Path loss aspects of a wireless communication system for sensors

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***Abstract*—**Over the past 10 years there have been rapid advances in wireless technologies and an importance of a radio frequency (RF) communication system is expanding day by day due to its advantages. In the meantime, a huge number of researchers are investigating from the various aspects of such field. Electromagnetic wave propagation in an indoor environment and, penetration trough environment medium is still under consideration. In this paper, we reveal a measured result from the different indoor environments for a various transmitted power levels and frequencies. The experience can be used to application of a wireless communication system between sensors and embedded system.

***Keywords*—**communication, penetration, propagation, sensor, and wireless.

I. Introduction

WIRELES communication system is becoming a more omnipresent in daily lives ranging from a mobile communication system to local and personal area networks [1]-[4]. Furthermore, a short – range indoor wireless communication system is playing a more important role with the emergence of a portable system as well as a prime significant demand is to reduce the number of wires needed to be connected [5]. Above all, it avoids obstacles such as crossing objects owned by others but also in industry, there was a large dream of generations of designers for wireless connections among sensors fixed on rotating parts of machines and control systems however, there are many problems in a realization of wireless communication in industrial applications [6]. Most wireless systems must propagate signals through the nonideal environments [7]. Thus it is urgent to be able to provide detailed characterization of the environmental effects on the different amount of the signal frequency which is transmitting.

A plethora of path loss models have been developed in order to calculate the average path loss (in dBm) [8], for instance, Okumura, Hata, COST-231, Dual – Slope, Ray – Tracing, FDTD, MoM, ANN, ITU, Log – Distance [9] – [12] and others. There are two main approaches for modeling path loss. First, empirical or statistical approach which has a complex mathematical equation, but the predictions are less precise. Second, site – specific models which are more accurate than the empirical models, but the models highly depend on specific information of the area.

On the other hand, indoor scenario can easily change its circumstance by changing the position of furniture hence; the indoor propagation modeling is relatively inconsistent. Even so, with a development of the material science and architecture of a construction could have an enormous impact on the RF communication system.

The most interesting situation is a correlation between a transmitted power and its loss for a different quantity. Thus we present the measured result in the different indoor scenarios for a different amount of transmitted power and frequencies in a same distance in order to study an impact of environmental factors. Identically, common three kinds of materials are tested for the penetration of the signals which are:

(a) glass door (Gdoor)
(b) fire resistance wooden door (Wdoor)
(c) wall

Structure of the paper as follows: Section 2 compares the most common propagation models and their parameter options. In Section 3 gives specifications of the tested scenarios and, Section 4 describes the measurement method for both propagation and penetration measurement. The next which is Section5 proposes an analysis of the measured data as well as uncertainty computation. And obtained results are displayed in the Section 6. The following Section 7 compares the measured results with the empirical models. Finally, Section 8 concludes the main points of the measurement.

II. Propagation path loss models

There are a variety of phenomena that occur when an electromagnetic wave is incident. These phenomena are: Reflection, Scattering, Diffraction, Refraction, Absorption, and Depolarization [7]. Path loss is the main constituent of propagation and is a measure of the average radio wave attenuation experienced by the propagated signal when it reaches the receiver, after having navigated through a path of several wavelengths. *Path loss* is given by [13]:

$$PL_{dB} = 10\log\frac{P_t}{P_r} \quad (1)$$

Where: P_t and P_r are the respectively transmitted and received powers.

There are number of indoor propagation models are available as mentioned before. Apparently, there are a number of the propagation model exist. The most famous or well – known model is *Friis transformation equation* is given as [14]:

$$P_r = 10\log_{10} P_t + 10\log_{10} G_t + 10\log_{10} G_r + \\ +147.558 - 20\log_{10} f - 20\log_{10} d \quad (2)$$

Where: P_t and P_r are the apparently transmitted and received powers respectively. G_t and G_r are the correspondingly transmitting and receiving antennas gains, d is the distance (m), f is the specified operating frequency (MHz).

In spite of the mentioned models, there are several site – specific models proposed by different resources, which are shown below.

The *ITU site-general model* for path loss prediction in an indoor propagation environment is given by [7]:

$$L_{total} = 20\log_{10} f + N\log_{10} d + Lf(n) - 28 \quad (3)$$

Where: N is the distance power decay index, f is the frequency (MHz), d is the distance (m) ($d > 1$), $Lf(n)$ is the floor penetration loss factor and n is the number of floors between the transmitter and the receiver.

The *log – distance path loss model* is another site general model and it is given by [15]:

$$L_{total} = PL(d_0) + N\log_{10}(d/d_0) + X_s \quad (4)$$

Where: $PL(d_0)$ is the path loss at the reference distance,usually taken as (theoretical) free-space loss at 1m, $N/10$ is the path loss distance exponent X_s is a Gaussian random variable with zero mean and standard deviation of σ dB.

