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Measurement of electromagnetic field attenuation by building walls in the mobile phone and satellite navigation frequency bands

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***Abstract*— The electromagnetic wave (EM) attenuation by building walls is experimentally investigated, focusing on the frequency range 700 MHz - 5 GHz. The results of this research can be used in the planning of the in-door radio coverage of wireless access networks like 2G, 3G, 4G, WiFi, and future 5G mobile phone systems, in the study of satellite navigation applications and in the evaluation of the resident population exposure to electromagnetic fields emitted by the radio base stations (RBS) of the mobile phone radio access network (RAN). Measurements are obtained using a portable vector network analyzer (VNA) connected to two light Vivaldi antennas. Time domain methods are used to reduce errors caused by multiple paths. Measurements of EM building wall attenuation have been carried out in the city of Rome in different buildings topologies: historical buildings from Roman Empire up to meddle 1900th century and modern reinforced concrete buildings. Measurements of EM shielding effectiveness (SE) show values even greater than 80 dB.**

***Index Terms*—Satellite Phone, Satellite Navigation Systems, Mobile phone, GSM, UMTS, LTE, WiFi electromagnetic field attenuation, building wall shielding effectiveness.**

I. Introduction

In the last twenty-five years mobile phone networks increased all over the world. Signals are transmitted and received by the radio base station (RBS) of the mobile network operators (MNO) and by mobile equipment (ME), this last more often located within apartments, offices, and every type of buildings. This is why MNO generally are interested in analyzing the “indoor” radio coverage of “outdoor signals”, the so-called outdoor-to-indoor communications. Specifically, in the outdoor-to-indoor transition, the coupling through windows, the building wall attenuation, and the indoor losses strongly affect the level of electromagnetic fields [1-2], determining the real radio coverage. The minimum required level of received signal for the ME, depends on the service type, i.e. voice or data and by the radio access network system. GSM, UMTS, LTE [3] radio access networks, have each one different requirements and different operating frequencies which in turn affect the electromagnetic propagation. The recent growing market of smartphones is pushing the MNO to increase the indoor radio coverage in order to grant the customer quality of experience in voice calls and above all in the high speed packet data services like internet, email, video streaming, gaming, social network and so on [4]. Next to this point there is the common concern about the effects of the electromagnetic fields on the human health [5]. The attenuation of the electromagnetic field emitted by the radio base station antennas depends primarily on the distance and on the urban Kenyon environment type. Moreover close to the buildings it depends on the floor level and on the type of buildings structure i.e. by the walls material and apertures topologies on the building walls . Frequencies in the range 700 MHz - 5 GHz are currently exploited for terrestrial mobile phones like GSM, UMTS, LTE, WiFi systems, satellite mobile phone like IRIDIUM system and satellite navigation system like GPS, Glonass and Galileo. Nowadays due to the diffusion of smartphones incorporating satellite navigation systems, it is important to understand why sometimes it is almost impossible to use such devices in indoor locations.

Even though electromagnetic shielding of concrete is reported in [6], no detailed studies have been conducted concerning the electromagnetic attenuation of building walls built with different materials and masonry techniques. This paper is focused on the measurement of EM attenuation of building walls built in many centuries in Rome (Italy) by using concrete composite, which could be representative of most urban buildings in Europe.

Paper is organized in four main sections: introduction, measurement method, results, discussion.

II. Measurement Method

Measurements of SE are performed using the Anritsu VNA Master MS2026C connected to two antennas as in the scheme in Fig.1. In particular the SE of walls is measured for normal incidence by comparing the module of scattering parameters of transmission S_{21}(dB) in free space with that obtained when the wall is placed between the antennas:

$$SE(dB) = S_{21(FreeSpace)} - S_{21(Wall)} \qquad (1)$$

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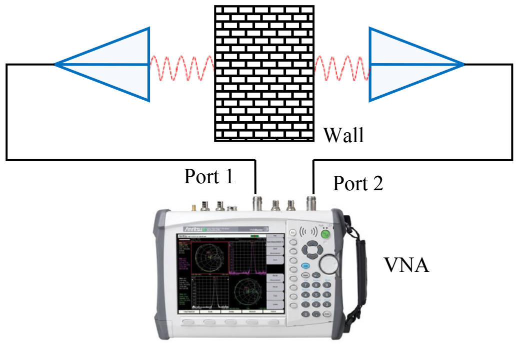

Fig. 1 General scheme of the walls SE measurements.

