FUTURE OF WLAN AND THE INFLUENCES TO THE ARCHITECTURAL FORMS AND DESIGN

by
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ABSTRACT

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The world is dynamic and technology as well. Different fields such as architecture and engineering have to solve some common problems due to the developments of the technology. We have not able to transform the networking systems wires to wireless due to some performance problems on the networking yet. Current wireless local area network (WLAN) applications for architecture need to be considered and designed carefully.

The main objectives of this study was to examine the current situation in architectural design, analyzing the materials which are used at the buildings in terms of how they respond to electromagnetic waves and getting some data to achieve better designed buildings that are equipped with wireless networking. Another aspect is human health issues; the study also mentions about the frequency and human health relation. Thus, the results of this study will assist to design interior and exterior forms of the future building which is integrated with the technology and will be helpful to design professionals to deal with such issues.

KEYWORDS: WLAN, Building Technology, Electromagnetic Wave Propagation, Wireless Networking, Construction Materials.

ÖZET

KABLOSUZ İLETİŞİM SİSTEMLERİNİN (WLAN) GELECEĞİ, BUNUN TASARIM VE MİMARİ FORMLAR ÜZERİNDEKİ ETKİLERİ

Dünya gibi teknolojide her gün dinamik bir şekilde ilerler. Günümüzde Mimarlık ve Mühendislik gibi farklı alanlar bu gelişmelere bağlı olarak ortak sorunlar yaşamaktadır. Performans problemleri yüzünden, iletişim sistemleri kabloludan kablosuza henüz tam olarak adapte edilememiştir. Güncel olan kablosuz iletişim sistemleri (WLAN) mimari uygulamalarda iyi incelenmeli ve bu durum göz önünde bulundurularak binalar dikkatlice tasarlanmalıdır.

Bu çalışmanın amacı kablosuz iletişim sistemlerindeki bu güncel problemleri mimari tasarım çerçevesinde değerlendirebilmek, yapı malzemelerinin analizini, elektromanyetik alanlar karşısındaki tepkilerini araştırmak ve bunun sonucunda bina tasarımlarında izlenecek metodların belirlenmesini kolaylaştırabilmektir. Üzerinde durulması gereken diger konu ise insan sağlığıdır. Bu çalışma aynı zamanda frekans ve insan sağlığı ilişkisinide değerlendirmiştir. Sonuç olarak bu çalışma, gelecekte kablosuz iletişim sistemleri ile iç içe olan yapılardaki iç ve dış formların tasarlanmasında mimarlara, karşılaşacakları sorunları çözebilmelerinde yardımcı olacaktır.

ANAHTAR KELİMELER: WLAN, Yapı Teknolojisi, Elektromanyetik Dalga Yayılımı, Kablosuz İletişim Sistemleri, Yapı Malzemeleri.

To my Parents

With all my Love

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LIST OF SYMBOLS / ABBREVIATIONS

WLAN	Wireless Local Area Network
mi	Miles
km	Kilometers
RF	Radio Frequency
IrDA	Infrared Data Association
LAN	Local Area Network
EMW	Electromagnetic Wave
WiMAX	Worldwide Interoperability for Microwave Access
UBW	Ultra Bandwidth
EMC	Electromagnetic Compability
EMI	Electromagnetic Interference
NIST	The United States National Institute of Standards and Technology
Hz	Hertz (formerly cycles per second)
KHz	Kilohertz
MHz	Megahertz (million Hertz)
GHz	Gigahertz (thousands of MHz)
cm	Centimeter
m	Meter (SI unit of length)
MM	Million
E	Electric field
H	Magnetic field
λ	Wavelength

MMAC	Multimedia Mobile Access Communication System
HiperLAN	High Performance Local Area Network (European)
IEEE	Institute of Electrical and Electronic Engineers
FHSS	Frequency Hopping Spread Spectrum
DSSS	Direct Sequence Spread Spectrum
RFR	Radio Frequency Radiation
ANSI	American National Standards Institute
ICNIRP	International Commission on Non-Ionizing Radiation Protection
NCRP	National Council on Radiation protection and Measurements
mW	Milliwatt
MAN	Metropolitan Area Network
Mbps	Megabits per Second
FCC	Federal Communications Commission for the United States
CEN	European Committee for Standardization
CENELEC	European Committee for Standardization
ETSI	European Telecommunications Standards Institute for Europe
BSI	British Standards for Britain
TSE	Turkish Standards Institute
IEC	International Electro technical Commission
RFI	Radio Frequency Interference
σ	Electrical conductivity
J	Current density
E	Electric field strength

μ	Magnetic permeability
B	Magnetic field
H	Magnetic field strength
D	Electric displacement field
E	Electric field
ε	Permittivity
E_{trans}	Transmitted field
E_{inc}	Incident electric field
τ	Transmission coefficient
α	Attenuation constant
L	Length of the material
P_r	Received Power
P_t	Transmitted Power
G_a	Maximum Gain of the antenna A
G_b	Maximum gain for B
W_{rec}	Received Power in dB
W_{tr}	Transmitted Power in dB
$G_{Rec(max)}$	Received Gain in dB
$G_{Tr(max)}$	Transmitter Gain in dB
S/m	Siemens/meter

PREFACE

I here would like to thank the people who made this thesis possible. I have the pleasure to thank Prof. Dr. Fatih Pakdil, my thesis supervisor who witnessed to my growth during these MArch years and for his trust prior to begin working on this subject.

I am honored for being given the chance of working with Dr. Cahit Canbay, my thesis co-advisor who showed me how to breaking the walls between different disciplines. He always encouraged me and provided me support. He taught me how to deal with the issues during this study. This thesis would not have been possible without his remarkable patience and prompt guidance in this complex EMW propagation issues.

I thank to Associate Prof. Dr. Ahmet Kızılay for helping me with his comments and many thanks to my friend Research Assistant İlhami Ünal for his help especially during the sample office room modeling experiment process.

I would like to thank my committee members for careful reading and for suggestions in improving the manuscript and many thanks to Prof. Dr. Yavuz Koşaner who is my chairman at interior architecture department for going through the thesis and correcting the format.

Hopefully, this research will help to highlight the importance of this issue and accelerate the developments in Turkey and also establish a well-built reference for my future studies about this topic. All in all, the future is bright waiting for us to solve more technology related issues, we just need to understand and show a bit effort.

Serhan Hakgüdener

November, 2007

CHAPTER 1

1. INTRODUCTION

There are two types’ problems as seen and unforeseen. People generally tend to ignore the unforeseen ones. Electromagnetic waves (EMW) are metaphysic for the most because not seen like light. They are basically *“oscillating electric and magnetic fields traveling together through space at a speed of nearly 186,000 mi/300,000 km per second. The (limitless) range of possible wavelengths or frequencies or electromagnetic waves, which can be thought of as making up the electromagnetic spectrum, includes radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.”* [1]

When you deal with electromagnetic waves, this design issue is not considered by the most professionals in architecture till users encounter technical difficulties on their wireless networking or any electronic devices they use. Thus, Wireless Local Area Networks (WLAN) uses Radio Frequency (RF) or infrared waves. They do not demand optical or copper wires to transfer the data. They are user friendly in terms of installing, full scope to act and broadband capability. [2] WLAN systems also uses small amount of infrared (IrDA) technologies besides RF. Infrared systems use waves that are below of visible light spectrum. This is how they transfer the data between antennas. However, Infrared radiation is sensitive to dust, moisture and light as physical affects. This technology also requires line of sight between equipments. Moreover, the coverage area is just 10 meters. [3] Because of those reasons above mentioned, Infrared technology is not appropriate for interior spaces. In contrast, hybrid combination of Local Area Network (LAN) and WLAN brings flexible design solutions in architecture. For instance, main line is brought by local telephone company to the building and distribution is made by WLAN.

The future of WLAN is wide open because of industrial organizations support and demand from the market. Those studies focus on non-licensed frequencies and pushes for new regulations for countries. [4]

The objective of this study is to determine both electromagnetic waves (EMW) propagation versus building materials and assisting to architecture society when they deal with WLAN related issues during their design process. To be able to approach the subject matter, this thesis is organized as follows:

- First Chapter has the brief introduction of electromagnetic waves (EMW) including electromagnetic radiation, the concept of WLAN, EMW propagation and the function of the buildings, frequency and human health relations plus detailed research about WLAN technologies such as; WiMAX, 802.11n and UBW so that it helps to understand in applications for architecture and interior design. [5]
- Second chapter deals with EMC (Electromagnetic Compability), EMI (Electromagnetic Interference) and case study for RF signals and material relations give us deeper understanding of both building materials and electromagnetic wave response such as; glass, brick, concrete, wood, etc. The results of the experimentations are analyzed and the best design approach is experimented using the basic construction materials.
- Third chapter is Megacells to Picocells applications. A sample office room plan layout is chosen to make the site survey. Moreover, HFSS (High Frequency Structure Simulation) is used to be able to understand electromagnetic propagation predictions for the room using the software. Finally, sample office room modeling experiment is done to spot electromagnetic propagation in 1/5 scaled model. As a result of this, For WLAN applications, different variables are analyzed in a real

environment so that the professionals might be using those as reference during the design process of buildings.

- Fourth chapter concludes and discusses future prospects of WLAN integrated design.

The results of this study would provide understanding electromagnetic propagation for building materials in WLAN frequencies and help to the designers such as; which materials they need to choose depends on the function of the buildings prior to start construction. Using these results also will shape new design code both buildings and future forms of the structures in case of they are considered carefully.

1.1 Electromagnetic Radiation

Electromagnetic radiation (also known as radiant energy) is the biggest of wave-like transfer way of the energy through deep space. It also includes visible light that have the same propagation features of the other wave types such as; Microwaves, Infrared, Ultraviolet, X-Rays, Gamma Rays, Radio Waves.[6]

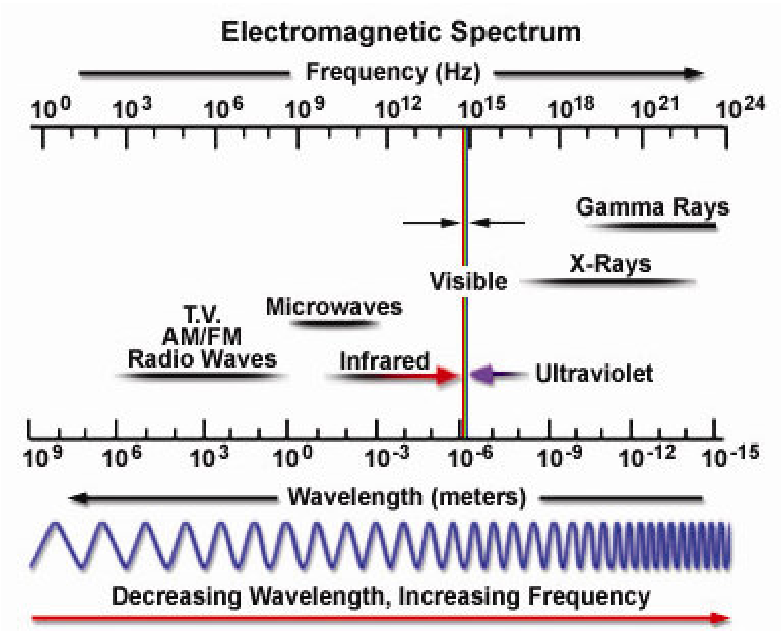


Fig 1.1.a: Electromagnetic spectrum [42]

Figure 1.1.a shows the entire spectrum of electromagnetic radiation including frequency wavelength relation as higher frequency means lower wavelength. In addition to that both the relation between wavelength and frequency (See Table1.1.b) and the main application in each frequency (See Table 1.1.c) are needed to be showed.

Band	**Frequency**	**Wavelength**
ELF	30-300 Hz	10-1 Mm
VLF	3-30 KHz	100-1 Km
LF	30-300 MHz	1 Km-100M
HF	3-30 MHz	100-10m
VHF	30-300 MHz	10-1m
UHF	300-3000 MHz	1m-10 cm
SHF	3-30 GHz	10-1 cm
EHF	30-300 GHz	1 cm-1 mm

Table 1.1.b: The relationship between wavelength and frequency [42]

Table 1.1.b demonstrates band-frequency and wavelength relation in mathematical form guiding us to be aware of this relation.

AM broadcast band	535-160 kHz
Short wave radio	3-30 MHz
FM broadcast band	88-108 MHz
VHF TV (2-4)	54-72 MHz
VHF TV (5-6)	76-88 MHz
UHF TV (7-13)	174-216 MHz
UHF TV (14-83)	470-890 MHz
Microwave Radio links and Satellite Communication	1GHz-20 GHz
Mobile Telephony	800 MHz-3GHz

Table 1.1.c: The main application in each frequency range [42]

Thus, we better concentrate on higher frequency above 1 GHz range in following chapters shown on Table 1.1.c in this study for WLAN application range. The contributions about EMW spectrum begin as the link between light, electricity, and magnetism. Infrared light, the first “invisible” form of electromagnetic radiation is discovered by British scientist and astronomer William Herschel. [7]

Ultraviolet radiation, the other type of the visible spectrum is discovered by Wilhelm Ritter. He investigates the energy association with visible light which has various colors stimulate darkening of paper saturated with a solution of silver nitrate. As a result, He discovers another invisible form of light, beyond the blue end of the spectrum. [8]

Danish physicist Hans Christian Ørsted associates electricity and magnetism in 1820. At the same time, Ørsted discovers that electrical current flowing through a wire could produce deflections of a compass needle. [9] After French scientist André-Marie Ampères' demonstration of two wires carrying electrical currents could be made to attract or repel each other which is strong evidence showing electricity and magnetism were very closely related to each other. [10]

Consequently, in 1865, Scottish scientist James Clerk Maxwell manages to explain mathematically his kinetic theory of gases. The result is the links between electricity and magnetism. They are so closely bound that often acts together as electromagnetism. Moreover, Maxwell discovers alternating current produces waves that radiates out into space at the speed of light. Those observations are concluded that visible light is a form of electromagnetic radiation. [11]

The basic definition of EMW is explained as; oscillating field vectors of both electric (E) and magnetic (H) is oriented at right angles to each other. Basically, a wave propagates or in other words continues his journey like that. It also transports energy from the radiation source to an unspecified final destination. [12] Those two oscillating fields are perpendicular two each other showing in Figure 1.1.d

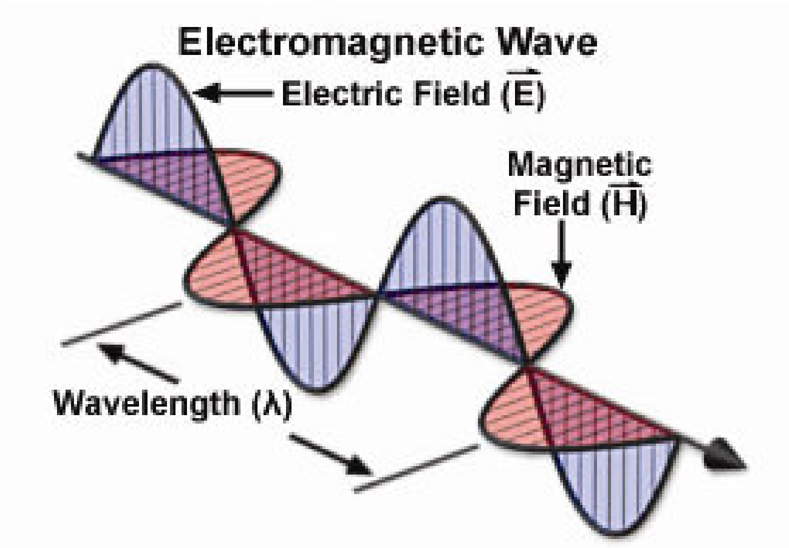


Fig 1.1.d Electromagnetic Wave [43]

And the vibration is sine wave in mathematical form. As shown in Fig 1.1.d

In addition to that "*Electric and magnetic field vectors are not only perpendicular to each other, but are also perpendicular to the direction of wave propagation*." [43] To simplify to understand illustrations magnetic oscillating fields of electromagnetic waves are often omitted though they are known as exist.

Another feature is defined that various type of electromagnetic radiation has identical wave-like properties. Every category which includes visible light oscillates in a periodic way and shows some characteristic as; amplitude, wavelength, frequency and intensity of the radiation. [13]

Thus, measurement of all electromagnetic waves is the magnitude of wavelength (in a vacuum). The unit is nanometers (one-thousandth of a micrometer) for the visible light portion of the spectrum.

Last definition is about the number of sinusoidal cycles called frequency (see Figure 1.1.d) which is usually expresses in quantities of hertz (Hz) or cycles per second (cps). [13]

Consequently, from visible light to the others as; Microwaves, Infrared, Ultraviolet, X-Rays, Gamma Rays, Radio Waves which have electric (E) and magnetic fields (H) perpendicular to each other are the parts of entire electromagnetic wave spectrum. Furthermore, the relationship between wavelength and the frequency is mentioned above as higher frequency means lower wavelength. After this brief introduction, the concept of WLAN can be introduced as follows.

1.2 Concept of WLAN

Early 90s is the period of wireless networking developments. Comparing both wireless and wired networking systems show the benefits of using the first one. The capability of fast data transferring makes the wireless systems become widespread. The data transfer of two or more digital devices as computers set up the structure of WLAN. This type of networking system might be used by the purpose of education, private, national, or public. In addition, WLAN has the all features of LAN (Local Area Networking) which uses cable for connection between devices. It also provides broadband internet access which means gateway to the e mails or shared folder options to the user. Moreover, WLAN is very efficient in open spaces as parks and streets. There are two standard technologies which are US based IEE 802.11x and European based HiperLAN. [14]

Beside of these Japanese based MMAC (Multimedia Mobile Access Communication System) is another alternative to use WLAN. Unfortunately, MMAC system uses 3-60 GHz frequency band and not suitable for European standards. [15]

IEEE (Institute of Electrical and Electronic Engineers) defines the most common standards worldwide. IEEE 802.11 works with 2.4 GHz frequency. The max capable limit is 2 Mbps by using FHSS (Frequency Hopping Spread Spectrum) and DSSS (Direct Sequence Spread Spectrum). The purpose of this protocol is that keeping the current LAN systems in one roof and make adaptation to WLAN. After successful achievements of those studies, IEEE published new WLAN protocols as 802.11 xs. The studies still continues to provide better service. IEEE 802.11b work with 2.4 GHz frequency. It is commonly used in Turkey and worldwide. It can transfer the data up to 11 Mbps. Nowadays, 802.11g protocol works with the same frequency mentioned above. Their limits are up to 54 Mbps and very popular in the market. [16]

Another protocol is HiperLAN (High Performance Radio LAN) that is developed in Europe and it is a different standard of WLAN. There are two types which are HiperLAN1 and HiperLAN2 work with 5 GHz frequency. They have some similarities with 802.11 in terms of speed and capacity. Moreover, HiperLAN uses ATM technology that provides better service quality. [17] Unfortunately, it is not very common like WLAN. As a result, HiperLAN might be considered as better alternative to WLAN.

All in all, early 90s is the period of acceleration for WLAN. IEE 802.11x and European based HiperLAN are introduced to the market and spread worldwide. Researches still continue and push the limits of WLAN in terms of standards, performance and technology. Next section shows us the function of buildings and EMW propagation that helps better understanding of WLAN.

1.3 EMW propagation and the function of buildings

Another aspect needs to be considered is electromagnetic wave and frequency relation. EMW penetrates variously to buildings due to the frequency. The function of the building becomes significant in terms of propagation such as; hospitals, apartments, schools, and military buildings. They require different needs for propagation. For instance, military orders total security that means full exterior sealing of the buildings using some materials as "*An electromagnetic wave absorption panel for use in building construction includes a* *protective tile layer, an absorber layer, a metal reflective layer, and a building support layer, such as concrete. The absorber layer utilizes novel materials including high dielectric constant materials, such as ABO.sub.3 type perovskites, layered superlattice materials, conducting oxides, and signet magnetics, ferroelectrics, such as ABO.sub.3 type perovskites and layered superlattice materials, garnets, a nickel-zinc ferrite, Ni.sub.0.4 Zn.sub.0.6 Fe.sub.2 O.sub.4, and polymer-ceramic composites of the above materials.*"[18] Nowadays technology is capable to see the heart beat of a man from the satellites. Thus, hospitals, residential buildings and schools need variety of design solutions to reach EMW and health friendly environments. However, we do not have chance to see good design solution samples around because EMW is not being aware of thread or necessity for most professionals and it is considered unforeseen factor for design. Next section covers this unforeseen factor.

1.4 Frequency and Human Health

The range of radio frequency (RF) spectrum spans 3 kHz to several hundred GHz. The microwave range starts from 1 GHz to 40 GHz is being used in contemporary point to point, wireless, and satellite communications. The public concern is that how radio frequency and microwave radiations affect on human health of exposure close to radio and television transmitters, mobile base stations, wireless networks and so on.

Several investigations of non-ionizing radiation as RFR (Radio Frequency Radiation) levels are done all over the world to resolve the safety levels of exposure on humans.

Specific guidelines and standards have been issued by ANSI (American National Standards Institute) /IEEE (Institute of Electrical and Electronics Engineers), ICNIRP (International Commission on Non-Ionizing Radiation Protection), NCRP (National

Council on Radiation protection and Measurements) and other organizations. These standards are expressed in power density in (mW/cm^2). For instance,

The 1992 ANSI/IEEE exposure standard for the general public is 1.2 mW/cm^2 with the antennas operating in the 1800-2000 MHz range. The RF levels produced by mobile base stations that can produce known biological effects are showed below. [19]

100 mW/cm^2	Clear Hazard
40 mW/cm^2	Reproducible effects
4 mW/cm^2	Unconfirmed reports of effects
1 mW/cm^2	FCC public exposure standard (2000 MHz)
0.5 mW/cm^2	FCC public exposure standard (00 MHz)
0.01 mW/cm^2	Maximum near a cell phone tower
0.0002 mW/cm^2	Typical near a modern phase tower

Table 1.4.a The RF levels and biological effects on human [19]

As a result, high frequency radiation exists both inside of the buildings and free space around us. They are variety of RF sources and cover a wide range of the electromagnetic spectrum. Mostly, rapidly expanding source is the mobile phone base stations.

The priority is that taking care of the design codes of new base stations. Moreover, meeting the guidelines set for the antennas and their mounting so that the minimum required distance can be observed for the public access. To reduce the radiation power levels next generation antennas might be developed. Thus, WLAN technologies reflect the developments about the field on the next part.

1.5 WLAN Technologies

WLAN technologies are evolving to allow for faster transmission speeds and greater bandwidth. To be able to transfer data WLAN has some options as RF (Radio Frequency) and infrared. They both have advantages and disadvantages. Making right choice affect efficiency of the system. Some criteria's as coverage and speed are main factors for a network. In application, RF is common because of high speed data transfer and passing through physical barriers. [20]

Another new approach is WiMAX (Worldwide Interoperability for Microwave Access). This is the recently approved IEEE 802.16 wireless metropolitan area network (MAN) standard for broadband wireless access. WiMAX is real wireless fidelity with connectivity up to several kilometers as opposed to a couple hundred meters for 802.11a/b/g. Nowadays, 802.11g standard is approved and IEEE looks at even faster standards like 802.11n. As mentioned above, 802.11g runs at rates up to 54Mbps which is more than adequate for most WiFi users. Even if they do not notice the difference between 50Mbps and 320Mbps, many applications runs better at a higher speed. [21]

UWB is similar to Bluetooth technology but 100 times faster. It refers to Ultra-wideband (UWB) is used to transmit data at high speeds over short distances. As a result, UWB is perfect choice for home market. UWB is that the standard works across a wide range of frequencies as opposed to most other.

However, main concern is interference problems with other networking and consumer electronic technologies which are assigned a narrow band of spectrum. Despite these concerns, UWB product development is moving forward in the home networking market due to its fast transmission rates. [22]

As mentioned above, it is seen that WiMAX (Worldwide Interoperability for Microwave Access and Ultra-wideband (UWB) compete with each other in near future to be able to get the WLAN market.

1.6 Summary

Chapter one starts with the definition of Electromagnetic Radiation including the full spectrum, frequency-wavelength relation to be able to understand the behaviors of EMW propagation easily. Then, The Concept of WLAN expresses how EMW is used by the technology for human beings. Furthermore, EMW propagation and the function of buildings is the other step to achieve deeper understanding for design professionals. Thus, Frequency and Human Health is the most crucial point for the designers to think. To be able to understand this, necessary information and peak values is showed in the Table 1.4.a. Consequently, the last section answer this question which is what is the future of WLAN? In addition to the topics above mentioned next chapter covers electromagnetic wave related issues to be able to highlight the bond between EMW propagation and building materials in architectural spaces. Those relations guide to architects informing current issues and what should be done as next step.

CHAPTER 2

2. EMW (Electromagnetic Wave) Issues

After giving brief introduction about electromagnetic waves in the first chapter, some topics as; electromagnetic compability, interference and building material relations needs to be revealed to improve design professionals' knowledge about electromagnetic propagation in a space. This chapter covers those as follows.

2.1 EMC (Electromagnetic Compability)

The brief definition of the term is "*Electromagnetic Compability (EMC) is the ability of a device to operate faultlessly in a prescribed electromagnetic environment without at the same time affecting its surroundings in an inadmissible way.*"[23]

The explanation above mentioned tends to explain unintentional generation, propagation and reception of electromagnetically energy. Thinking about an environment might be an office or a school laboratory having full of electronic devices such as computers, cell phones, TVs, lighting fixtures, and wireless gadgets that causes electromagnetic phenomena in their operation. The goal of EMC (Electromagnetic Compability) is to harmonize the conflicts between devices.

To be able to fix this problem, EMC deals with emission issues which are related to the reduction of unintentional generation of electromagnetic energy. For the buildings, countermeasures should be taken in order to avoid the external environment propagation towards to the space as EMW isolation. This design solution is the major step to avoid electromagnetic disturbances due to the incorrect operation of electrical equipments.

In order to achieve such an objective in architecture, during the design process susceptibility issues needs to be considered. The importance of EMC has taken account in many countries and standardization has been made by The FCC (Federal Communications Commission) for the United States, CEN (European Committee for Standardization), CENELEC (European Committee for Standardization) and ETSI (European Telecommunications Standards Institute) for Europe, BSI (British Standards) for Britain and TSE (Turkish Standards Institute) for Turkey. Moreover, the most important international organization is the International Electrotechnical Commission (IEC), which has several committees working full time on EMC issues. [24]

To sum up, electromagnetic compability solution purpose is getting the harmonious environment for electronic devices for them to operate functionally. Now, it is time to address electromagnetic interference issue as next step.

2.2 EMI (Electromagnetic Interference)

Electrical circuits emit electromagnetic radiation knows as Radio Frequency Interference (RFI). The devices carry rapidly changing signals which is the result of unwanted signals called interference or noise in other circuits. EMI (Electromagnetic Interference) interrupts or limits the effective performance of those other circuits. Sometimes it is intended action as some forms of electronic warfare.

In this case, the EMI issue is urgent to be able to protect military buildings which include some electronic defense system devices from this type of hustle actions. For instance, EMI is a vital problem for hospital buildings. According to extensive study carried out in 2004, at Massachusetts General Hospital, *"Cellular phones placed in close proximity to some commercially available intensive care ventilators can cause malfunctions, including irrecoverable cessation of ventilation. This is most likely to occur if the cellular phone is <30 cm from the device and ringing. Based on our data and the available literature, we believe it is reasonably safe to permit the use of cellular phones in the intensive care unit, as long as they are kept > or =3 feet from all medical devices. The current electromagnetic* *compatibility standards for mechanical ventilators are inadequate to prevent malfunction."* [25]

There are generally two techniques to be able to seal EMI at higher frequencies like 500 MHz. Wave shaping with series resistors and inserting the traces between the two planes. As we know most of digital equipment is made of metal, coated plastic and cases. In the case of too much EMI, shielding such as RF gaskets and copper tape can be used.

Most of countries have legal codes to prevent EMI on electrical hardware and still work on to be able to fix this issue. [26]

Electromagnetic Interference is a vital disturbance for WLAN environment. Thus, the codes are the key to prevent this issue. Next section gives detailed information about this bond between building materials and EMW.

2.3 Building Materials and EMW (Electromagnetic Wave) bond

Building materials are the core of architecture. Sometimes they are like skin or skeleton of the structures. In the building environment, EMW propagates differently due to the material inside. To be able to understand this issue, the relation between conductivity, magnetic permeability and electric permittivity are handy. First of all, *"Electrical conductivity is a measure of a material's ability to conduct an electric current. When an electrical potential difference is placed across a conductor, its movable charges flow and gives rise to an electric current. The conductivity σ is defined as the ratio of the current density J to the electric field strength E."* [27] The equation is $\mathbf{J} = \sigma . \mathbf{E}$

Secondly, The definition of magnetic permeability is *"Relative increase or decrease in the resultant magnetic field inside a material compared with the magnetizing field in which the given material is located; or the property of a material that is equal to the magnetic flux density B established within the material by a magnetizing field divided by the magnetic* *field strength H of the magnetizing field. Magnetic permeability μ is thus defined as* $\mu = B/H$*. Magnetic flux density B is a measure of the actual magnetic field within a material considered as a concentration of magnetic field lines, or flux, per unit cross-sectional area. Magnetic field strength H is a measure of the magnetizing field produced by electric current flow in a coil of wire."* [28]

Finally, *"in electromagnetism, electric displacement field D represents how an electric field E influences the organization of electrical charges in a given medium, including charge migration and electric dipole reorientation. Its relation to permittivity is* ***D= εE****"* [29]. Adding the issues above mentioned such as EMI (Electromagnetic Interference) and EMC (Electromagnetic Compability), it becomes more complicated problem to be able to solve in the space. Thus, next paragraphs emphasize building material versus EMW propagation interaction as follows.

Based on the material/EMW bond data on NIST (See Appendix A for detailed information) experimentation, [30] both a table and figure is created so that the professionals can compare the transmitted field and frequency relations of the materials. (See Table 2.4.a, Fig. 2.4.b and Fig.2.4.c)

Prior to looking at figures and the table some equations needs to be understood as;

$\tau = \frac{\left|\vec{E}_{trans}\right|}{\left|\vec{E}_{inc}\right|}$ In this equation, τ is transmission constant, $\vec{E}_{trans}$ is transmitted field

and $\vec{E}_{inc}$ is the incident electric field also the amplitude of incident electric field represents. The transmitted electric field can be written in terms of incident electric field amplitude and the transmission coefficient as $E_{trans} = E_{inc}.\tau.e^{-\alpha.L}$. For this equation τ

stands for transmission coefficient, α is attenuation constant [31] and L stands for the thickness of the material.

	Average Max.Trans.Field (0.5-2.0 GHz)	Average Max.Trans.Field (3.0-8.0 GHz)
Brick	0,7583	0,126
Brick faced concrete wall	0,186	0,0085
Brick faced masonry block	0,385	0,036
Plain Concrete	0,1516	0,0415
Masonry Block	0,22	0,0326
Drywall	0,98183	1
Glass	0,87	0,86
Lumber (Dry)	0,7575	0,3425
Lumber (Wet)	0,75	0,325
Plywood (Dry)	0,96625	0,9825
Plywood (Wet)	0,86	0,763
Reinforced Concrete	0,516	0,00283
Rebar Grid	0,6375	0,88

Table 2.4.a: Average Maximum Transmitted Electric Field ratio and Material relation due to the frequency

Table 2.4.a shows the average of different thicknesses of the materials as one sample transmitted electric field value (τ) to create the charts.

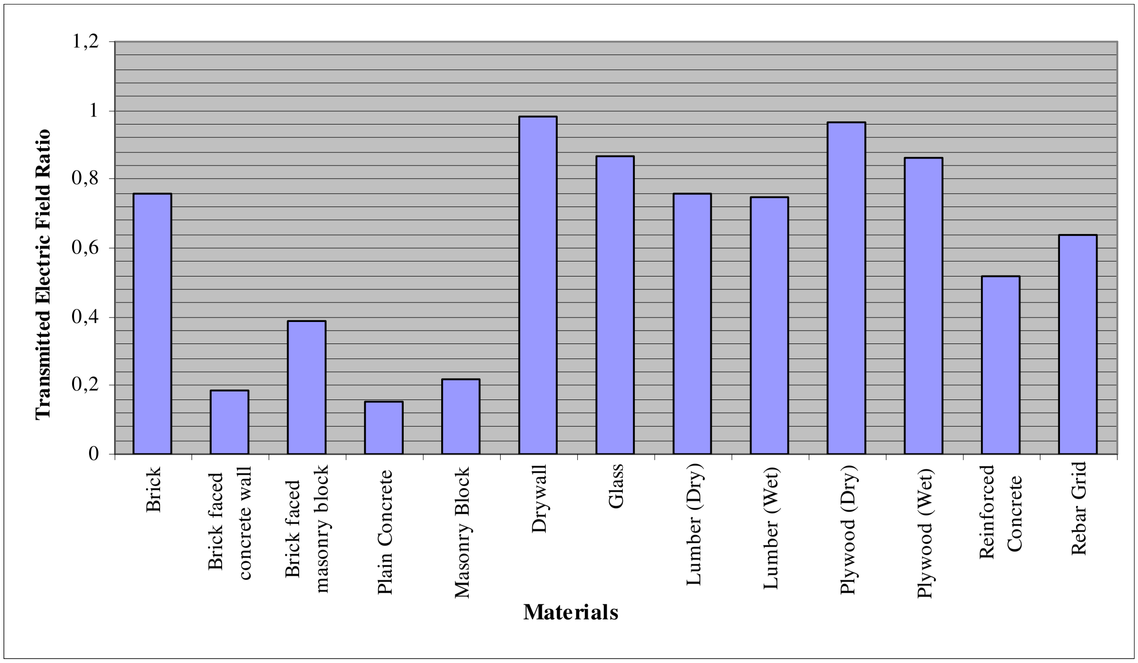


Fig.2.4.b: Transmitted Electric Field-Material Relation in low frequencies (0.5-2.0 GHz)

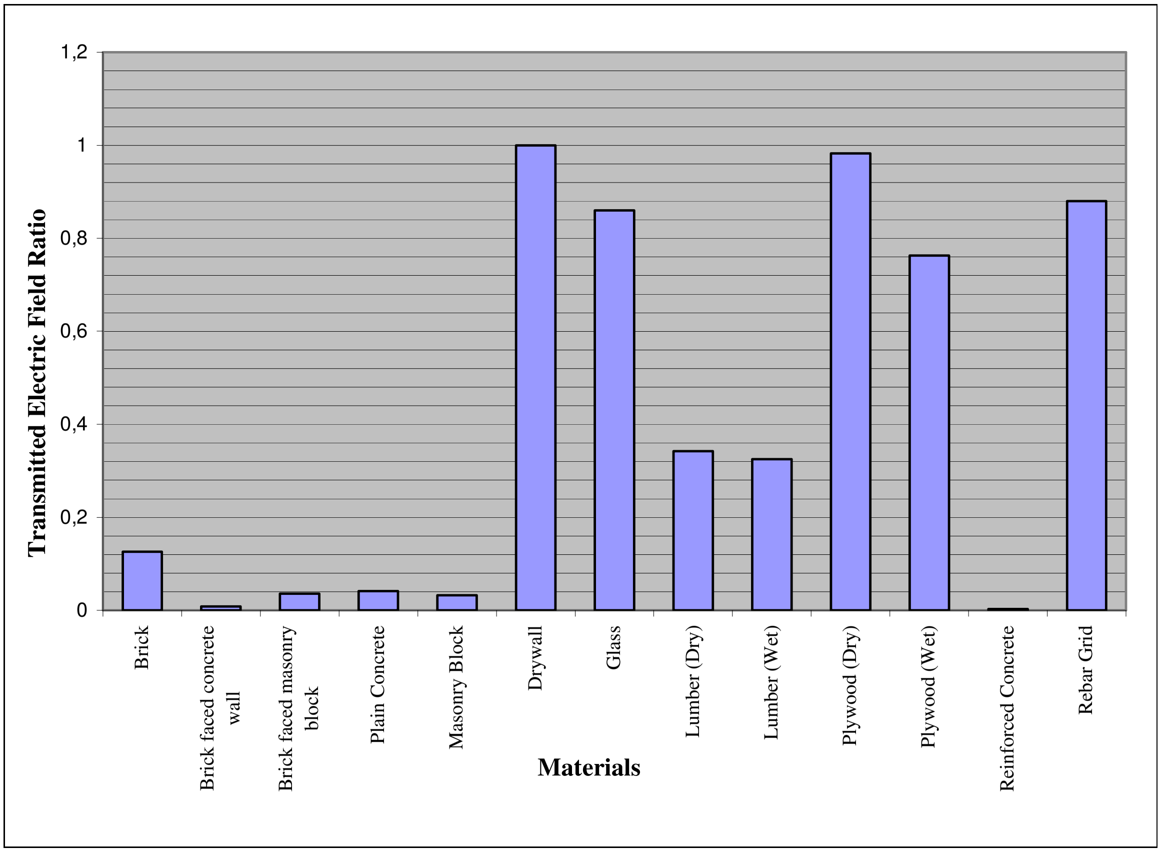


Fig.2.4.c: Transmitted Electric Field-Material Relation in high frequencies (3.0-8.0 GHz)

Most of the materials such as; brick, brick faced masonry block, plain concrete, reinforced concrete lose their transmission due to the frequency increase. Fig.2.4.c. needs to be underlined to design wireless networking by the design professionals.

2.4 Summary

Two important definitions as EMC (Electromagnetic Compability) which is to harmonize the conflicts between devices and EMI (Electromagnetic Interference) are explained in this chapter to be able to define the other variables effecting EMW propagation in an environment. Moreover, the data above mentioned is a fairly comprehensive set of information for the penetration to the most common used construction materials which are exposed by electromagnetic (EM) radiation in the 0.5 to 8.0 GHz (60 cm to 4 cm wavelength) range.

As it is appeared on the figures, as an example, in the 0.5 to 2.0 GHz, 3-wythe thick (267 mm) brick wall is get 40% of the transmitted signal power. And, similar characteristics apply to masonry block walls, a staple of commercial construction practice. Thus, the most common residential construction materials such as; plywood, lumber studs, glass, and drywall penetrate even more easily. On the other hand, the strongest signal absorption occurs for concrete specimens.