For frequencies between 800 MHz and 1.9 GHz, COST 231 reports the following values for the path loss exponent [16]:

TABLE 1
EXPONENT FUNCTION FOR DIFFERENT ENVIRONMENT

Environment	Exponent	Propagation mechanism
Corridors	1.4-1.9	Wave guidance
Large open room	2	FSL
Furnished room	3	FSL+multipath
Densely furnished room	4	Non-Los, diffraction, scattering
Different floors	5	Loss of floor (wall)

The COST231-Hata Model is designed for a frequency range from 1.5 to 2 GHz and is given by [17]:

$$L_{total} = 46.3 + 39.9\log f - 13.82\log h_{te} - ah_{re} + \\ + (44.9 - 6.55\log h_{te})\log d + C_m \quad (5)$$

Where: f is the frequency (MHz), d is the link distance (m), h_{te} is the transmitter height (m), h_{re} is the receiver height (m), and C_m is the 0 dB for soft and suburban areas, 3 dB for dense urban areas.

The path loss model referred in [18], the ECC-33 model is defined as:

$$PL = A_{fs} + A_{bm} - G_b - G_r \quad (6)$$

Where: A_{fs}, A_{bm}, G_b and G_r are the free space attenuation, and individually defined as:

$$\begin{aligned} A_{fs} &= 92.4 + 20\log_{10} d + 20\log_{10} f \\ A_{bm} &= 20.41 + 9.83\log_{10} d + 7.894\log_{10} f + 9.56[\log_{10} f]^2 \\ G_b &= \log_{10}(h_b/200)\{13.958 + 5.8[\log_{10} d]^2\} \\ G_r &= [42.57 + 13.7\log_{10} f][\log_{10} h_r - 0.585] \end{aligned} \quad (7)$$

Where: f is the frequency (Ghz), d is the distance between two antennas (km), h_b is the transmitting antenna height (m), and h_r is the receiver antenna height (m).

As noted by [18], the predictions produced by the ECC-33 model do not lie on straight lines when plotted against distance having a log scale.

III. DESCRIPTION OF THE MEASUREMENT SITES

During the measurement of the propagation three kinds of laboratory rooms and some corridors are considered as the environments. Each room is equipped by different devices and equipments. Furthermore, the corridors are differed by its architecture from each other.

A. Laboratory room 306

This is intended to study a classical sensor system and equipped by corresponding devices. Prevailing equipments are: power suppliers, multimeters, several PCs, and sensor units such as a strain gauge, capacitive sensors, PID regulator and other. However, there were no wireless sensor systems and all the time during the measurement the laboratory devices were inactive. A floor plan of the room is given by Appendix A.

B. Laboratory room 309

With compared to the former room this room does not comprise such sensor devices but, equipped by Laboratories of Integrated Automation, which are new modern laboratories accessible locally and remotely in an Internet. There are about 10 PCs furnished in the room. See Appendix B.

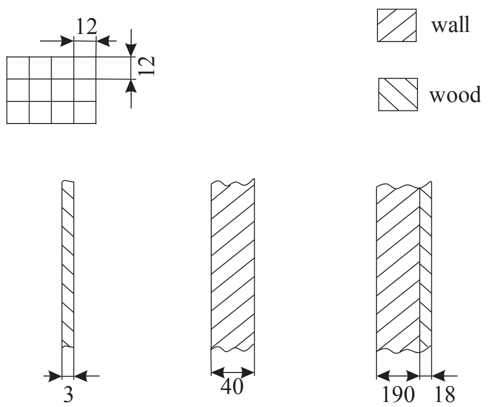
C. Industrial hall 107

This room is dedicated for production engineering students. Therefore, the laboratory room is a well equipped with production machines such as CNCs, drilling stations, laser cutter, as well as one robot. This room is expected to be industrial hall or environment with a noise (Appendix C).

D. Corridors

The corridor has a U – shape. Each sleeve of the corridor is assumed to be a different environment due to its architecture. For instance, in a Corridor 1 there is a wireless router, a Corridor 2 is widest, and Corridor 3 leads to spectrum analyzer laboratory room.

Measurement of the penetration is tested on three medium as mentioned before.



(a) Glass door (b) Wooden door (c) Wall

Fig. 1 tested penetration medium

As can be seen in Fig.1, the wdoor was fire resistance specific application door, and gdoor contains 12x12mm metal wire set. The wall is constructed by usual bricks and wooden attachment for the clothes hanger.