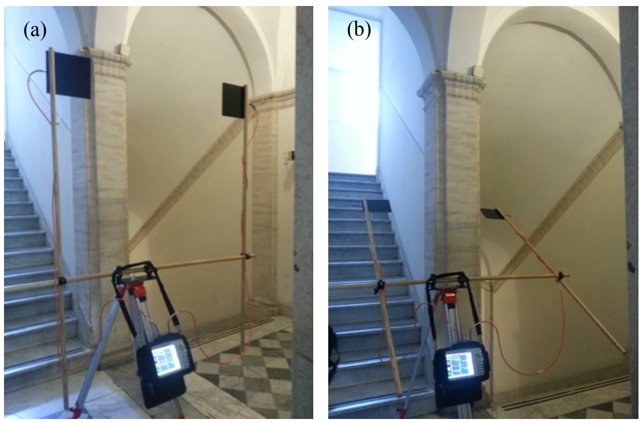

Fig. 2 VNA connected to Vivaldi antennas couple by using a dielectric support made by wood and plastic interconnections. (a) Free space attenuation measurements. (b) Attenuation measurement of the interior wall of 16th century building.

Main problems in these measurements are maintaining a constant distance and alignment between antennas and reducing the errors due to multiple paths caused by wall boundary under test and other walls and objects in the vicinity of antennas. The first issue has been taken into account by providing a dielectric antenna support able to be located in free space and around the wall without changing the antenna distance/alignment. Fig.2 shows the measurement setup, in which the distance between the antennas is 1.44 m. The second source of errors is minimized by using the time domain technique to gate only the first useful delayed component of the directed transmitted signal between antennas. The *time domain* representation of the measurement data allows distinguishing components having different time delays, related to waves propagating along various paths. *Time domain gating* refers to the process of selecting a region of interest in a portion of the time domain, removing unwanted responses, and displaying the result in the frequency domain. Gating can be thought of as multiplying the time domain response by a mathematical function with a value of one over the region of interest, and zero outside this region [7]. The gated time domain function can then be forward transformed to display the frequency response without the effect of the other responses in time. When implementing this procedure, it is very important to correctly identify the contribution of waves pertaining to the wall penetrating path, which, in case of strongly attenuating walls, could be very small compared to the components pertaining to other paths, such as the diffracted propagation path by the wall edge and/or reflected paths by surrounding objects (e.g. other walls). In that case, the time response of the penetrating component may be very small with respect to the others and the first visible arriving time response might not be the penetrating component. The contribution of the penetrating wave can be identified by the analysis of a sequence of measurements, obtained by shifting the antennas along the wall, so that a larger portion of the wall falls between the two antennas at each measurement. The geometry of the antenna position during the measurement sequence is shown in Fig.3, ranging from free space into the deepest part of the wall. The first three measurements are substantially in free space condition. The first part of wall is surrounded by a 3 cm thick of additional travertine for decoration, shown in solid gray in Fig.3. The standard deviation in measurements varies with the frequency and are around 1.5dB (700 MHz), 1.8 dB (900 MHz), 2.4 dB (1.8 GHz), 2.3 dB (2.7 GHz), 3.6 dB (5 GHz). It has been computed by repeating 15 times the same measurement of attenuation shown in Fig.2. Resolution of the time domain measurements depends on the adopted frequency span (700 MHz – 5 GHz in our case) and on the window function used in the Inverse Fourier Transform processing (a rectangular window in our measurement). For these settings, the VNA user manual returns a pulse with of 0.28 ns, corresponding to a spatial resolution of 8.4 cm in free space.