Next chapter analyzes some computation methods as computer aided and manually solving process to find the best suitable design approach for structures. In addition to that, sample office room model experiment shows us how EMW propagates in a space depends on different variables.

CHAPTER 3

3. Megacells to Picocells

Understanding the issues such as; EMC, EMI, and the EMW relation between basic building materials are given in previous chapter that guide designers to the type of networking coverage as megacell and picocell applications so that architects can reach the problem solution methods in a space. This chapter emphasizes those terminologies and gives information about solutions to be found in the next paragraphs.

3.1 Brief introduction about Megacells

Megacells are the mobile systems designed so that they can provide truly global coverage. They use low and medium orbit satellites which have separate spotbeams. Those beams move rapidly across the Earth’s surface. Signals are generally receive at very high elevation angles by those satellites. Just environmental features affect the EMW propagation process. The figure above shows the Megacell propagation geometry.

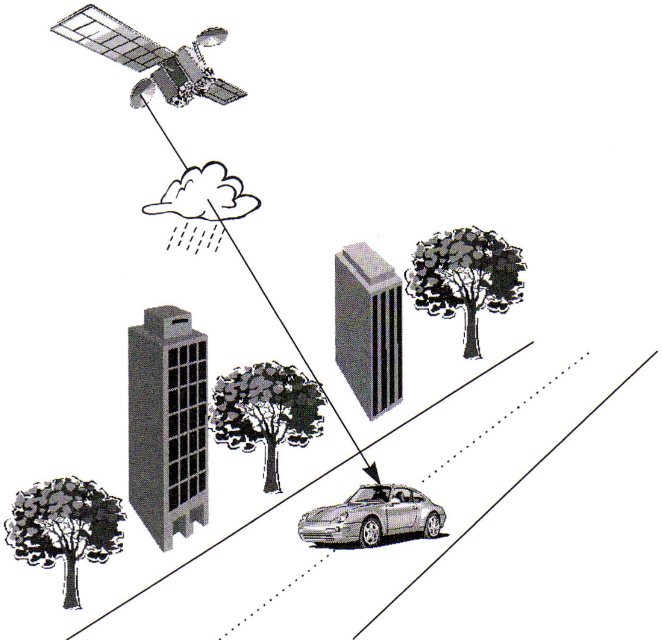


Fig.3.1.a: Megacell propagation geometry [32]

3.2 Picocells

3.2.1. Introduction

Basically, Picocells is formed by a base station which is located inside a building. Picocells are generally used in high traffic areas such as; airports, railway stations, office buildings and university campuses. As mentioned in chapter one, wireless local area networks require high data rates. Both macrocellular and microcellular systems might cause interference in the buildings. Thus, spectrum analysis needs to be done prior to design WLAN for structures. The nature of Picocells is demonstrated below in figure 3.2.1.a

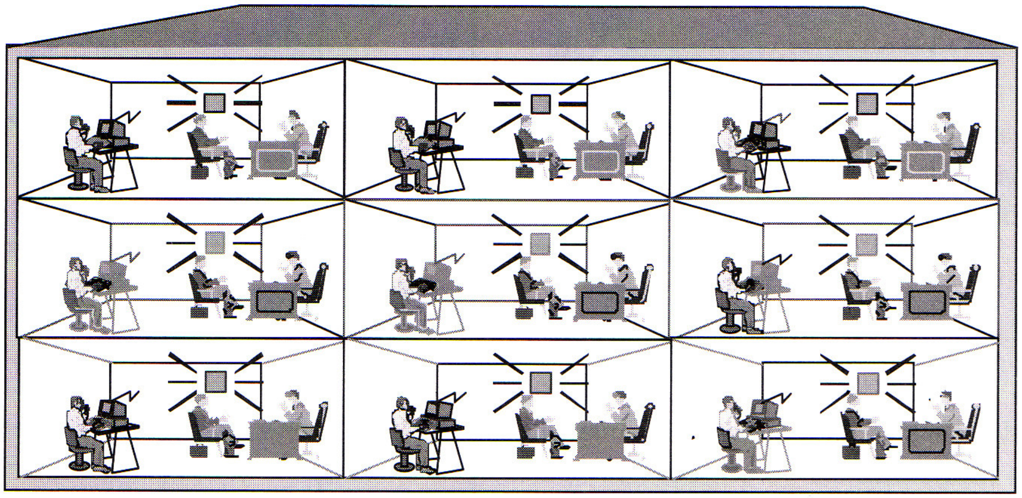


Figure 3.2.1.a: Picocells [32]

When professionals deal with simulations to design wireless local area networks for buildings, Empirical Models of propagation come out as handy tools to solve the problems. Some models as The Friis Formula that is a good starting point to analyze buildings. Basically, the formula helps to calculate propagation loss in free space. The equation is $\frac{P_r}{P_t} = G_a.G_b\left(\frac{\lambda}{4\pi r}\right)^2$. In this equation, P_r refers to received and P_t refers to transmitted power. G_a stands for the maximum gain of the antenna A, G_b refers to maximum gain for

B and λ is the wavelength. Therefore, it is useful for us to state the equation in decibels as;

$W_{rec}\,(dB_m) \cong W_{tr}\,(dB_m) + G_{Rec(max)}\,(dB) + G_{Tr(max)}\,(dB) - 20 \log R\,(km) - 20 \log f\,(MHz) - 32.44$

In this formula, W_{rec} is for received power in dB, $W_{tr}\,(dB_m)$ for transmitted power in dB, $G_{Rec(max)}\,(dB)$ for received gain in dB and $G_{Tr(max)}\,(dB)$ for transmitter gain in dB. [33]

The others as Wall and Floor Factor, COST231 Multi-wall, Ericsson Models are handy to create simulations. There is multiplicative noise arises between transmitter antenna and the receiver antenna. It also needs to be clarified before starting the calculations of the buildings. Here are some of them such as;

- The directional characteristics of both the transmitter and receiver antennas (In this case, direct polarization is considered for the building)
- Reflection from the smooth surfaces of walls and hills around the building (especially in corridors)
- Absorption by walls, trees, interior space elements and by the atmosphere (See Table 2.4.a for the percentage of transmitted ratio due to building material and the frequency)
- Scattering from the rough surfaces as rough ground, leaves, branches of tress around the buildings
- Diffraction from edges of the building interior and exterior corners, rooftops even hilltops around it.
- Refraction due to both layered or other materials like insulation of the building.

On the other hand, manually solving process using the models takes so much time to be able to get the accurate results. Nowadays, Computer simulation methods are used widely in the world. HFSS (High Frequency Structure Simulation) is one of the solution software for engineers. (See Appendix A for detailed information)

All in all, Sample Office Layout is created and analyzed to predict the EMW propagation in buildings as follows.

3.2.2. Sample Office Room Layout

To be able to understand the EMW Propagation in interior spaces in the buildings, there are three options as; modeling of the propagation medium (interior spaces in building environment), calculations and approximations, computer aided design predictions and real life measurements. The last procedure includes all variables and helps to the designer how to be accomplished solving the problem. HFSS uses Finite Element Method (FEM) for EMW propagation parameters of the building environment (See Appendix A for further information). In this study, as a building environment 3D Sample Office Room Layout and as a transmitter antenna the Omni directional antenna is used to be able to research the relation between material, location of the source, and the geometry of propagation media.

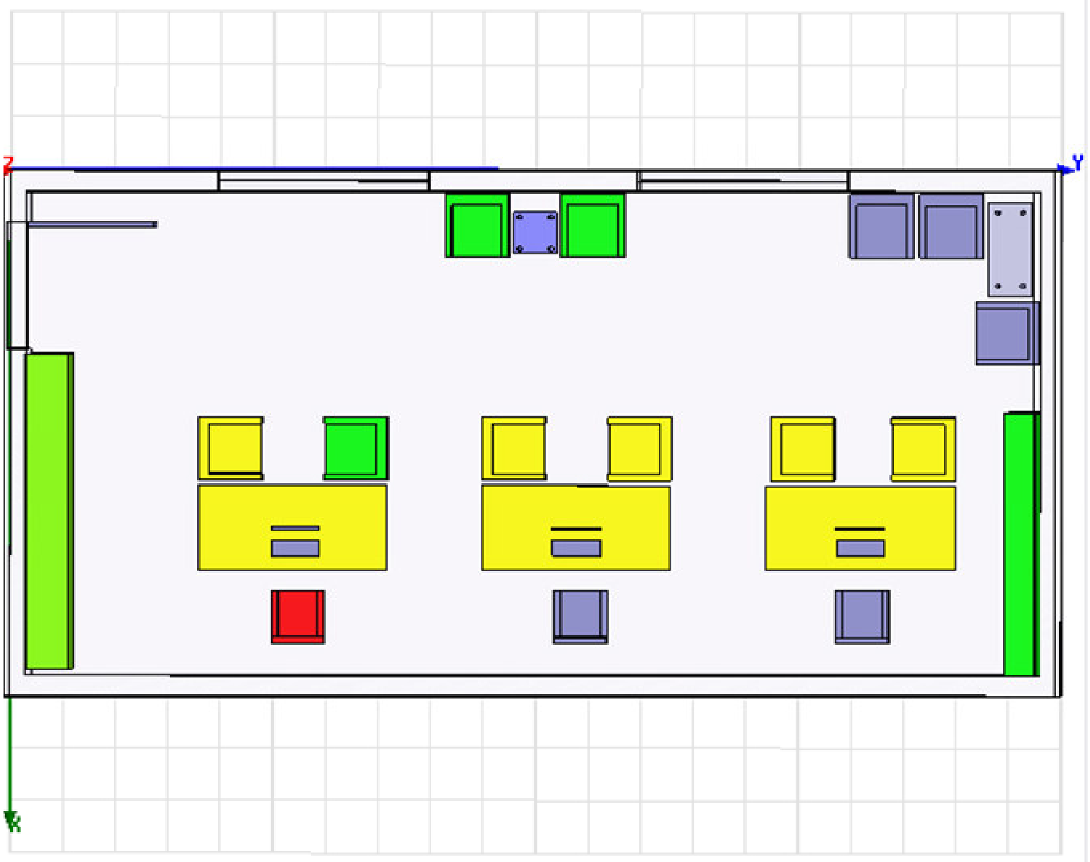


Figure 3.2.2.a: Sample Office Room (Plan)

The dimension of the office room is considered as 10 m X 5 m X 3.5m. Basic office equipments such as; task chairs, tables, desk computers, file cabinets and seating in the space are located in different places and conditions in the room. (See Fig. 3.2.2.a) The source which is the antenna of WLAN is located in different places around the space and propagation simulations has been developed and accomplished.

3.2.2.1 Scenario I

In the fist scenario, the source is put in the middle of the room above 5m (Z=500 cm) higher from the ground level in z direction. (See Fig. 3.2.2.1.c) Typical interior space materials are chosen as; painted walls, ceramic granite flooring, drop ceiling, glass tables with aluminum legs, leather seats, and wood tables and aluminum file cabinets as shown in Fig. 3.2.2.1.b.

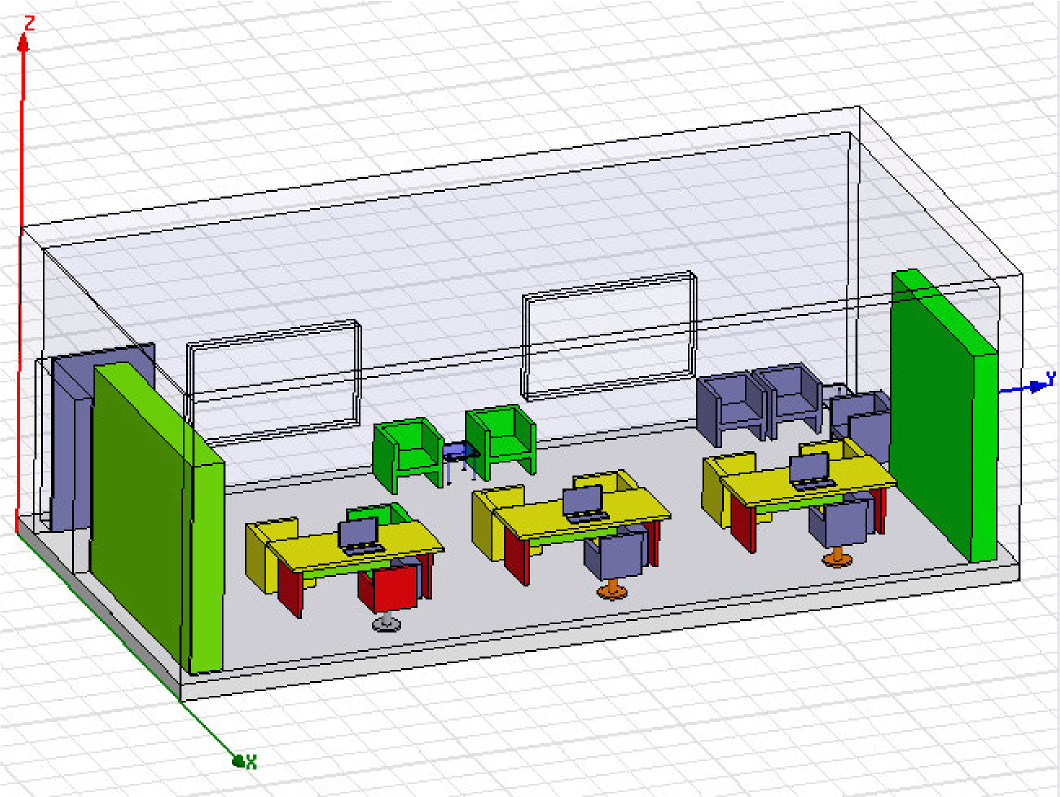


Figure 3.2.2.1.a: Sample Office Room (Perspective)

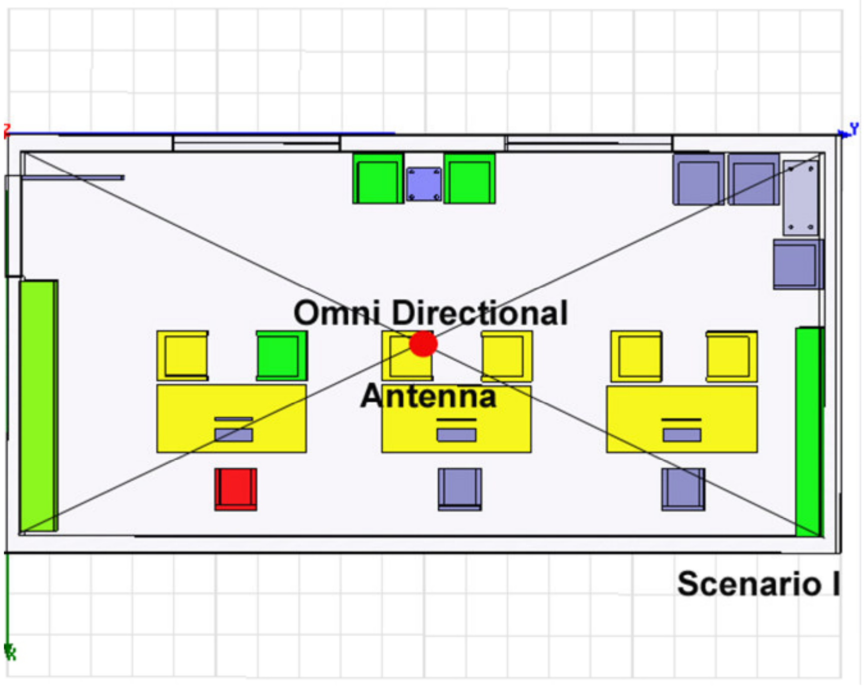


Figure 3.2.2.1.b: Sample Office Room (Scenario I)

HFFS is designed to solve electromagnetic propagation design problems. Due to dimensions and complexity of the structure in architectural area are extremely hard to solve this problem in HFFS. The model can be created in real dimension but in this case, problem can not be solved.

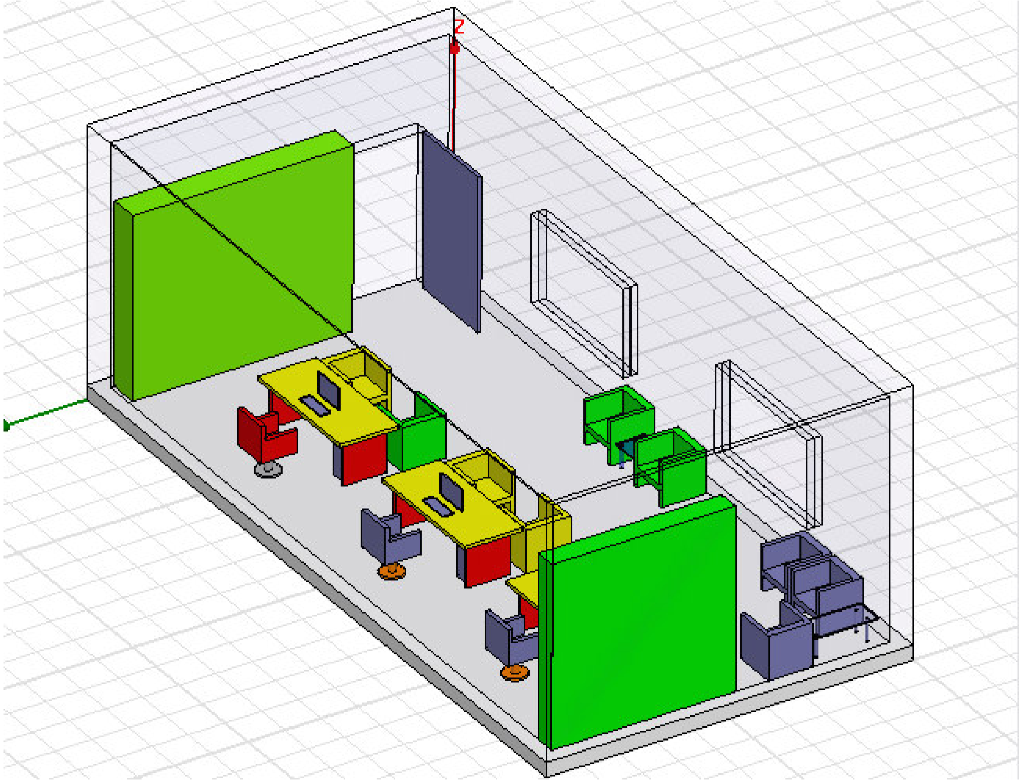


Figure 3.2.2.1.c: Sample Office Room (Perspective)

3.2.2.2 Scenario II

In the second scenario, the source is placed in the middle of the room above Z=3.5m higher from the ground level. All conditions stays still just 1.5 m height difference bring different results as reflection from the interior walls and diffraction from the corners. Aluminum file cabinets and table legs act like sources in the room. In this scenario, this is very beneficial for WLAN application in the space.

3.2.2.3 Scenario III

In the third scenario, the source is located X=250 cm Y=50 cm and Z=350cm coordinates.

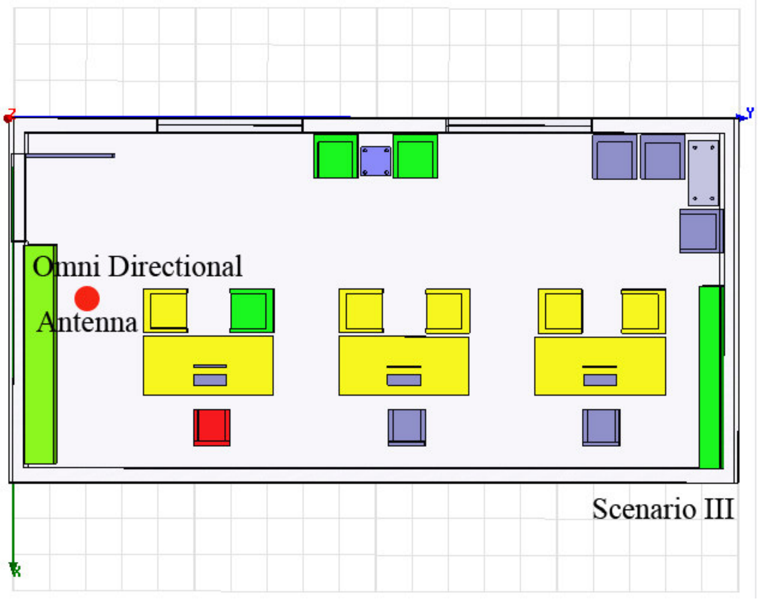


Figure 3.2.2.3.a: Sample Office Room (Scenario III)

Looking at the plan and the location of the source display how close the antenna to the aluminum files cabinet. Diffraction is the reason for this result and sometimes it is necessary to increase the value of the electromagnetic wave propagation as mentioned in previous section.

Third Scenario is the last step of completing the location triangle which is very handy tool for the designer to compare the value changes of the field.

3.2.2.4 Location Triangle

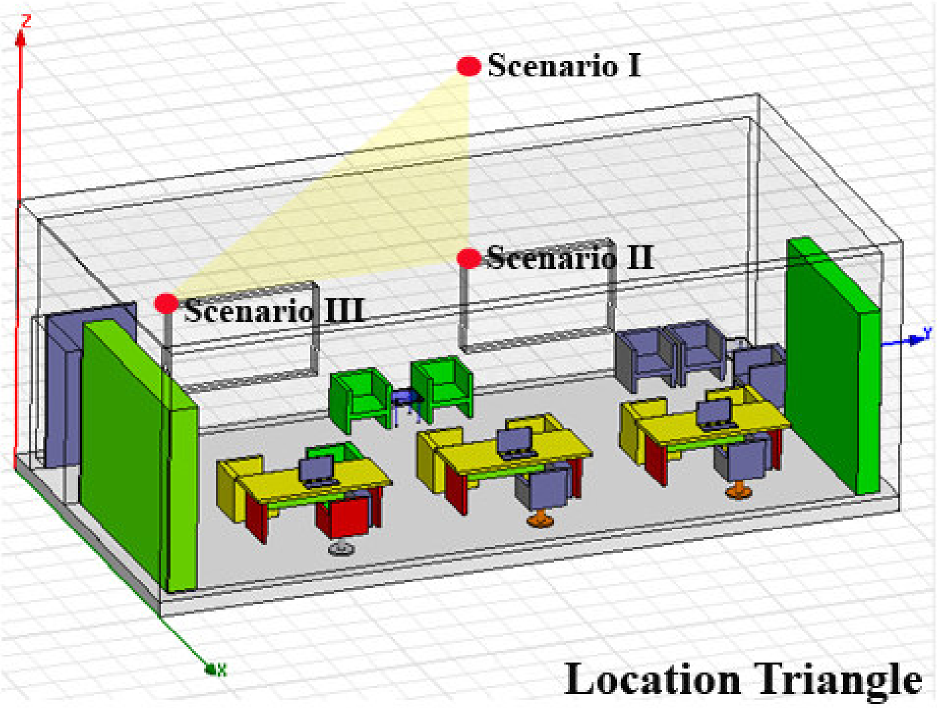


Figure 3.2.2.4.: Location Triangle

The first recognized feature is diffraction from edges of the room interior corners, furniture including aluminum file cabinets. Comparing the minimum values starting from Scenario I to III proves the file cabinet acts like source. Thus, the min and max values increase (See Figure 3.2.2.4). The location triangle is practical for the design professionals to be able to judge different propagation principles in the environment.

The purpose of those simulations is to predict EMW propagation before the structure is being built and help to resolve problems mentioned before in the previous chapters. Next sections underline site computations to be able to predict EMW propagation in existing environments.

3.2.3. Yeditepe University's Campus Layout (Site Computation)

26 August Campus is located at Kayisdagi region in Istanbul/TURKEY. The campus has 236 thousand square meters closed area with 125 thousand square meters open area which include *"319 classrooms, 22 lecture halls, 32 computer and 74 professional labs belonging to Fine Arts, Architecture, Communication, Engineering and Sciences Faculties. Also, 2 professional photographic studios, 34 academic administration units, 287 Faculty Offices, 28 student club rooms, a 3000 square meters Central Library, Residence Halls, multipurpose Conference Hall, cinema complex, a theatre Hall. Moreover, a 524 square meters and 384 square meters two television studios, 200 square meters educational TV studio lab, 150 square meters educational radio facilities, 550 square meters indoor basketball court, 620 square meters outdoor basketball courts, outdoor volleyball, tennis courts, Indoor and outdoor half Olympic sized swimming pools, 300 square meters fitness and aerobics center, 783 square meters modern shopping complex, 79000 square meters of open grassy area, and 400 vehicle capacity indoor parking lots."* [34]

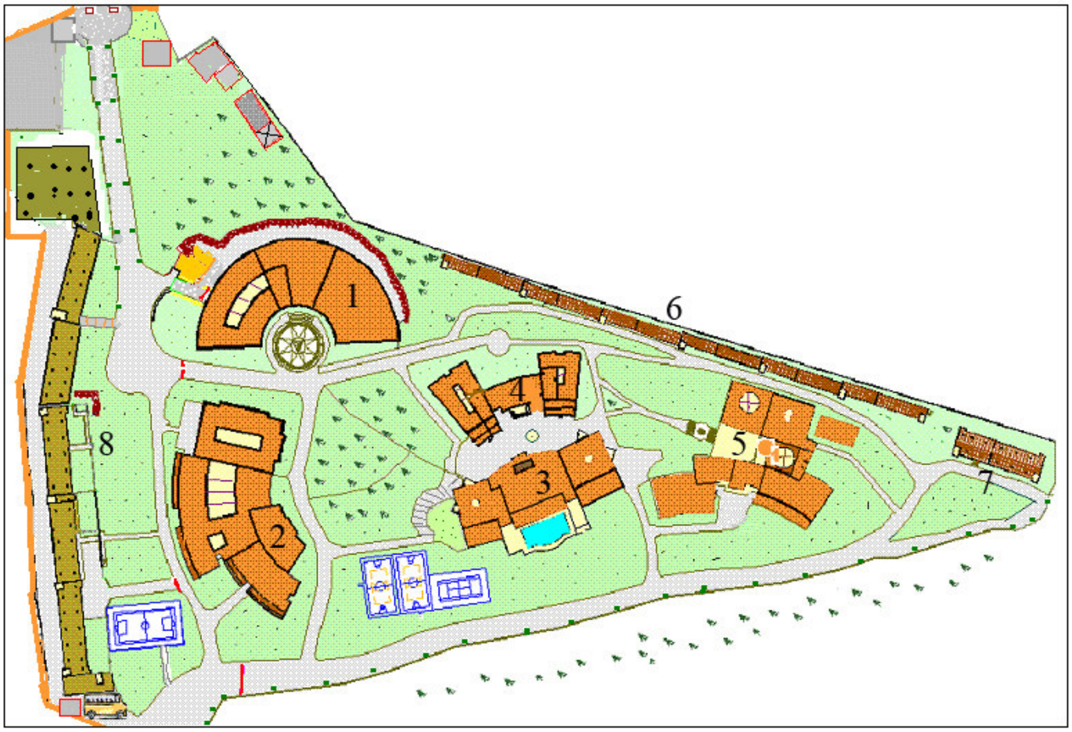


Fig. 3.2.3.a: Yeditepe University's Campus Layout [36]

From number 1 to 8;

1. Rectorate,

2. Architecture and Engineering,

3. Social Facilities,

4. Law Faculty,

5. Fine Arts Faculty,

6. Dormitories and North Preparation School,

7. Hotel,

8. Dormitories and Merchandising Academy buildings are illustrated on Fig. 3.2.3.a.

3.2.3.1 Yeditepe University's Architecture / Engineering Building

The Building has constructed in sloped surface close to Rectorate structure. (See Fig. 3.2.3.a. number 2). It has six floors above the ground and tree floors below the entrance floor. The Seljuk post modern style building has different basic construction materials such as; concrete, stone, steel, drywall, glass, and aluminum. The building form has both curvilinear and linear which makes it hard site survey in terms of electromagnetic wave predictions. The shell of the building is assembled by façade, insulation and masonry block. The partitions are mostly made of drywall. Granite and PVC combination is used for flooring. Interior doors are made of aluminum frame and glass interior. And all the windows are made by PVC (vinyl) based material. That gives a general building material analysis of the building to start the simulation calculations. (See Fig.3.2.3.1.a)

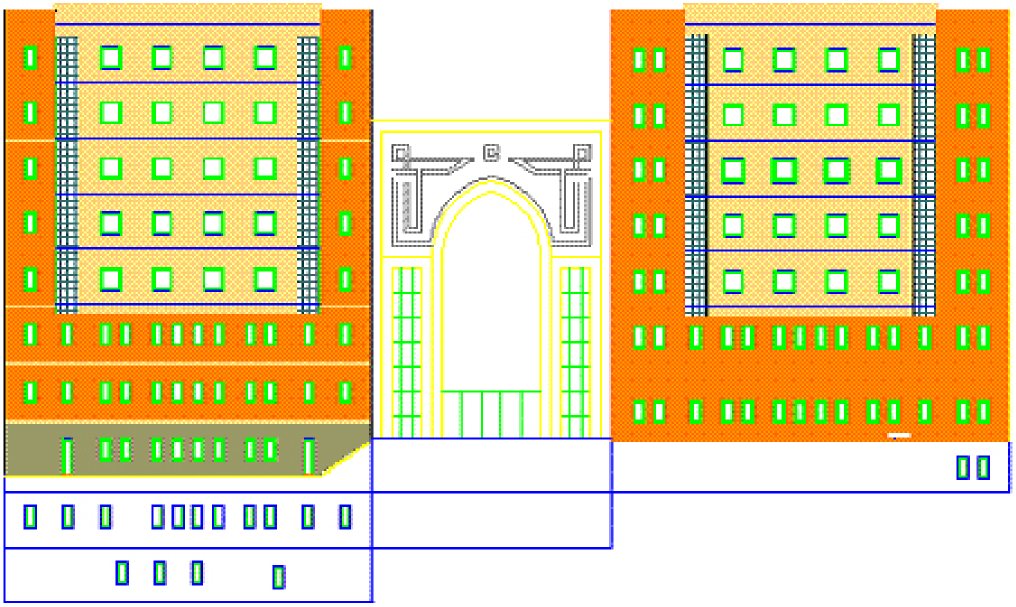


Fig.3.2.3.1.a: Architecture Engineering Building Main Entrance Elevation [36]

3.2.3.2 The Architecture / Engineering Building Computation Method

Prior to start the computation, Dielectric theory needs to be revised. Appendix B gives detailed information about Dielectric theory, electromagnetic propagation and dielectric mechanism. The Computation method based on free space lost and transmission losses through the building. As mentioned in previous sections (See 3.2.1.), free space lost is being showed as;

W_{rec} (dB_m) $\cong W_{tr}$ (dB_m) + $G_{Rec(max)}$ (dB) + $G_{Tr(max)}$ (dB) – 20 log R (km) – 20 log f (MHz) -32.44

And for the transmission losses the formula below mentioned is being used as;

$$E_{inc} = E_0 (V/m)$$ (See 2.4)

$$E_{trans} = E_0 . \tau . e^{-\alpha . L}$$

$\alpha = \dfrac{\pi \sqrt{\varepsilon_r}}{\lambda} \tan \delta$ In this formula, ε_r is Relative Permittivity, (λ = *c/f*) λ wavelength, c=$3x10^8$ m/sn, *f=2.4 GHz* in this situation and the losses in the dielectric depend on the loss tangent (tanδ) of the material, which depends inversely on the wavelength of the signal and is directly proportional to the frequency. (See Appendix C)

To be able to make the calculation we need to know Transmission coefficient, the relative permittivity and tan delta values for specific frequency. Table 3.2.3.2.a and 3.2.3.b gives necessary information below.

Material	Est. er	Est. Tand	Reported er	Reported tand
Pexiglass (7.1mm)	2.74	3.20E-04	2.59	5.70E-03
Pexiglass (2.5mm)	2.5	9.37E-03	2.59	5.70E-03
Blinds (closed)	3.49	5.96E-05		
Blinds (open)	1.96	5.96E-05		
Red brick (dry)	5.86	1.16E-01		
Red brick (wet)	5.92	1.17E-01		
Carpet (back)	1.31	6.69E-04		
Carpet (weave)	1.32	5.96E-05		
Ceiling Tile	1.32	1.44E-02		
Fabric	1.49	5.96E-05		
Fiberglass	1.02	9.21E-04	3.9	0.026
Glass	6.38	2.60E-02	4.05	0.0106
Drywall (12.8mm)	2.19	1.11E-02		
Drywall (9mm)	2.49	4.25E-03		
Light cover (front)	1.66	6.88E-03		
Light cover (back)	1.64	1.19E-02		
Linoleum (back)	3.04	6.31E-05		
Linoleum (front)	3.08	1.45E-03		
Fir	2.58	2.00E-01	1.7-3.8	0.022-0.26
Particle Board	2.7	1.10E-01	2.7-3.07	0.07-0.09
Plywood	2.47	1.27E-01	1.7	0.036
Stucco (back)	7.3	4.45E-01		
Stucco	1.07	4.29E-01		

Table 3.2.3.2.a Relative Permittivities and Loss Tangents [35]

Material	**T(dB)**			**R(dB)**		
	2.3 GHz	**5.25 GHz**	△	**2.3 GHz**	**5.25 GHz**	△
Plexiglass (7.1mm)	-0.356	-0.9267	0.5707	-12.23	-5.65	-6.5753
Plexiglass (2.5mm)	-0.0046	-0.2041	0.1994	-21.69	-13.25	-8.447
Blinds (closed)	-0.0016	0.02	-0.0035	-30.97	-20.39	-10.578
Blinds (open)	0.0137	0.0315	-0.0178	-44.23	-46.95	2.721
Red brick (dry)	-4.4349	-14.621	10.186	-12.53	-8.98	-3.5459
Red brick (wet)	-4.5119	-14.599	10.087	-12.52	-9.41	-3.1185
Carpet (back)	-0.0361	-0.0318	-0.0044	-25.19	-15.8	-9.408
Carpet (weave)	-0.0271	-0.0056	-0.0214	-26.94	-18.7	-8.271
Ceiling tile	-0.0872	-0.1795	0.0923	-21.07	-18.7	-2.347
Fabric	0.0216	0.0133	0.0083	-41.7	-30.1	-11.57
Fiberglass	-0.0241	-0.034	0.0099	-39.4	-28.8	-10.581
Glass	-0.4998	-1.6906	1.1908	-11.29	-4.9	-6.3446
Drywall (12.8mm)	-0.4937	-0.5149	0.0211	-12.11	-11.5	-0.639
Drywall (9mm)	-0.5095	-0.847	0.3376	-12.03	-8.87	-3.1596
Light cover (front)	-0.004	-0.0533	0.0494	-28.47	-20	-8.449
Light cover (back)	-0.007	-0.532	0.0462	-28.07	-18.8	-9.239
Linoleum (back)	-0.0186	-0.1164	0.0977	-26.05	-17.3	-8.761
Linoleum (front)	-0.0198	-0.1278	0.1081	-23.69	-16	-7.669
Fir lumber	-2.7889	-6.1253	3.3364	-17.45	-14.8	-2.689
Particle Board	-1.6511	-1.9508	0.2997	-8.59	-14.1	5.5359
Plywood	-1.9138	-1.8337	-0.0801	-9.05	-30.5	21.422
Stucco (back)	-14.582	-13.906	-0.676	0.62	0.04	0.5785
Stucco (front)	-14.863	-13.235	-1.628	-2.38	-9.24	6.8587
Tiles	-2.2163	-1.4217	-0.7946	-6.24	-14.9	8.6093
Tar Paper	-0.0956	-0.1341	0.0385	-28.88	-17.8	-11.067
Cinder block (dry)	-6.7141	-10.326	3.6119	-7.67	-6.13	-1.5324
Cinder block (wet)	-7.3527	-12.384	5.0313	-5.05	-7.55	2.508
Diamond mesh	-20.985	-13.165	-7.82	-0.53	0.89	-1.4216

Table: 3.2.3.2.b Transmission and Reflection Coefficients at 2.3GHz and 5.25GHz [35]

The antenna considered R=50 m away from the building and free space loss graph is being established. The values for X coordinates R is meters and for Y axis values W_{rec} in dB_m.

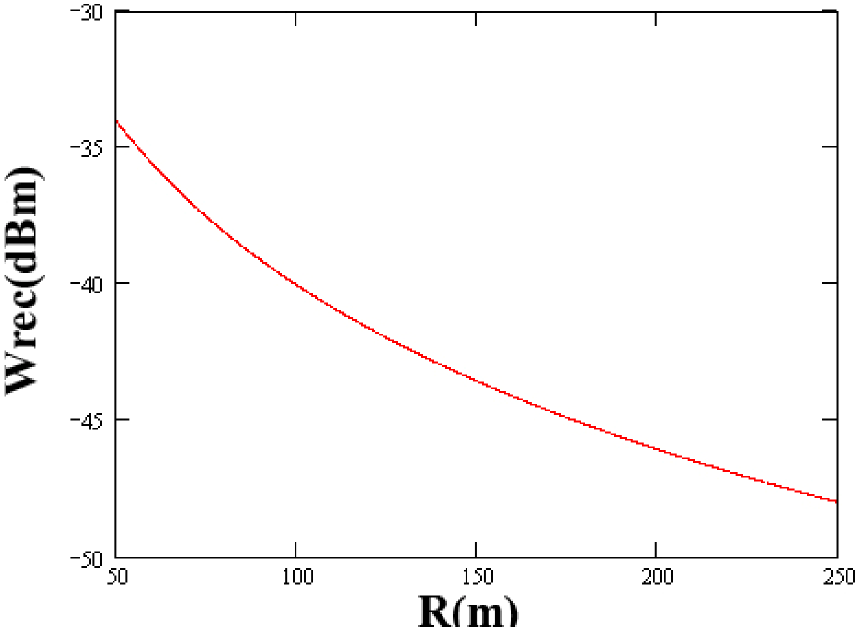


Fig.3.2.3.2.a: Free space loss values in dB between 50-250 m

Analyzing the floor shows two exterior shell and 6 interior partitions. Computation is being done due to this situation. (See W_{rec} and W_{out} reference points in Fig.3.2.3.2.b)

The calculation of W_{out} in dBm starts considering interior geometry of the floor in the building. Thus, each floor has different geometrical characteristics including two exterior walls, interior partitions and free space. The other variables have been omitted as; interior furniture, human factor, directional characteristics of antennas, reflection, absorption, scattering, diffraction, refraction, environmental effects and so on (See Page 66 for further information). The value of W_{rec} is -34.024 dBm in 50 meters away from the antenna.