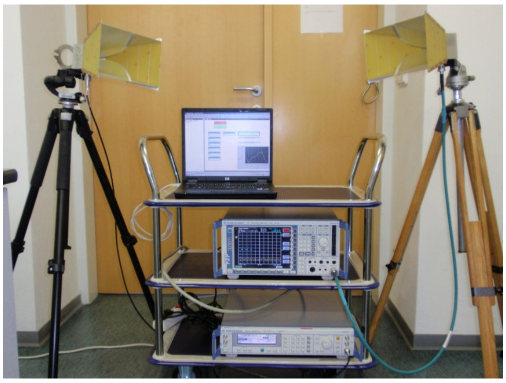


Fig. 2 A photo of measurement set

IV. Measurement Setup

In study case, a SMR20 microwave signal generator and FSP spectrum analyzers are used. For the 2.4 GHz frequency measurement, the same condition applied with a later description. Photo of the measurement set is given by Fig. 2.

The wireless signal with five different power levels in the range from 1 GHz to 8 GHz signal is transmitted from the generator to the receiver. And the data are acquired in PC by using software Agilent VEE Pro version of 7.5. Fig. 3 shows a main measurement window.

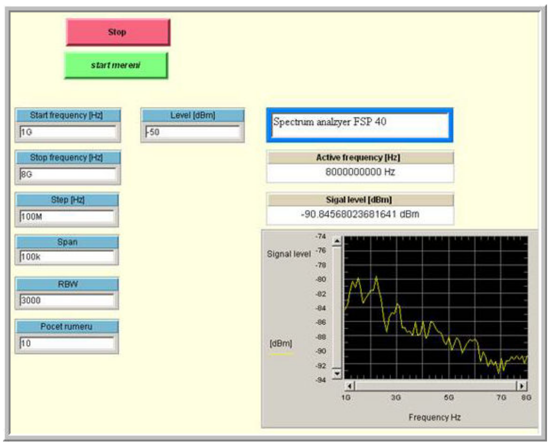


Fig. 3 A measurement window

The following Table 2 shows the measurement constants and holds during both propagation and absorption measurement procedure.

TABLE 2
MEASUREMENT CONSTANTS

Constants	Value	Unit
Step	100	MHz
Span	100	KHz
Resolution Bandwidth	3000	-
Sweep Time	10	s

A. Propagation scheme

During the measurement of the indoor propagation, a following situation can be drawn, which means

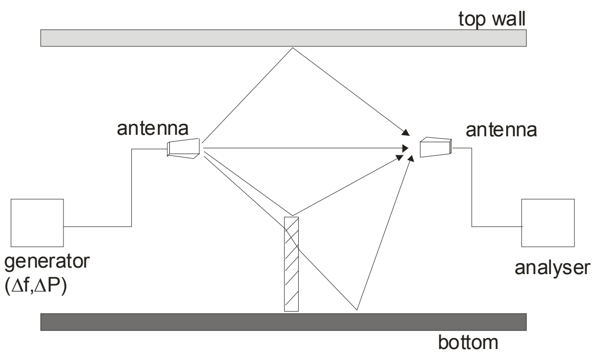


Fig. 4 Scheme of the measurement system of propagation

FSL+Multipath.

B. Absorption measurement scheme

In contrast to, the scheme of measurement of absorption is given by Fig. 5. The antennas were located 0.25 m from the each tested materials.

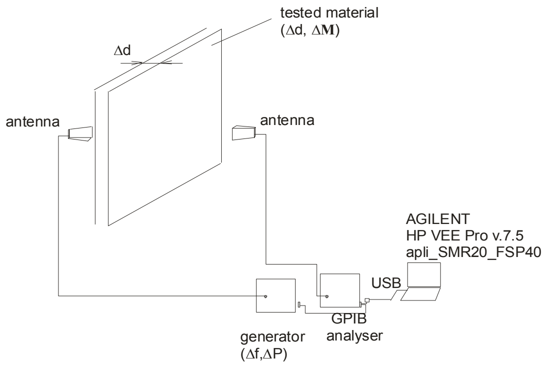


Fig. 5 Scheme of the measurement of absorption

V. Data and uncertainty analysis

The measured result was associated with environmental noises. Therefore, first we considered a mean value of signal coverage of the measurement site. Second, uncertainties of the measurement devices were subtracted from the measured result in order to get precise loss of the signal. The following equation is used to evaluate the total loss of the signal:

$$P_{TL} = P_R - P_{ref} - P_{SC} \tag{8}$$

Where: P_R and P_{ref} are the received and reference signal level (dBm), respectively, and P_{SC} is the measured signal coverage (dBm), (without signal generator).

A. Propagation analysis

The measured data should have been compared with the suitable site – specific models and a difference or closeness for the test of an appropriate fitting model.

