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Comparison of Signal Strength Prediction Models for Indoor-to-Outdoor and Outdoor-to-Indoor Wireless Communications

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Abstract

In wireless communication system, the propagation characteristics of the radio coverage areas such as indoor, outdoor, indoor-to-outdoor and outdoor-to-indoor are very important to acquire the accurate received signal strength. In this paper, the experiments are conducted for both indoor-to-outdoor and outdoor-to-indoor wireless communication environments to investigate how much the received signal strength values are different between them. To obtain the accurate received signal strength between the outdoor-to-indoor and indoor-to-outdoor areas, the COST 231 radio wave propagation model is extended by including additional path loss factors (A_f) such as the building parameters, the heights of the transmitter and receiver, the distance between the transmitter and the receiver for each scenario. The proposed received signal strength prediction models for indoor-to-outdoor and outdoor-to-indoor wireless communication are validated by comparing with the experimental and predicted the received signal strength indicator (RSSI) values. According to the comparison results, the received signal power from the outdoor to indoor communication is higher than that of indoor-to-outdoor ones about -2 dBm or -3 dBm.

Keywords: COST 231 model; Indoor-to-outdoor; Outdoor-to-indoor; Path loss; Received signal strength.

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1. Introduction

Nowadays, the use of wireless communication system has become popular to provide the sufficient rate of data transmission in the local, metropolitan and wide areas. Depending on the coverage areas, there are four types of wireless communication environments such as indoor, outdoor, indoor-to-outdoor and outdoor-to-indoor [1]. The indoor-to-outdoor wireless communication is defined as only when the transmitter is inside of the building and the receiver is outside area. In this case, the propagated signal from the transmitter penetrates the building wall and reached to the outside receiver, for example, the user is sitting in the garden and using a laptop which is connected to the internet via indoor base station [2-4]. For the outdoor-to-indoor environment, the transmitter is placed outside of the building and the receiver is positioned at the inside area [5-7].

With the growth of wireless communication in both indoor-to-outdoor and outdoor-to-indoor areas, getting the strong received signal power is also essential for the users [8]. Therefore, it has become a need to predict the received signal strength between the indoor base station and outdoor receiver and vice versa. In this paper, the received signal strength are predicted by accomplishing the experiments, generating the proposed model based on the original COST 231 model (European Co-operation in the field of Scientific and Technical research) for both indoor-to-outdoor and outdoor-to-indoor wireless communication environments. Then, the results of both indoor-to-outdoor and outdoor-to-indoor scenarios are compared in order to show the differences between these two scenarios. The main aim of this paper is to propose the received signal strength prediction models for both the indoor-to-outdoor and outdoor-to-indoor wireless communication areas.

This paper is organized as the following sequences. The radio wave propagation model is briefly described in section II. The optimization process of radio wave propagating model for indoor-to-outdoor and outdoor-to-indoor wireless communication environments is discussed in detail in section III. The experimental region is depicted in section IV. The experimental procedures are expressed in section V. The experimental results and discussion are shown in section VI. Conclusion is finally presented in section VII.

2. Cost 231 Radio Wave Propagation Model

To implement the wireless communication system, radio wave propagation models are required to determine propagation characteristics for any type of coverage area. For only outdoor areas, the Okumura model and Hata model are well-known [8]. Ray tracing model, multiple floor models are used for indoor wireless system [9]. For both indoor and outdoor radio wave propagation system, the COST 231 model is the most appropriate model because it provides the accurate prediction results of not only indoor and outdoor loss but also the building penetration loss [10].

The COST 231 model is one of the well-known models to predict the path loss outside of the building, the building penetration loss and the inside propagation loss. In the COST 231 model, the radio waves from the transmitter travelled to the building external wall which is in direct view of line of sight (LOS) and then to the receiver inside the building as shown in figure 1[10].