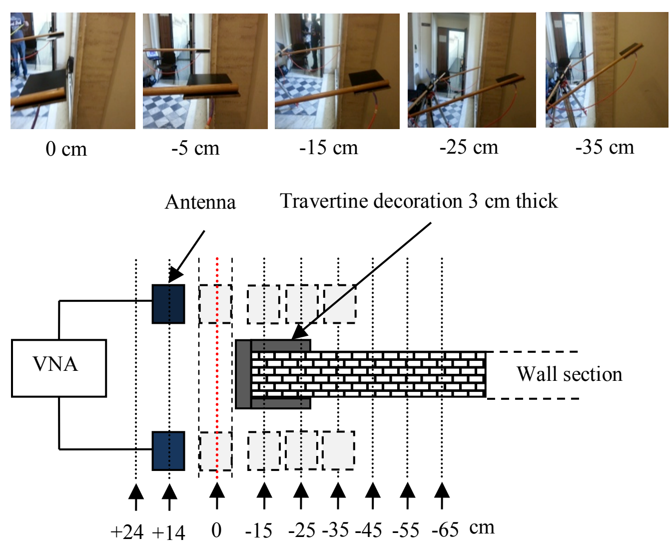

Fig.3 Positions of the antenna to perform the sequence of measurements. The positions are: +24, +14, 0, -5, -15, -25, -35, -45, -55, -65 cm

The results of gating in each measurement position are shown in Fig.4. The delay as a function of the antenna position introduced by wall on the useful first component of signal is highlighted by a line connecting the main peak of each measurement. In the positions +24,+14,0, the delay of the main peak corresponds to the component of RF signal directly transmitted and received by the antennas in free air at a distance of 1.44m. The scattered multipath components appear delayed and with lower amplitudes. In the position -5 cm, where the antenna is by one half partially overlapped with the wall corner, the gating shows two main peaks. The one with

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no delay pertains to the direct path in free air. The delayed one (about 2.56 ns) is due to the contribution of scattered components. These two peaks are roughly of the same amplitude, meaning that no significant attenuation of the wall is involved, but only a delay due to the longer path of the scattered component. When the position of antennas is −15 cm, the direct path between the antennas is obstructed by the wall, including the travertine decoration. As a consequence, the direct path component is strongly attenuated and the highest peak pertains to the scattered component. In the measurement at −25 cm, two main delayed peaks with similar magnitude are observed. This is due to the partial overlapping of antennas between the naked and the part of wall covered by the travertine, resulting in a lower attenuation of the direct path with respect to the previous measurement. The measurements of the deep part of the wall (−35cm, −45cm, −55cm and −65cm) show an evident direct path peak, with a delay of about 1.1 ns with respect to the direct path in free air, due to the reduced speed of light within the wall. The other scattered components are strongly attenuated, which leads us to conclude that in the last four measurements we are properly measuring only the direct path contribution through the wall.

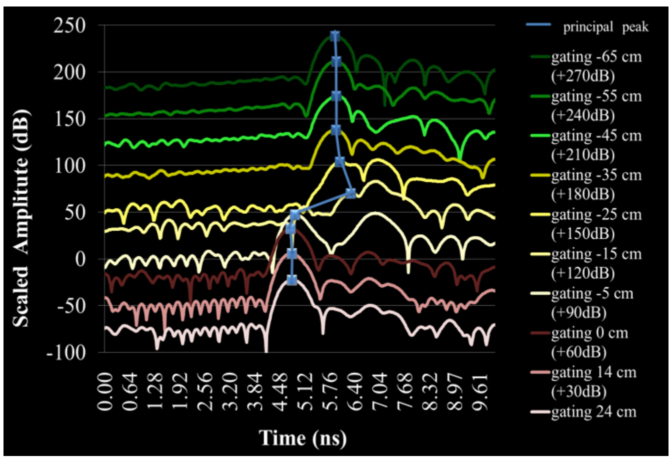

Fig.4 Gating in different positions of the antenna (see Fig. 3). For better graphical visualization, curve overlapping in the plot is avoided adding a fictitious constant (in dB) to the reported amplitudes, in increments of 30dB each.

The procedure of measurement sequence outlined, using the time response, evidences which responses are the penetrating path and scattered path, showing clearly their time delays and verifying that the penetrating path is correctly extracted and the measured attenuation is showing the penetrating loss appropriately.

III. RESULTS

Table I reports the measurement of SE for different kinds of building wall (for more detailed pictures of building walls of Table I, please see the Supplementary Information). Measures are rounded to the nearest integer. Concrete refers to buildings after 1960. Brick refers to buildings after 1920, (i.e. public housing built during Fascism period and after the end of Second World War). Concrete and marble refer to buildings after 1920, (i.e. offices and public building, during Fascism period like University Sapienza).