B. Penetration analysis

During the measurement of the penetration of the signal trough some material or absorption of signal a following formulation should be considered:

As can be seen in Fig. 6, the penetration of the signal to be caused by following parameters: ε_0 is the permittivity (F/m), μ_0 is the permeability (H/m), E is the intensity of electric field (V/m) and H is the intensity of the magnetic field (T/m). The area of material creates a loss of intensities as K_s :

$$K_s = \left(\frac{E_t}{E_i}\right) = \left(\frac{H_t}{H_i}\right) \tag{9}$$

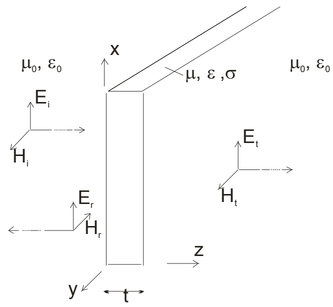


Fig. 6 Scheme of penetration

Alternatively, Shielding Effectiveness (SE):

$$SE = 20\log\left(\frac{1}{K_s}\right) = 20\log\left(\frac{E_i}{E_t}\right) = 20\log\left(\frac{H_i}{H_t}\right) \tag{10}$$

If we derive the above parameters with respect to the to the Maxwell formula:

$$K_s = \left(\frac{1}{\cosh\gamma t\left[1 + \frac{1}{2}\left(\frac{Z_0}{Z_M} + \frac{Z_M}{Z_0}\right) tgh\,\gamma t\right]} \right) \tag{11}$$

and

$$SE = 20\log\left\{\left(\frac{(Z_0 + Z_M)^2}{4Z_0 Z_M}\right)e^{\gamma t}\left[\left(1 - \frac{Z_0 - Z_M}{Z_0 + Z_M}\right)^2 e^{-2\gamma t}\right]\right\} \tag{12}$$

Where: Z_0 is the free space impedance, Z_M is the material impedance which is tested, and γ is the path loss exponent parameter as follows:

$$Z_0 = \sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)} = 120\,\pi = 377\,\Omega$$
$$Z_M = \sqrt{\left(\frac{j\omega\mu}{\sigma}\right)} \tag{13}$$
$$\gamma = \sqrt{j\omega\mu\sigma} = (1 + j)\sqrt{\frac{j\omega\mu\sigma}{2}} = \alpha + j\beta$$

Then SE formula is:

$$SE = R + A + M \tag{14}$$

Where: R is the reflection (dB), A is the absorption (dB), and M is the penetration (dB).

For the reflection there is the formula:

$$R = 20\log\left(\frac{(Z_0+Z_M)^2}{4.Z_0.Z_M}\right) \Rightarrow$$
$$\Rightarrow 20\log\left\{\left(\frac{(Z_0+Z_M)}{2.Z_M}.\frac{(Z_0+Z_M)}{2.Z_0}\right)\right\} = R_1 + R_2 \quad (15)$$

(R_1- is the reflection before, and R_2 is the reflection behind the face of area)

The absorption is given by:

$$A = 20\log(e^{\gamma t}) = 20\log\left(e^{\frac{t}{\sigma}}\right) \Rightarrow$$
$$\Rightarrow 8{,}69\frac{t}{\sigma} = 0{,}0069\,.t.\sqrt{\omega\mu_r\sigma} \quad (16)$$

C. Uncertainty analysis

The uncertainty associated with the measurement result can be computed by using Table 3 as given by a manufacturer company [19]:

TABLE 3
UNCERTAINTY OF THE INSTRUMENTS

Uncertainty	Value	Unit
SMR20	1	dB
FSP40	0.259	dB

Moreover, uncertainties of the cables and antennas must have considered as given by below.

Attenuation of the LMR – 195 coaxial cable is given by Eq 17.

$$A_{LMR195} = (1.17086)\sqrt{f} + (0.00154)f \quad (17)$$

Where: f is the frequency (MHz), and

Maximum cable assembly attenuation for UFA147B cable can be calculated by using the following equation:

$$A_{UFA147B} = L\times(0.148\sqrt{f} + 0.004f) + C_1\sqrt{f} + C_2\sqrt{f} \quad (18)$$

Where: L is the length (f), f is the frequency (GHz), and C_1 and C_2 - are connector constants (0.03 for straight connector)

HF906 antenna is designed with a low voltage standing ratio (VSWR) which is allowing the generation of high field – strength levels without any significant return loss as well as the measurement of weak signals. VSWR can be calculated as follows:

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+\rho}{1-\rho} \quad (19)$$

Where: $\rho = |\Gamma|$ is the magnitude of the reflection coefficient

By using the reflection coefficient, we can compute Return Loss and Mismatch Loss with respect to the mW range as follows:

$$RL = -20\log(\Gamma)$$
$$ML = -10\log(1-\Gamma^2) \quad (20)$$

Then an expanded uncertainty of the system can be found a root sum square (RSS) formula as follows:

$$U_{System} = \sqrt{U_{SMR20}^2 + U_{LMR195}^2 + U_{FSP}^2 +}$$
$$\sqrt{+U_{UFA147B}^2 + 2U_{Antenna}^2} \quad (21)$$