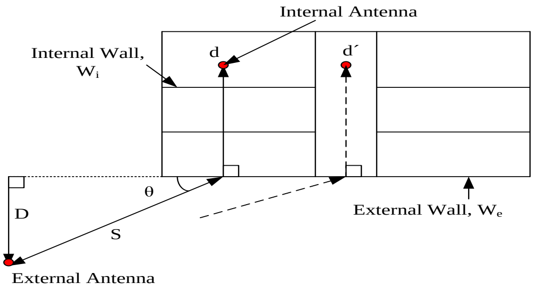

Figure 1: The Principle of COST 231 Radio Wave Propagation Model

The total path loss between the transmitted antenna and the received antenna is shown as:

$$L = 32.44 + 20log_{10}(f) + 20log_{10}(S + d) + W_e + WG_e(1 - D/S)^2 + max(\Gamma_1, \Gamma_2) \tag{1}$$

$$\Gamma_1 = W_i p \tag{2}$$

$$\Gamma_2 = \alpha(d - 2)\left(1 - {}^{D}\!/_{S}\right)^2 \tag{3}$$

The term L represents the total path loss including the outside building loss or free space loss, the building penetration loss and the inside building loss. The distance d is a path from the internal building wall to the received antenna and the distance d' is a path through a corridor without internal walls. D and d are the perpendicular distances and S is the physical distance between the outside antenna and the external wall at the actual floor. All distances are in meters, frequency is in GHz. W_i is the internal wall loss in dB. W_e is the external wall penetration loss in perpendicular grazing angle, i.e., $\theta = 90$ degrees. WG_e is the additional loss in the external wall due to $\theta = 0$ degrees. θ is the grazing angle. p is the number of penetrated internal walls. α is the specific indoor attenuation constant in dB/m.

2.1. Received Signal Strength Indicator (RSSI)

The received signal strength indicator is a measurement of the signal strength at the destination. Higher RSSI values indicate the stronger signal. The received signal strength power can be calculated as

$$P_r = P_t + G_t + G_r - L \tag{4}$$

where P_r is the received signal strength power (dBm). G_t and G_r are the transmitter and receiver antenna gains (dBi). L is the propagation loss or path loss.

3. Optimization of Radio Wave Propagation Model

Although the original COST 231 model is generally characterized to be relevant for all types of indoor and outdoor environments with a carrier frequency of 900-1800 MHz, this frequency range is certainly low for wireless communication standards [10]. The COST 231 model is needed to be more frequency range. Moreover, in spite of composing with three different path loss (indoor, outdoor and penetration) in the COST 231 model, some building parameters are not included such as width and length of the building, the heights of the transmitter and the receiver in the calculation of the total propagation loss. To fulfil this requirement, the existing propagation model is becoming necessary to be optimized, and the new schemes and techniques are needed to be proposed. Therefore, the COST 231 model is optimized for the indoor-to-outdoor and outdoor-to-indoor radio wave propagation system.

For the optimization process, the values of W_i, W_e and WG_e are obtained from measurements at the operating frequency of 2.4 GHz. b_w, b_l and b_h are the width, length and height of the measurement room. h_t and h_r are the transmitter and receiver heights. d_θ is the reference distance of the outside or free space environment (d_0=1 m). All the building parameters and distances are expressed in meter.

For developing the proposed signal strength prediction models of indoor-to-outdoor and outdoor-to-indoor wireless areas, the experimental and estimated values for each measurement points are firstly analysed. As the consequence of this analysis, the most interesting fact is found that the difference between the estimated model and the experimental results are relatively quite high. In order to adjust of the different outcomes, the additional path loss factor is considered. The additional path loss factor for the indoor-to-outdoor wireless area is expressed as follows:

$$A_{f\,(In-Out)} = \left(\frac{h_t.h_r}{b_h.d_0} + \left| \frac{\Delta d}{d_0}.10log\,\frac{b_w.b_l.\lambda}{d_{\,factor}.b_h.d_0} \right| \right) \qquad (5)$$

Where d_{factor} is the distance factor when the transmitter is placed from 2.2 m distance for measurement points (1, 2, 3) , 4.4 m distance for measurement points (4, 5, 6) and 6.6 m distance for measurement points (7, 8, 9). λ is the wavelength of the signal which is estimated for the received power based on speed of light (3×10^8 m/s) and frequency (2.4 GHz). Δd is the difference of the two distances which are the direct distance from the transmitter and receiver, and the distance from the transmitter to the building wall and the building wall to the receiver. In order to acquire the exact signal strength for the experimental results, the building parameters and distance factor is becoming needed to be a logarithmic ratio of power. Besides, the results are taken as the absolute values to be positive. For the proposed indoor-to-outdoor signal strength prediction model, the additional path loss factor is subtracted from the estimated received signal strength values as shown in the following equation.

$$P_{r(proposedIn-Out)} = P_{r(estimated)} - A_{f\,(In-Out)} \qquad (6)$$

Like the indoor-to-outdoor radio wave propagation model, the additional path loss factor (A_f) is also considered in the optimization of outdoor-to-indoor radio wave propagation model. The outdoor-to-indoor additional path loss factor is expressed in the following:

$$A_{f(Out-In)} = 10log_{10} \frac{b_h b_w d_1}{h_t b_l d_0} \tag{7}$$

Where, d_1 is the distance from the outdoor transmitter to the building external wall and then to the indoor receiver.