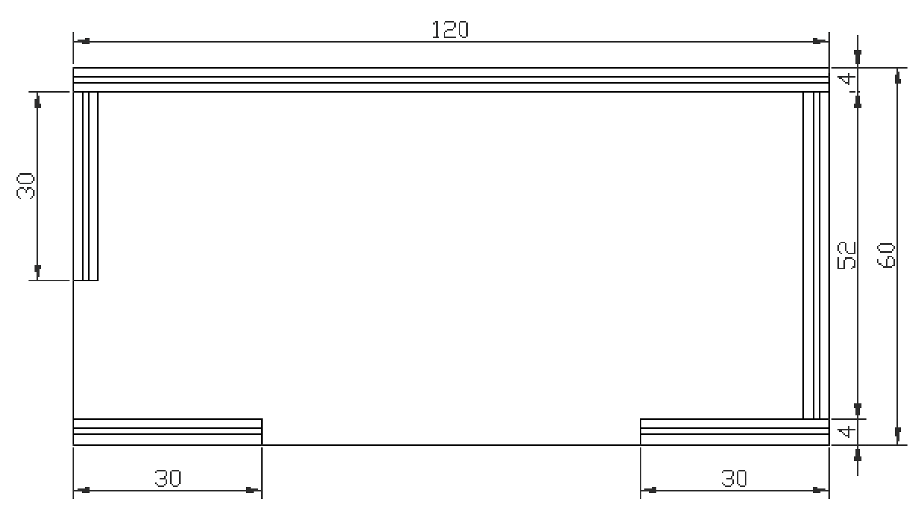
$W_{out\ (free\ space)}$ = -38.106 dBm in front of the building. When interior partitions have been measured W_{out} is equal to -53.307 dBm value which is very low. This method can be adapted to any floor to get the results and the design professional is able to learn the rough values of the propagation losses in the building. (See Fig.3.2.3.2.b)

Fig.3.2.3.2.b: The building entrance floor plan [36]

3.2.3.3. Sample Office Room Modeling Experiment

The experiment is done in Yeditepe University's Department of Electrical & Electronics Engineering microwave and antennas laboratory. 1/5 scaled sample office room and furniture models are made to be able to create real life environment. As remembered in previous sections, WLAN applications work with 2.4 GHz frequency. Using 1/5 scaled model requires 2.4X5=12 GHz frequency in experiment to be able to maintain same wavelength of electromagnetic waves in lab environment as real life application.

Figure 3.2.3.3.a shows both shop drawing and main materials of the room model below for construction purpose.



Shop Drawing Material List (h=60 cm)

60X120 cm /4 pieces OSB Board
30X60 cm /6 pieces OSB Board
52X60 cm /2 pieces OSB Board

30X30 cm Ceramic Granite Tile (34 pieces)
100 meters 1.5 mm thick copper wire
1880 brass pins to connect the wires

Fig.3.2.3.3.a: Shop drawing for the 1/5 scaled experiment modeling

In addition to the main materials as seen above, silicone to connect the parts and aluminum foil for window frame are being used. Fig.3.2.3.3.b shows main modeling materials as cut OSB board (15 mm thickness) pieces and 30X30 cm ceramic granite tiles. This model is designed as self standing object. (See Table 3.2.3.2.a for Relative Permittivities and Loss Tangents and Table: 3.2.3.2.b Transmission and Reflection Coefficients of the materials) When the parts assembled, the room stands still that makes it very modular and makes the work practical in terms of measurement process. For two slabs, peeled copper wires are modified as rebar grid. The distance between grids are 30 mm in 1/5 scale. Fig.3.2.3.3.c shows creating rebar grids and connections for floor and ceiling of the room. Above this level, ceramic granite tiles are oriented. (See Fig.3.2.3.3.d and Fig.3.2.3.3.e for completed one unit)

Fig.3.2.3.3.b: Main modeling materials as cut OSB board pieces and ceramic granite tiles

Fig.3.2.3.3.c: Rebar grid installation for flooring and ceiling

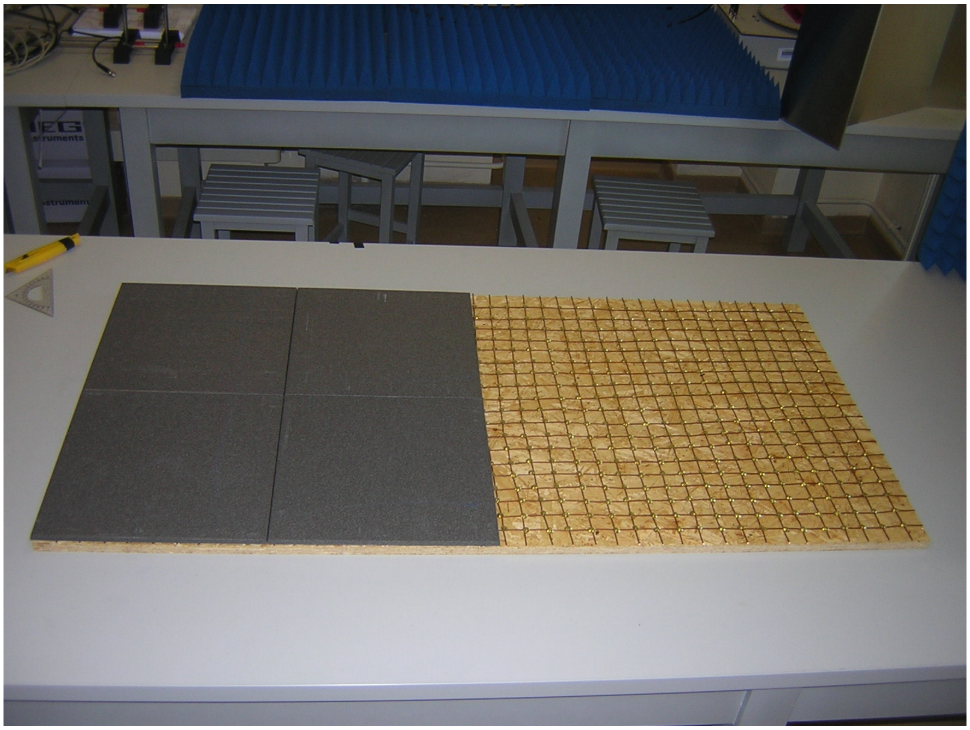


Fig.3.2.3.3.d: Ceramic tiles and rebar grid

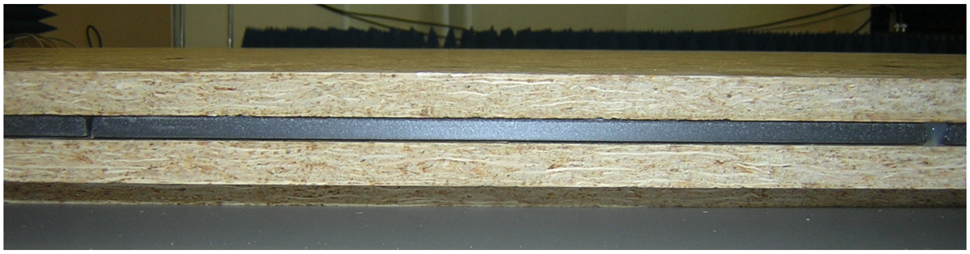


Fig.3.2.3.3.e: Section view of the wall

As a result of being assembled parts, the room shell is created. (See Figure 3.2.3.3.f).For completed empty room model with absorbers (See Figure 3.2.3.3.g)

To be able to take accurate measurements, the model needs to be sealed with absorbers those don’t allow the electromagnetic waves pass through it. See Figure 3.2.3.3.h for electromagnetically sealed room model.

Fig.3.2.3.3.f: The Room shell

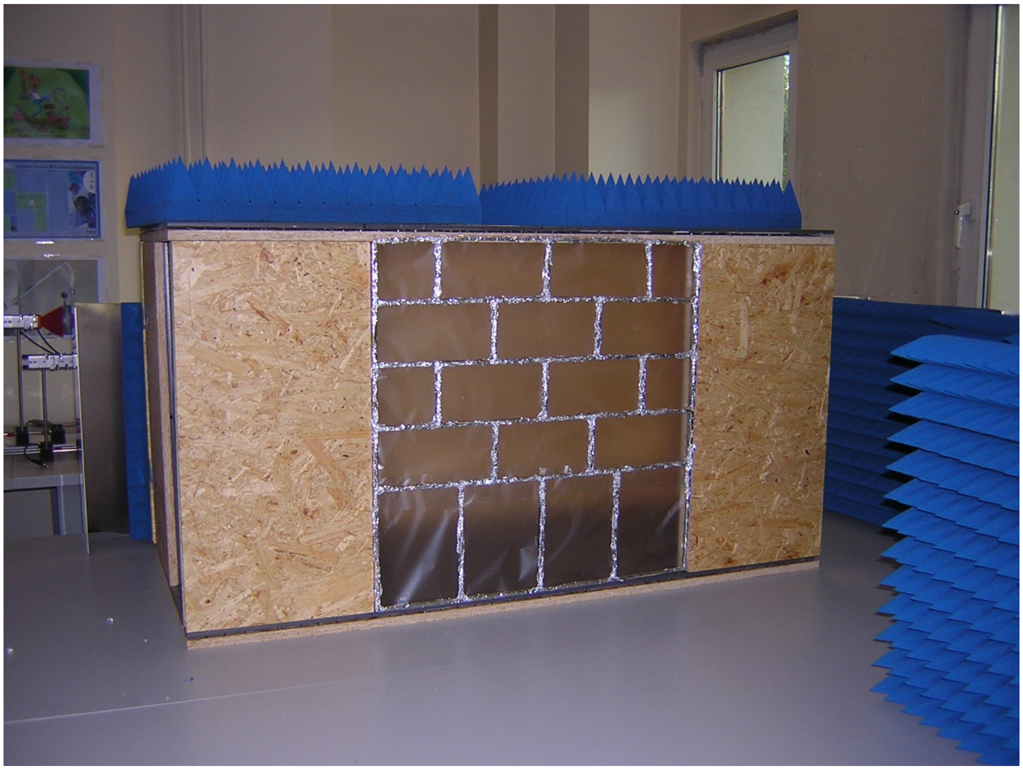


Fig.3.2.3.3.f: Completed empty room model with absorbers

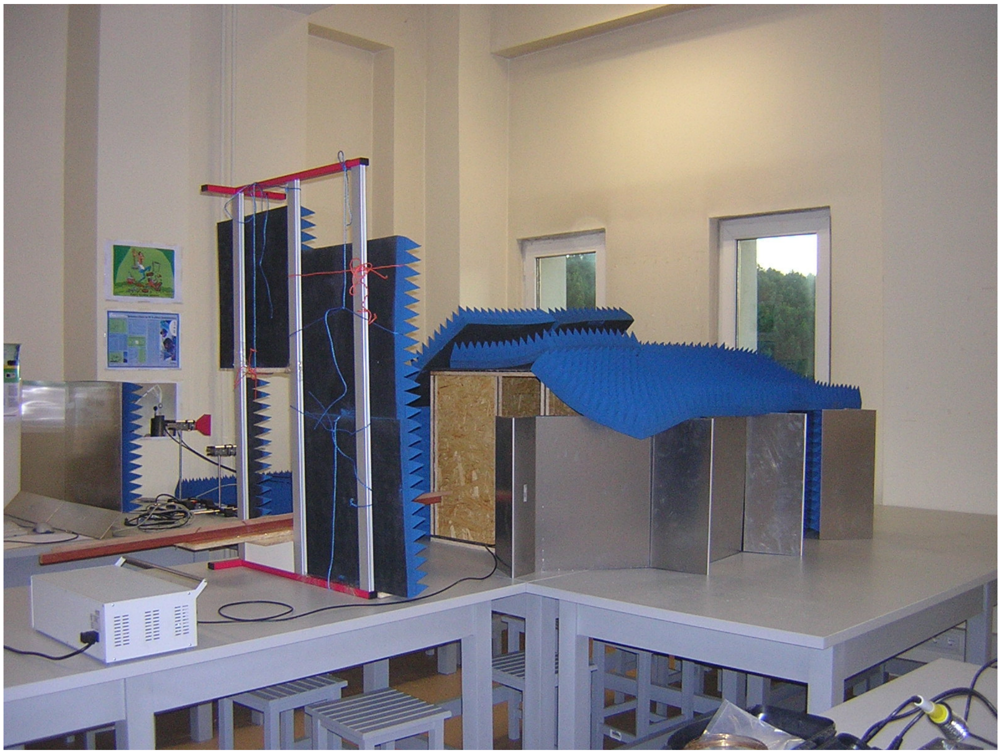


Fig.3.2.3.3.h: Electromagnetically sealed room model

The other step is measurement for the experiment. Two antennas which are mini horn (transmitter) and dipole (receiver) used to get the data of indoor electromagnetic environment. (See Figure 3.2.3.3.j)

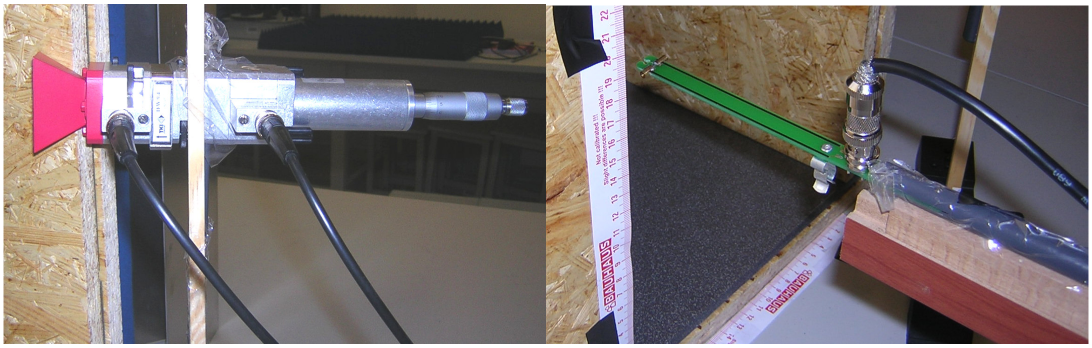


Figure 3.2.3.3.j: Left to Right Mini Horn and Dipole antennas

In addition to that, LD Gunn Power Supply with SWR Meter transfers the data which is taken from receiver to the computer with an interface. This gadget works as a combo that provides both power supply and measurement. The crucial point is how to transfer this accurate data to the computer in this case. Cassy Lab software integrated with an interface is connected to the LD test gadget using by USB port of the computer. This method is very handy to take the very accurate measurement instead of writing the results from the scale of the LD test equipment. See Figure 3.2.3.3.k for measurement process.

Fig. 3.2.3.3.k: Test equipment (from left to right desktop, the interface, and LD Power Supply&SWR meter)

Different scenarios are applied such as empty room, room with furniture, human modeling with furniture, and full room with electronic device that represents a laptop inside. Some basic office room furniture which are one storage and a file cabinet, a desk with task chair, two visitor chairs and coffee tables produced in 1/5 scale. See Figure 3.2.3.3.l for the room furniture.

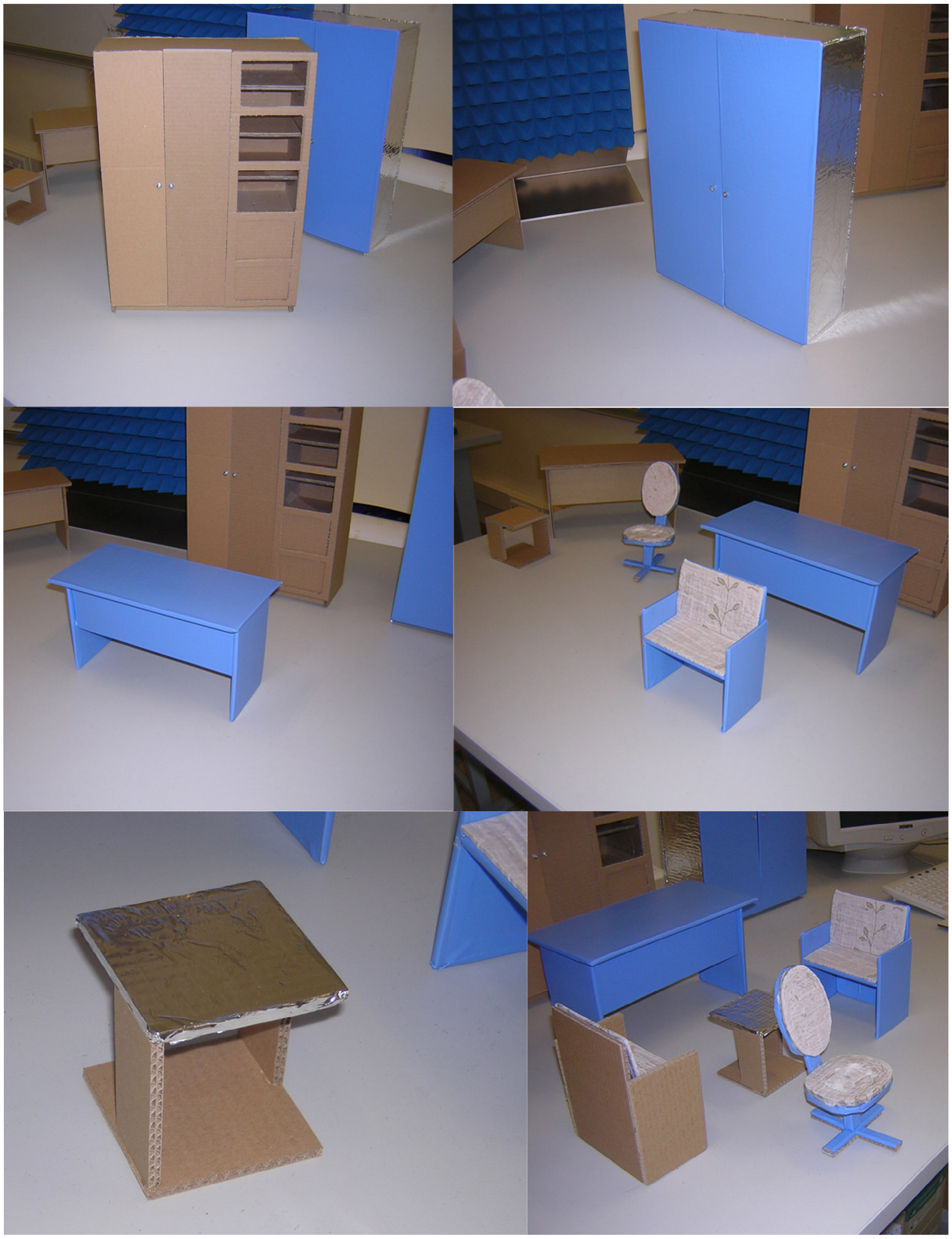


Figure 3.2.3.3.l: The Model Room Furniture

Human existence is also a variable for electromagnetic propagation in an environment. It is known that conductivity of human body is in the range of 0.1-0.5 S/m for 2.4 GHz. [37] Moreover, using sea water in proper percentage as 1/7 gives the fraction of human model. Electrical conductivity of sea water starts from 1.7 to 6 S/m due to the temperature and salinity of the sea. [38] Our percentage allows to produce the 32 cm height in 1/5 scale human model.

The last piece of the model is laptop modeling for the experiment. A working digital clock is put inside to the room to observe the changes of the EMW propagation. There are also some letters such as; h = the height of transmitter antenna, z = the height of receiver antenna, x and y refer to the coordinate system of the receiver.

The first measurement is done for empty room by the h=41.9, z=23.35, x=21-115, y=37-1 coordinates. The polarization of the horn antenna is horizontal. Contour Graph for the empty room clearly shows us the propagation of EMW. The scale (E) between 0-10 V/m. (See Figure 3.2.3.3.m below)

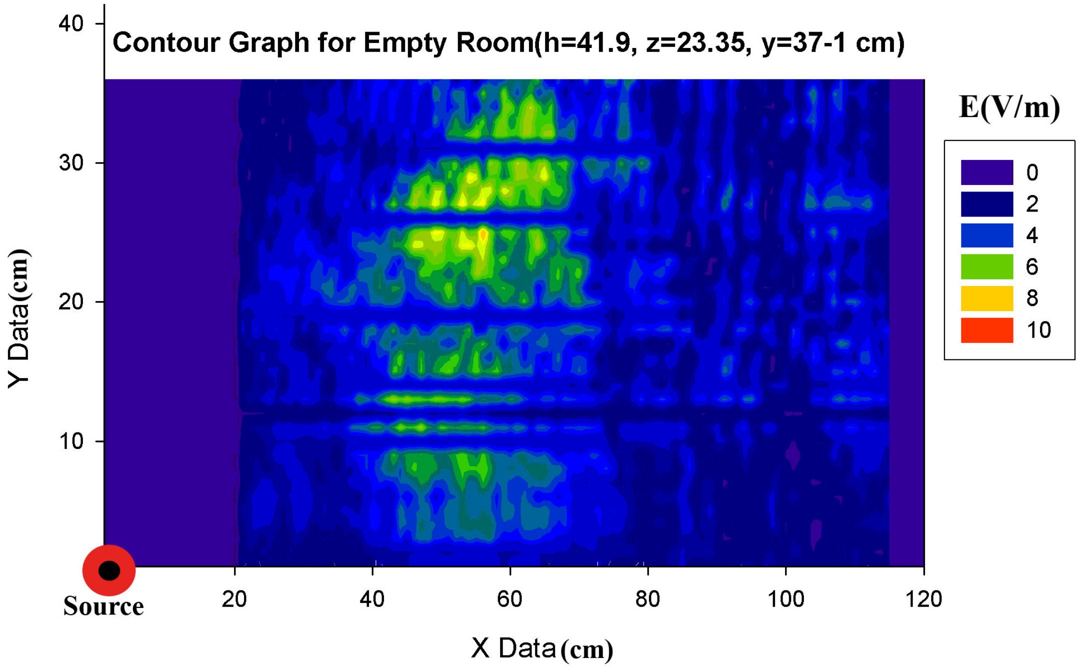


Figure 3.2.3.3.m: Contour Graph for the Empty Room

The highest values of electric field between x=40-70 range. As known as the room has aluminum window frame, the location of the window is on this range. Thus, the refraction might cause this pattern for the highest value in this range. See Fig.3.2.3.3.a for the plan of the room where the furniture including storage cabinet, file cabinet, table, task chair, two seating chairs, and two coffee tables changes the pattern of EMW propagation. See Figure 3.2.3.3.o for furniture layout of the room.

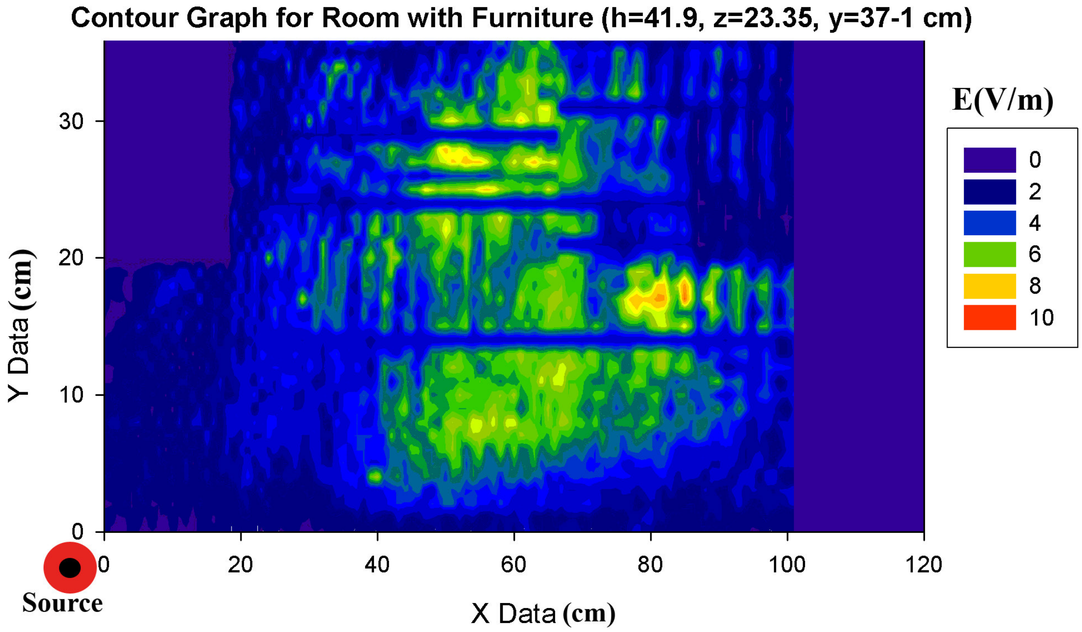


Figure 3.2.3.3.n: Contour Graph for Room with Furniture

It is obviously seen that putting the furniture change the propagation pattern. In Figure 3.2.3.3.n, wider and stronger electric field is seen on the graph. Especially above seating group and table areas has the level of 6-10 V/m values as seen on the graph. The nature of the table made of dielectric material as laminated wood and seating group has the same specialty. The coffee table has an aluminum top. Thus, this must boost the value. In this study, just electric field has been considered, the other issues which are mentioned in previous chapters as Electromagnetic Compability or Interference need to work on separately.

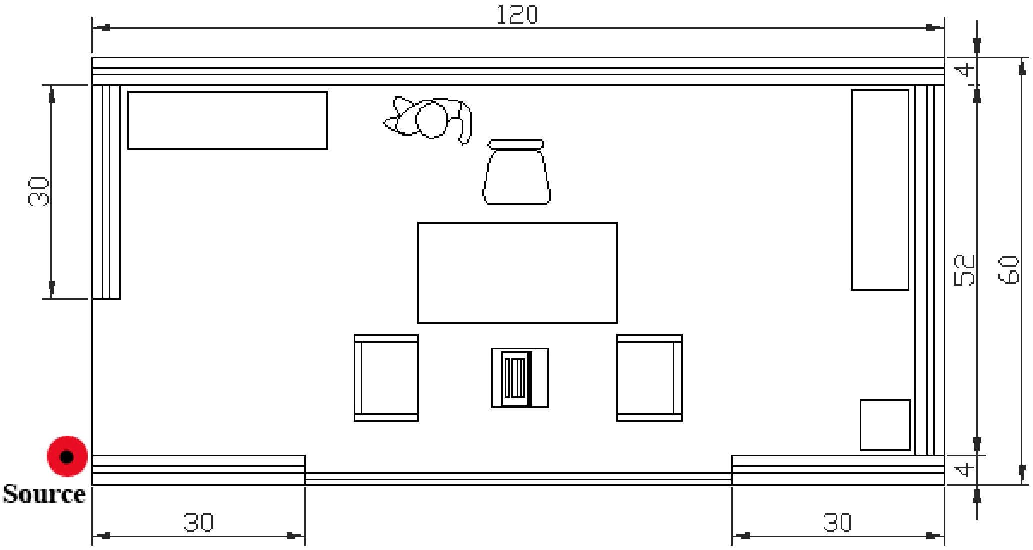


Figure 3.2.3.3.o: Furniture layout of the room (Not in Scale)

Changing the height of transmitter antenna as h=29 cm comes out very accurate measurement due to the closeness of the receiver. Moreover, highest peak values are also seen in that session. Figure 3.2.3.3.p Empty Room Contour Graph explains the electromagnetic propagation pattern in visual form. The pattern is wider and stronger in this case. In the graph, the direction of the horn antenna reflection is seen and makes the propagation area so wide and strong.

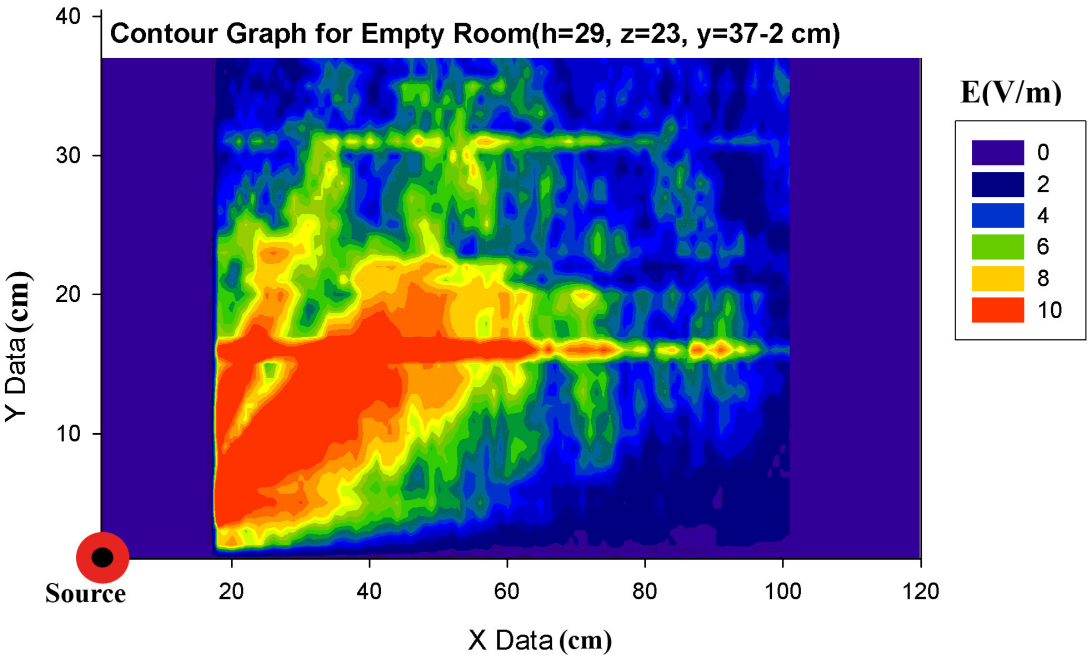


Figure 3.2.3.3.p: Contour Graph for Empty Room

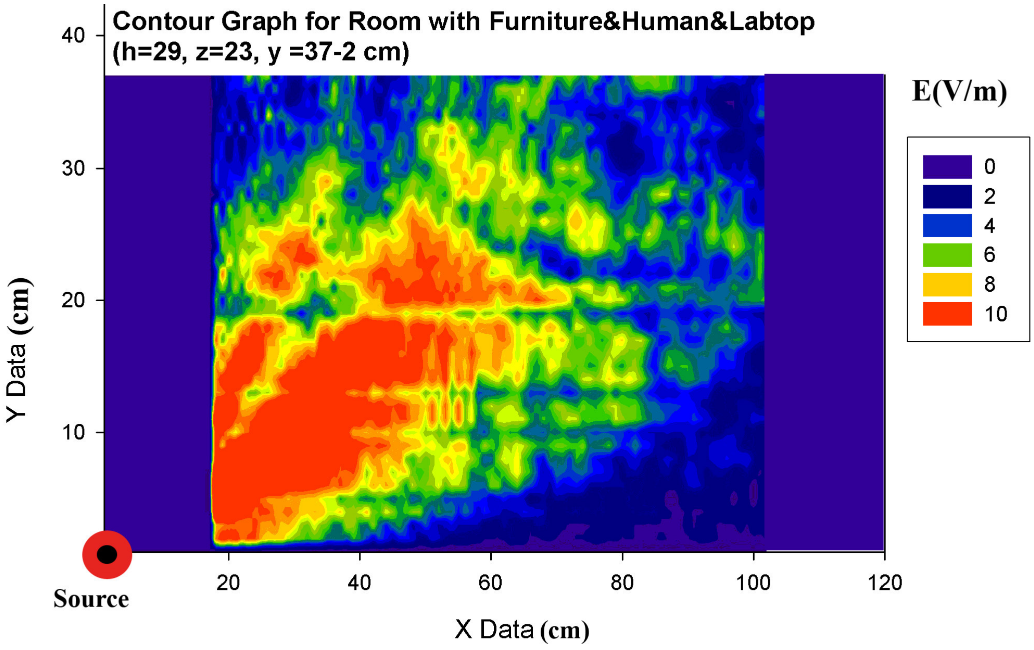


Figure 3.2.3.3.r: Contour Graph for Room with Furniture

In all cases up to now prove for the Room EMW propagations with Furniture that have higher values than empty room configurations. The pattern in Figure 3.2.3.3.r is wider and stronger comparing with the previous one.

Another configuration for the transmitter (horn) antenna is vertical polarization. The receiver antenna (dipole) is mismatched and data has been measured. See Figure 3.2.3.3.s for both empty and room with furniture layout.

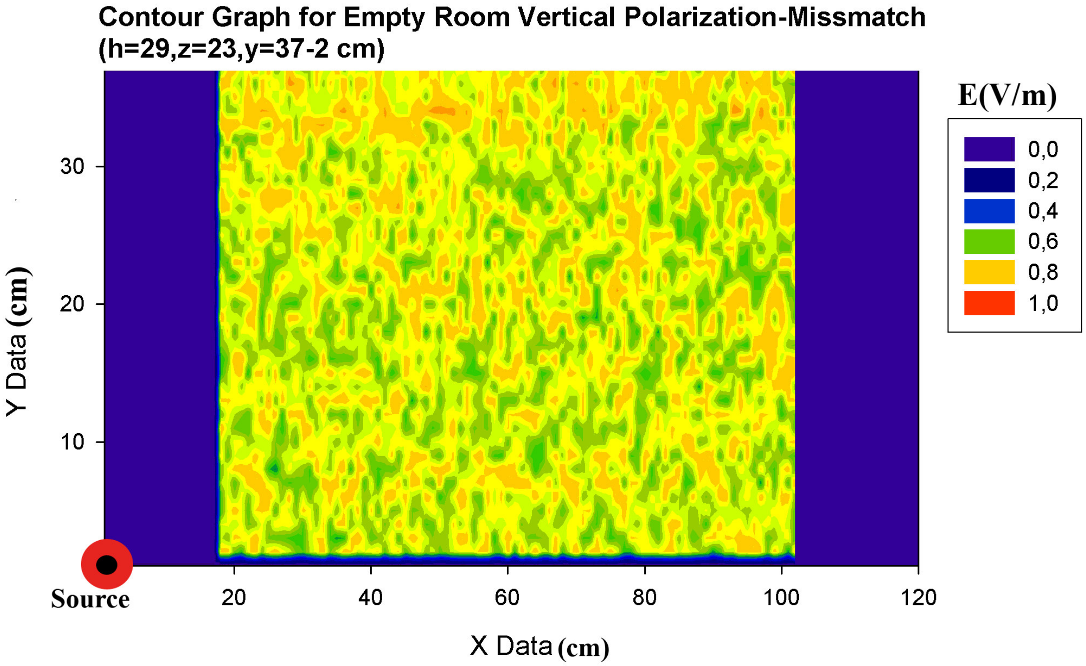


Figure 3.2.3.3.s: Both Empty and Room with Furniture (See page 51)

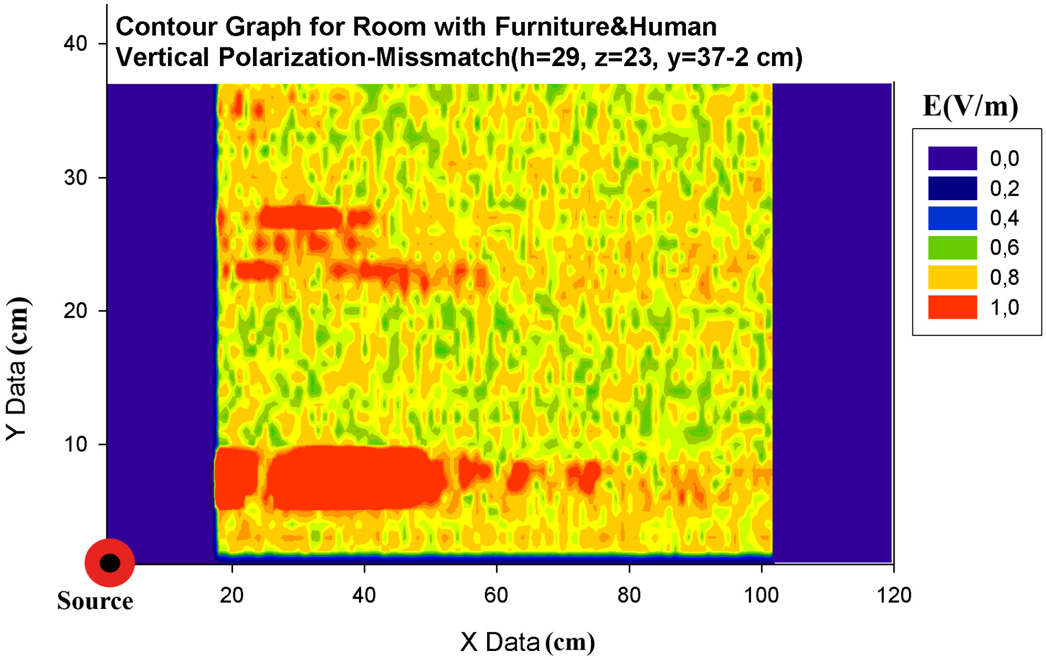


Figure 3.2.3.3.s: Both Empty and Room with Furniture

In the vertical polarization with mismatch configuration, the max scale is set to 1 because of the values are too low. Both empty and room with furniture the pattern almost the same except some spots y<10 and 20<x<60 coordinates. This is another plus observing the full room effect on the experiment.