However, during the measurement of 2.4 GHz frequency only two uncertainties which are a spectrum analyzers and its cable are affiliated plus Zstar3 kit its own uncertainty as follows:

$$U_{System} = \sqrt{U_{FSP}^2 + U_{UFA147B}^2 + U_{Antenna}^2 + U_{ZSTAR}^2} \quad (22)$$

VI. EXPERIMENTAL RESULT

Table 4 reveals an average path loss model from 1 to 8 GHz frequency range. As can be seen from the table the propagation path loss values were almost stable but differing by a few dB values. However, during a transmission of -30 dBm value the results were unstable comparison with the rest of the cases.

The penetration losses were randomly spread but, there are differed by a several dB power with the same transmission of powers.

TABLE 4
EXPERIMENTAL RESULT

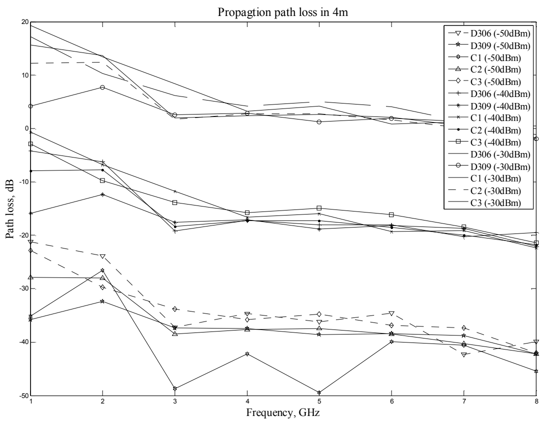
Reference	-50 dBm	-40 dBm	-30 dBm	-20 dBm	-10 dBm
D=4 m					
D306	-34.69	-15.13	4.82	24.93	44.78
D309	-35.27	-15.20	4.78	24.79	44.78
C1	-37.09	-14.67	5.35	25.36	45.38
C2	-34.73	-14.64	5.38	25.43	45.40
C3	-34.49	-14.41	5.61	25.63	45.64
D=5.35 m					
D306	-37.17	-16.22	3.89	23.77	43.92
D309	-37.03	-17.07	2.94	22.94	42.96
C1	-38.63	-17.39	0.54	20.59	40.62
C2	-39.36	-19.53	0.50	20.52	40.53
C3	-38.49	-18.69	1.37	21.40	41.37
D=7 m					
D306	-37.03	-17.07	2.94	22.94	42.96
D309	-38.63	-17.39	0.54	20.59	40.62
C1	-39.36	-19.53	0.50	20.52	40.53
C2	-37.17	-16.22	3.89	23.77	43.92
C3	-37.03	-17.07	2.94	22.94	42.96
Penetration measurement					
Gdoor	-23.45	-3.71	16.33	36.33	56.30
Wdoor	-22.19	-2.73	17.67	37.72	57.61
Wall	-30.98	-8.58	11.44	31.58	51.42

D – is the distance between transmitter and receiver (m)
C1, C2,and C3 – are the corridors 1 to 3 respectively

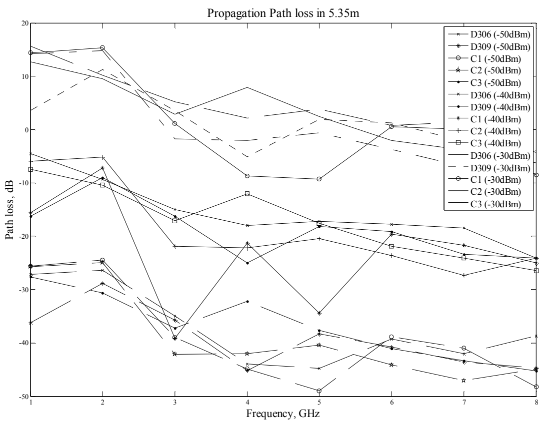
TABLE 5
PATH LOSS MEASUREMENT OF ZSTAR3 KIT IN dB

D306	D309	D107	C1	C2	C3	Wdoor	Gdoor	Wall
-64.0	-61.3	-58.3	-67.4	-63.1	-65.7	-49.2	-49.7	-60.0

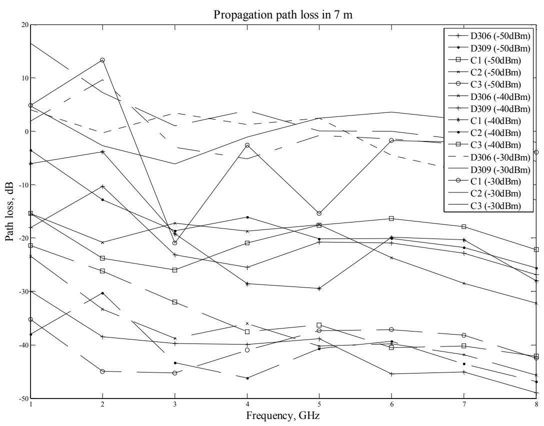
In order to investigate a hypothesis of measurements with signal generator and Zstar3 kit the measured results are given by Table 5. A reference value of the kit is considered to be 0 dBm.