As in the proposed indoor-to-outdoor model, the outdoor-to-indoor additional factor is also subtracted from the estimated RSSI values to model the outdoor-to-indoor experimental RSSI values. The proposed outdoor-to-indoor received signal strength prediction model is described as

$$P_{r(proposedOut-In)} = P_{r(estimated)} - A_{f(Out-In)} \tag{8}$$

The Table 1 shows the parameter values used in the proposed indoor-to-outdoor and outdoor-to-outdoor models.

Table 1: Parameter values of proposed model (2.4 GHz)

Parameters	Proposed Value
W_e	5.7 dB (brick wall of room)
W_i	2.407 dB (wooden partition of room)
WG_e	17.72 dB
α	0.6 dB/m [11]
b_w	10 m
b_l	7.5 m
b_h	3.17

4. Experimental Region

Both the indoor-to-outdoor and outdoor-to-indoor measurement campaigns are carried out at the Software Development and Simulation Lab of the department of Computer Engineering and Information Technology in Mandalay Technological University.

The measurement building is mainly constructed with brick wall, glass windows and wood frames. As shown in figure 2, the experimental area is demonstrated in the shaded form.

In the research lab, all of the nine measurement points are settled in the matric pattern. The horizontal distance among points is 2.5 m and the vertical distance is 2.2 m.

The measurements are conducted in a large room with no penetrated internal walls. However, there is a thin wooden partition near the measured points 1, 4 and 7.

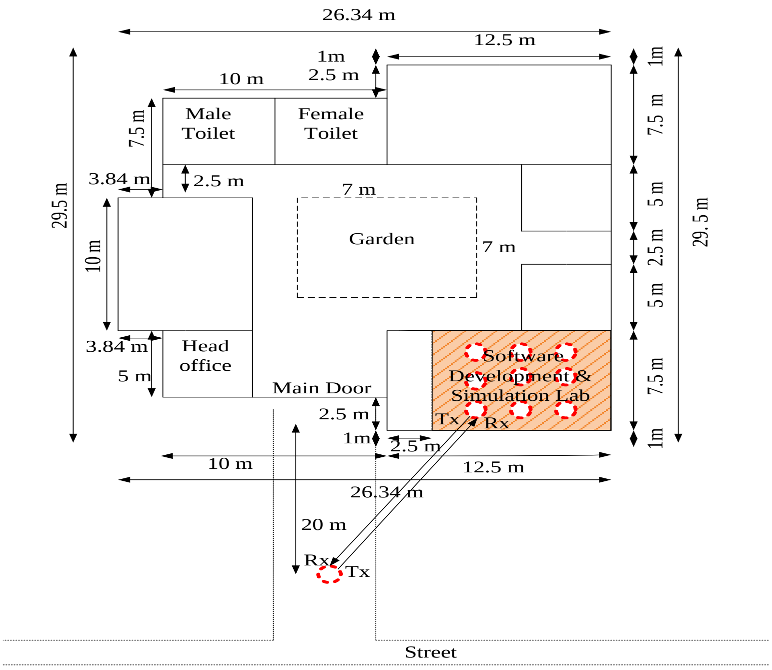

Figure 2: The Top View of the CEIT Building

5. Experimental Procedure

The Rohde & Schwarz SMBV100A Vector Signal Generator and Rohde & Schwarz EMI ESL Test Receiver are used as the transmitter and receiver for the collection of experimental data. The signal generator is placed at 20 m distance in line of site condition with the external building wall and the test receiver is located at the arranged points inside the experimental room. The transmitter and receiver are mounted on the trolley. To avoid undesirable attenuation of the received signal values, the received antenna of the test receiver and the transmitted antenna of the signal generator are tightly tilted as shown in the following figure.