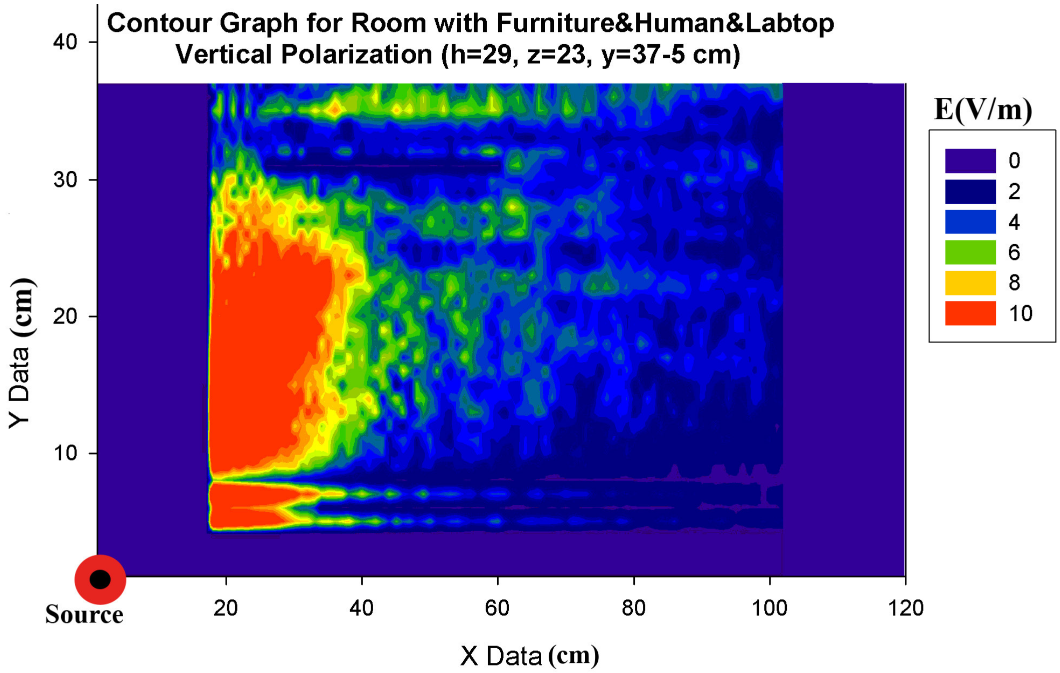


Figure 3.2.3.3.t: Vertical Polarization - Room with Furniture

Comparing Horizontal and Vertical Polarization for transmitter (horn) antenna is thought different facts as in horizontal polarization pattern is wider. Moreover, the smooth EMW propagation is observed rather than the vertical layout of the antenna.

Figure 3.2.3.3.t shows the strong hotspot close to the transmitter antenna area. It is collected below y<30 and above 20<x<40 coordinates.

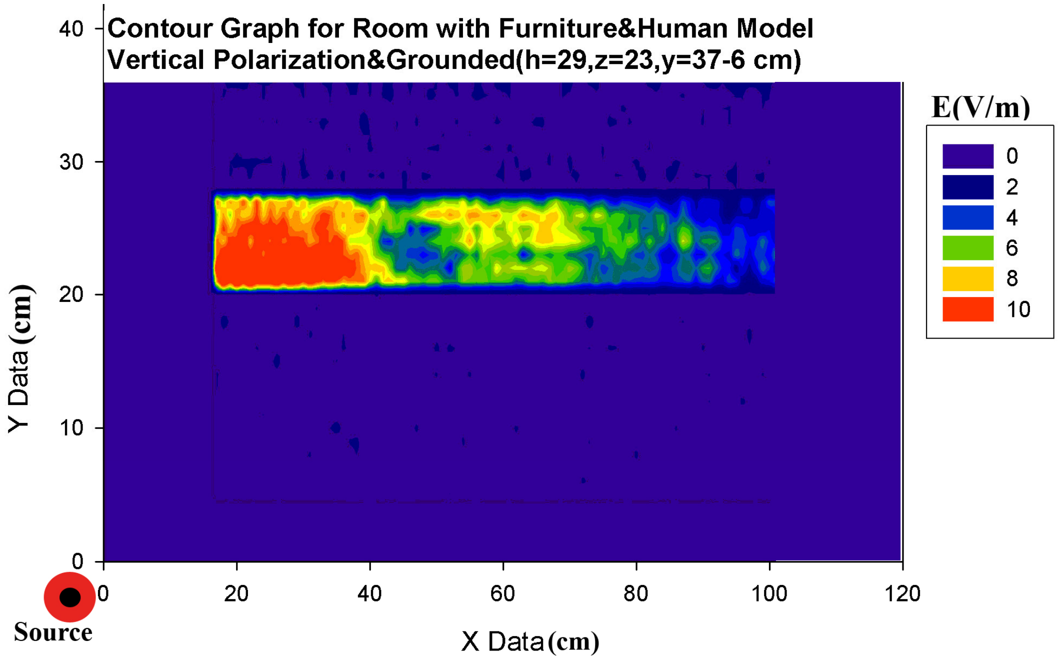


Figure 3.2.3.3.u: Vertical Polarization - Room with Furniture & Grounded

Grounded room brings the result of one hot spot which reduces its value till the end of the room. Between 20<x<40, it has its maximum range over 10 V/m. All surfaces of are grounded. Thus, the room responses as Faraday cage which is an ideal hollow conductor. Instead of refraction of excess charges on the outer face, they go to the ground. That makes the room remain neutral. Besides the hotspot, the rest of the areas values around 2 V/m. And comparing with the Figure 3.2.3.3.t proves totally different pattern on the grounded room.

Application of this feature in architecture helps to use cordless phones and wireless networks inside buildings and houses in different cases. On the other hand, this feature is very vital for some buildings which require total security mitigation against electromagnetic pulse.

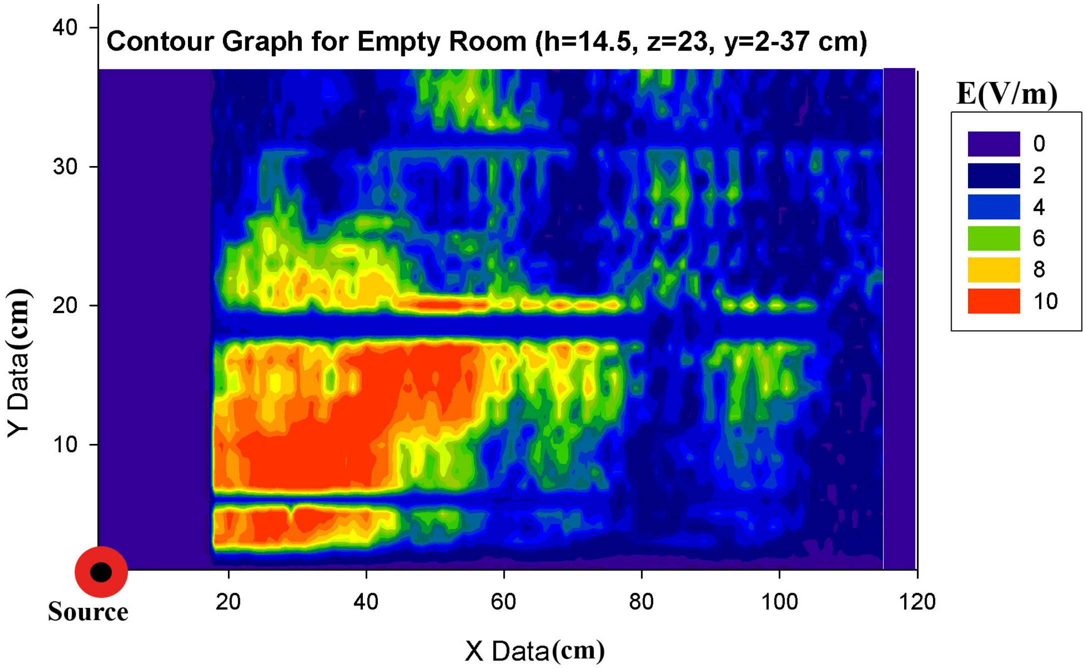


Figure 3.2.3.3.v: Contour Graph for Empty Room

Locating of the transmitter (mini horn) to below level of the receiver (dipole) antenna carries different patterns seen in Figure 3.2.3.3.v, Figure 3.2.3.3.y and Figure 3.2.3.3.z.

The hot spot in Figure 3.2.3.3.v close to the transmitter antenna as expected. Adding the furniture and human model distribute the hot spot till x<80 cm.

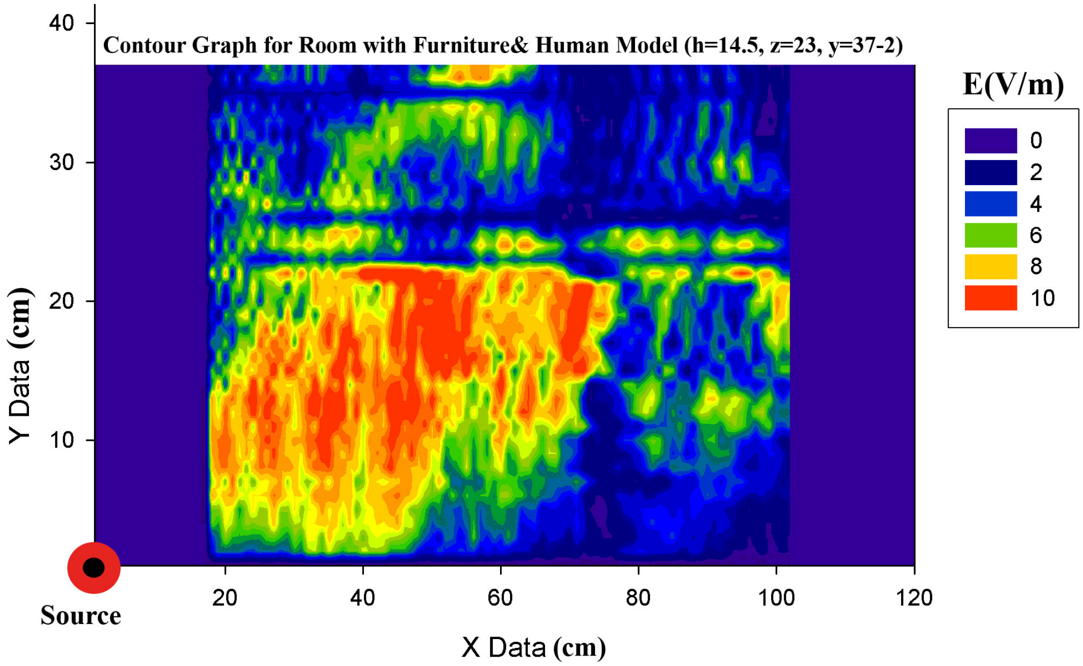


Figure 3.2.3.3.y: Contour Graph for Room with Furniture& Human Model (h=14.5, z=23, y=37-2)

On the other hand, putting the laptop model to the room effectively changes the values. (See Figure 3.2.3.3.z) This configuration is basically reduced the results as seen on the graph.

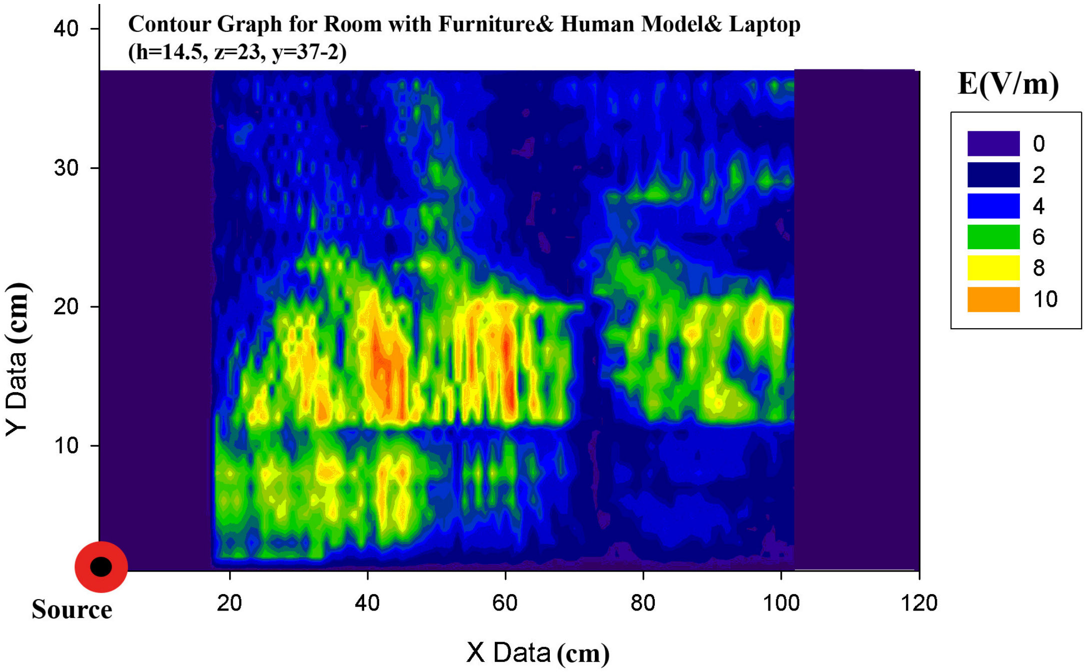


Figure 3.2.3.3.z: Contour Graph for Room with Furniture& Human Model& Laptop (h=14.5, z=23, y=37-2)

Very narrow hot spot is seen between 40<x<65, 12<y<22 and the rest are small ones. It is clearly seen that how any electronic device is effective changing the propagation in the work environment.

Finally the last configuration is done the coordinates h=41.9, z=16, y=20-1 cm by horizontal polarization. The purpose is to get the values of head level range of sitting person in the room.

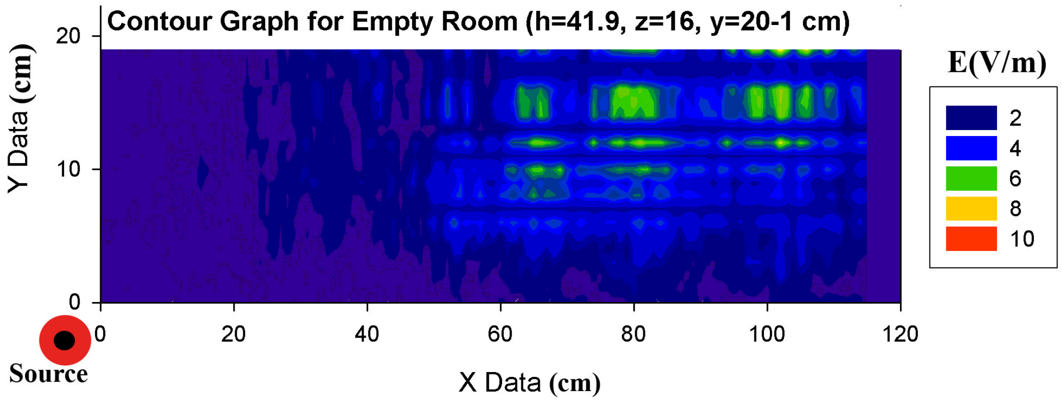


Figure 3.2.3.3.za: Contour Graph for Empty Room

The highest values around 6 V/m when the transmitter is put on higher position as h=41.9 cm. The density of the pattern starts from x=60 till the end of the room. The height of the transmitter is one of the dominant factors to get this value. As remembered from previous pages, the seating area is in the range of 30<x<90 and 0<y<30 cm. (See Figure 3.2.3.3.o) Thus, there is no significant hot spot in this coordinates.

Consequently, those configurations are limitless just for the empty room the measurement numbers goes up to 864,000 for both horizontal and vertical polarizations. In this experiment, 41,515 measurements are taken which makes the experiment as accurate as possible.

3.3 Summary

Wireless communication systems as WLAN require a versatile and accurate EMW propagation for indoor environment. In particular, the investigation of EMW transmission into buildings is very important. As presented above, modeling for three dimensional electromagnetic wave propagation prediction models for indoor wireless communications takes into consideration. Three dimensional models can predict any complex indoor environment composed of arbitrarily shaped walls for efficient prediction and computation. In the pre design phase of an interior space, analysis of the electromagnetic wave environment is a prerequisite for efficient wireless communications, and this investigation needs to be successfully done using a simulation technique rather than a measurement of wave strength in a test site. On the other hand, site measurements are mandatory for the existing buildings to solve the current issues. For accurate analysis, the outdoor environment should also be included. A wave penetrating buildings from an outdoor source is sometimes too strong and cannot be neglected for the accurate prediction of an indoor electromagnetic environment. In this study, transmission loss is analyzed accurately by considering the thickness and material characteristics of building-walls with a window model. This model includes three-dimensional penetrated waves diffracted by the window. However, HFSS has drawbacks in its computation time when the number of building-walls and details in the interior space increases. To solve this problem, powerful computers need to modified and employed for the analysis of complex indoor arrangements. All of the indoor walls and furniture, such as desks and filing cabinets, are assumed to consist of mostly rectangular geometry. Then, the computer program has information on edge coordinates and material composition. The material characteristics of walls are usually represented by permittivity and conductivity, and reflection and diffraction coefficients are computed using those parameters. These coefficients are stored for each wall with its coordinate as input variables for the computer program. Figure 3.2.2.4 shows the indoor model used for the computer program, which consists of walls, doors, and windows for a sample office environment. Walls in the Figure have thickness, and the characteristics of penetrated waves through the walls are analyzed using the simulation program. Figure 3.2.2.4 also shows the way to compare the results. The material of the inside wall to face the passage is a concrete wall containing a door made with aluminum. The outside wall contains windows. This model considers building transmission loss for an accurate prediction in the case where the antenna is located in three different locations. As a result, computer aided design software is expected to be used for the design of wireless networks in pico-cells more effectively in near future.

The other achievement is the prediction of propagation losses. With this method, the design professional can predict rough propagation losses for either pre design status or existing building in case of the need.

The last step is the experiment process before making spectrum analysis on the site for total survey of any environment. Following the steps are vital to be able to go deep in issues mentioned in previous chapters and finding to solve the problems. The experiment results give very accurate values to be able to understand EMW propagation in the closed spaces such as, how the furniture, polarization, location of the transmitter and receiver antennas and human being affect it.

CHAPTER 4

4. Conclusions

Technology is evolving. Thus, what should be done? Adapting the buildings to the technology or adapting the technology to the buildings. Actually, for the performance improvements, the designer needs to know and consider the bond of electromagnetic waves and building materials well. Unfortunately, this interdisciplinary topic has not been able to underline by the architecture society yet. To solve EMW related design problems, the first step is trying to reach theoretical solutions by using propagation models for prediction. Thus, there is an ongoing need for the solution of basic electromagnetic problems. There are lots of variables such as; type of building materials, frequency, environmental effects, design geometry and more. For the different scenarios and multiple conditions, new prediction models might need to permit rapid evaluation compared to brute-force numerical techniques and allow predictions to be able to get the accurate results. Moreover, experimentations also need to be done in laboratories as second step. Real-time channel predictions support both theoretical predictions and measurements. Another crucial aspect is anechoic chambers which are basically constructed as shielded rooms. All over the walls and the ceiling, absorbing materials and/or ferrite tiles are attached for EMW free environment. Moreover, anechoic chambers show superb shielding performance and are mainly applied in EM emission testing according to commercial and military standards. [44] Thus, for the real time experiments, it is a must to have one. As if, surgeon cannot do his surgery in the street, this type of research cannot be done without the chamber. Thus, the following results need to be underlined for future studies about EMW propagation related issues in architecture field:

1. WLAN require a versatile and accurate EMW propagation for indoor environment.

2. The investigation of EMW transmission into buildings is very important for design professionals so that they can understand propagation needs of the structures.
3. Three dimensional models can predict any complex indoor environment composed of arbitrarily shaped walls for efficient prediction and computation.
4. HFSS has drawbacks in its computation time when the number of building-walls and details in the interior space increases. To solve this problem, powerful computers need to modified and employed for the analysis of complex indoor arrangements.
5. The experiment results give very accurate values to be able to understand EMW propagation in the closed spaces such as, how the furniture, polarization, location of the transmitter and receiver antennas and human being affect it.

Lastly, this research is focused on 2.4 GHz which is used in most of country's WLAN frequency because of today's standard but it can be adapted to any frequency range to analyze the building materials and set the codes for the buildings of future. In addition, this research covers all both gives the idea of the future of wireless local area networking and the effect of architectural forms and design.

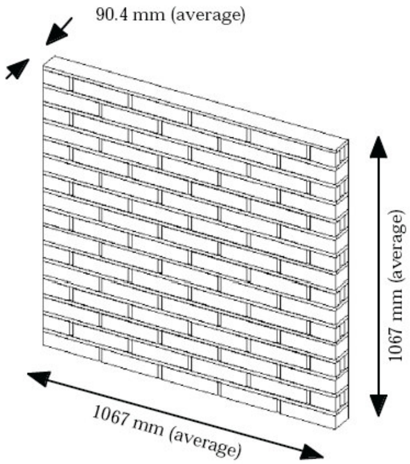
APPENDIX A:

Building Materials and EMW (Electromagnetic Wave) bond

Due to the NIST (The United States Department of Commerce Technology Administration National Institute of Standards and Technology) research which is called Electromagnetic Signal Attenuation in Construction Materials Report October 1997 Number 3 , The main building materials and combinations are analyzed below as; Brick, Masonry Block, Plain Concrete, Reinforced Concrete and Rebar Grid, Glass, Lumber (dry and wet), Plywood (dry and wet), Drywall, Brick-Faced Concrete Wall, Brick-Faced Masonry Block, various Plain Concrete Mixtures and Rebar Grid.

A.1 Brick

The red clay brick is widely used material in both residential and commercial building construction. Figure A.1.a shows three different brick wall thickness configuration used in NIST experiment. Moreover, 1x1 meter single Wythe brick walls were fabricated for convenience.



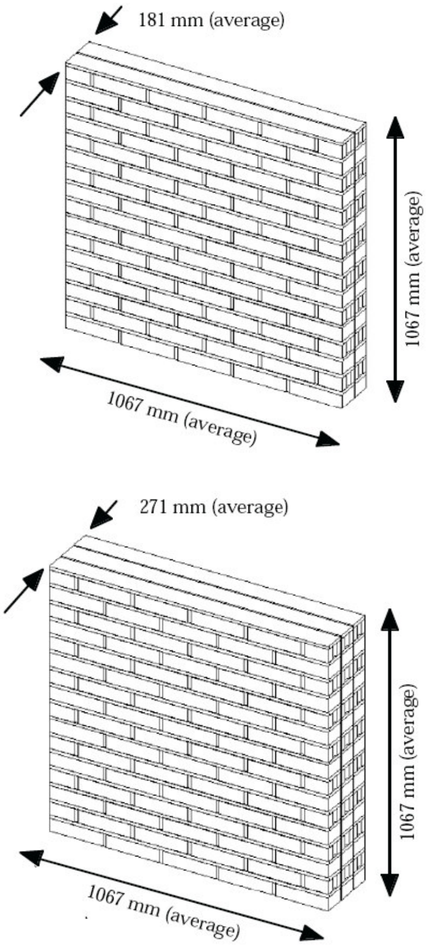


Figure A.1.a: Brick wall geometries. Top to Bottom: single Wythe, double Wythe, triple Wythe construction. (C. Stone, William, October 1997 p. 32)

A.1.1 Response data for Brick

In this study, both low and high frequency ranges (0.5-2.0 GHz / 3.0-8.0 GHz) response of the building materials` spectra results are being analyzed. Moreover, figures are showed below for each material. Thus, transmission coefficient (decimal) ranges 1 to 0 that means full transmission of the electromagnetic wave or full attenuation includes absorption or reflection of the waves.

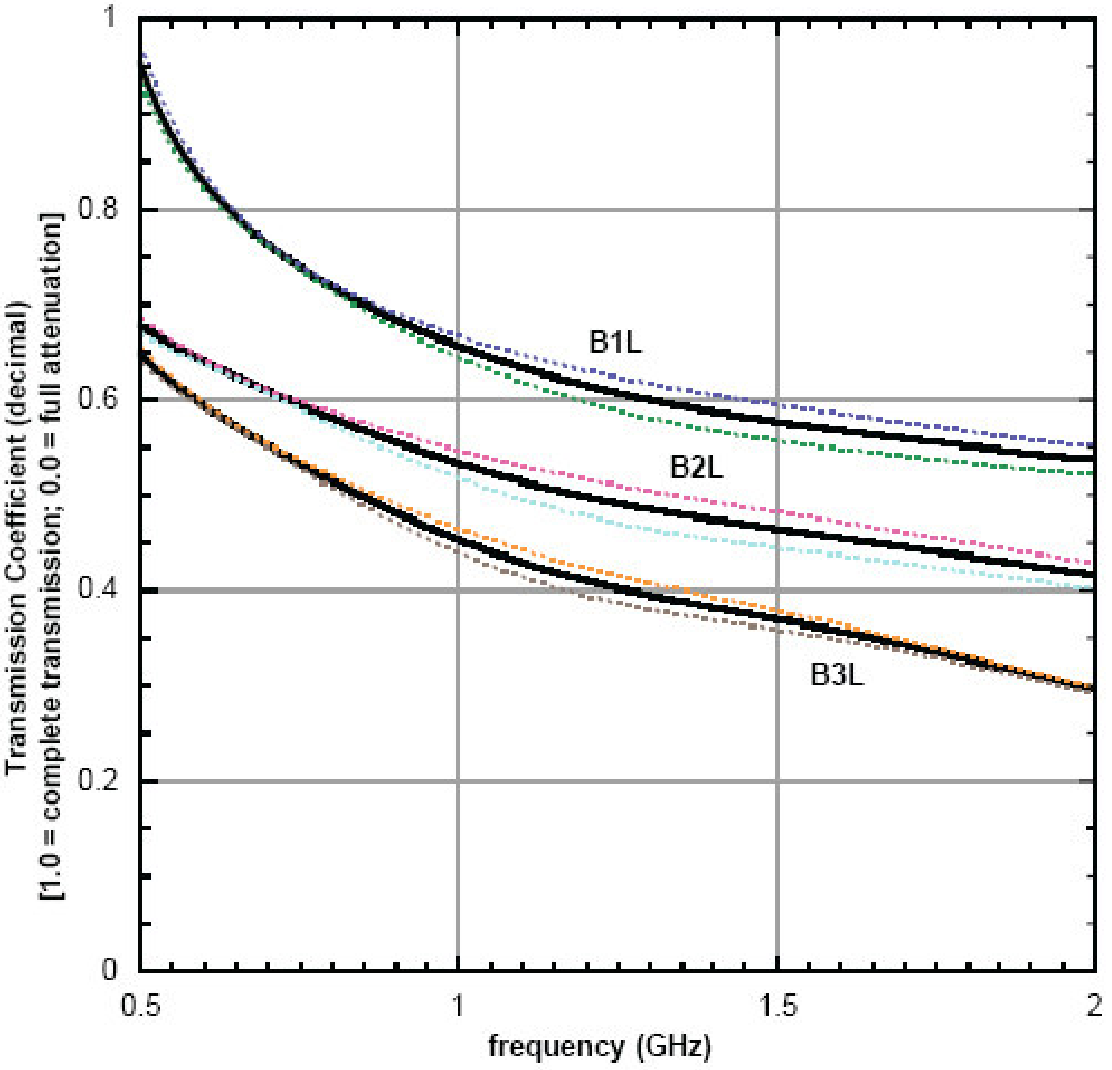


Figure A.1.1.a: Transmission Coefficients for Brick B1L = 89 mm; B2L = 178 mm; B3L = 267 mm nominal Target Thickness. Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz. Amplitude Units: (decimal) (C. Stone, William e, October 1997 p.64)

Experimenting low range data as 0.5 to 2.0 GHz for BL1=89 mm thick brick wall response is that transmission coefficient drops 0.95 to 0.55 due to the frequency from 0.5 to 2.0 GHz. B2L= 178 mm thick brick wall and B3L= 267 mm thick brick walls act much the same that is shown above.(Figure A.1.1.a)

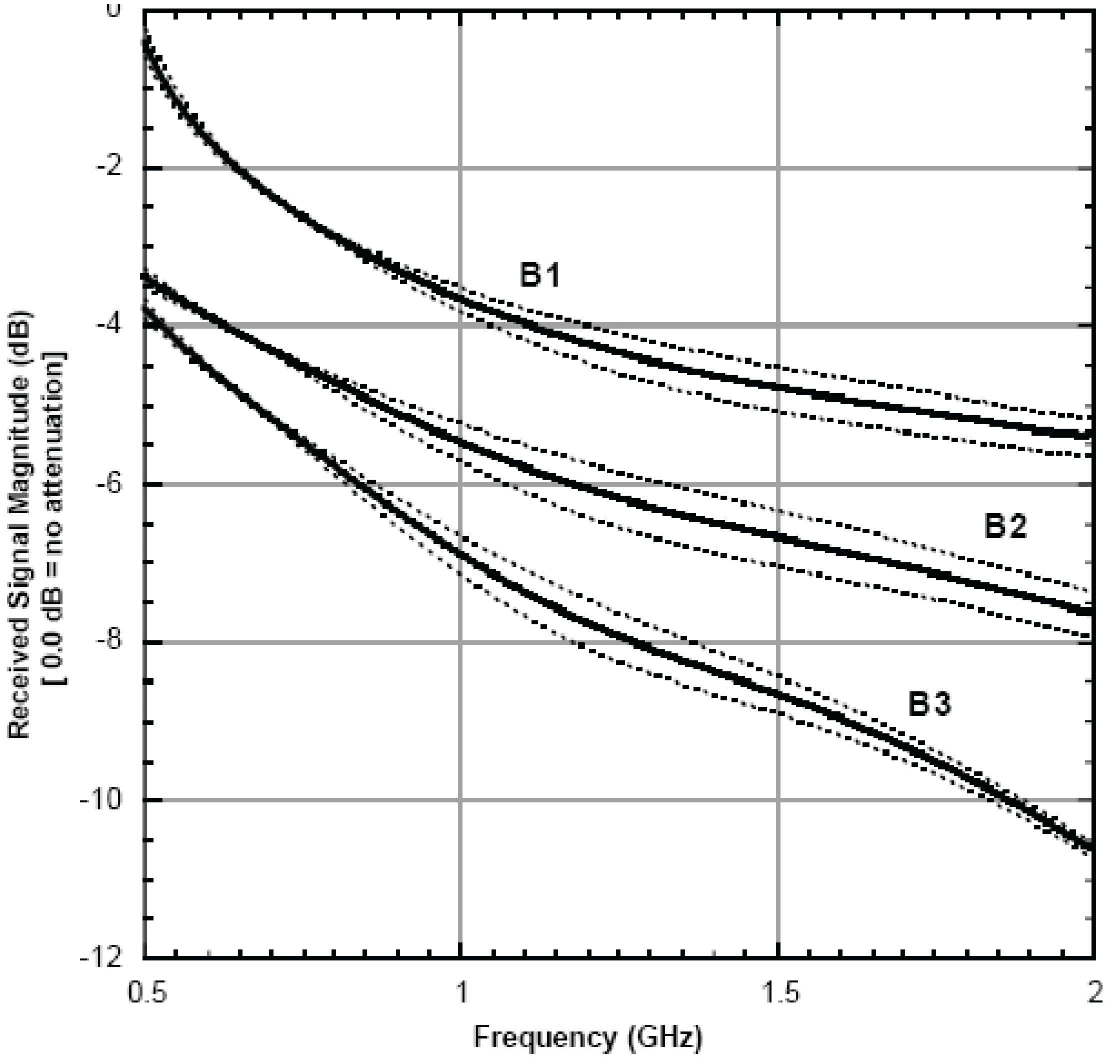


Figure A.1.1.b: Received Signal Magnitude for Brick (relative to free space) B1L = 89 mm; B2L = 178 mm; B3L = 267 mm nominal Target Thickness. Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz. Amplitude Units: (dB)
(C. Stone, William, October 1997 p.65)

Another aspect is Received Signal Magnitude for low frequencies. Figure A.1.1.b shows the three types of brick walls which are 89, 178 and 267 mm receive the attenuation below 0 due to the frequency. When dealing with low frequency range 0.5 to 2.0 GHz, higher frequency means both lower transmission and lower received magnitude.

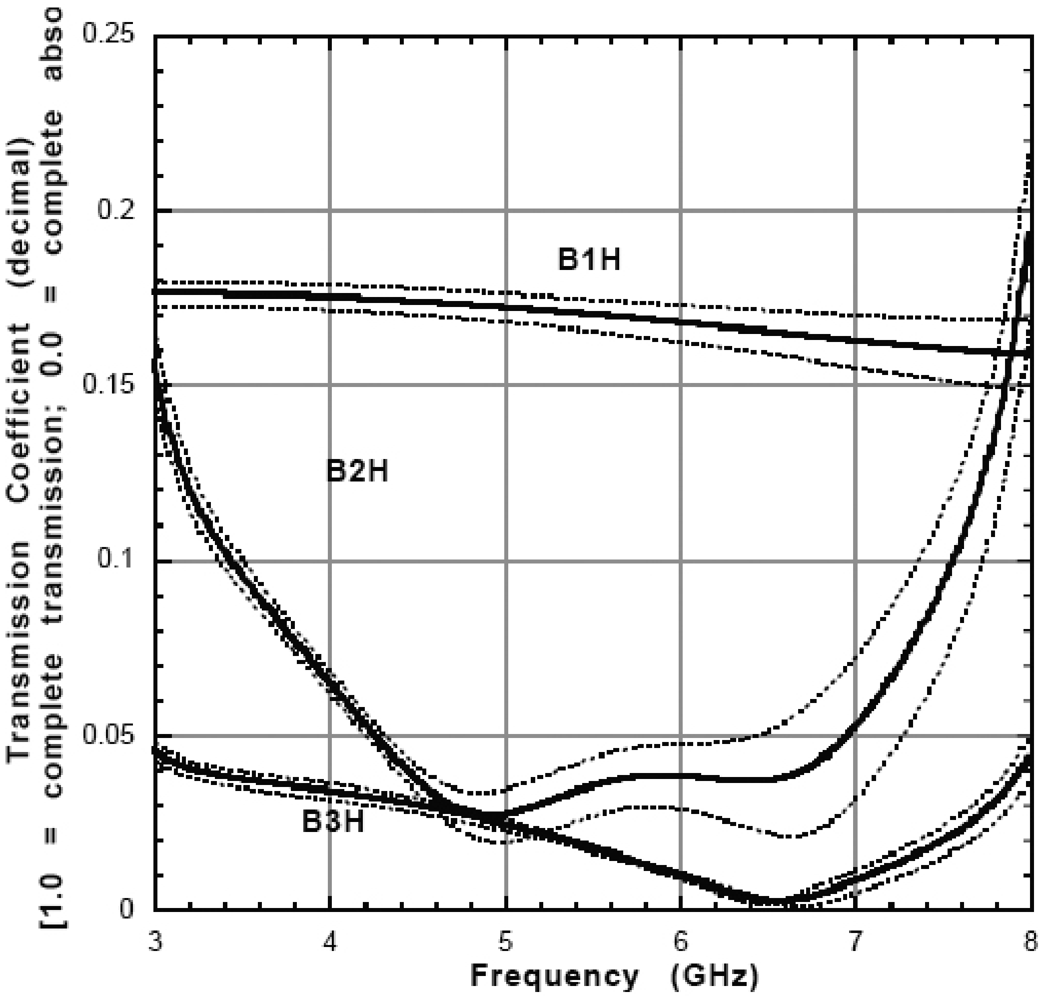


Figure A.1.1.c: Transmission Coefficients for Brick B1L = 89 mm; B2L = 178 mm; B3L = 267 mm nominal Target Thickness. Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0-8.0 GHz. Amplitude Units: (decimal)
(C. Stone, William, October 1997 p.66)

Comparing with the lower frequency range, higher frequency from 3.GHz to 8 GHz has lower transmission of electromagnetic waves. The all types of brick walls have the transmission below 0.2 that means loosing more than 80 percentage of the signal power. B1L=89 mm thick brick wall acts almost stable to the frequency changes but the other brick walls respond in very unsettled to the frequency changes. (Figure A.1.1.c)

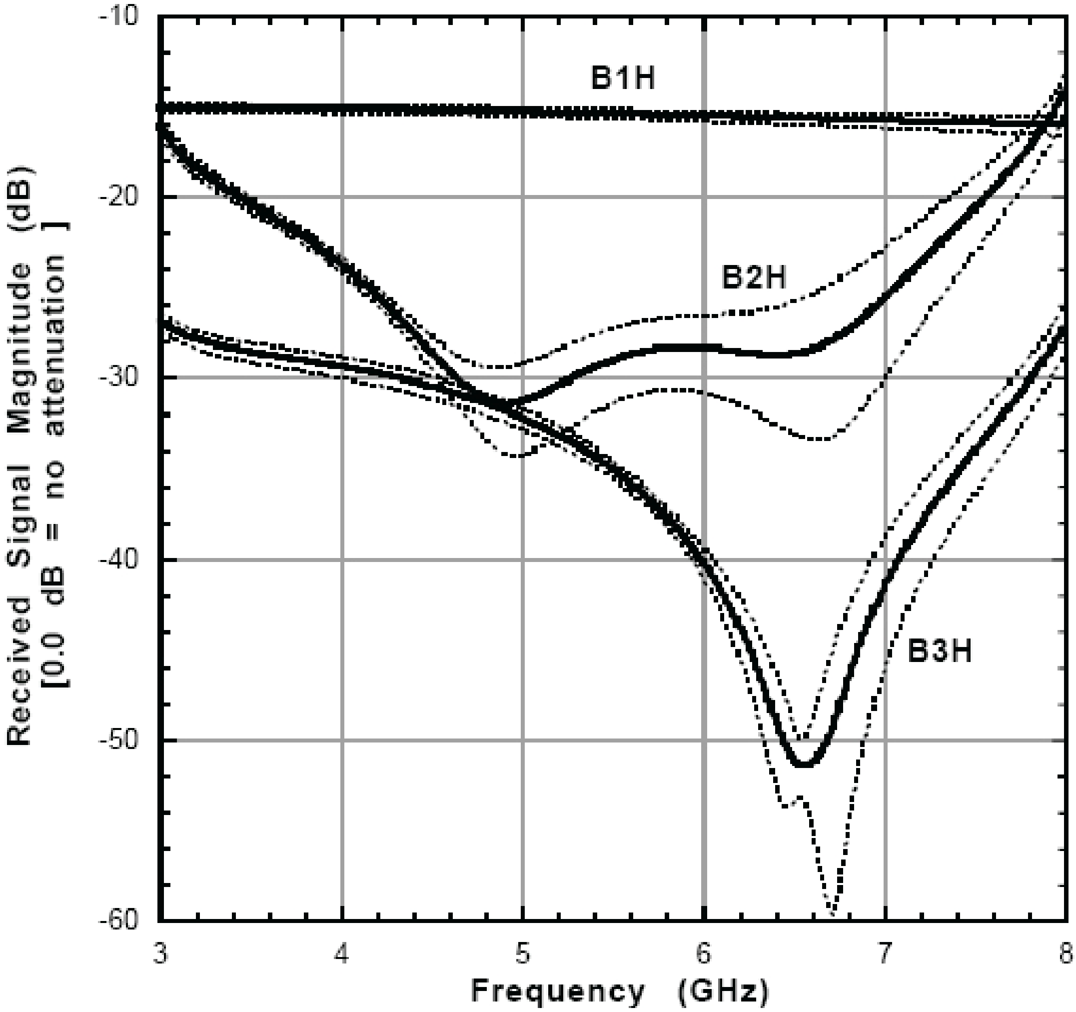


Figure A.1.1.d: Received Signal Magnitude for Brick (relative to free space) B1L = 89 mm; B2L = 178 mm; B3L = 267 mm nominal Target Thickness. Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0-8.0 GHz. Amplitude Units: (dB)
(C. Stone, William, October 1997 p.67)

The reflection of the transmission behaviors are the same in received signal magnitude as 89 mm brick wall and the others above mentioned. All of the walls have below -10 (db) in high frequencies. (Figure A.1.1.d)

A.2 Masonry Block

The concrete masonry block another commonly used material in both residential and commercial buildings. The geometry of masonry block includes two large rectangular holes and in the middle there is thin rectangular slot to be able to use for window frame setting.