(a) 4m compared result



(b) 5.35m compared result



(c) 7m compared result
Fig. 7 Path loss comparison for different reference values

As shown in Fig.7 (a) to (c), the path loss measurement results are evaluated for -50dBm, -40dBm, and -30dBm transmitted powers. The rest of the experimental results are given by next chapter and compared with empirical models.

The most interesting situation of the measurement is relevance between transmitted power and frequency range. From the measured result, it can be seen that the maximum difference between two measurements regarding to the -20 dBm reference value is estimated to be 15.2 dBm for propagation measurement. In contrast, by a minimum of 3.0 dBm value has differed.

On the second hand, the results of penetration are varied by a maximum of 1.1 dBm and by a minimum of -5.1 dBm.

VII. COMPARED RESUTS

The corresponding statistic evaluations in the term of the Standard Deviation (SD) and the uncertainty of the measurement are given in Table 6.

TABLE 6
EXPERIMENTAL RESULT

Frequency, GHz	RSS (dB)	SD	Frequency, GHz	RSS (dB)	SD
1	1.76	0.10	1.5	2.03	0.08
2	2.26	0.23	1.6	2.07	0.08
3	2.67	0.28	1.7	2.12	0.12
4	3.04	0.09	1.8	2.17	0.10
5	3.36	0.13	1.9	2.22	0.12
6	3.64	0.06	2.0	2.26	0.23
7	3.91	0.07			
8	4.16	0.07			

As can be in Table 6, the maximum uncertainty of the experimental system is found to be 4.16 dB, and with the SD of 0.28.

The Fig. 7 to Fig9 show the compared results the empirical models with the measured results in three different distances between transmitter and receiver.

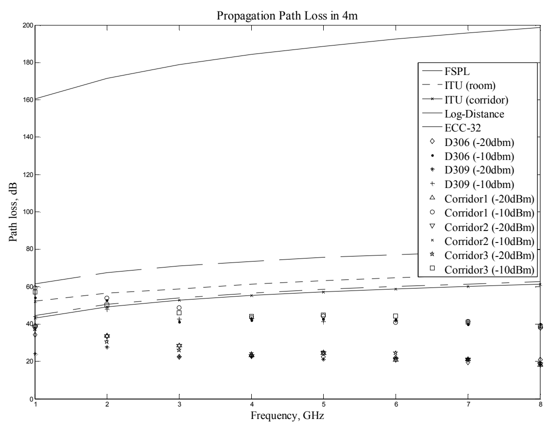


Fig. 7 Path loss comparison in 4m

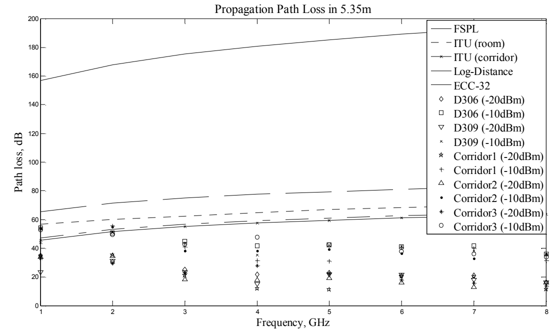


Fig. 8 Path loss comparison in 5.35m

As can be seen from the Figures, in generally ITU and Log – Distance models are closer than that other FSPL and ECC-32 models. However, it should be noted that the transmitted reference powers were quite low which are – 20 dBm, and – 10 dBm. A reason is obvious to investigate a possibility to save energy consumption for the modern wireless sensors.

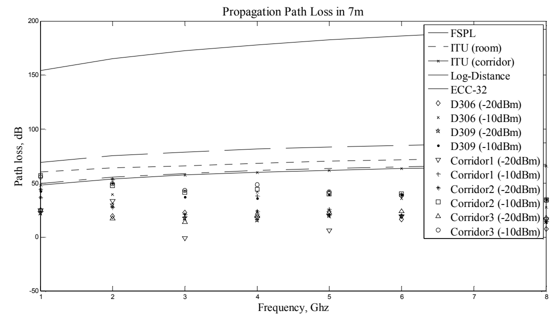


Fig. 9 Path loss comparison in 7m

In contrast to, 1.5 to 2 GHz frequency range propagation path loss comparison is given by Fig. 10-12.