Figure 3: The Transmitter and Receiver Setup

After allocating the signal generator and test receiver, the signal strength values are collected. In each point, the measurement course takes at least 3 minutes which is time to get accurate number of samples for each measurement data. Experiments are carried out on sunny days. The experimental set up of the signal generator and test receiver used in the experiments is described in Table 2.

Table 2: Experimental setup

Frequency (f)	2.4 GHz
Transmitter height (h_t)	1.25 m
Receiver height (h_r)	1.25 m
Transmitted power (P_t)	10 dBm
Transmitter gain (G_t)	3 dBi
Receiver gain (G_r)	3 dBi

6. Results and Discussion

Figure 4 (a) and (b) show the experimental RSSI values of the indoor-to-outdoor and outdoor-to-indoor coverage areas. For the both situations, the strongest signal is achieved at points 1, 2 and 3 because any obstacles do not exist between the antennas and the building wall except from the thin wooden wall. However, the points which the signal strength is weak are not similar with the indoor-to-outdoor and outdoor-to-indoor radio wave coverage area as shown in figures. For the indoor-to-outdoor measurement section, the received signal strength is gradually weak near at points 4, 5, 6 and 9. For the outdoor-to-indoor wireless region, the signal strength is steadily decreased in around points 4 and 7 because the signal from the transmitter outside area needs to penetrate both the building external wall and the partition according to the direct distance of the transmitter and receiver. Therefore, as depicted in figure 4 (b), the received signal strength near of point 4 and 7 is obviously less than that of other points. The RSSI values measured in experimental indoor-to-outdoor area are low about -2 dBm or -3 dBm compared with that of outdoor-to-indoor area.

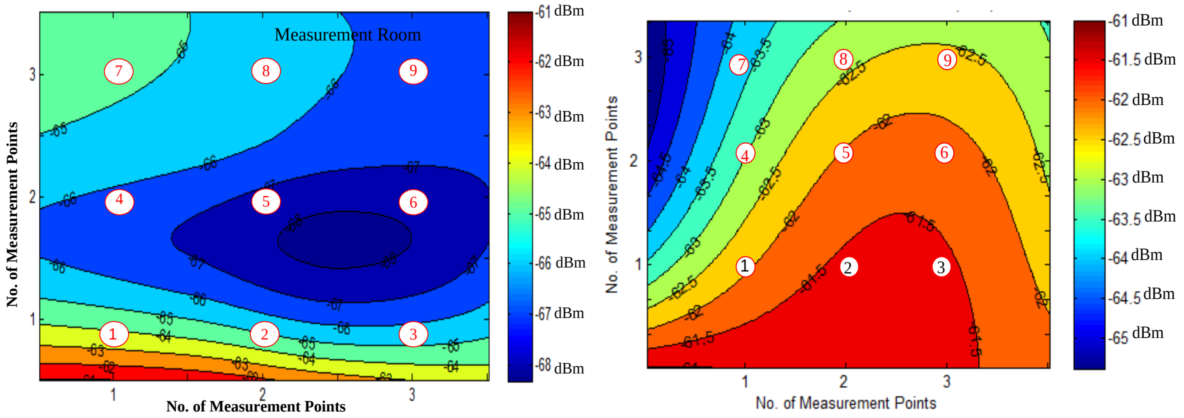

Figure 4: The Experimental RSSI Values of (a) the Indoor-to-Outdoor Area and (b) Outdoor-to-Indoor Wireless Area

Figure 5 shows the comparison result of RSSI values among the COST 231, experiment and proposed model of indoor-to-outdoor wireless communication area. In the indoor-to-outdoor area, the estimated values are higher than both the predicted and measured RSSI values because the width and length of the measurement campaign are not taken in the original model as in the proposed model. The values of the predicted and experimental values are not quite different. The proposed indoor-to-outdoor model is more accurate than the estimated model about -2 dBm to -5 dBm.