Three types of walls are used in the research shown below.

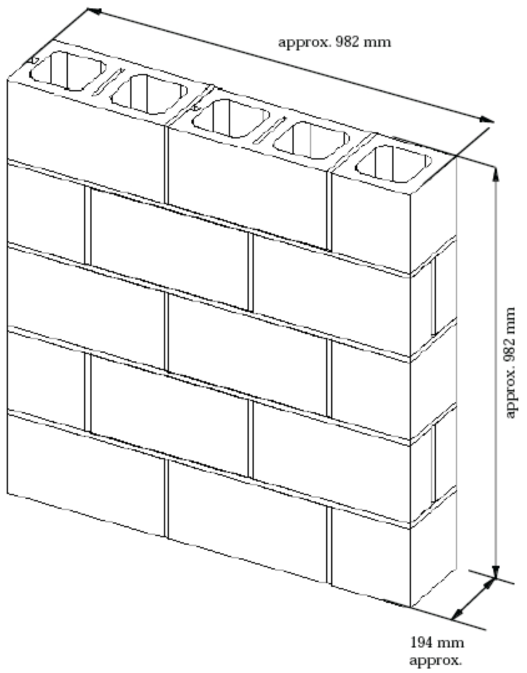


Fig A.2.a: Masonry blocks wall geometries. Top to Bottom: single row, double row, and triple row construction. (C. Stone, William, October 1997 p.38)

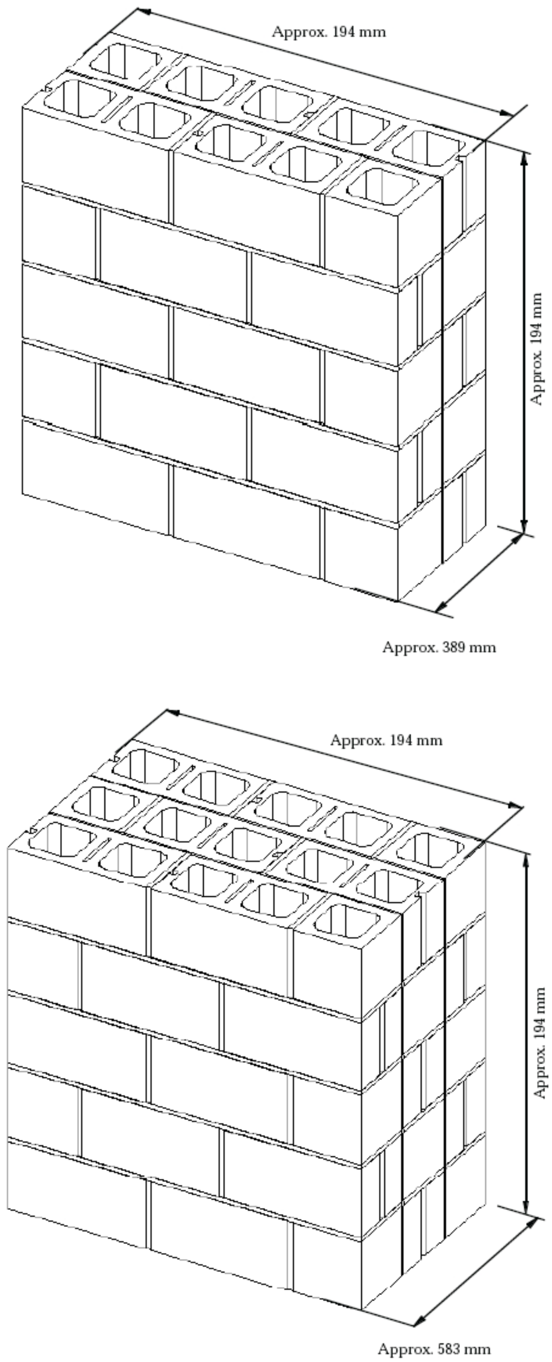


Fig A.2.a: Masonry blocks wall geometries. Top to Bottom: single row, double row, and triple row construction. (C. Stone, William, October 1997 p.38)

A.2.1 Response data for Masonry Block

Masonry Block walls are another commonly used construction solution in building design worldwide. In the research, three specimen thicknesses, 203 mm, 406 mm, and 609 mm, are tested. The average material density was 1.84 g/cc. The responses of the walls are shown below “low” (0.5 to 2.0 GHz) and “high” (3.0 to 8.0 GHz) frequency bandwidths.

CB1L = 203 mm wall starts below 0.4 transmission which means more then %60 absorption of the wave in 0.5 GHz. The transmission drops till 1 GHz and then it smoothly raises the value below 0.3 transmissions until 1.5 GHz. The range between 1.5-2.0 GHz shows a smooth curve the range between 0.25-0.3 transmission coefficients shown in Figure A.2.1.a.

CB2L = 406 mm masonry walls transmission value begins above 0.2 and drops till 1.5 GHz below the coefficient 0.15 then stands still to 2.0 GHz. (See Figure A.2.1.a)

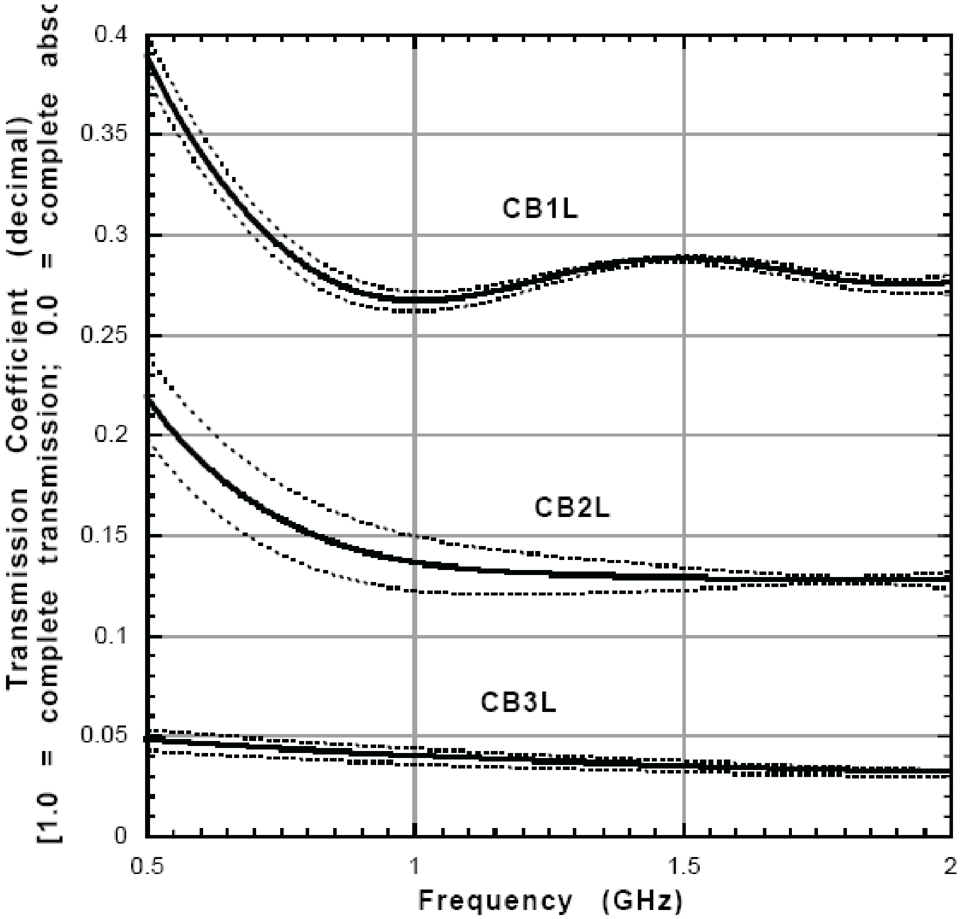


Figure A.2.1.a: Transmission Coefficients for Masonry Block walls. Nominal thicknesses: CB1L = 203 mm; CB2L = 406 mm; CB3L = 610 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.130)

CB3L = 610 mm masonry wall response value starts the lowest as 0.05 transmission coefficient and it makes a stable drop till 2.0 GHz, if we compare with the other walls. The absorption is more than %90 for the wave.

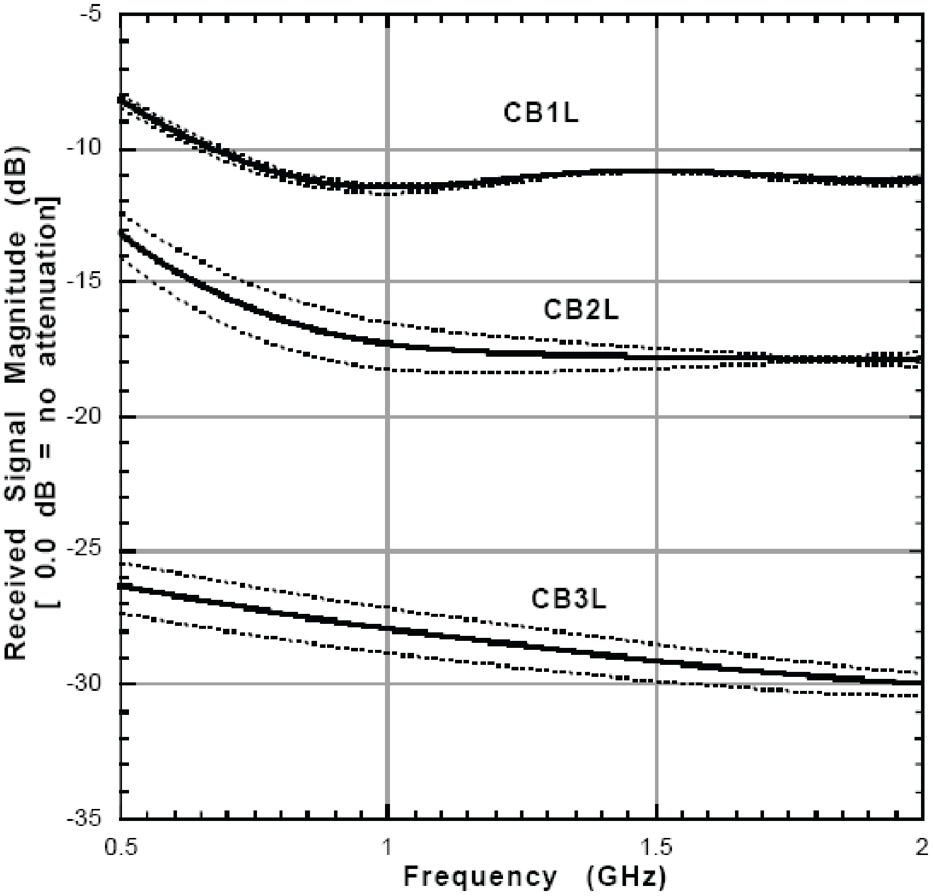


Figure A.2.1.b: Received Signal Magnitude (dB) for Masonry Block Walls. Nominal thicknesses: CB1L = 203 mm; CB2L = 406 mm; CB3L = 610 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.131)

The responses of Received Signal Magnitude for the walls (CB1L = 203 mm; CB2L = 406 mm; CB3L = 610 mm) are like the reflection of transmission coefficients geometry shown in Figure A.2.1.b.

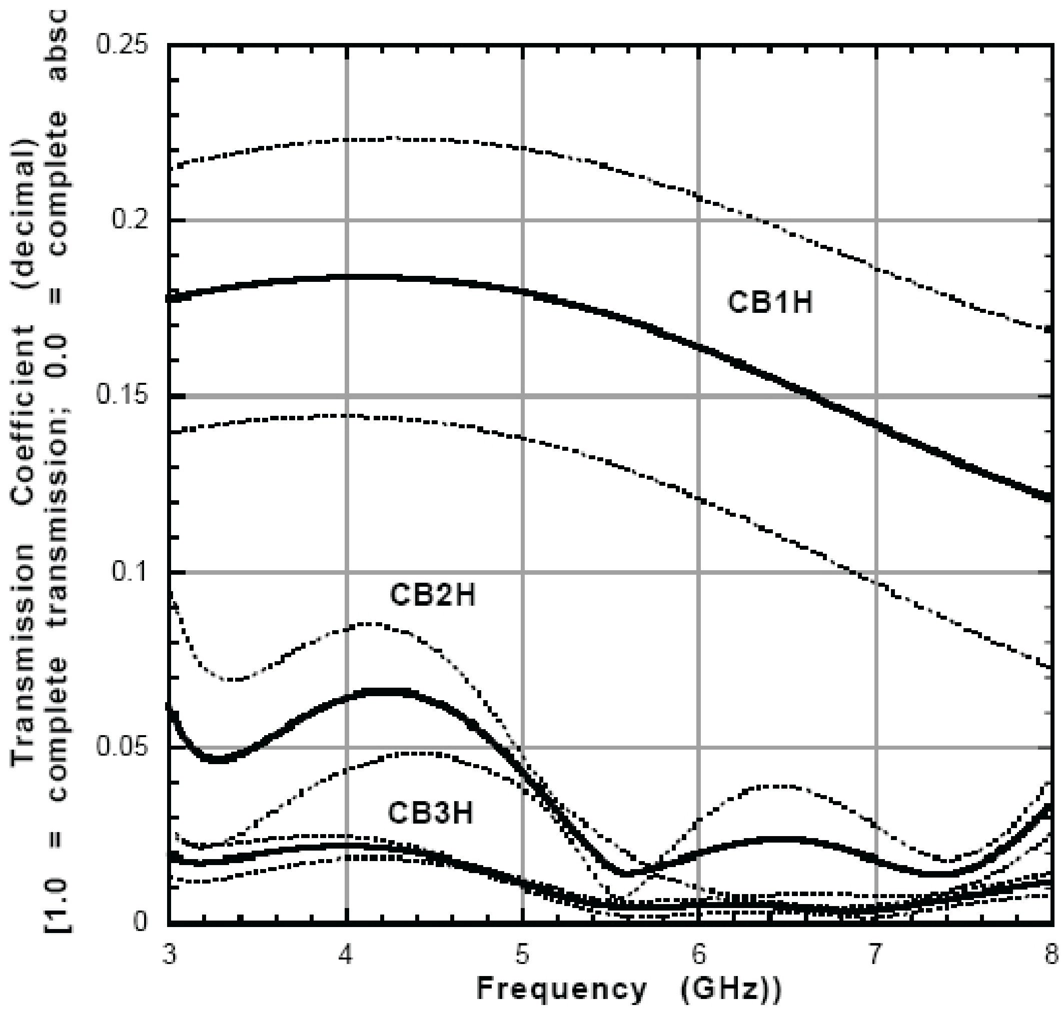


Figure A.2.1.c: Transmission Coefficients for Masonry Block walls. Nominal thicknesses: CB1H = 203 mm; CB2H = 406 mm; CB3H = 610 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.132)

Higher frequencies (3.0 to 8.0 GHz) are unstable responses for CB2H = 406 mm; CB3H = 610 mm masonry walls. On the other hand, CB1H = 203 mm wall value begins between 0.15- 0.2 transmission coefficient in 3.0 GHz frequency and decreases smoothly below 0.15 in 8.0 GHz shown in Figure A.2.1.c.

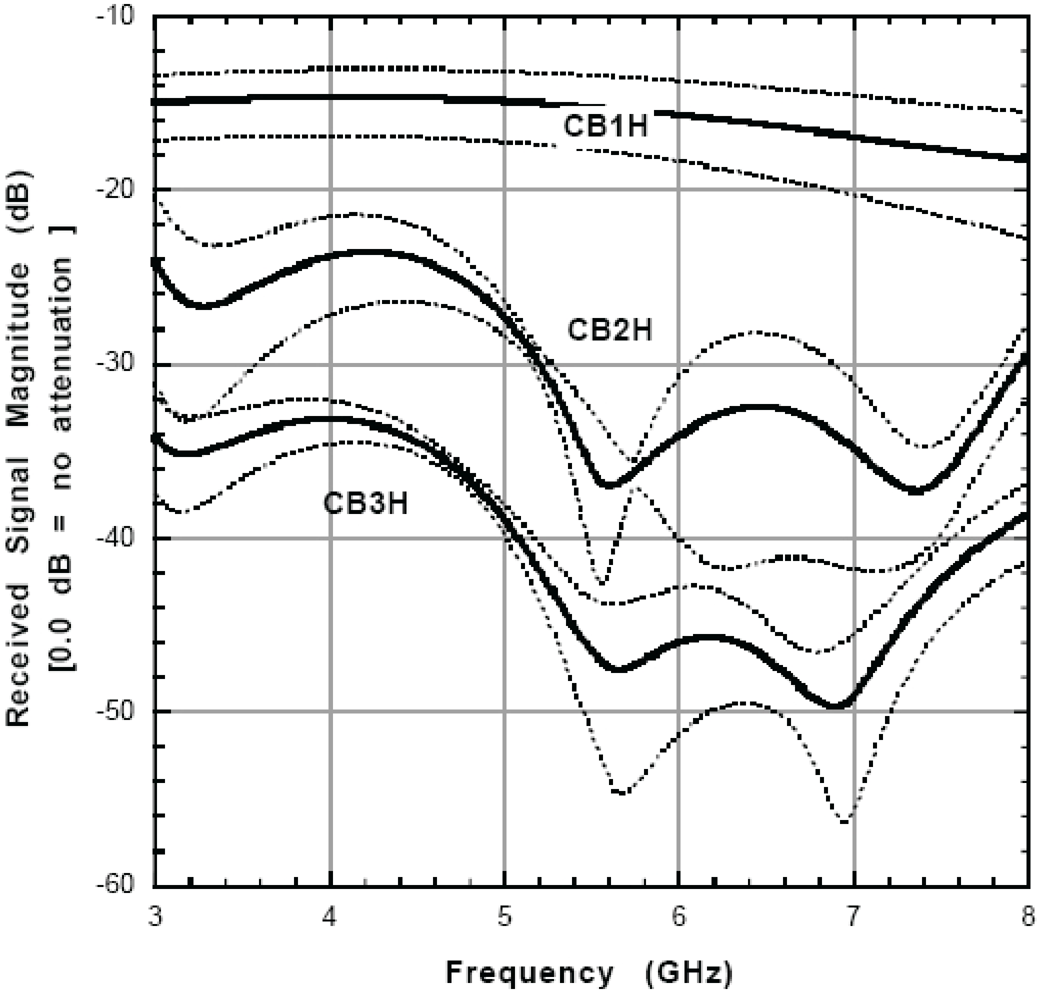


Figure A.2.1.d: Received Signal Magnitude (dB) for Masonry Block Walls. Nominal thicknesses: CB1H = 203 mm; CB2H = 406 mm; CB3H = 610 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.133)

Similar type of behavior of the waves on high range data (3.0 to 8.0 GHz) is seen in Figure 2.3.2.1d. CB1H = 203 mm masonry block is stable then the others (CB2H = 406 mm; CB3H = 610 mm).

A.3 Plain Concrete

Plain concrete has different variables such as; geometry, thickness, aggregate size, water/cement ratio, and slump. Three main form is beings used to experiment the material in NIST research.

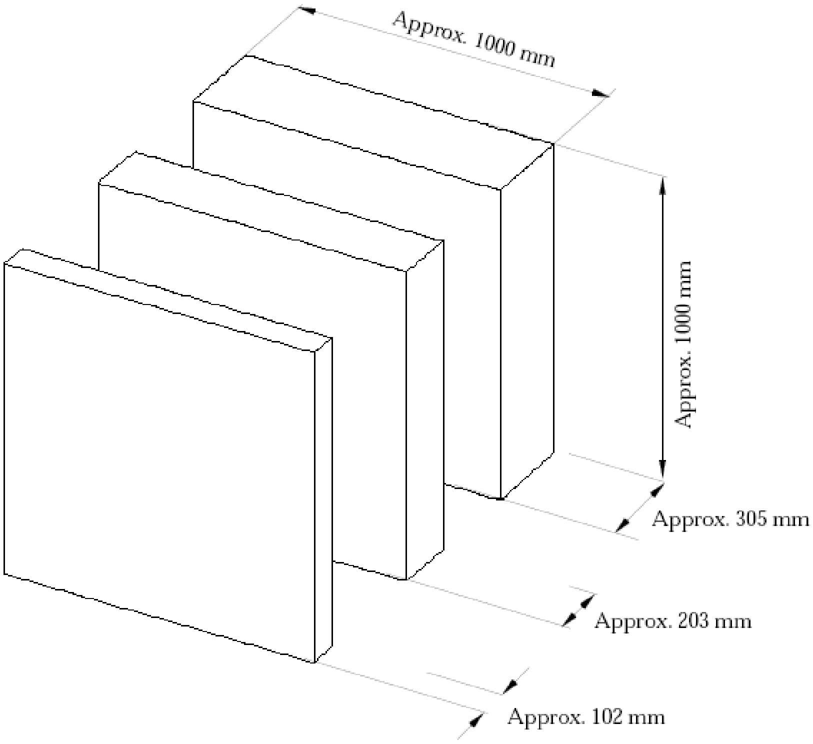


Figure: A.3.a: Plain concrete specimen geometry. (C. Stone, William, October 1997 p.42)

A.3.1 Response data for Plain Concrete

Different batch concrete specimens are used for the research. The first one have an approximate water cement ratio of 0.4, a slump of 57 mm, a nominal maximum crushed aggregate size of 12.7 mm, a cement content by weight of 22% and an average density of 2.31 g/cc.

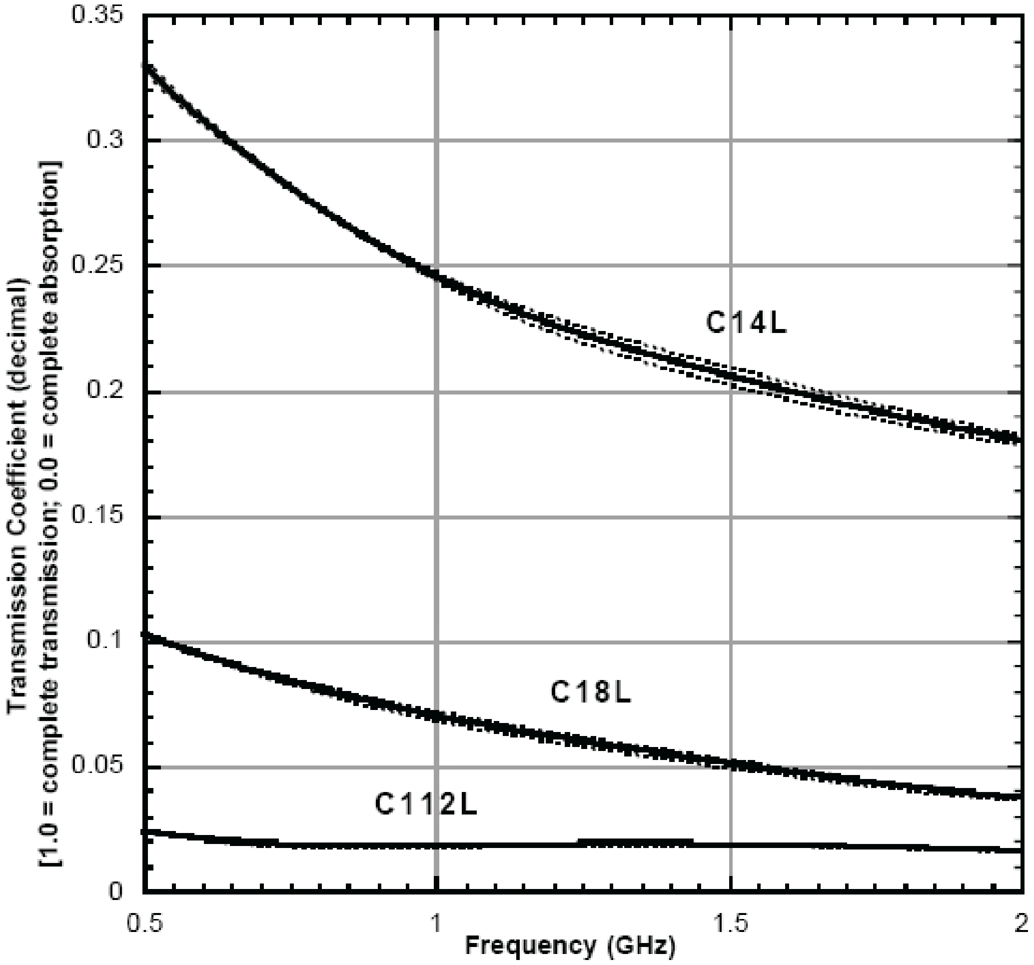


Fig. A.3.1.a: Transmission Coefficients for Concrete Type 1 walls. Nominal thicknesses: C14L = 102 mm; C18L = 203 mm; C112L = 305 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.82)

Transmission for C14L = 102 mm type concrete wall value initiates above 0.3 then it decreases to below 0.2 in 2.0 GHz. Secondly, C18L = 203 mm concrete wall approximately establish the response 0.1 in 0.5 GHz frequency almost absorbing %90 of the waves and drops below 0.05 in 2.0 GHz. Finally, C112L = 305 mm wall responses more stable starting like 0.025 transmission coefficient and ends above 0.020 in 2.0 GHz frequency. (See Fig. A.3.1.a)

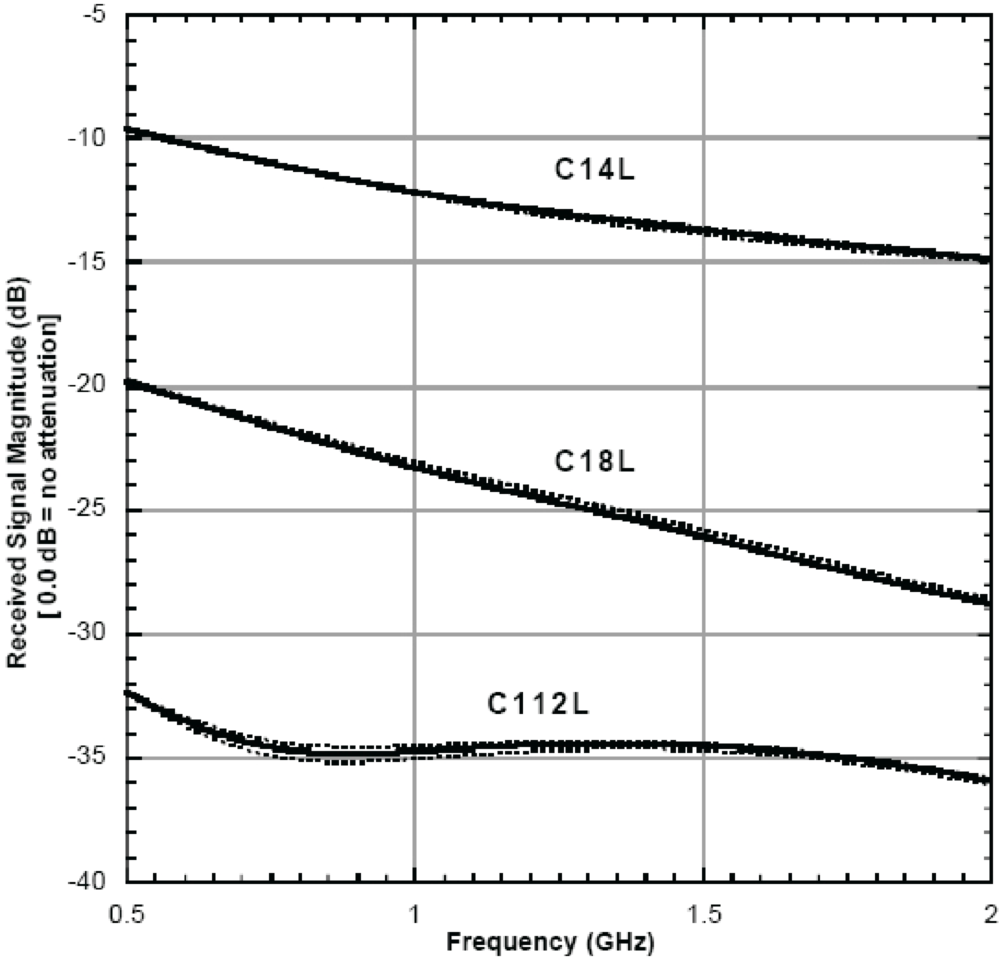


Fig. A.3.1.b: Received Signal Magnitude (dB) for Concrete Type 1 Walls. Nominal thicknesses: C14L = 102 mm; C18L = 203 mm; C112L = 305 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.83)

Received Signal Magnitude (dB) for Concrete Type 1 Walls for C14L = 102 mm; C18L = 203 mm; C112L = 305 mm concrete walls acts same as transmission coefficient above mentioned in terms of responses. (See Fig. A.3.1.a)

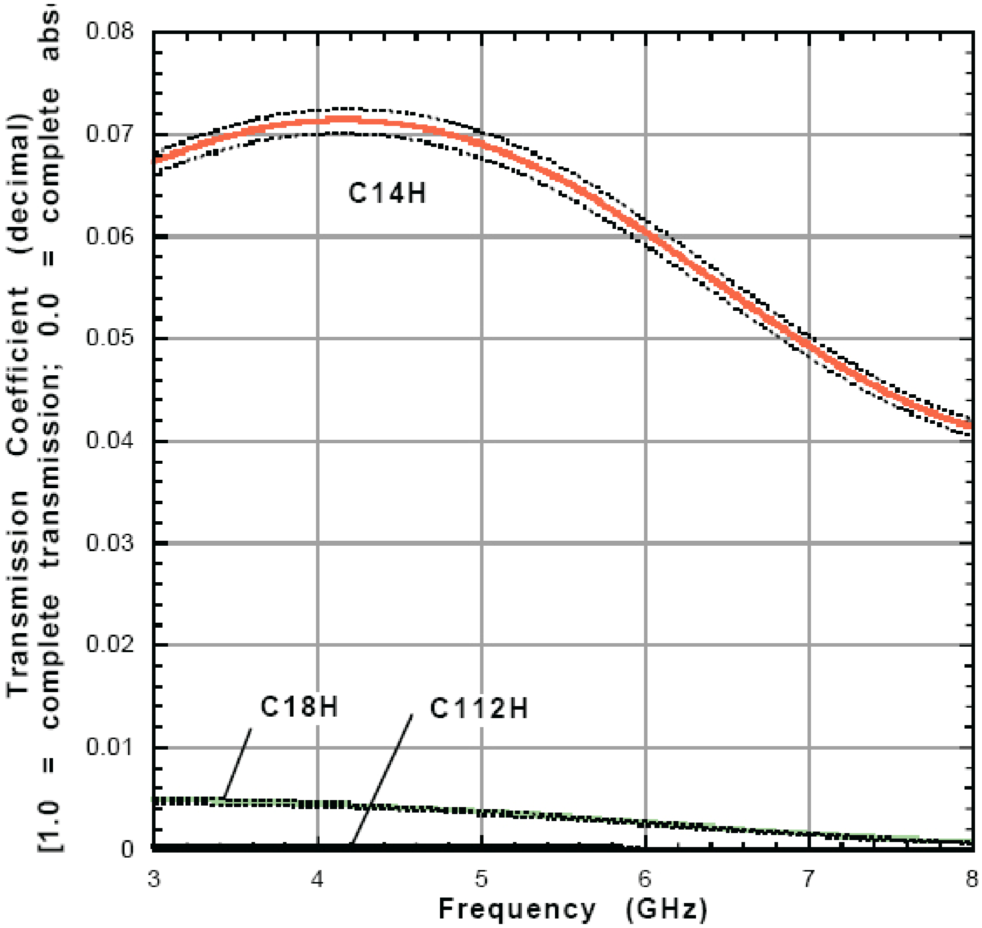


Fig. A.3.1.c: Transmission Coefficients for Concrete Type 1 walls. Nominal thicknesses: C14H = 102 mm; C18H = 203 mm; C112H = 305 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.84)

Higher frequency response for C14H = 102 mm is different than lower frequencies of the same wall as increasing transmission between 3.0- 4.8 GHz frequencies. The other type concrete walls (C18H = 203 mm; C112H = 305 mm) have dramatic transmission loss below 0.01 till almost complete absorption in 8.0 GHz frequency. (See Fig. A.3.1.c)

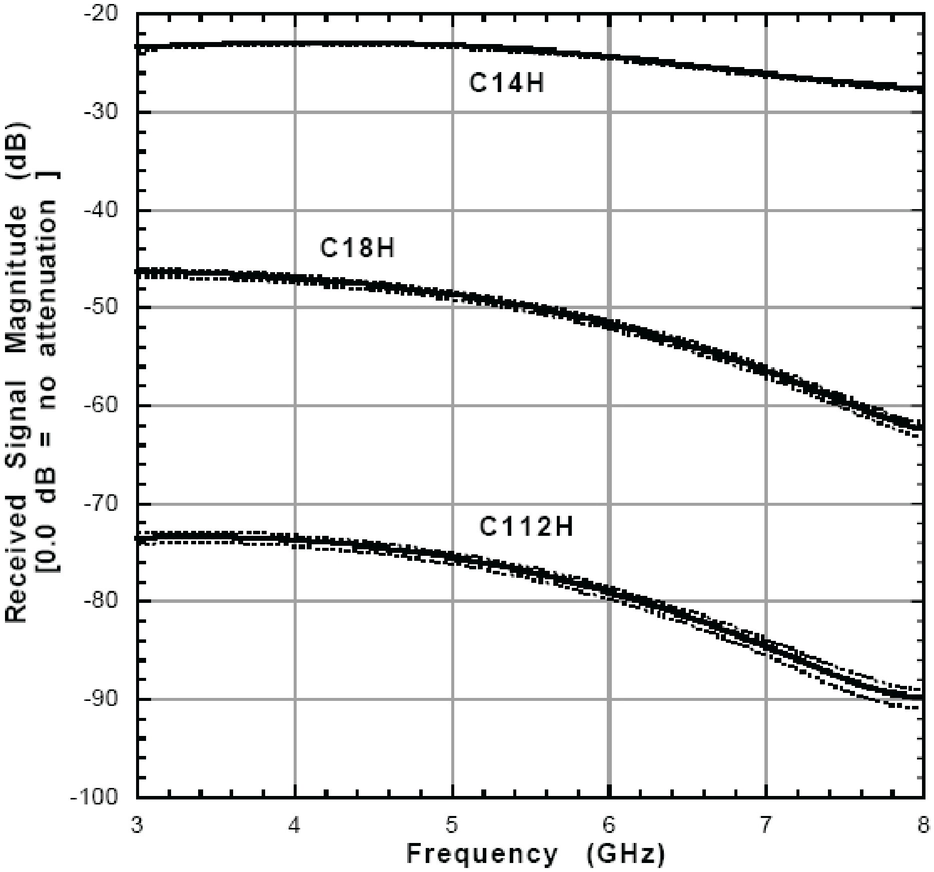


Fig. A.3.1.d: Received Signal Magnitude (dB) for Concrete Type 1 Walls. Nominal thicknesses: C14H = 102 mm; C18H = 203 mm; C112H = 305 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.85)

Received Signal Magnitude range for C14H = 102 mm, C18H = 203 mm and C112H = 305 mm concrete walls are -30 to -20 db, -58 to -46 and -90 to -74 db between high range frequencies shown in Fig. 3.1.d.

A.4 Reinforced Concrete and Rebar Grid

Two type of concrete and rebar grid combination is used in the research shown above. The first one has 140 mm square grid and the second has 70 mm square grid with 203 mm concrete thickness.