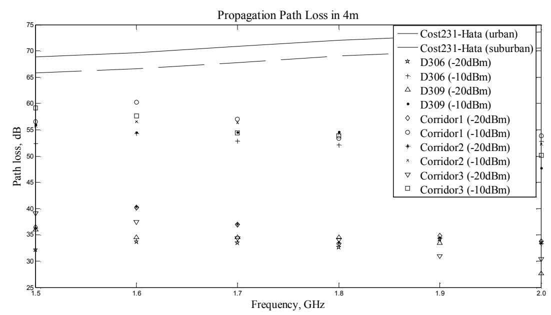


Fig. 10 Path loss comparison in 4m

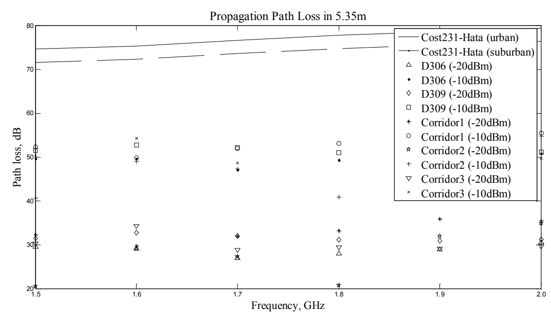


Fig. 11 Path loss comparison in 5.35m

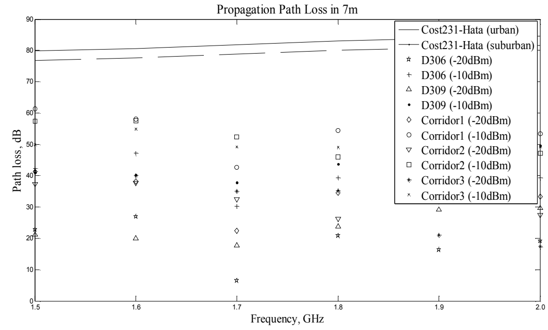


Fig. 12 Path loss comparison in 7m

As shown in above Figures, a prediction of Cost231-Hata model shows a quite high loss of energy with respect to the measured result. This model is widely used for the prediction of path loss in mobile wireless communication system. The reference power values were the same with former measurement.

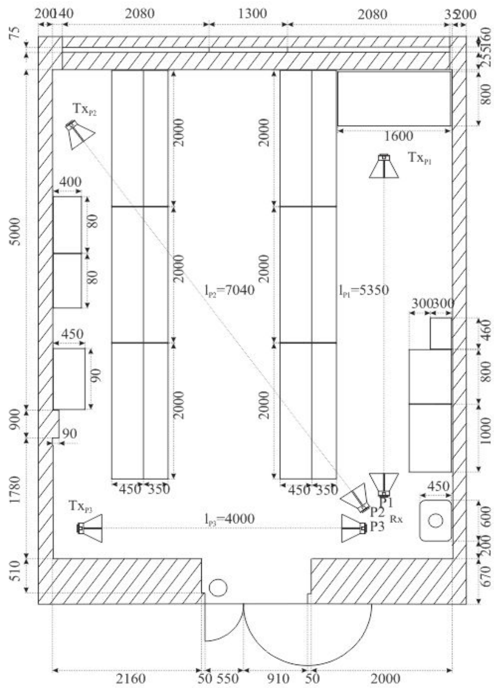
VIII. Conclusion

In this paper, we have studied propagation of RF signal from 1 to 8 GHz frequency range. As an example of 2.4 GHz frequency communication system the ZSTAR3 kit has chosen, and a result has been compared with the measurement of the signal generator, including an uncertainty of the system. Moreover, penetrations of 1 to 8 GHz frequency signals have studied and shielding effectiveness model has discussed.

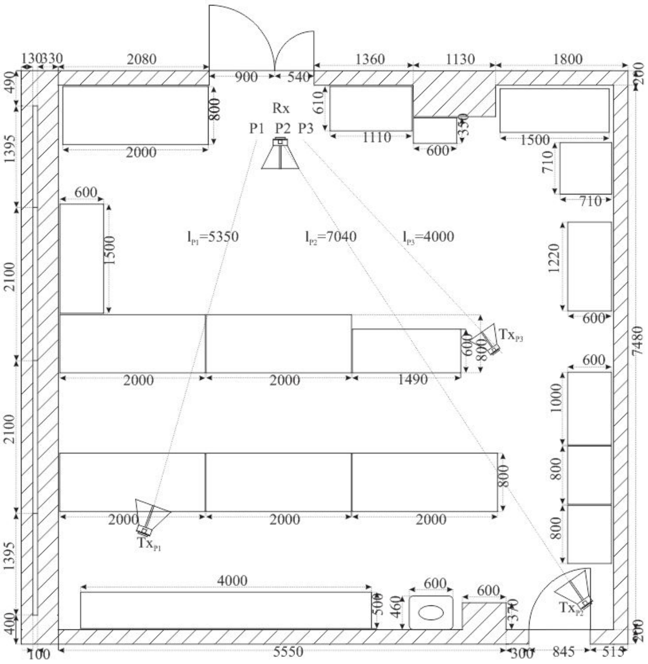
Appendixes

The floor plans of the tested sites are given below.