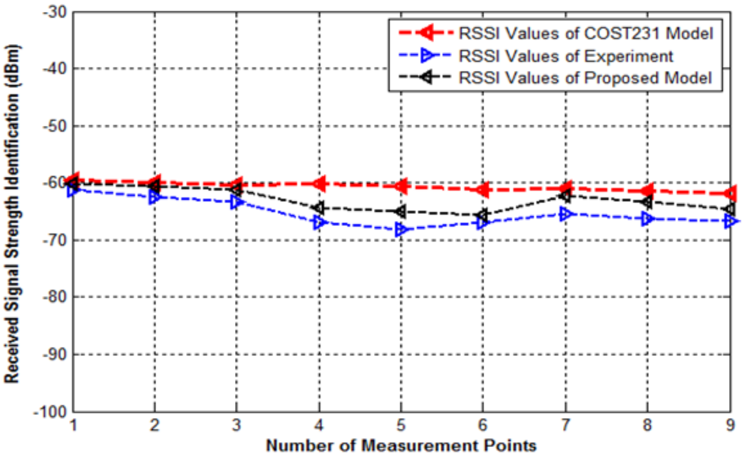

Figure 5: Comparison of RSSI Values among the COST 231, Experiment and Proposed Model of Indoor-to-Outdoor Area

Figure 6 depicts the comparison result of RSSI values among the COST 231, experiment and proposed model of outdoor-to-indoor scenario. In the outdoor-to-indoor case, the received signal strength of the estimated model is very strong because of only taking the height of the building not including the width and length of the building. As shown in figure 6, the proposed model and the experimental are almost similar. The proposed model can predict the RSSI values very exactly than the COST 231 model.

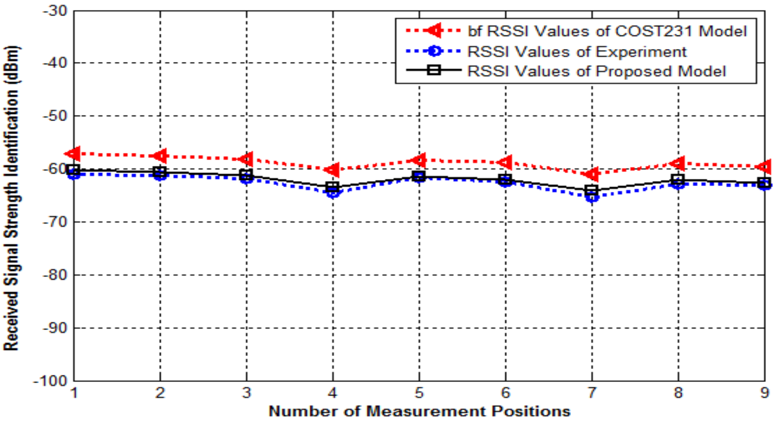

Figure 6: Comparison of RSSI Values among the COST 231, Experiment and Proposed Model of Outdoor-to-Indoor Area

After investigating the received signal strength for each communication area, the cumulative distribution function (CDF) is applied to compare the received signal strength values between the indoor-to-outdoor and outdoor-to-indoor scenarios over the measured frequency range. By depicting with this function, the differences between these two areas are becoming more obvious as shown in figure 7. The received signal strength of indoor-to-outdoor proposed model is less than that of the outdoor-to-indoor model about -2 dBm to -3 dBm.

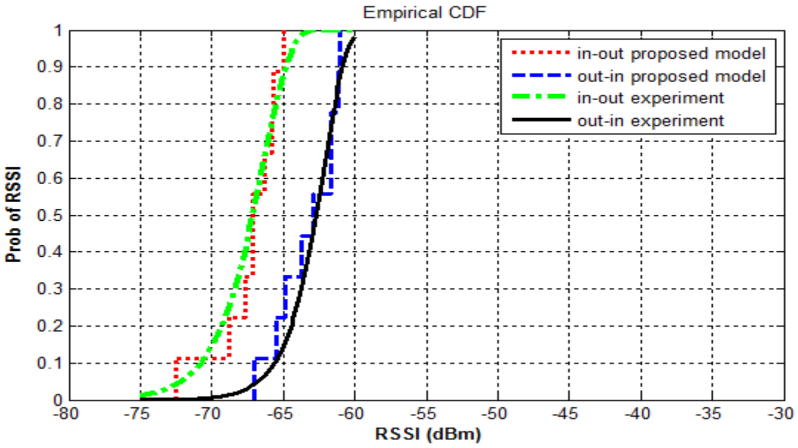

Figure 7: Comparison of Indoor-to-Outdoor and Outdoor-to-Indoor Area using Cumulative Distribution Function

The received signal to noise ratio (SNR) is an important parameter in characterizing the quality of wireless channel. The channel capacity of outdoor-to-indoor proposed model is briefly higher than that of indoor-to-outdoor proposed model. Although the minimum rate of channel capacity for outdoor-to-indoor model is 19.85 bps/Hz and the maximum is 21.5 bps/Hz, the minimum for indoor-to-outdoor model is 18.55 bps/Hz and the maximum is about 20.45 bps/Hz. The performance comparison between the indoor-to-outdoor and the outdoor-to-indoor proposed models is shown with the channel capacity versus signal-to-noise ratio (SNR).