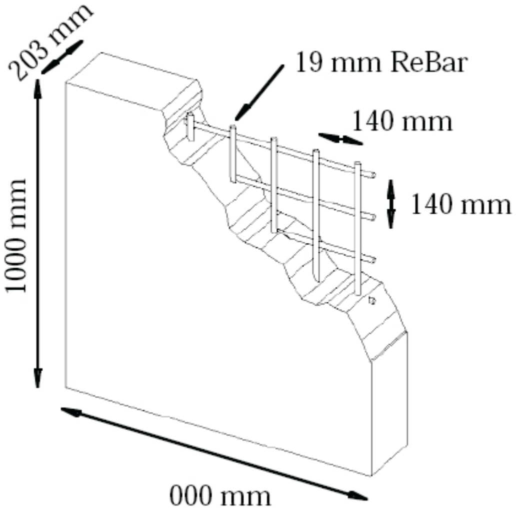


Fig. A.4.a: Reinforced concrete, nominally 203 mm thick with 140 mm square grid rebar.
(C. Stone, William, October 1997 p.47-48)

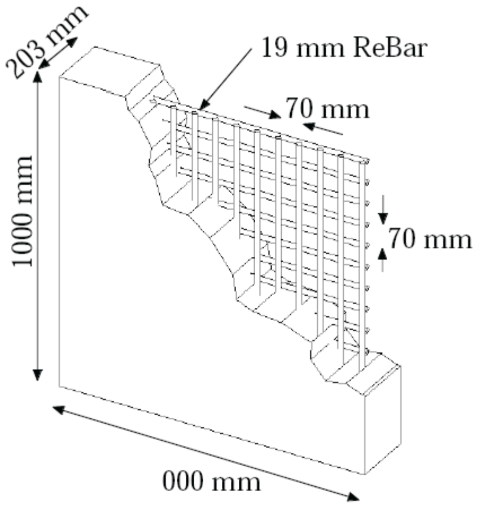


Fig. A.4.b: Reinforced concrete, nominally 203 mm thick with 70 mm square grid rebar.
(C. Stone, William, October 1997 p.47-48)

A.4.1 Response data for Reinforced Concrete

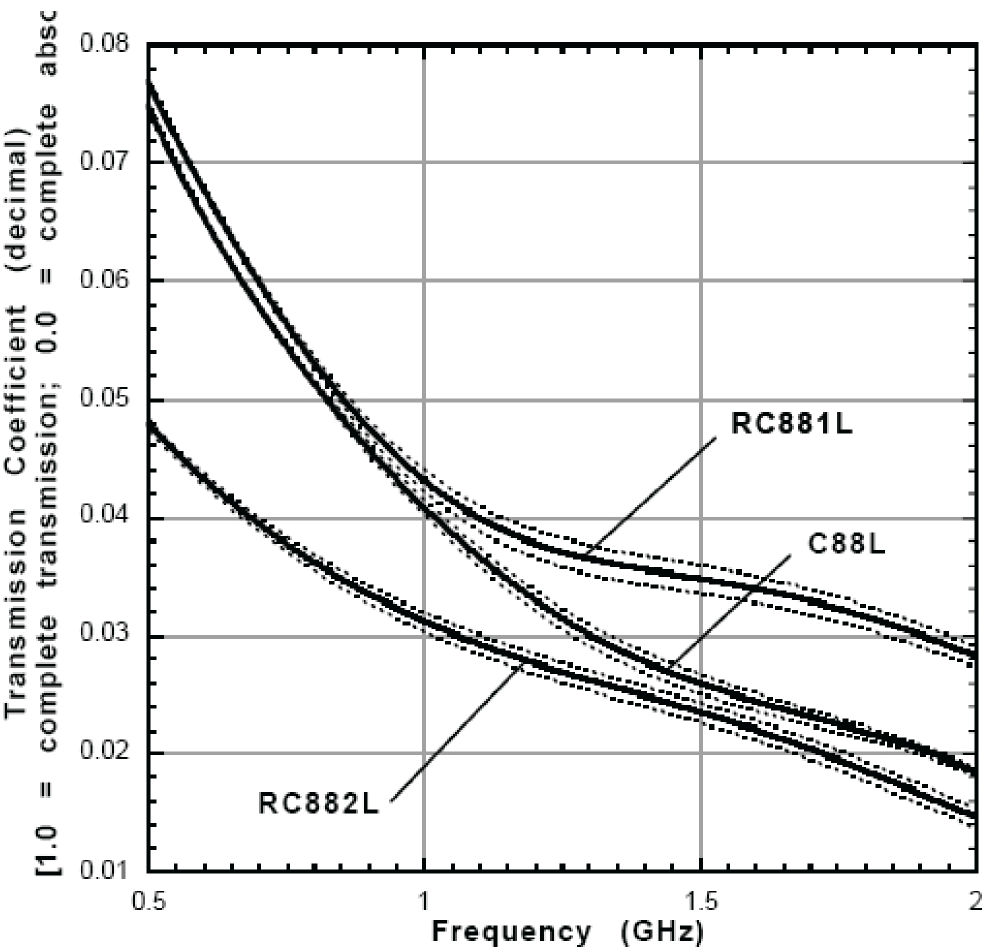


Fig. A.4.1.a: Transmission Coefficients for Reinforced Concrete Walls (relative to free space). Nominal thicknesses: All Specimens are 203 mm Thick. Low Range Data: 0.5 to 2.0 GHz C88L = Unreinforced Reference; RC881L = 1% Steel; RC882L = 2% Steel Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
(C. Stone, William, October 1997 p.172)

Same thickness for all specimens is used with different percentage of steel as unreinforced 1%, 2%. The three curves from unreinforced concrete to 2% steel included shows a smooth drop. RC881L = 1% Steel concrete value stops approximately 0.018 in 2 GHz and RC882L = 2% Steel concrete value keeps close to 0.015 value in 2 GHz frequency.

Surprisingly, C88L = Unreinforced concrete value is between two reinforced concrete sample but close to the RC882L in value at the same frequency. (See Fig. A.4.1.a)

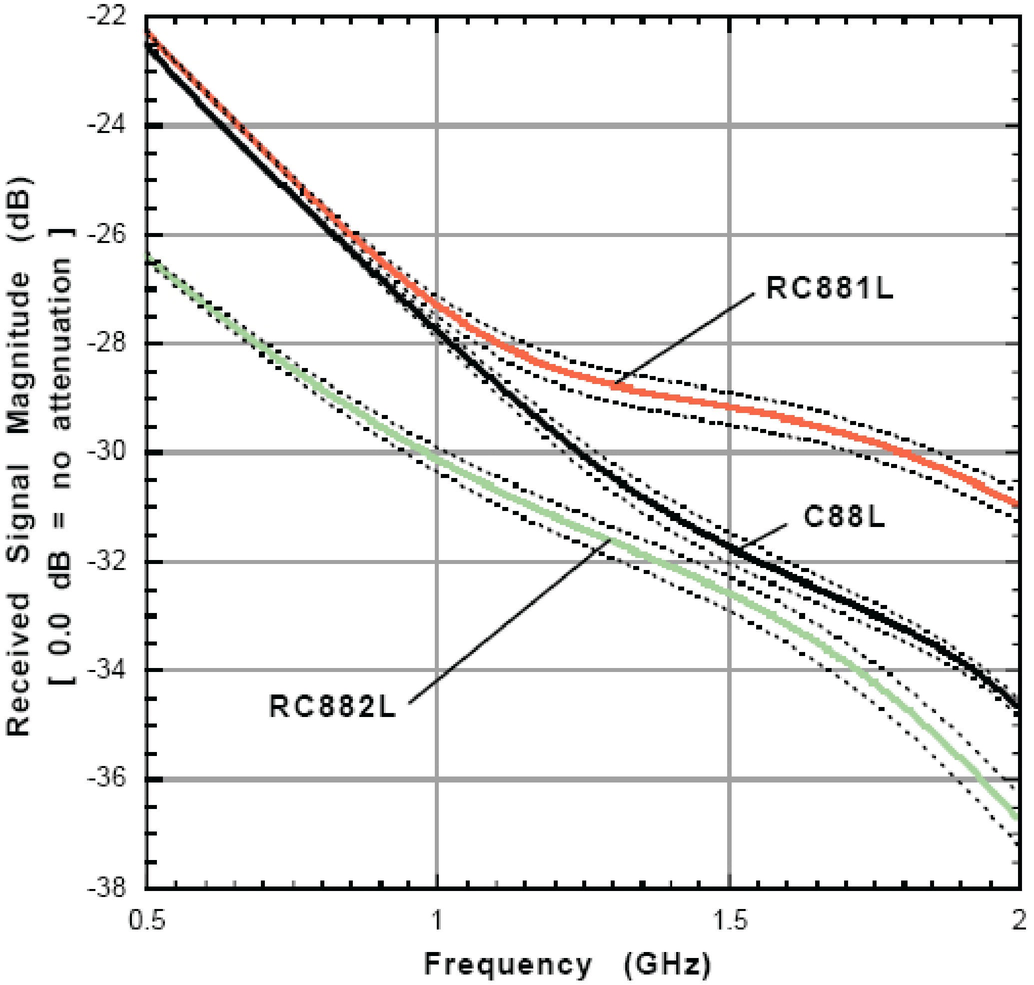


Fig. A.4.1.b: Received Signal Magnitude (dB) for Reinforced Concrete Walls (relative to free space). All Specimens are 203 mm Thick. Low Range Data: 0.5 to 2.0 GHz C88L = Unreinforced Reference; RC881L = 1% Steel; RC882L = 2% Steel Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). (C. Stone, William, October 1997 p.173)

Received Signal Magnitude (dB) figure for Reinforced Concrete Walls has the similar type of response in terms of geometrical form. (See Fig. A.4.1.b)

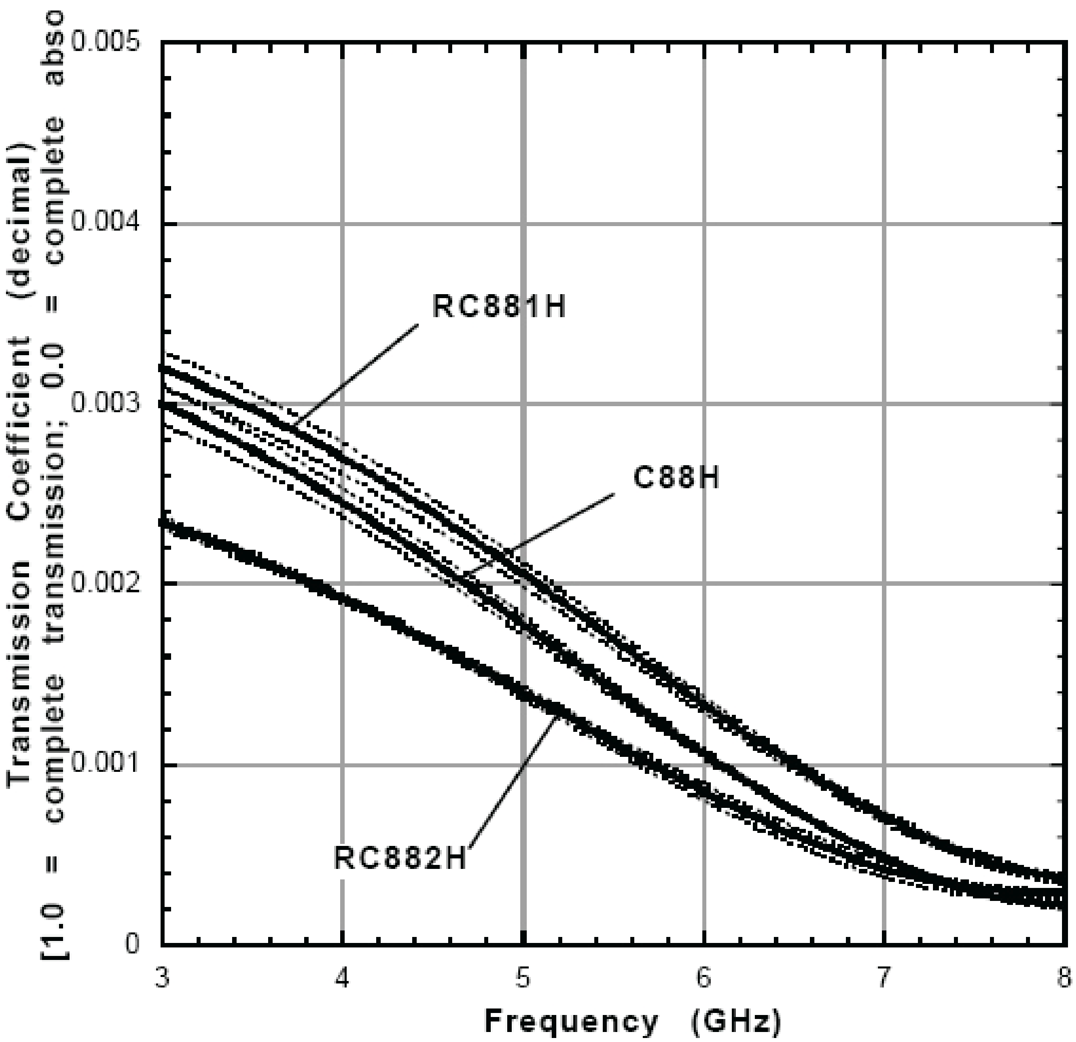


Fig. A.4.1.c: Transmission Coefficients for Reinforced Concrete Walls (relative to free space). Nominal thicknesses: All Specimens are 203 mm Thick. High Range Data: 3.0 to 8.0 GHz C88L = Unreinforced Reference; RC881L = 1% Steel; RC882L = 2% Steel Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). (C. Stone, William, October 1997 p.174)

Higher frequencies (3-8 GHz) keeps continue to decrease the value of transmission coefficient till 8 GHz. As a result of this, the higher frequency holds the pretty much same values below 0.001 for 3 different types of concrete samples. (See Fig. A.4.1.c)

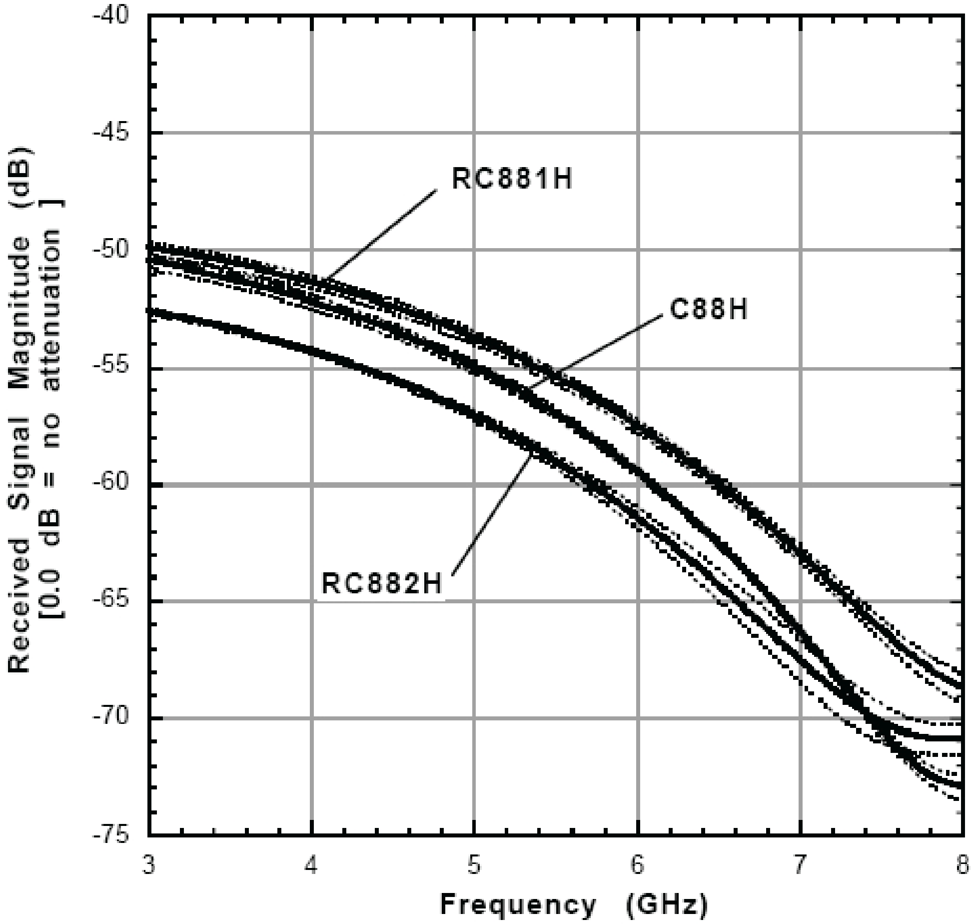


Fig. A.4.1.d: Received Signal Magnitude (dB) for Reinforced Concrete Walls (relative to free space). All Specimens are 203 mm Thick. High Range Data: 3.0 to 8.0 GHz. C88L = Unreinforced Reference; RC881L = 1% Steel; RC882L = 2% Steel Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). (C. Stone, William, October 1997 p.175)

Received Signal Magnitude (dB) for Reinforced Concrete Walls in higher frequencies starts with similar response as transmission coefficient but ends a bit different not very close value in 8 GHz frequency. (Fig. A.4.1.d)

A.5 Glass

NIST study uses ordinary architectural window glass that made of soda-lime silica float glass with the dimension shown above.

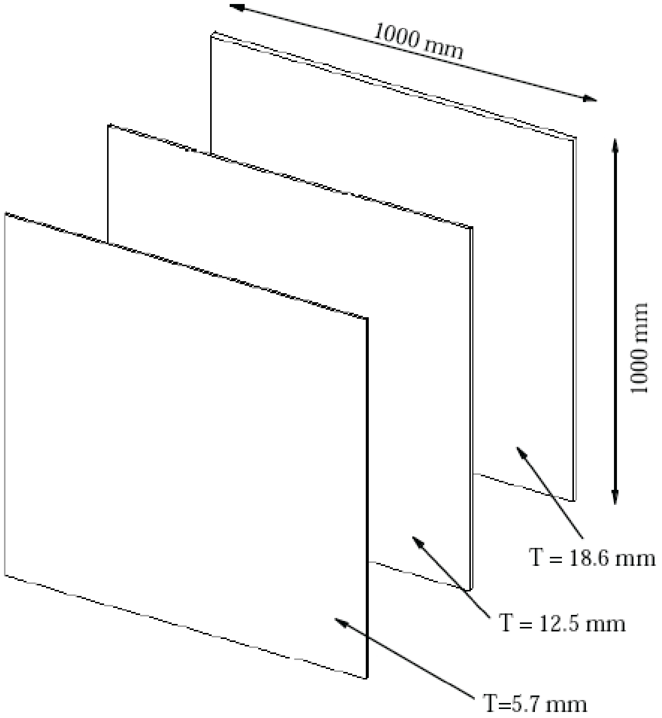


Fig. A.5.a: Glass panel specimens used in the NIST study. (C. Stone, William, October 1997 p.49)

A.5.1 Response data for Glass

Fig. 2.3.5.1 a shows one of the best transmission coefficiency value comparing with the other building materials. G25L = 6 mm thick glass starts almost complete transmission and ends to close to 0.85 value in 2 GHz. G50L = 13 mm and G75L = 19 mm thick glasses also begins higher transmission end ends satisfactory responses in lower frequencies.

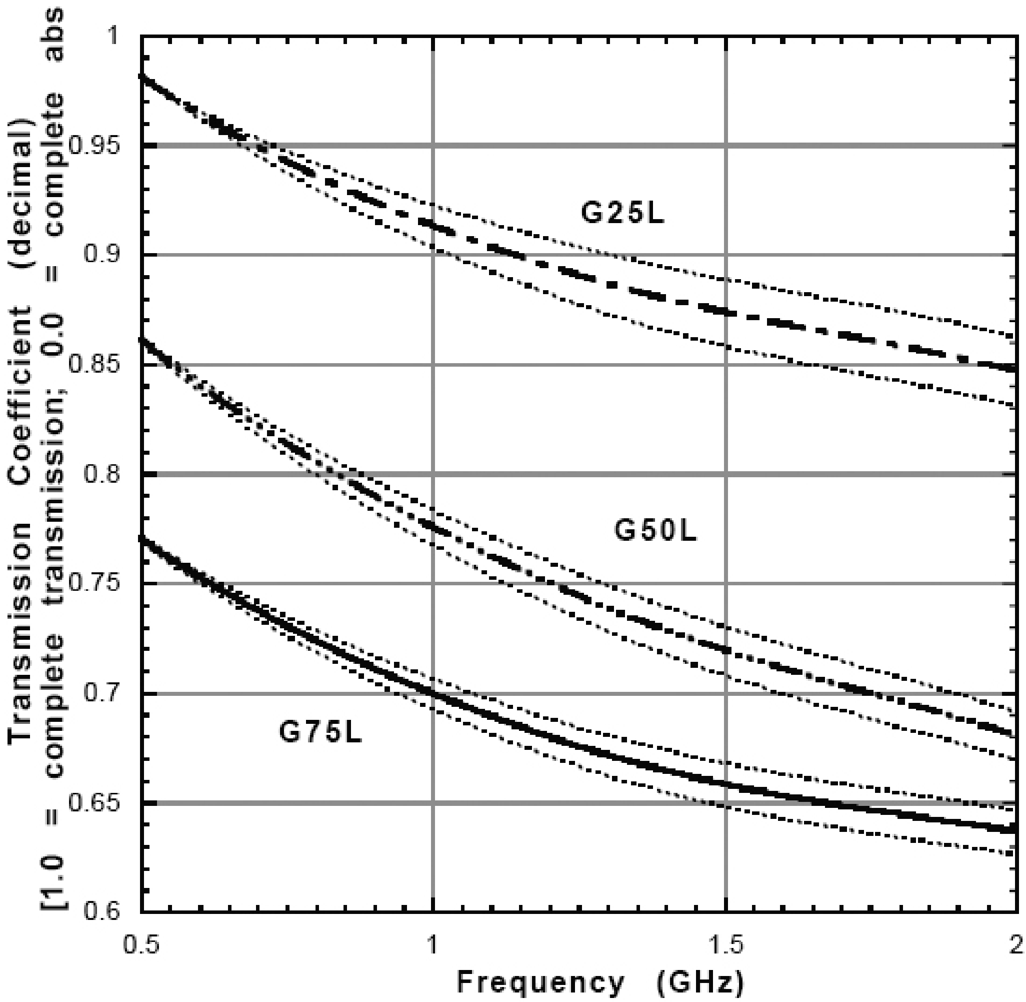


Fig. A.5.1.a: Transmission Coefficients for Glass Panels (relative to free space). Nominal thicknesses: G25L = 6 mm; G50L = 13 mm; G75L = 19 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.142)

The curves of the three glass panels are almost similar. They all smoothly drop till 2 GHz frequency. (See Fig. A.5.1.a)

Received Signal Magnitude (dB) for Glass Panels in lower frequencies illustrate parallel responses in geometrical form as it is expected. (Fig. A.5.1.b)

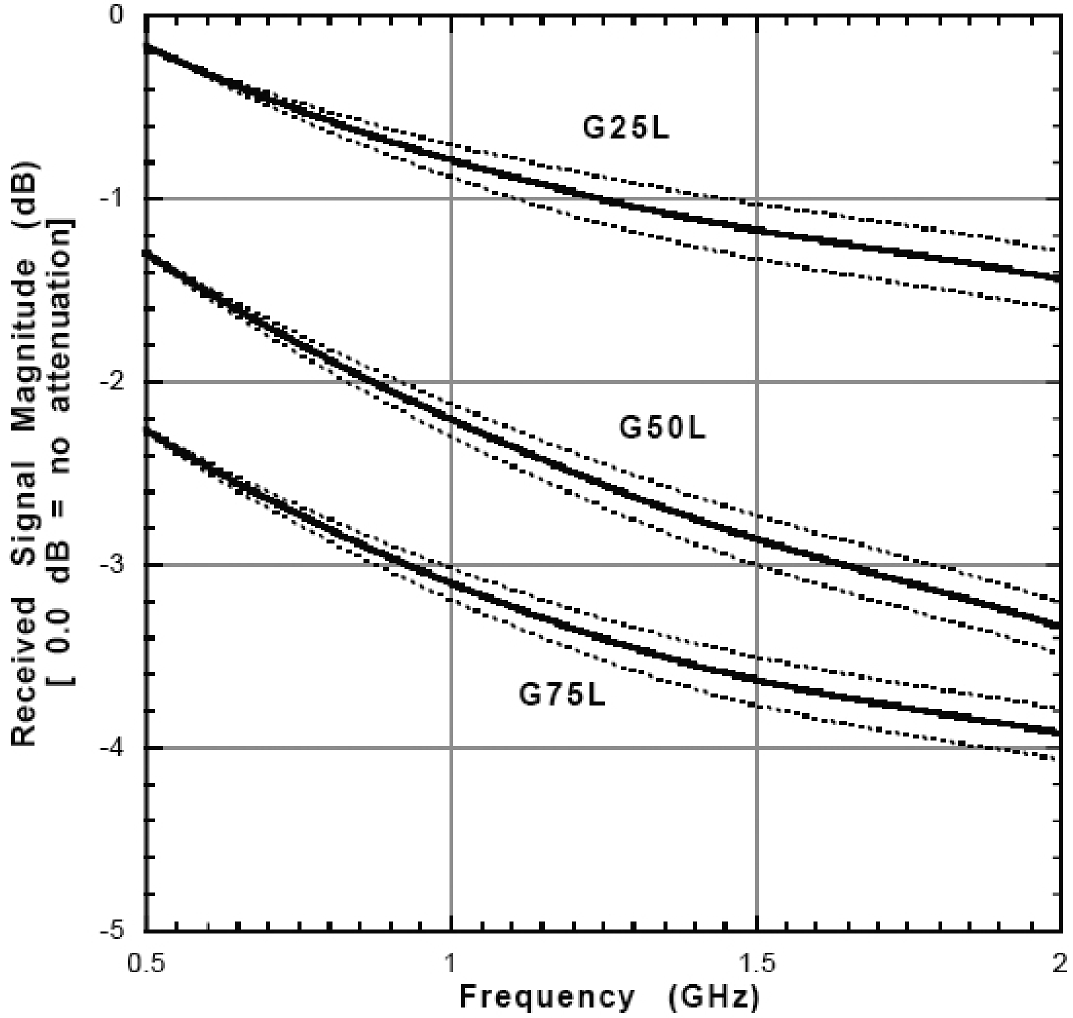


Fig. A.5.1.b: Received Signal Magnitude (dB) for Glass Panels (relative to free space).
G25L = 6 mm; G50L = 13 mm; G75L = 19 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.143)

In contrast, G25H= 6 mm, G50H = 13 mm and G75H = 19 mm thickness glass panels response totally different if we compare with the lower responses in higher frequencies (3-8 GHz). G50H = 13 mm glass panel commence below 0.95 transmission in 3 GHz frequency and continue to increase it value approximately 4.5 GHz frequency close to complete transmission rate.

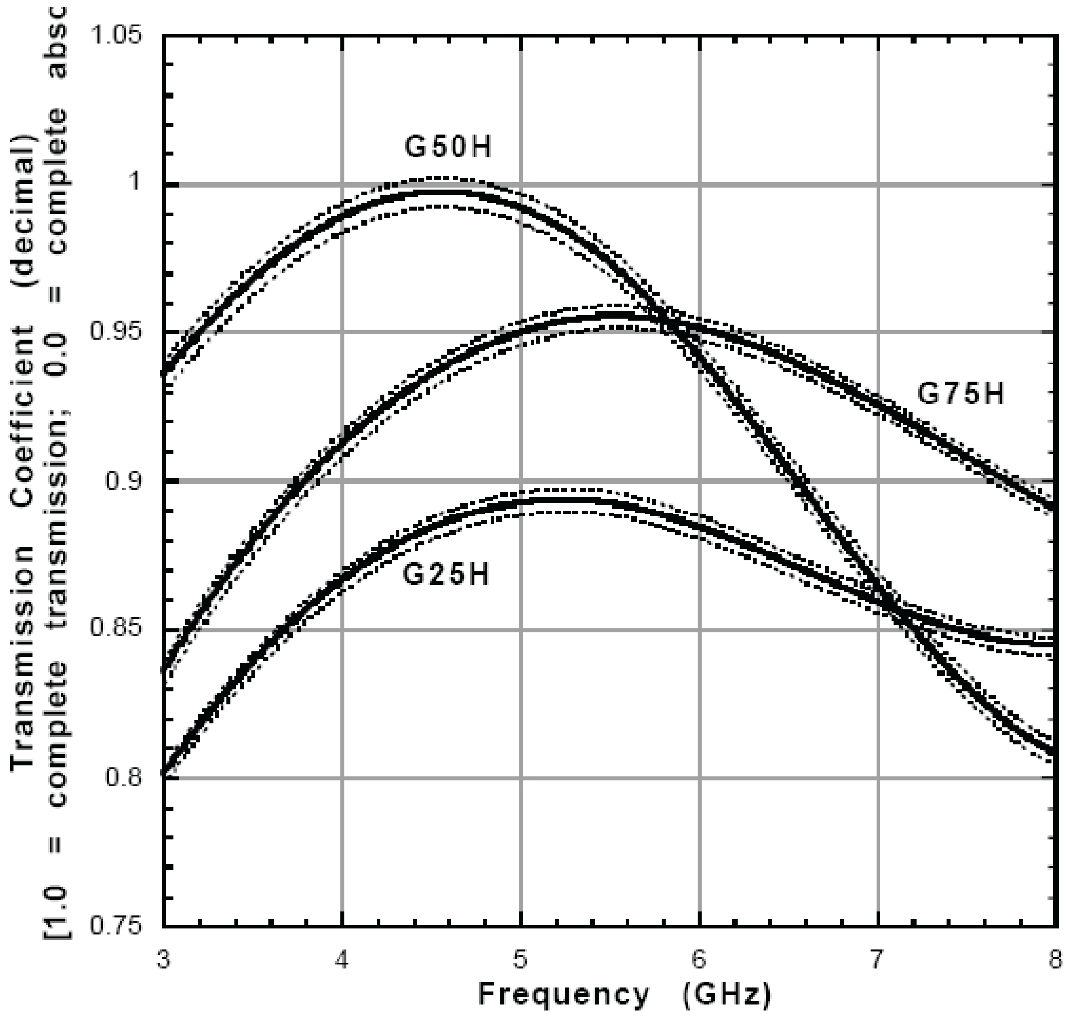


Fig. A.5.1.c: Transmission Coefficients for Glass Panels (relative to free space). Nominal thicknesses: G25H = 6 mm; G50H = 13 mm; G75H = 19 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.144)

Above 5 GHz, the transmission value decreases till 8 GHz for G25H = 6 mm glass panel. The other two acts like related response to the electromagnetic waves but in term of frequency range changes. They both G75H = 19 mm and G25H = 6 glass panels get their peak transmission value between 5-6 GHz frequencies. Above these frequencies till 8 GHz, they all continue to decrease their charges. (See Fig. A.5.1.c)

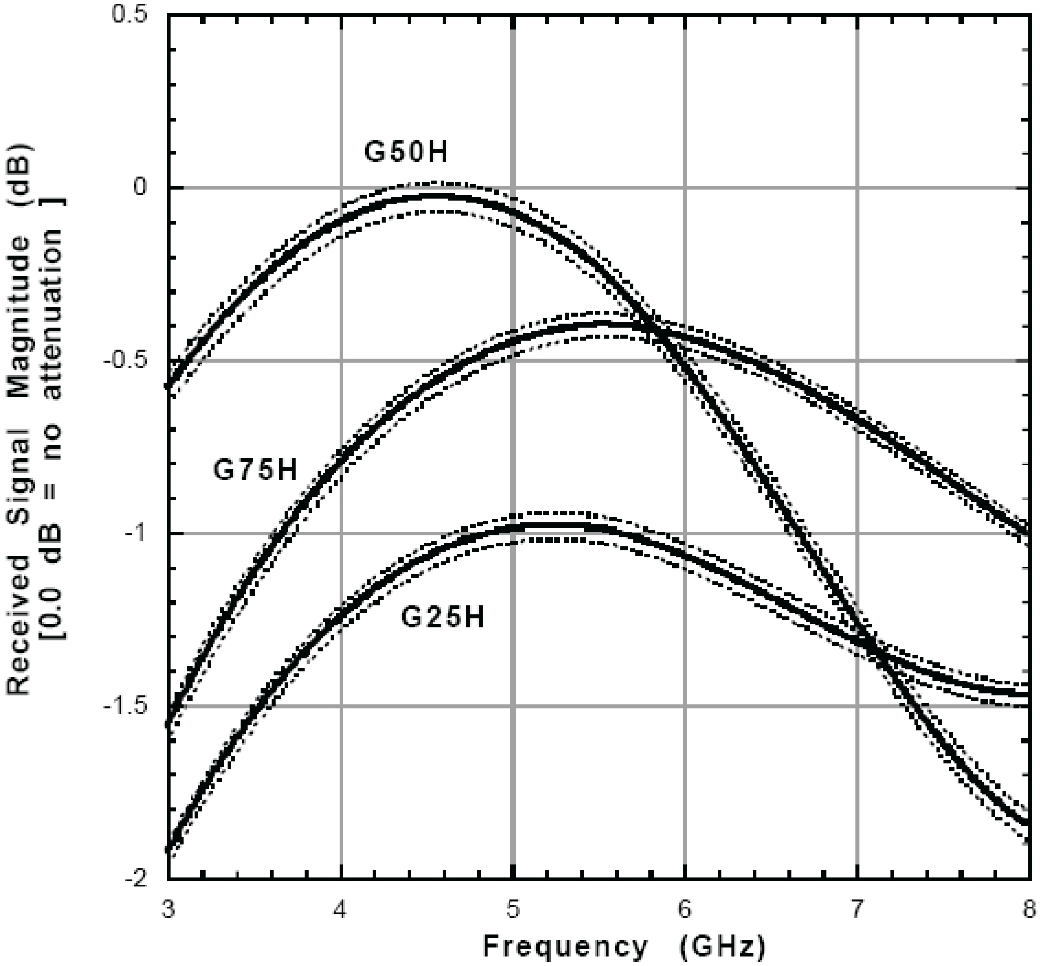


Fig. A.5.1.d: Received Signal Magnitude (dB) for Glass Panels (relative to free space). G25H = 6 mm; G50H = 13 mm; G75H = 19 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.145)

Received Signal Magnitude (dB) for Glass Panels is the likeness of the transmission coefficient form in higher frequencies. (Fig. A.5.1.d)

A.6 Lumber

In terms of commercial lumber species, Spruce-Pine-Fir; Douglas Fir-Larch; Hemlock-Fir, and Southern Pine are used in the research. Those species grow up in North America but the experimentation results help us to understand Lumber-EMW relation and show a path in design process in architecture. Both dry and wet specimens tested. Combinations and dimensions of frames are shown below.

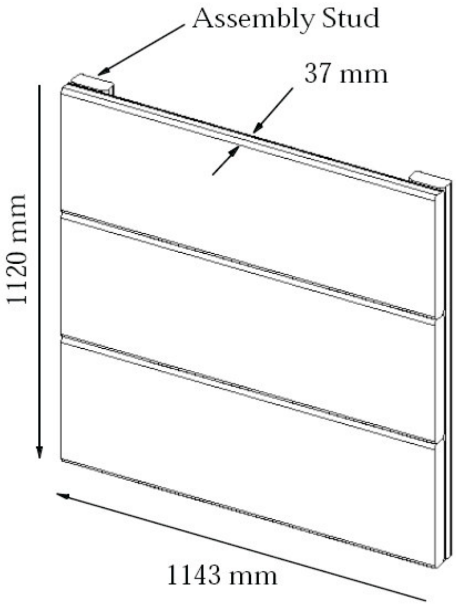


Fig. A.6.a: A single layer built-up lumber specimen consisting of three planks mounted on exterior frame. (C. Stone, William, October 1997 p.53)

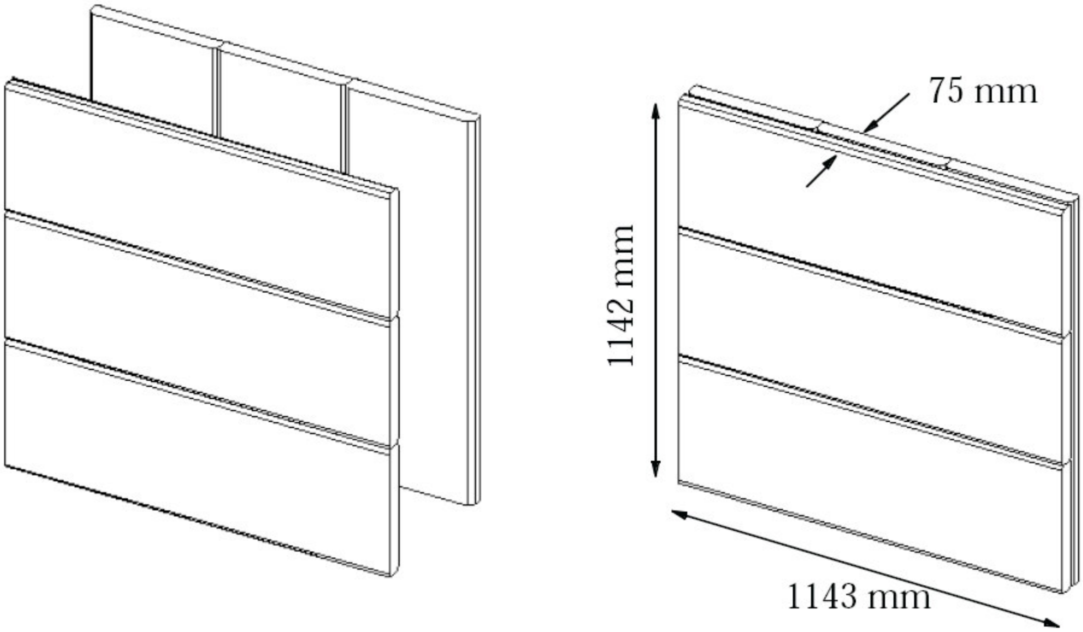


Fig. A.6.b: A double layer built-up lumber specimen consisting of six planks. (C. Stone, William, October 1997 p.53)

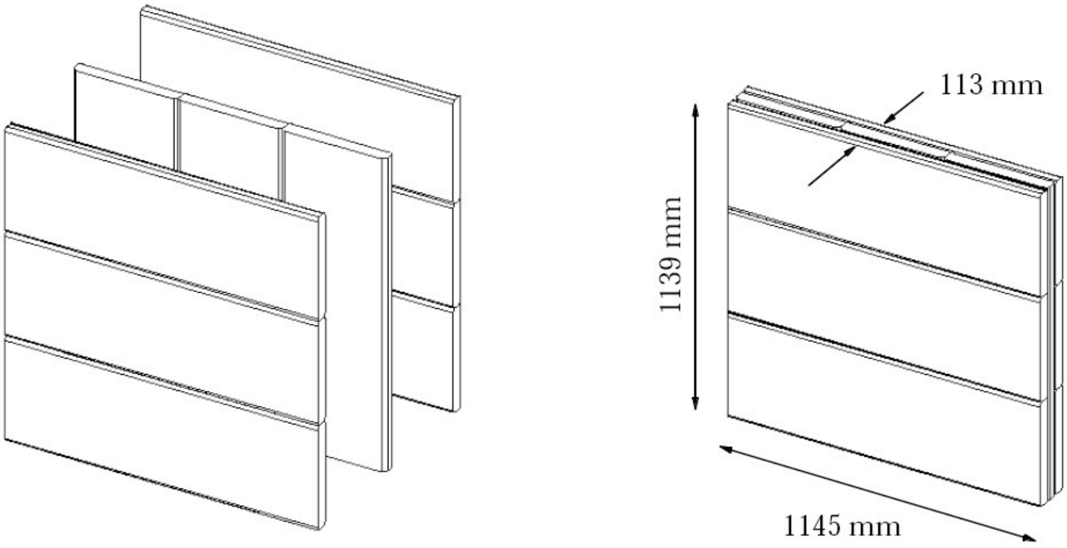


Fig. A.6.c: A triple layer built-up lumber specimen consisting of nine studs.
(C. Stone, William, October 1997 p.54)

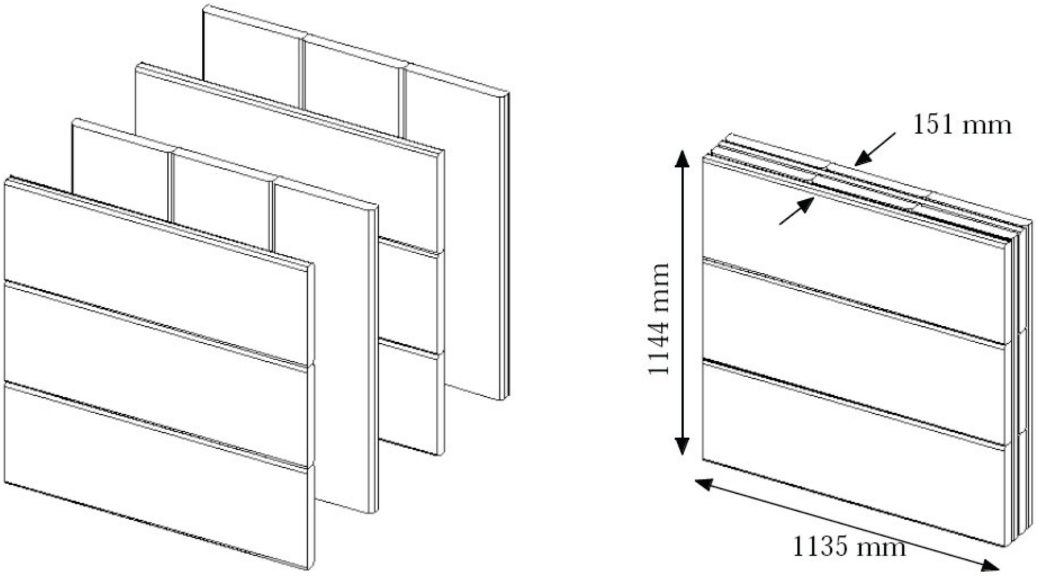


Fig. A.6.d: A quadruple layer built-up lumber specimen consisting of twelve studs.
(C. Stone, William, October 1997 p.54)

A.6.1 Response data for Lumber

Lumbers` transmission appears very efficient begins the value of above 0.85 for L30DL = 76 mm lumber.

