovations, like dedicated apertures in wall insulation materials or windows, could be an alternative possibility. Impacts of such aperture were also preliminary studied and demonstrated in this paper, with promising looking results, but the size of the aperture is in practice limited by thermal insulation requirements, which in turn then limits the indoor area of influence where RF signal coverage can be improved. Finally, the provided mobile network measurement results can also be seen beneficial for dedicated indoor network solutions, as increased indoor-outdoor RF signal attenuations also reduce e.g. femto-macro interference and other possible signal leakage problems from indoors to outdoors if coexisting at the same frequency. Hence, probably the most efficient solution will be dedicated indoor network solutions realized using e.g. femto or other small cell technologies.

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