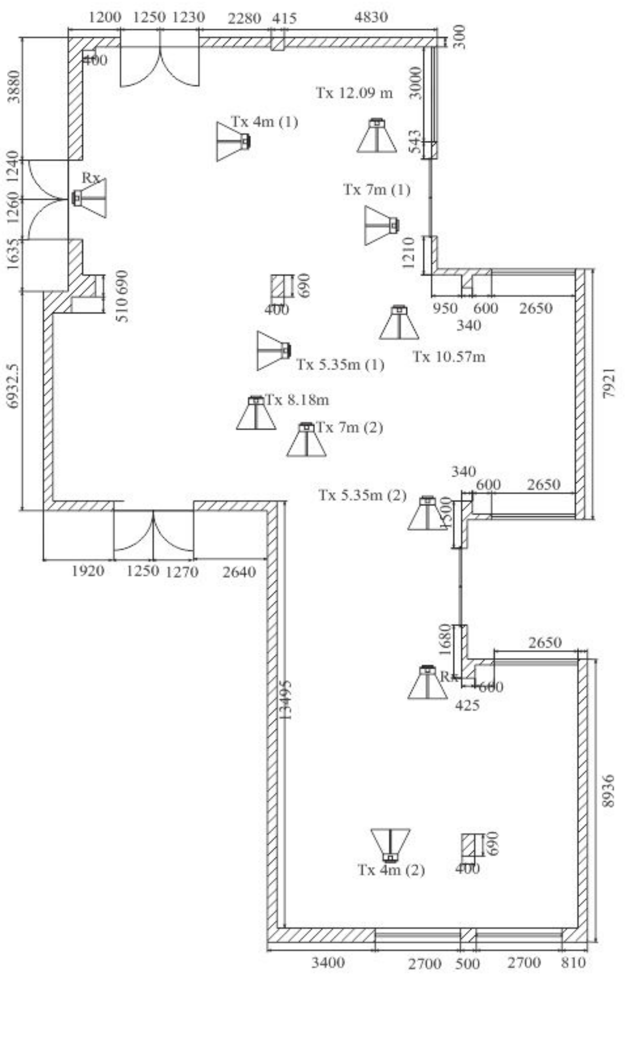
Appendix – A D306



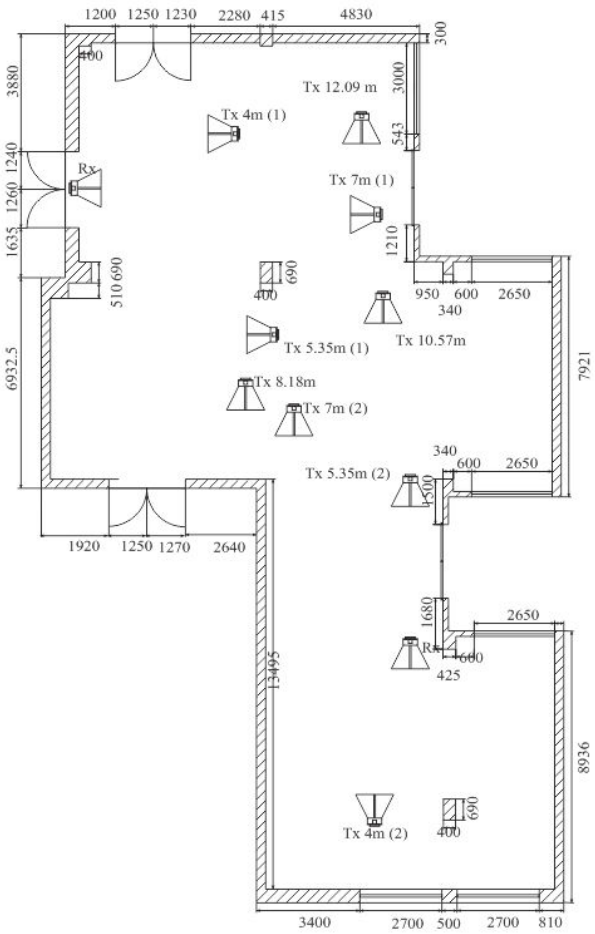
Appendix – B D309



Appendix – C D107



Appendix – D C1-C3



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