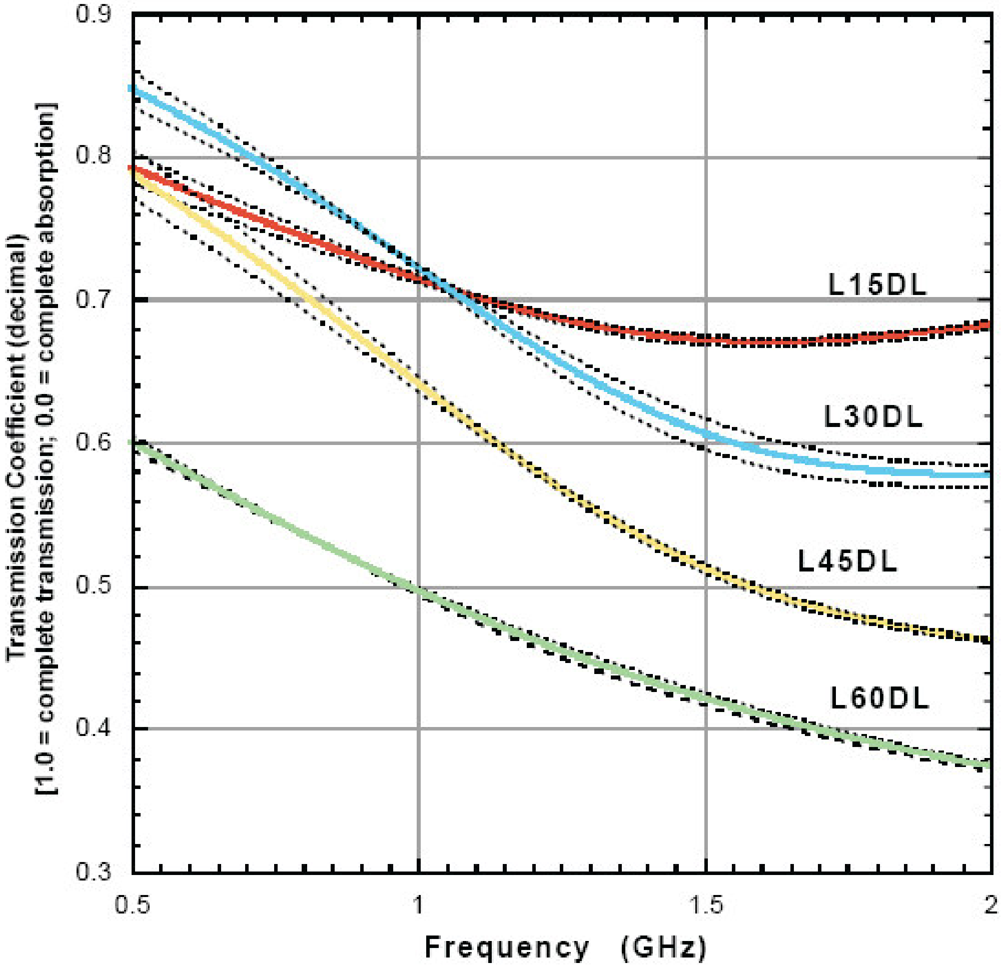


Fig. A.6.1.a: Transmission Coefficients for Lumber (Spruce-Pine-Fir) (Dry) Panels (relative to free space). Nominal thicknesses: L15DL = 38 mm; L30DL = 76 mm; L45DL = 114 mm; L60DL = 152 mm
Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.148)

The other samples as; L15DL = 38 mm, L45DL = 114 mm; L60DL = 152 mm smoothly drops till 2 GHz frequency. (See Fig. A.6.1.a)

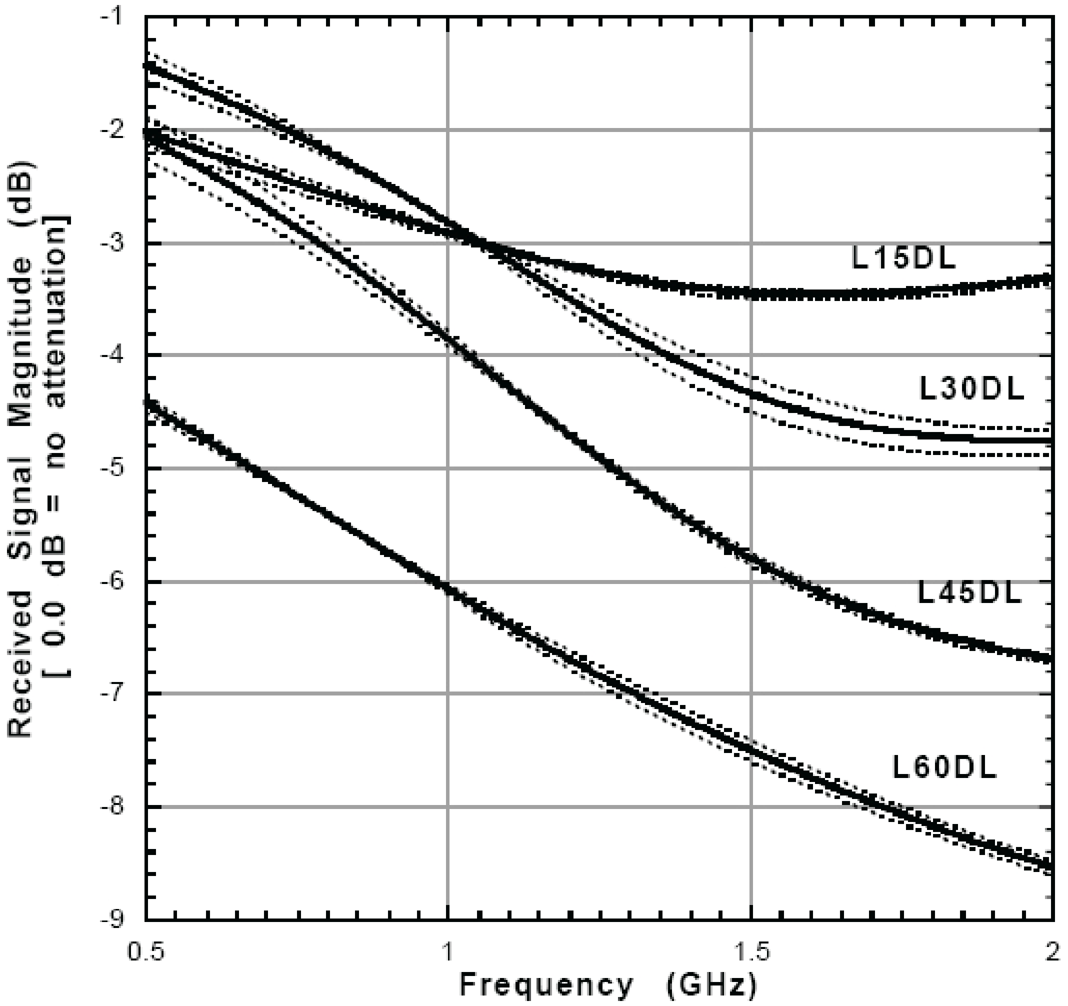


Fig. A.6.1.b: Received Signal Magnitude (dB) for Lumber (Spruce-Pine-Fir) (Dry) Panels (relative to free space). L15DL = 38 mm; L30DL = 76 mm; L45DL = 114 mm; L60DL = 152 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz
(C. Stone, William, October 1997 p.149)

As expected, Received Signal Magnitude (dB) for Lumber Spruce-Pine-Fir Dry Panels is the image of Transmission coefficient Figure above seen.

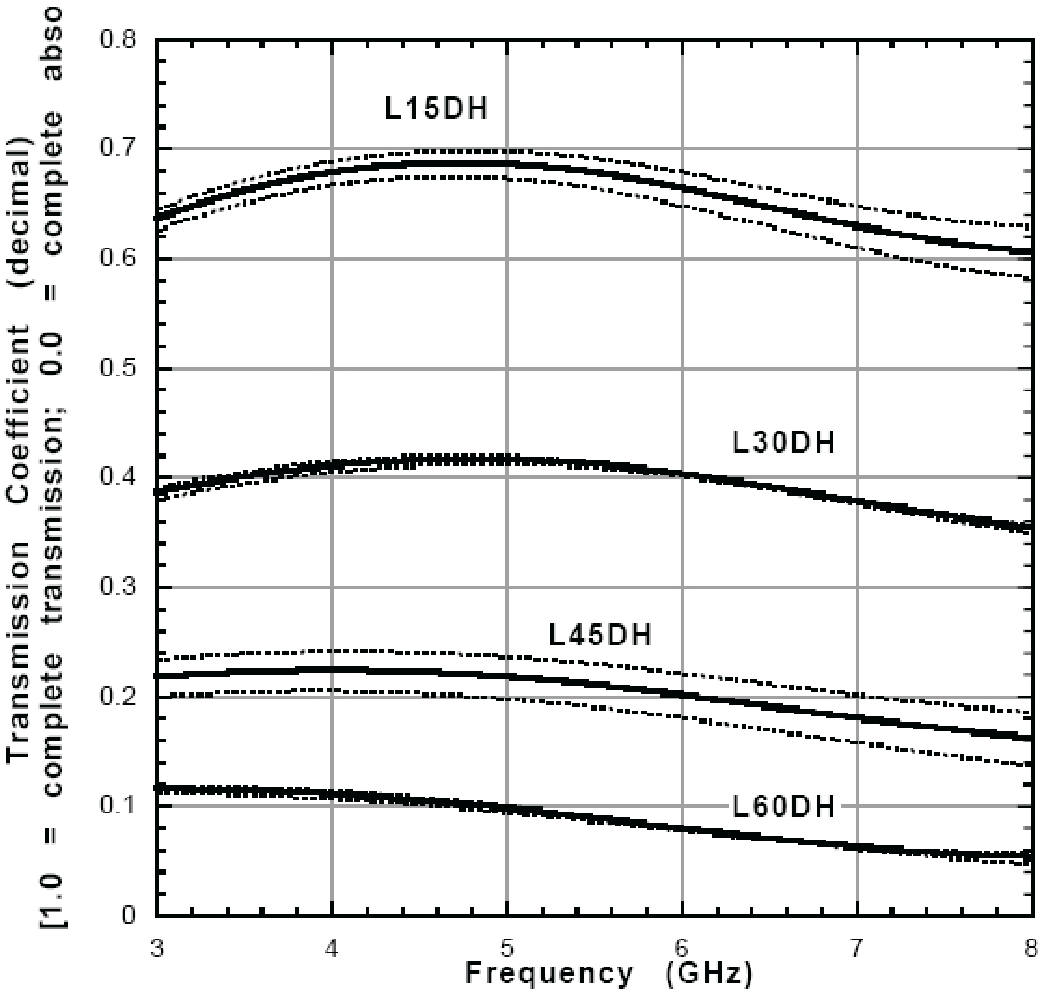


Fig. A.6.1.c: Transmission Coefficients for Lumber (Spruce-Pine-Fir) (Dry) Panels (relative to free space). Nominal thicknesses: L15DH = 38 mm; L30DH = 76 mm; L45DH = 114 mm; L60DH = 152 mm
Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.150)

Higher frequency range (3 GHz-8 GHz) is more stable when comparing the lower ones. As see in the Fig. A.6.1.c a bit loss has been identified.

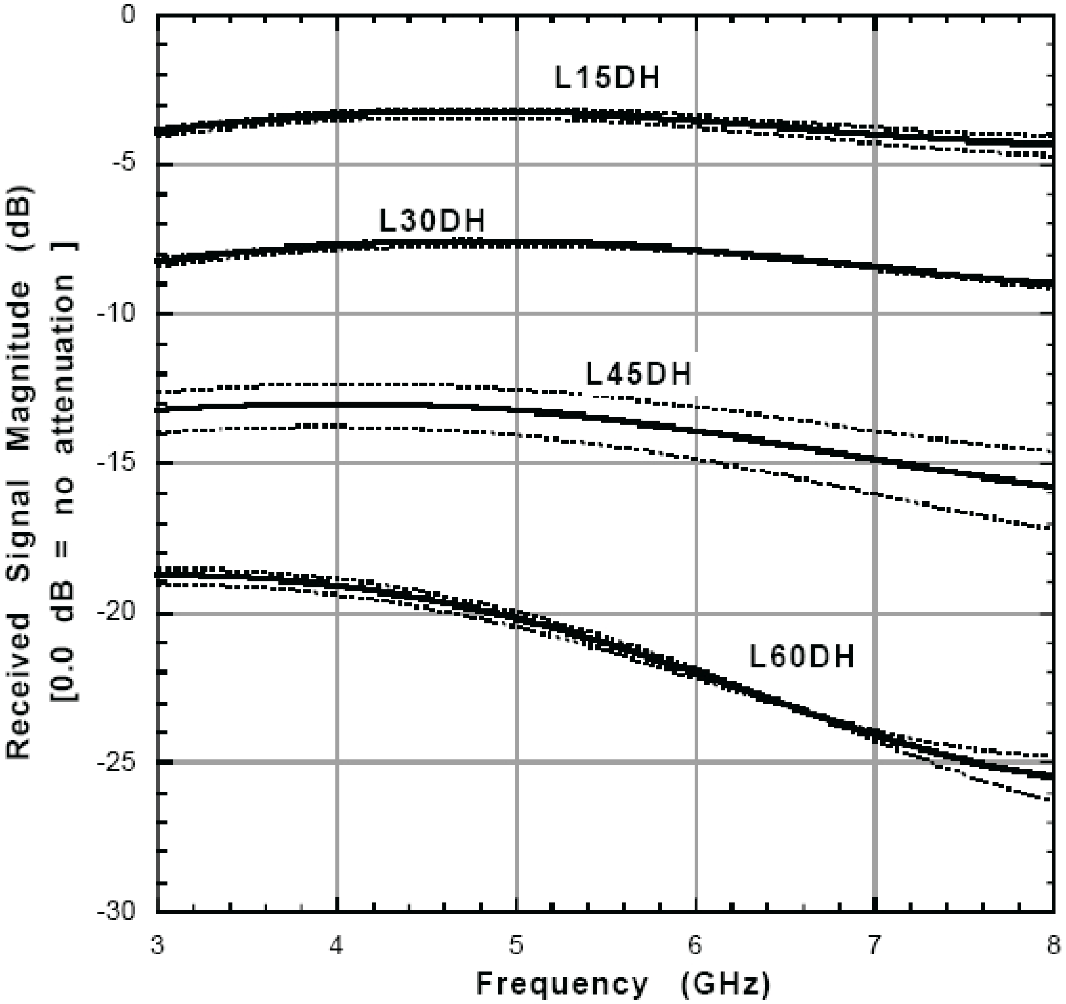


Fig. A.6.1.d: Received Signal Magnitude (dB) for Lumber (Spruce-Pine-Fir) (Dry) Panels (relative to free space). L15DH = 38 mm; L30DH = 76 mm; L45DH = 114 mm; L60DH = 152 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz
(C. Stone, William, October 1997 p.151)

As usual, Received Signal Magnitude (dB) for Lumber Spruce-Pine-Fir Dry still acts like Transmission Coefficient figure. (See Fig. A.6.1.d)

A.7 Plywood

Three types of plywood panel specimens are used by NIST study. Those nominal thicknesses are 6.3 mm, 11.8 mm and 18.8 mm as shown above. (Fig. A.7.a)

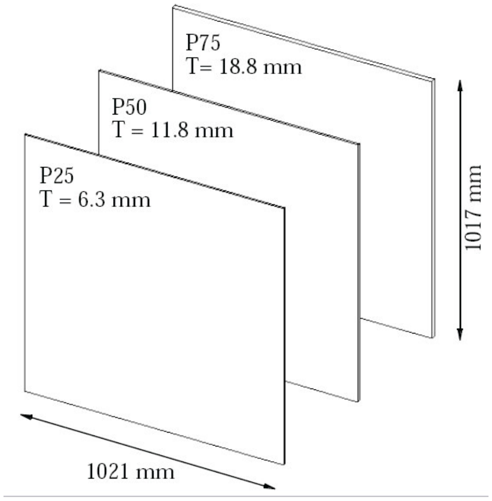


Fig. A.7.a: Nominal Geometry for Plywood Specimens. (C. Stone, William, October 1997 p.56)

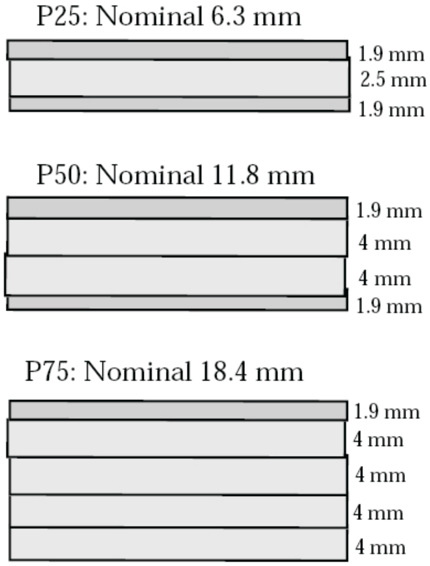


Fig.A.7.b: Measured nominal cross sections for typical three types of Plywood.
(C. Stone, William, October 1997 p.57)

A.7.1 Response data for Plywood

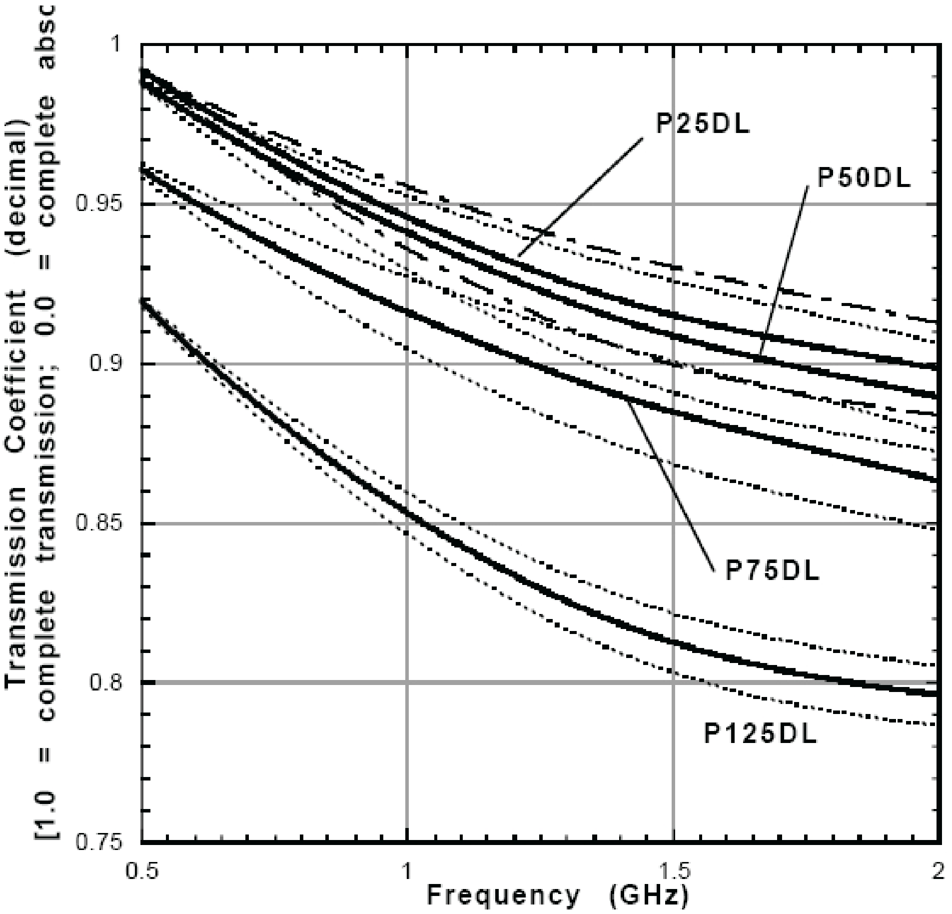


Fig. A.7.1.a: Transmission Coefficients for Plywood (Dry) Panels (relative to free space). Nominal thicknesses:
P25DL = 6 mm; P50DL = 13 mm; P75DL = 19 mm; P125DL = 32 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). Low Range Data: 0.5 to 2.0 GHz
(C. Stone, William, October 1997 p.160)

Another friendly material for electromagnetic waves is Plywood. As seen in Fig. A.7.1.a, P25DL = 6 mm panels` transmission co efficiency starts almost the value 1.0 that means complete transmission and ends below 0.9 in 2 GHz frequency. For the others, smooth drops are seen in the figure.

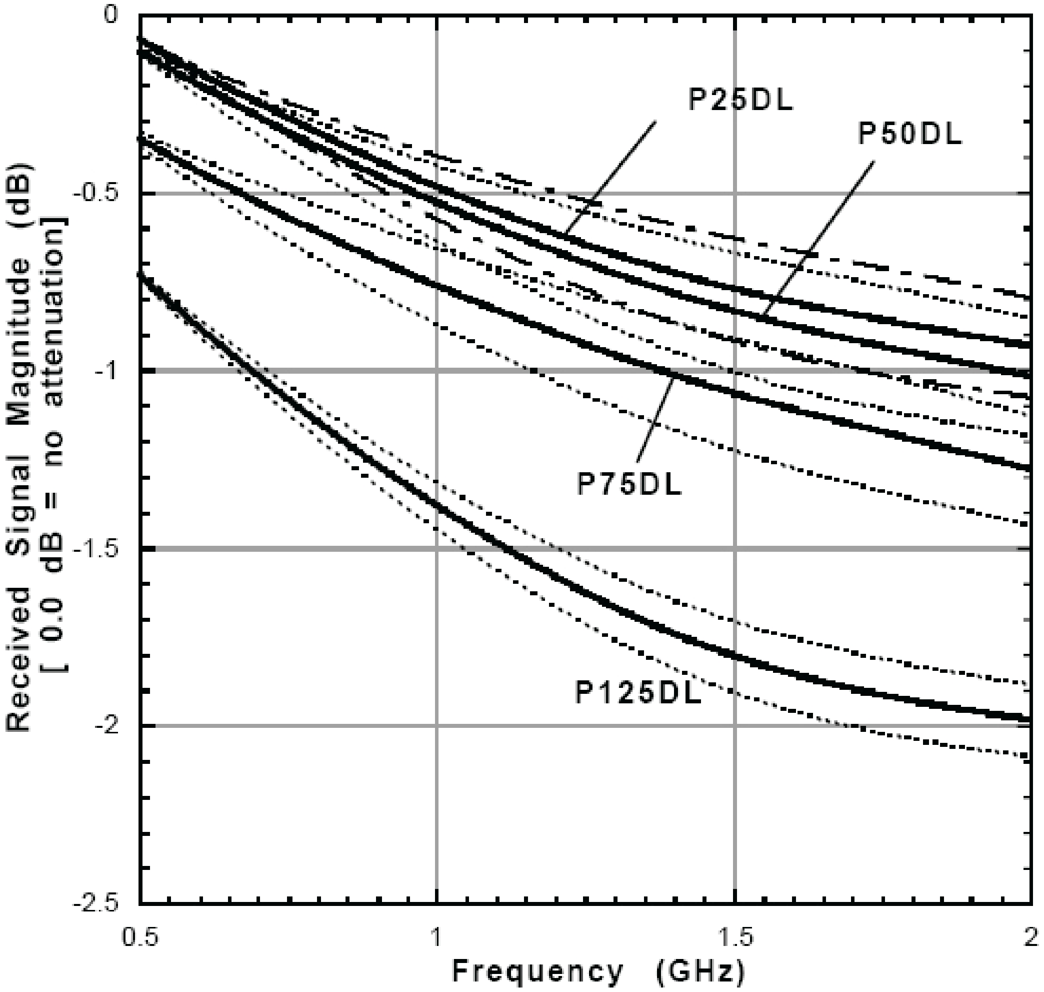


Fig. A.7.1.b: Received Signal Magnitude (dB) for Plywood (Dry) Panels. P25DL = 6 mm; P50DL = 13 mm; P75DL = 19 mm; P125DL = 32 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.161)

Received Signal Magnitude (dB) for Plywood Dry Panels for P25DL = 6 mm, P50DL = 13 mm, P75DL = 19 mm and P125DL = 32 mm respond similarly as the transmission. (See Fig. A.7.1.b)

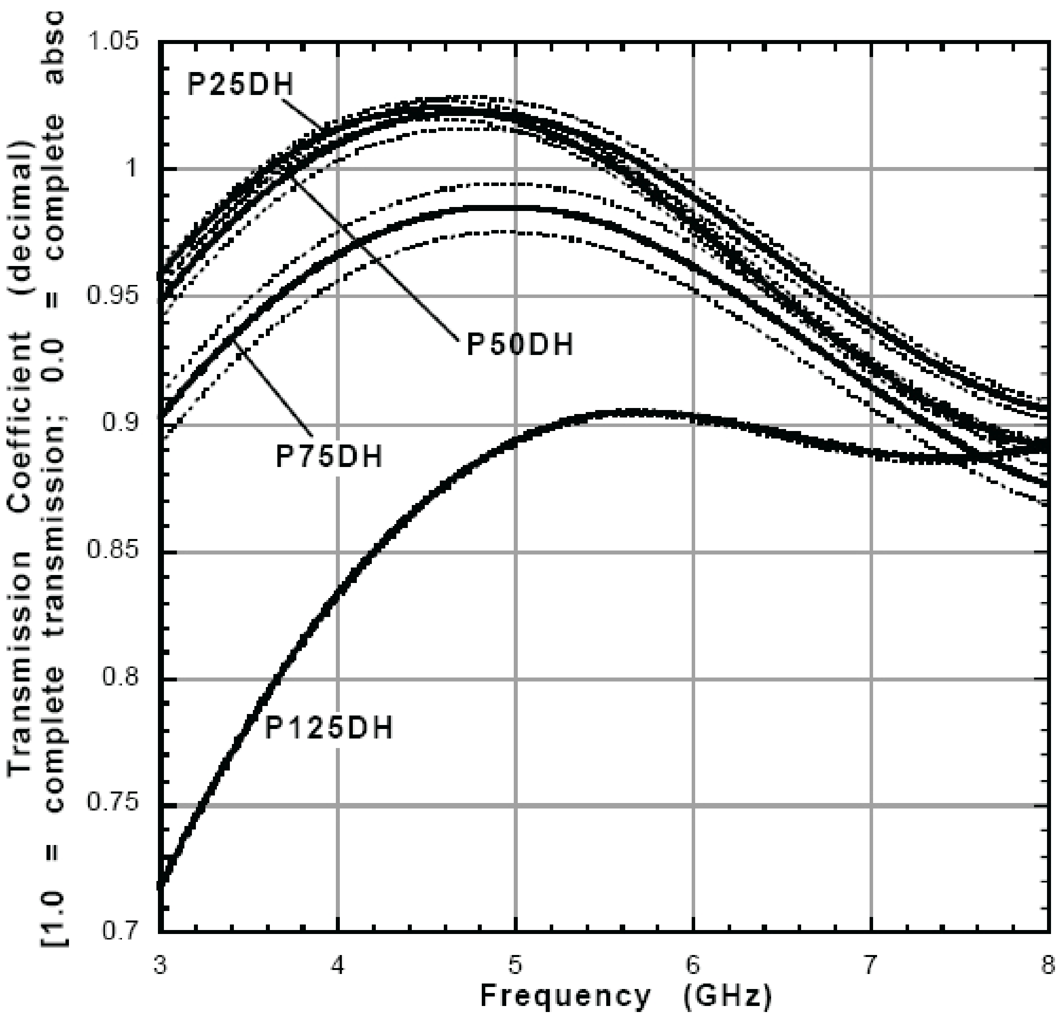


Fig. A.7.1.c: Transmission Coefficients for Plywood (Dry) Panels (relative to free space). Nominal thicknesses:
P25DH = 6 mm; P50DH = 13 mm; P75DH = 19 mm; P125DH = 32 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz
(C. Stone, William, October 1997 p.162)

Higher frequencies` (3 GHz-8 GHz) responses are different than the lower ones for P25DH = 6 mm, P50DH = 13 mm, P75DH = 19 mm, P125DH = 32 mm plywood panels. Between 3GHz -5 GHz frequency shows increase of the transmission value. Over 5 GHz, The curves decreases and increase a small amount again. (See Fig. A.7.1.c)

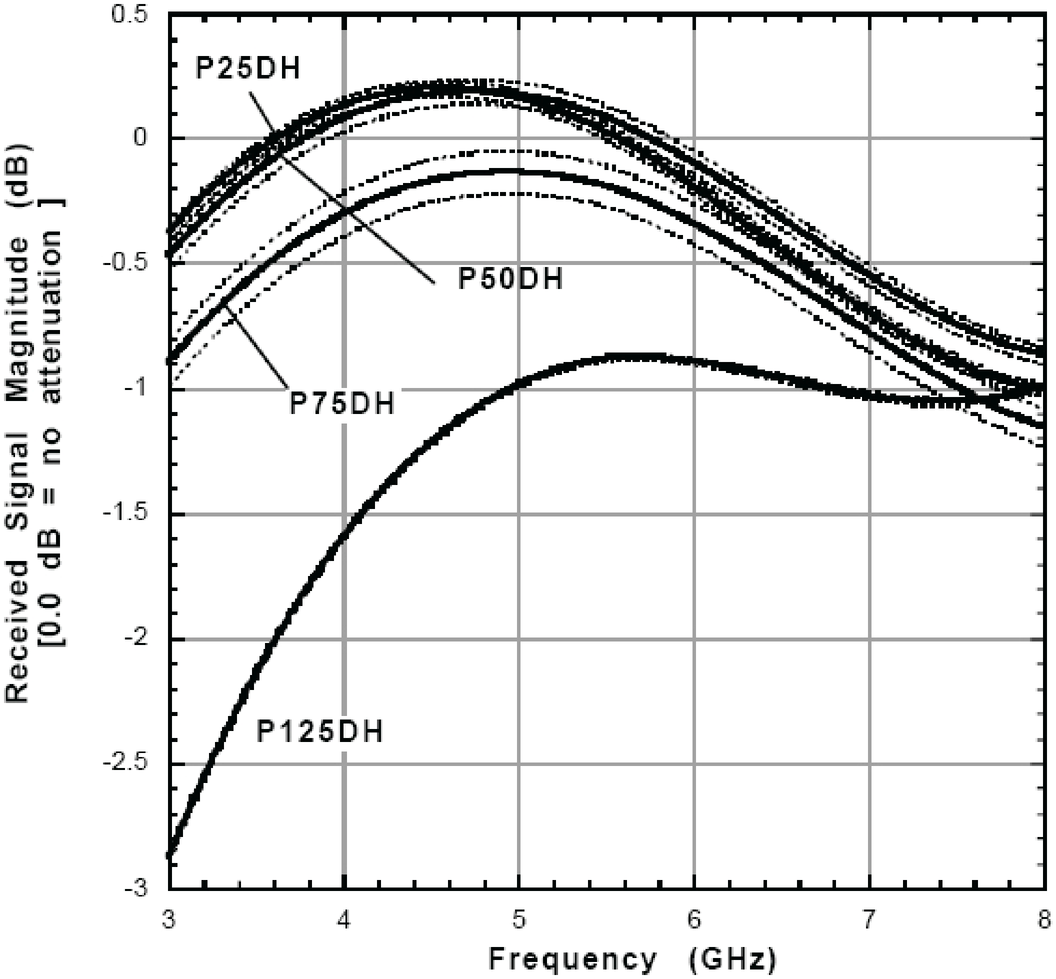


Fig. A.7.1.d: Received Signal Magnitude (dB) for Plywood (Dry) Panels (relative to free space).
P25DH = 6 mm; P50DH = 13 mm; P75DH = 19 mm; P125DH = 32 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves). High Range Data: 3.0 to 8.0 GHz
(C. Stone, William, October 1997 p.163)

Received Signal Magnitude (dB) for Plywood Dry Panels is the mirror image of transmission coefficient as usual.

A.8 Drywall

Drywall is widely used for interior wall, ceiling panels in both residential and commercial construction. Typically 12.7 mm panels are used for ceilings and 9.5 mm panels are used for double wall systems. Moreover, 6.3 mm panels are used for base layer so that it can improve sound control in the buildings. The material made of 85-95 percentage of Gypsum, 3-9 percentages of Paper (cellulose fiber), 0.3-1 Glass fiber, 0-1 Sucrose, and the other ingredients. The three type of drywall is shown below with dimensions tested by NIST research.