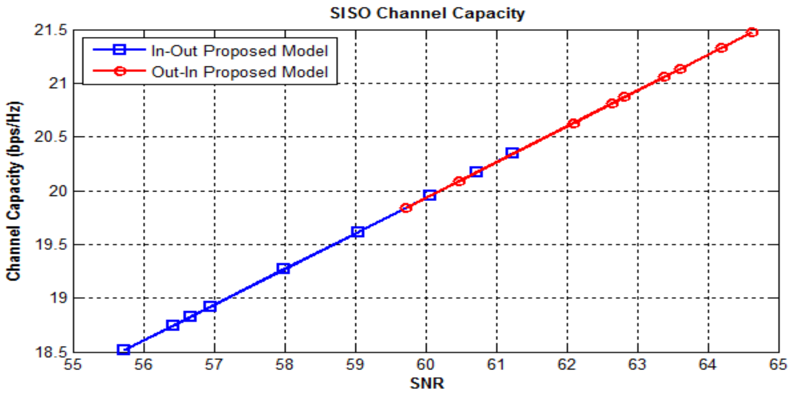

Figure 8: Channel Capacity versus SNR for COST 231 Model, Indoor-to-Outdoor Proposed Model and Outdoor-to-Indoor Proposed Model

7. Conclusion

In this paper, the received signal strength prediction models for both indoor-to-outdoor and outdoor-to-indoor wireless communication environments are proposed to acquire the accurate received signal strength based on the

COST 231 model. The received signal strength is computed by using the measurement based data. The measurement results of the indoor-to-outdoor and outdoor-to-indoor areas are compared with the results of the COST 231 model and the proposed models. Although the antennas in both indoor-to-outdoor and outdoor-to-indoor regions are the same in configuration, the received signal strength values are not as symmetric as each other. In the indoor-to-outdoor scenario, the transmitted signal inside room is affected by the lab materials such as the computers, desks and chairs. Moreover, the reflections are occurred from ceiling, floor and wall. After penetrating the building external wall, the signal strength is progressively decreased. As the consequence, the received signal of the outside antenna is not strong enough. In the outdoor-to-indoor region, the transmitted signal is firstly passed in free space. The signal strength is strong enough to penetrate the building external wall. When reaching at the receiver inside the room, the strength of the signal is still good. Therefore, the RSSI values of indoor-to-outdoor wireless area are less than that of outdoor-to-indoor area about -2 dBm or -3 dBm. The two proposed models for indoor-to-outdoor and outdoor-to-indoor wireless scenarios can be applied for the same building layout with the frequency of 2.4 GHz. As for further works, 433 MHz and 915 MHz in addition to 2.4 GHz will be studied for measurements and models of the same building and the high storied building.

8. Recommendations

As the recommendation results, the experimental received signal strength values with the outdoor distance (20 m) from external building wall are in the range of -45 dBm and -75 dBm with the operating frequency of 2.4 GHz. Therefore, the signal strength is strong enough for wireless communication. And also, the proposed model can be applied in all type of indoor-outdoor and outdoor-to-indoor wireless areas to estimate received signal strength using such building type. Moreover, the wireless designer can easily estimate the received signal values according to this proposed model with respect to the distance between antennas, the heights of transmitter and the placements of receivers.

For the system limitations, since the minimum and maximum frequency range of the signal generator and test receiver used in the proposed system are 3kHz and 3GHz, the operating frequency can be analyzed ranging from 3 kHz and 3 GHz if Rohde&Schwarz SMBV100A Vector Signal Generator and Rohde&Schwarz EMI ESL Test Receiver are used.

For the further extension, it is also needed to conduct all useful experiments not only one storied building but also two-storied building, three-storied building as well as skyscraper by using high transmitter and receiver to estimate received signal power. Other types of signal analyzer machines, or analyzer software will be used to compare with these results in next future experiments. By using the modernize signal analyzer, the reflection, diffraction and scattering caused by walls, floors, ceiling, the inside reflected objects and building edges will be estimated to achieve the most accurate received signal strength power.

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