TABLE I
AVERAGE SE AT DIFFERENT FREQUENCIES. VALUES ARE ROUNDED TO THE NEAREST INTEGER

Material of wall	Internal or External wall	Thick (cm)	SE (dB) 900 (MHz)	SE (dB) 1800 (MHz)	SE (dB) 2700 (MHz)	SE (dB) 5 (GHz)
Concrete (~1960)	Internal	50	12	15	20	
	External	50	17.5	25	29	
	External	40	11	13.5	19.5	
	External	50	27	32	34	
	External	60	26	32	34.5	
	Internal	70	30	35	39	45
	External	20	12	15	15	11
	External	20	8	9	10	11
Brick (Fascism ~1920)	Internal	30	9	10.5	13	
	Internal	30	9	12	13.5	
	External	50	11	14	24.5	
	External	30	7	14	22.5	
	Internal	25	6	15	20	
	Internal	30	8.5	10	11	
	Internal	30	9.5	10	12.5	
	External	30	13	15	17	
	External	30	11	13	16	
	Internal	40	6	10	22	14.5
	Internal	40	11	14	16.5	15
	Internal	40	4	7	10	
	Internal	40	6	8	12	
Concrete & marble (Fascism ~1920)	External	70	80	80	75	60
	External	50	8	12	15	34
	External	65	16	23	27	30
	External	80	30	33	34	36
	External	50	7	11	18	20
	Internal	25	4	8	9	7
	Internal	*50*	*4*	*4*	*4*	*5*
	Internal	*70*	*12.5*	*16*	*22*	*34*
	Internal	*70*	*6.5*	*8.5*	*12*	*12*
	Internal	*70*	*7.5*	*10*	*12.5*	*9*
	Internal	*70*	*4*	*5*	*11*	*11*
	Internal	*70*	*3*	*3*	*3*	*6*
Historic (~150 and ~1500)	External	80	75	83	69	
	External	35	25	26	26	30
	Internal	25	13	17	22.5	25
	Internal	40	25	37	47	60
	Internal	50	10.5	13	17	
	Internal	50	6	11	19	
Indoor light partition (drywall &perfo-rated)	Internal	20	2	3	4	
	Internal	20	2	2	3	
	Internal	20	8.5	11	15	
	Internal	20	8	8	9	
	Internal	20	4	6	9	
	Internal	20	7	10	13	

Historic part identifies buildings of Roman and Renaissance periods (i.e. Domus Aurea built in the emperor Nero and Engineering Faculty of Sapienza University within the Monastery of Canonici Regolari next to San Pietro in Vincoli Cathedral, built in 1500, see Fig.2). Indoor light partitions are walls made of light materials i.e. perforated and drywall built recently within offices and apartments. In some cases interior walls of large thickness show surprisingly a very low value of SE (few dB, see SE of interior walls reported in Italics in Table I). The related post-analysis of the building structure showed that such internal walls are almost empty and the apparent thickness is only architectural, to provide continuity with concrete walls. As far as the external walls are concerned, the SE of concrete buildings show values up to 40 dB (see Fig. 5a,b,c). Modern reinforced concrete walls of Telecom Italia Headquarter were built around 1960. The

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related SE measurements show values up to 45 dB (see Fig. 5d,e). In Fig. 5 almost all the plots report an increase of the SE with the frequency. This is due to the EM absorption component of SE which increases with frequency due to resistive losses of walls [6]. Plot in Fig. 5h,i seems to behave lightly differently but this is an effect due to an insufficient dynamics of the measurement setup. In fact, Roman wall attenuates the RF so much that it was difficult to clearly detect the transmitted RF component even restricting the IF bandwidth to 10 Hz. The expected SE should be even greater than 85-90 dB measured.