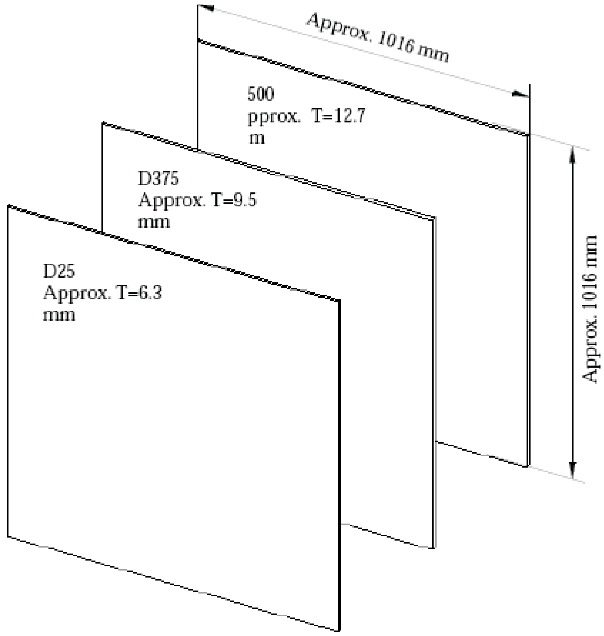


Fig.A.8.a: Nominal Geometry for Plywood Specimens. (C. Stone, William, October 1997 p.59)

A.8.1 Response data for Drywall

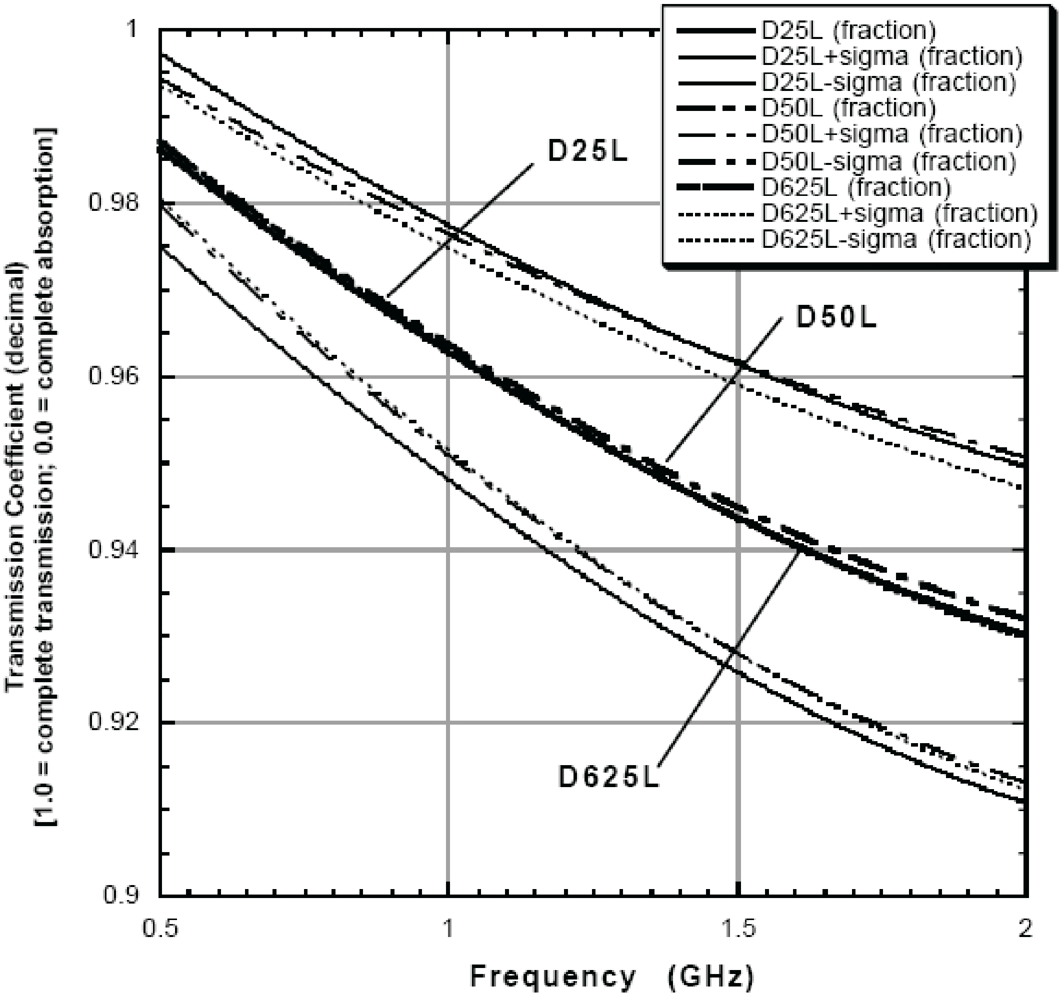


Fig. A.8.1.a: Transmission Coefficients for Drywall Panels. Nominal thicknesses: D25L = 6 mm; D50L = 13 mm; D625L = 16 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.136)

The other EMW friendly building material is Drywall Panels. For Low Range Data (0.5 to 2.0 GHz), D25L = 6 mm, D50L = 13 mm and D625L = 16 mm panels response very efficient data shown in Fig. A.8.1.a

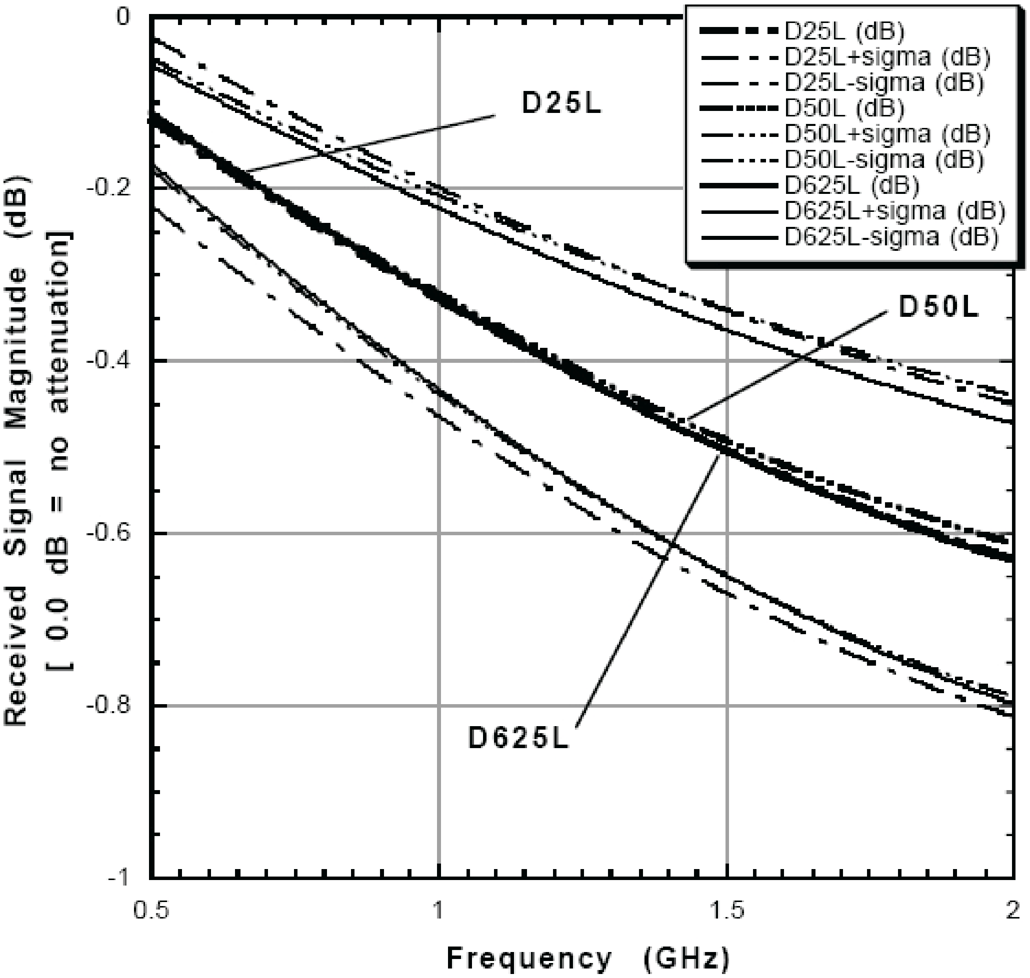


Fig. A.8.1.b: Received Signal Magnitude (dB) for Drywall Panels.D25L = 6 mm; D50L = 13 mm; D625L = 16 mm Dotted Curves represent +/- 1 standard deviation from mean. Low Range Data: 0.5 to 2.0 GHz (C. Stone, William, October 1997 p.137)

The percentage is 90% efficiency for all type of panels between 0.5 GHz- 2 GHz. Received Signal Magnitude (dB) for Drywall Panels proves that image. (See Fig. A.8.1.b)

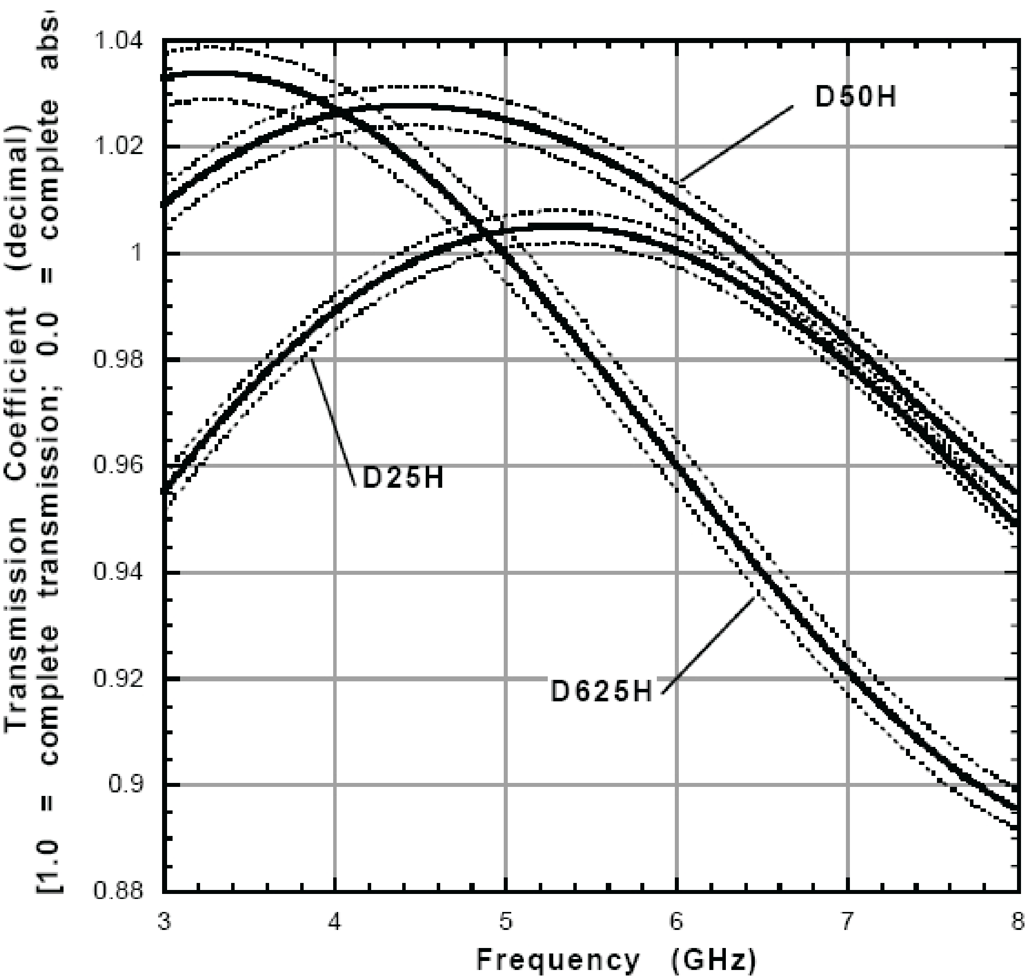


Fig. A.8.1.c: Transmission Coefficients for Drywall Panels. Nominal thicknesses: D25H = 6 mm; D50H = 13 mm; D625H = 16 mm Dotted Curves represent +/- 1 standard deviation from mean (Solid Curves).
High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.138)

In higher frequencies (3.0 GHz – 8.0 GHz), D50H = 13 mm and D625H = 16 mm drywall panels have the value above full transmission. Even if they loose their value, they all have 90% efficiency. (See Fig. A.8.1.c)

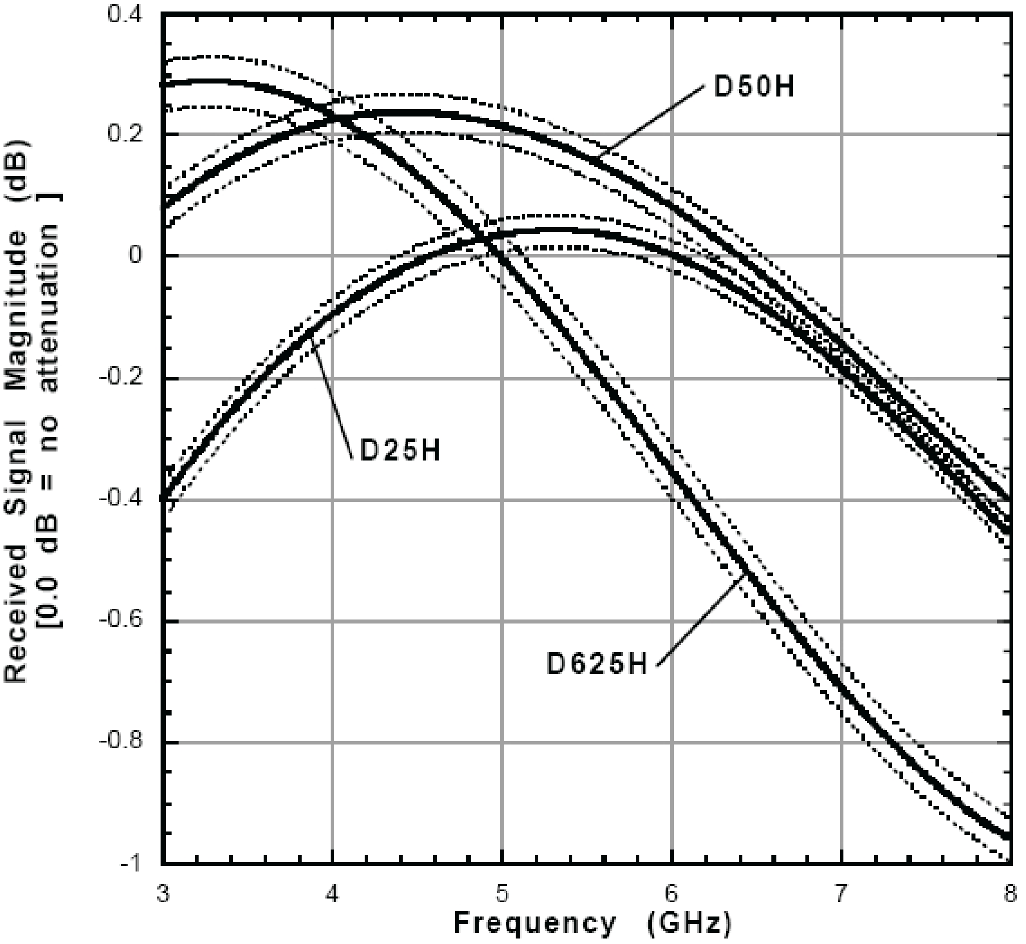


Fig. A.8.1.d: Received Signal Magnitude (dB) for Drywall Panels. D25H = 6 mm; D50H = 13 mm; D625H = 16 mm. Dotted Curves represent +/- 1 standard deviation from mean. High Range Data: 3.0 to 8.0 GHz (C. Stone, William, October 1997 p.139)

Received Signal Magnitude (dB) for Drywall Panels have the similar answer as the transmission figure in the range of 3.0 GHz – 8.0 GHz frequency. [30]

APPENDIX B:

HFSS (HIGH FREQUENCY STRUCTURE SIMULATOR)

B.1. What is HFSS?

HFSS is a high-performance full-wave electromagnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface. It integrates simulation, visualization, solid modeling, and automation in an easy-to-learn environment where solutions to your 3D EM problems are quickly and accurately obtained. Ansoft HFSS employs the Finite Element Method (FEM), adaptive meshing and brilliant graphics to give you unparalleled performance and insight to all of your 3D EM problems. Ansoft HFSS can be used to calculate parameters such as S-Parameters, Resonant Frequency and Fields. Typical uses include:

- **Package Modeling –** BGA, QFP, Flip-Chip
- **PCB Board Modeling –** Power/Ground planes, Mesh Grid Grounds, Backplanes
- **Silicon/GaAs –** Spiral Inductors, Transformers
- **EMC/EMI –** Shield Enclosures, Coupling, Near-or Far-Field Radiation
- **Antennas/Mobile Communications –** Patches, Dipoles, Horns, Conformal Cell Phone Antennas, Quadrafilar Helix, Specific Absorption Rate (SAR), Infinite Arrays, Radar Cross Section (RCS), Frequency Selective Surfaces (FSS)
- **Connectors –** Coax, SFP/XFP, Backplane, Transitions
- **Waveguide –** Filters, Resonators, Transitions, Couplers
- **Filters –** Cavity Filters, Microstrip, Dielectric

HFSS is an interactive simulation system whose basic mesh element is a tetrahedron. This allows you to solve any arbitrary 3D geometry, especially those with complex curves and shapes, in a fraction of the time it would take using other techniques.

The name HFSS stands for High Frequency Structure Simulator. Ansoft pioneered the use of the Finite Element Method (FEM) for EM simulation by developing/implementing technologies such as tangential vector finite elements, adaptive meshing and Adaptive Lanczos-Pade Sweep (ALPS). Today, HFSS continues to lead the industry with innovations such as Modes-to-Nodes and Full Wave Spice™.

Ansoft HFSS has evolved over a period of years with input from many users and industries. In industry, Ansoft HFSS is the tool of choice for high-productivity research, development and virtual prototyping. [39]

APPENDIX C:

Dielectric Theory/Electromagnetic Propagation & Dielectric Mechanism

Dielectric Theory

The dielectric properties that will be discussed here are permittivity and permeability. Resistivity is another material property which will not be discussed here. Information about resistivity and its measurement can be found in the Agilent Application Note 1369-11. It is important to note that permittivity and permeability are not constant. They can change with frequency, temperature, orientation, mixture, pressure, and molecular structure of the material.

Dielectric constant

A material is classified as “dielectric” if it has the ability to store energy when an external electric field is applied. If a DC voltage source is placed across a parallel plate capacitor, more charge is stored when a dielectric material is between the plates than if no material (a vacuum) is between the plates. The dielectric material increases the storage capacity of the capacitor by neutralizing charges at the electrodes, which ordinarily would contribute to the external field. The capacitance with the dielectric material is related to dielectric constant. If a DC voltage source V is placed across a parallel plate capacitor (Figure 1), more charge is stored when a dielectric material is between the plates than if no material (a vacuum) is between the plates.

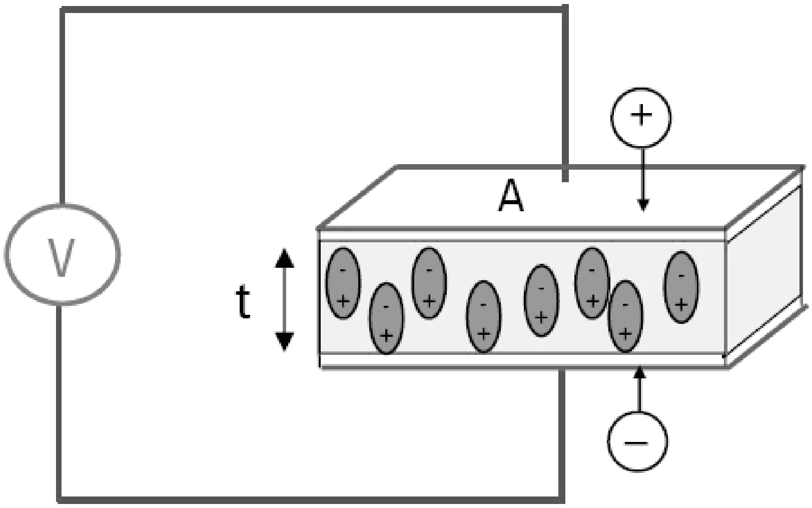


Figure 1. Parallel plate capacitor, DC case

$$C_0 = \frac{A}{t}$$

$$C = C_0 \kappa'$$

$$\kappa' = \varepsilon_r' = \frac{C}{C_0}$$

Where *C* and *Co* are capacitance with and without dielectric, $\kappa' = \varepsilon_r$ ' r is the real dielectric constant or permittivity, and *A* and *t* are the area of the capacitor plates and the distance between them (Figure 1). The dielectric material increases the storage capacity of the capacitor by neutralizing charges at the electrodes, which ordinarily would contribute to the external field. The capacitance of the dielectric material is related to the dielectric constant as indicated in the above equations. If an AC sinusoidal voltage source V is placed across the same capacitor (Figure 2), the resulting current will be made up of a charging current I_c and a loss current I_l that is related to the dielectric constant. The losses in the material can be represented as a conductance (*G*) in parallel with a capacitor (*C*).

$$I = I_c + I_l = V(j\omega C_0 \kappa' + G)$$
$$\text{If} \quad G = \omega C_0 \kappa'', \text{ then}$$
$$I = V(j\omega C_0)(\kappa' - j\kappa'') = V(j\omega C_0)\kappa$$
$$\omega = 2\pi f$$

The complex dielectric constant k consists of a real part k' which represents the storage and an imaginary part k" which represents the loss. The following notations are used for the complex dielectric constant interchangeably $\kappa = \kappa^* = \varepsilon_r = \varepsilon_r^*$. From the point of view of electromagnetic theory, the definition of electric displacement (electric flux density) D_f is: $D_f = \varepsilon E$ where $\varepsilon = \varepsilon^* = \varepsilon_0 \varepsilon_r$ is the absolute permittivity (or permittivity), ε_r is the relative permittivity, $\varepsilon_0 \approx \frac{1}{36\pi} X10^{-9}$ *F/m* is the free space permittivity and *E* is the electric field. Permittivity describes the interaction of a material with an electric field *E* and is a complex quantity. $\kappa = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r - j\varepsilon_r''$

Dielectric constant (κ) is equivalent to relative permittivity (ε_r) or the absolute permittivity (ε) relative to the permittivity of free space (ε_0). The real part of permittivity (ε_r') is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity (ε_r'') is called the loss factor and is a measure of how dissipative or lossy a material is to an external electric field. The imaginary part of permittivity (ε_r'') is always greater than zero and is usually much smaller than (ε_r'). The loss factor includes the effects of both dielectric loss and conductivity.

When complex permittivity is drawn as a simple vector diagram (Figure 3), the real and imaginary components are 90° out of phase. The vector sum forms an angle d with the real axis ($\varepsilon_r{}'$). The relative “lossiness” of a material is the ratio of the energy lost to the energy stored.

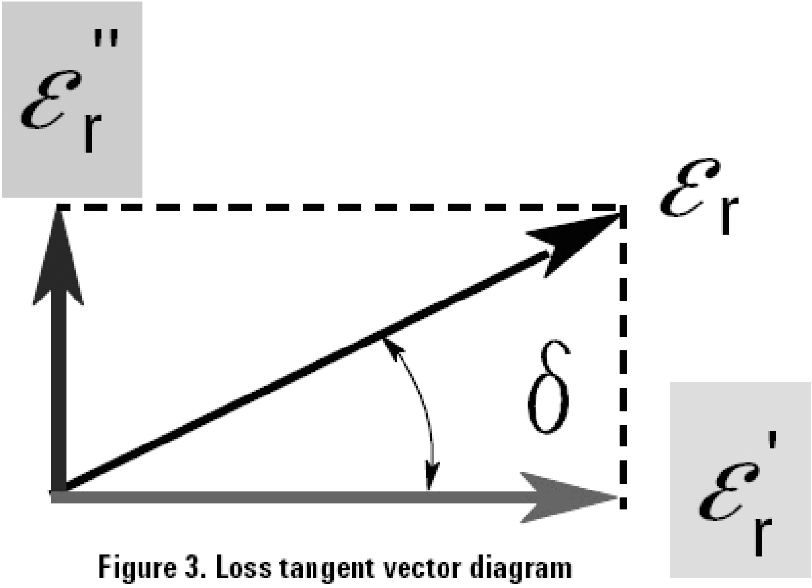


Figure 3. Loss tangent vector diagram

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = D = \frac{1}{Q}$$
$$= \frac{\text{Energy Lost per Cycle}}{\text{Energy Stored per Cycle}}$$

The loss tangent or $\tan\delta$ is defined as the ratio of the imaginary part of the dielectric constant to the real part. *D* denotes dissipation factor and *Q* is quality factor. The loss tangent tan δ is called tan delta, tangent loss or dissipation factor. Sometimes the term “quality factor or *Q*-factor” is used with respect to an electronic microwave material, which is the reciprocal of the loss tangent. For very low loss materials, since tan $\delta \approx \delta$, the loss tangent can be expressed in angle units, milliradians or microradians.

Permeability

Permeability (μ) describes the interaction of a material with a magnetic field. A similar analysis can be performed for permeability using an inductor with resistance to represent core losses in a magnetic material (Figure 4). If a DC current source is placed across an inductor, the inductance with the core material can be related to permeability.

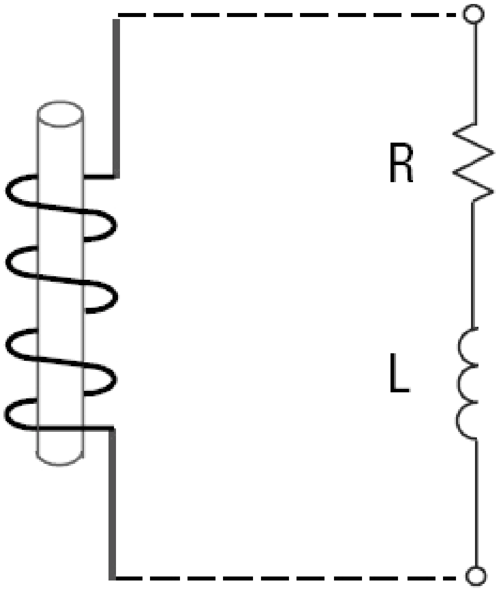


Figure 4. Inductor

$$L = L_0 \mu'$$

$$\mu' = \frac{L}{L_0}$$

In the equations L is the inductance with the material, L_0 is free space inductance of the coil and μ' is the real permeability. If an AC sinusoidal current source is placed across the same inductor, the resulting voltage will be made up of an induced voltage and a loss voltage that is related to permeability. The core loss can be represented by a resistance (*R*) in series with an inductor (*L*). The complex permeability (μ* or μ) consists of a real part (μ') that represents the energy storage term and an imaginary part (μ") that represents the energy loss term.

Relative permittivity μ_r is the permittivity relative to free space:

$\mu_r = \frac{\mu}{\mu_0} = \mu_r - j\mu_r"$ $\mu_0 = 4\pi x 10^{-7}$ *H/m* is the free space permeability Some materials such as iron (ferrites), cobalt, nickel, and their alloys have appreciable magnetic properties; however, many materials are nonmagnetic, making the permeability very close to the permeability of free space (μ_r = 1). All materials, on the other hand, have dielectric properties, so the focus of this discussion will mostly be on permittivity measurements.

Electromagnetic Wave Propagation

In the time-varying case (i.e., a sinusoid), electric fields and magnetic fields appear together. This electromagnetic wave can propagate through free space (at the speed of light, c = 3 x 10^8 m/s) or through materials at slower speed. Electromagnetic waves of various wavelengths exist. The wavelength λ of a signal is inversely proportional to its frequency *f* (λ = *c/f)*, such that as the frequency increases, the wavelength decreases. For example, in free space a 10 MHz signal has a wavelength of 30 m, while at 10 GHz it is just 3 cm. Many aspects of wave propagation are dependent on the permittivity and permeability of a material. Let’s use the “optical view” of dielectric behavior. Consider a flat slab of material (MUT) in space, with a TEM wave incident on its surface (Figure 5).

There will be incident, reflected and transmitted waves. Since the impedance of the wave in the material Z is different (lower) from the free space impedance η (or Z_0) there will be impedance mismatch and this will create the reflected wave. Part of the energy will penetrate the sample.

Once in the slab, the wave velocity v is slower than the speed of light c. The wavelength λ_d is shorter than the wavelength λ_0 in free space according to the equations below. Since the material will always have some loss, there will be attenuation or insertion loss. For simplicity the mismatch on the second border is not considered.

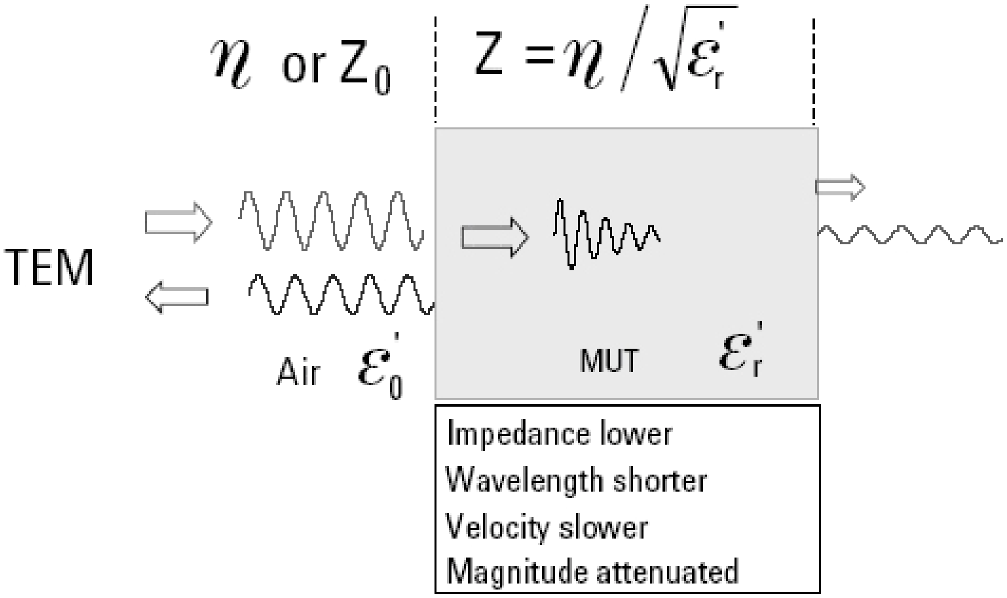


Figure 5. Reflected and transmitted signals

$$Z = \frac{\eta}{\sqrt{\varepsilon_r'}} \qquad \eta = Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi$$

$$\lambda_d = \frac{\lambda_0}{\sqrt{\varepsilon_r'}} \qquad v = \frac{c}{\sqrt{\varepsilon_r'}}$$

Figure 6 depicts the relation between the dielectric constant of the Material Under Test (MUT) and the reflection coefficient $|\Gamma|$ for an infinitely long sample (no reflection from the back of the sample is considered).

For small values of the dielectric constant (approximately less than 20), there is a lot of change of the reflection coefficient for a small change of the dielectric constant. In this range dielectric constant measurement using the reflection coefficient will be more sensitive and hence precise. Conversely, for high dielectric constants (for example between 70 and 90) there will be little change of the reflection coefficient and the measurement will have more uncertainty.

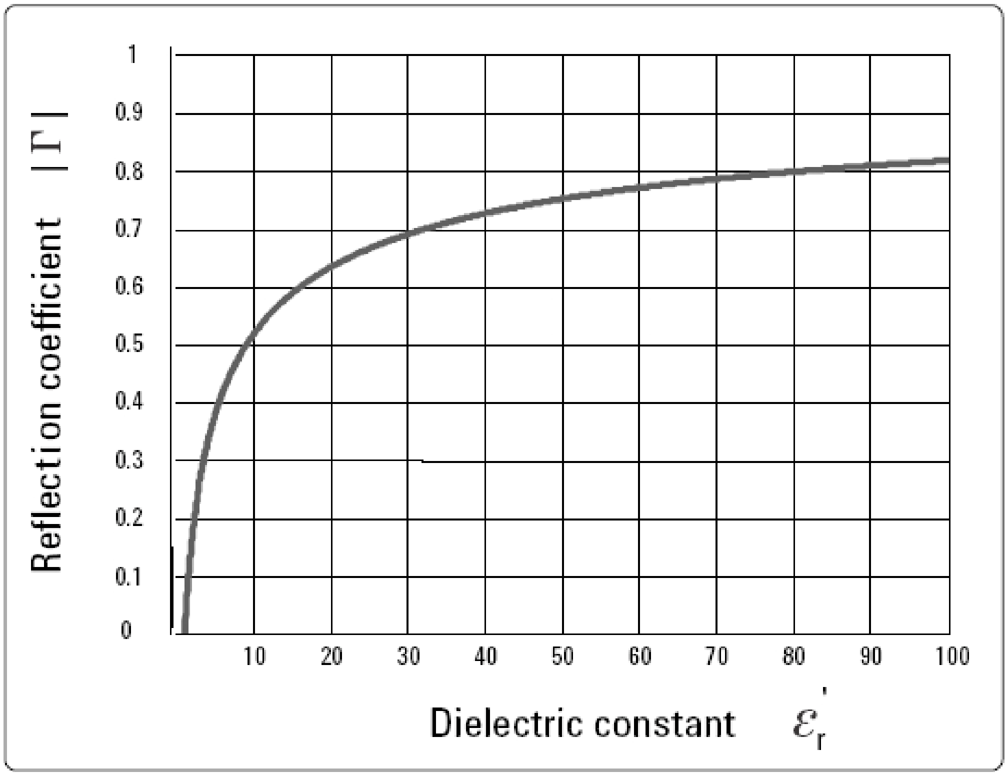


Figure 6. Reflection coefficient versus dielectric constant

Dielectric Mechanisms

A material may have several dielectric mechanisms or polarization effects that contribute to its overall permittivity (Figure 7). A dielectric material has an arrangement of electric charge carriers that can be displaced by an electric field. The charges become polarized to compensate for the electric field such that the positive and negative charges move in opposite directions.

At the microscopic level, several dielectric mechanisms can contribute to dielectric behavior. Dipole orientation and ionic conduction interact strongly at microwave frequencies. Water molecules, for example, are permanent dipoles, which rotate to follow an alternating electric field. These mechanisms are quite lossy – which explains why food heats in a microwave oven. Atomic and electronic mechanisms are relatively weak and usually constant over the microwave region. Each dielectric mechanism has a characteristic "cutoff frequency." As frequency increases, the slow mechanisms drop out in turn, leaving the faster ones to contribute to ε'. The loss factor (ε_r'') will correspondingly peak at each critical frequency. The magnitude and "cutoff frequency" of each mechanism is unique for different materials. Water has a strong dipolar effect at low frequencies – but its dielectric constant rolls off dramatically around 22 GHz. Teflon, on the other hand, has no dipolar mechanisms and its permittivity is remarkably constant well into the millimeter-wave region.

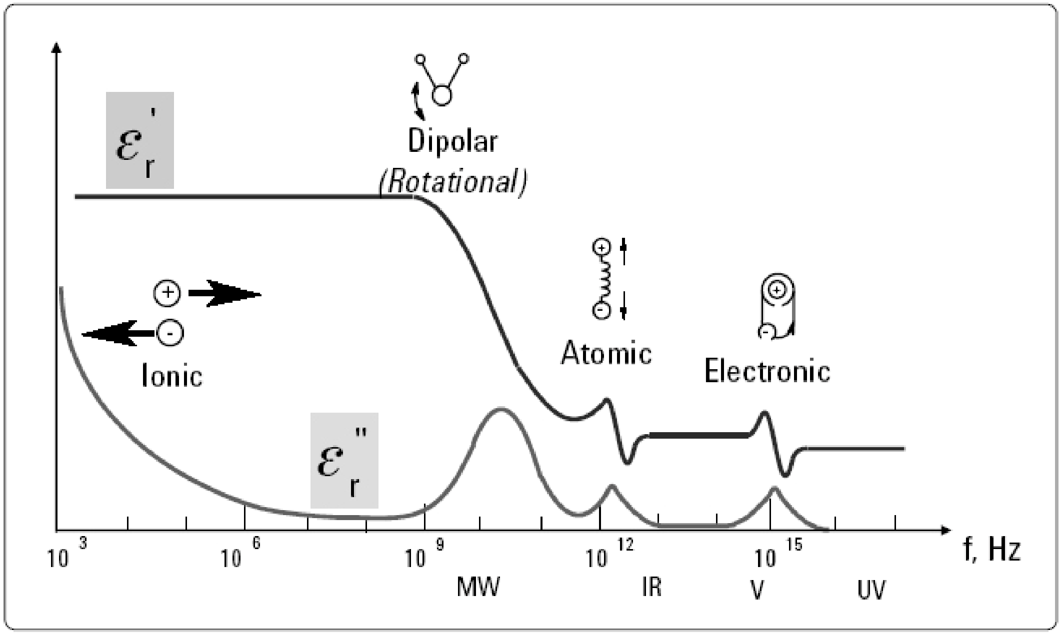


Figure 7. Frequency response of dielectric mechanisms

A resonant effect is usually associated with electronic or atomic polarization. A relaxation effect is usually associated with orientation polarization.

Orientation (dipolar) polarization

A molecule is formed when atoms combine to share one or more of theirs electrons. This rearrangement of electrons may cause an imbalance in charge distribution creating a permanent dipole moment. These moments are oriented in a random manner in the absence of an electric field so that no polarization exists. The electric field *E* will exercise torque *T* on the electric dipole, and the dipole will rotate to align with the electric field causing orientation polarization to occur (Figure 8). If the field changes the direction, the torque will also change.

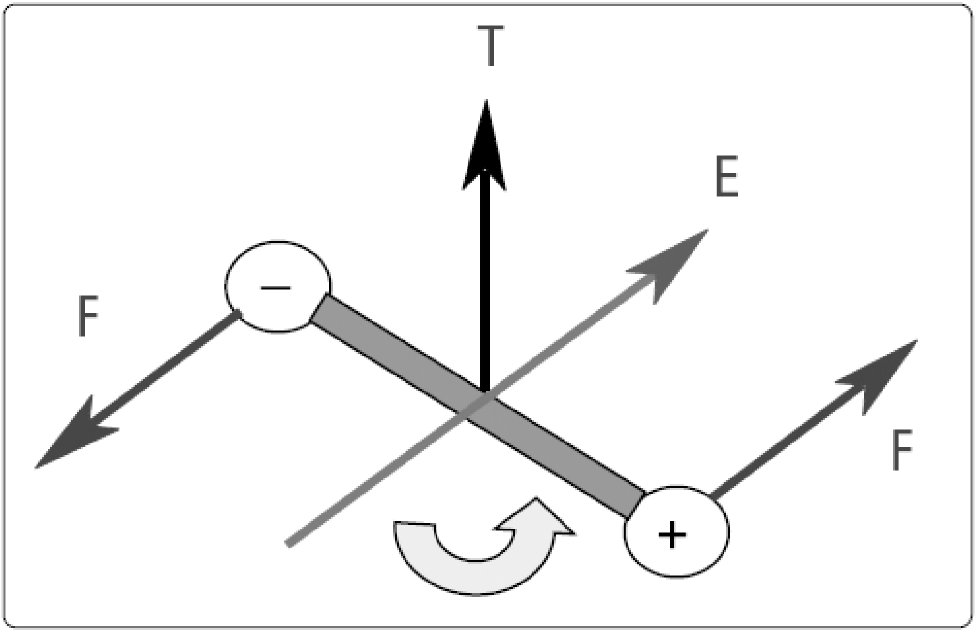


Figure 8. Dipole rotation in electric field

The friction accompanying the orientation of the dipole will contribute to the dielectric losses. The dipole rotation causes a variation in both $\varepsilon_r{}'$ and $\varepsilon_r{}''$ at the relaxation frequency which usually occurs in the microwave region. As mentioned, water is an example of a substance that exhibits a strong orientation polarization.

Electronic and atomic polarization

Electronic polarization occurs in neutral atoms when an electric field displaces the nucleus with respect to the electrons that surround it. Atomic polarization occurs when adjacent positive and negative ions "stretch" under an applied electric field. For many dry solids, these are the dominant polarization mechanisms at microwave frequencies, although the actual resonance occurs at a much higher frequency.

In the infrared and visible light regions the inertia of the orbiting electrons must be taken into account. Atoms can be modeled as oscillators with a damping effect similar to a mechanical spring and mass system (Figure 7). The amplitude of the oscillations will be small for any frequency other than the resonant frequency. Far below resonance, the electronic and atomic mechanisms contribute only a small constant amount to ε_r' and are almost lossless. The resonant frequency is identified by a resonant response in ε_r' and a peak of maximum absorption in ε_r''. Above the resonance, the contribution from these mechanisms disappears. [40]

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