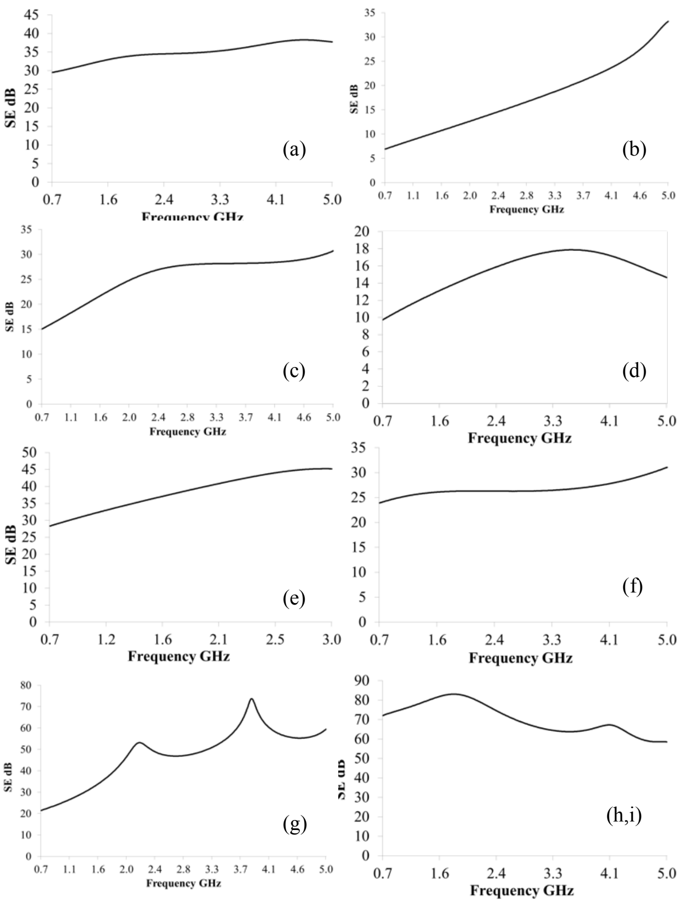

Fig. 5 Plot of SE. (a,b,c) External reinforced concrete walls of University Sapienza (1935), (d,e) Indoor wall and reinforced concrete bearing wall of Telecom Italia (1960), (f) external brick wall of University Sapienza next to San Pietro in Vincoli Cathedral (1500), (g) internal brick wall of University Sapienza next to San Pietro in Vincoli Cathedral, (h,i) Roman wall of Domus Aurea close to Colosseum (2000 years ago).

IV. Discussion

Table 1 shows the measured wall attenuations. The values of the attenuation significantly vary even for one kind of material. For instance, for concrete and marble, the values are from several dB to 80 dB even at a single frequency. This fact is due to a non-uniformity not only in the thickness material but also in the concrete characteristics. The 50 cm thick walls are both located at the second floor of the building, so that the density of the walls is lower than at the ground floor. The high-thickness walls at the ground floor (70 and 80 cm) show an apparently inexplicable difference in the attenuation due to a different use of the walls themselves. In fact the 70 cm wall is a real load bearing wall, while the 80 cm wall, even if external is not a bearing wall. Furthermore in these two measures we can appreciate the effect of a marble covering of the wall. The 65 cm wall in the same category is, in fact, without marble even it is a bearing wall. As we look at the internal values, we don't have to be led astray by the dimensions, because there are some vacuums in the walls that lower the attenuation. For the other categories we can say that the variability of the attenuation is probably due to the quality of every single wall. For instance in the concrete section we have to consider the quality of the additives of the concrete as sand, gravel, clay or others and their granulometric composition, that is an index of uniformity. A good additive is characteristic of a compact wall by mean of its granulometric composition: more the value of the granulometric composition is low (1 is the most compact) more the additive is compact, more the concrete is compact and more the attenuation is high. The reinforced concrete composites and hybrid steel and concrete framed structures, which consist of bare steel (BS), reinforced concrete (RC) and steel-concrete composite (SCC) are able to produce not homogeneous electromagnetic responses even when similar thickness of walls. It is also interesting the analysis of Roman wall (Domus Aurea close to Colosseum). Roman concrete, also called opus caementicium, was a material used in construction during the late Roman Republic through the whole history of the Roman Empire. Roman concrete, like any concrete, consists of an aggregate and hydraulic mortar – a binder mixed with water that hardens over time. The aggregate varied, and included pieces of rock, ceramic tile, and brick rubble from the remains of previously demolished buildings. Reinforcing elements, such as steel rebar, were not used [8]. From the high attenuation values obtained from the measurements, the quality of concrete seems quite good as also testified by age of walls.

V. Conclusion

This paper presents the results of a campaign of measurements of the electromagnetic wave attenuation by building walls in the city of Rome. The measurement technique has been analyzed by displacing the antennas from free space into the deep part of a wall. Different types of urban buildings were considered and SE up to 85-90 dB was found. We think the results of measurement campaign could be useful to better explain the electromagnetic attenuation phenomena happening in outdoor-to-indoor environments, above all when they are located in historical cities like Rome.

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