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An Investigation into the Diffraction Effects of Building Façade for Propagation Modelling

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Abstract—This paper investigates the problem of wave propagation on periodic building façade with ray tracing method. Compared with the common practice, which is to replace a complex building structure with a flat surface and cause reduction in simulation accuracy, in this research, the Uniform Theory of Diffraction (UTD) is utilized with ray tracing method to include diffraction effects on building facades in propagation simulation. Two scenarios have been modelled which are Moore Hall's façade and Malaysia shophouses, respectively. First, the façade models were created based on real buildings, and propagation simulations were conducted for flat surface and knife edge approximations. Then, for different approximations, the accuracy of simulation results was further examined which varied with the degree of simplification and the frequency of the signal. Also, the computation time was evaluated to consider the speed of simulation. This study is beneficial to the improvement of accuracy in propagation prediction and supports the development of ray-tracing propagation prediction software and the design of wireless communication system.

1. INTRODUCTION

Investigation on the behaviour of electromagnetic (EM) field interacting with objects and buildings is becoming more and more important due to the rapid development of wireless communication system these years. Wave propagation simulation is a fundamental tool for wireless communication system design in predicting the interaction between EM waves and buildings, including the estimation of the direct rays, reflected rays, diffracted rays, and scattered rays. Although the equations of EM wave can be solved by Maxwell's Equations with proper boundary conditions, it is not possible to have an analytical solution in a complicated propagation environment in real life. By limiting the frequency of EM wave so that the wavelength is much smaller than the obstacles in propagation channel, geometrical optics (GO), or ray optics, can be used as an approximation to wave propagation. A solution can be obtained using GO by computing the superposition of rays from different paths (incident and reflected rays). The lack of diffracted rays is compensated by Keller in Geometrical Theory of Diffraction (GTD) [1], and it was further improved by Kouyoumjian and Pathak with Uniform Theory of Diffraction (UTD) [2].

Although there have been methods to predict diffracted rays, in some papers, like [3] to [6], diffraction was not taken into consideration. It was shown that in these papers the simulations aligned with measurements, since the direct incident and reflected rays were too strong, so diffraction effects were negligible. On the other hand, diffraction is a significant component in received signal for some scenarios, for example, environments with a considerable quantity of corner or edge on buildings or structures. In a shadowed region where diffracted fields become the only signal source, diffraction effects cannot be ignored. UTD is a widely used method and was utilized by papers [7] to [12] in predicting diffracted fields as part of the simulation.

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Recently, studies on ray tracing techniques for propagation prediction have been shifting to the millimetre wave bands (24–86 GHz) after the introduction of 5G wireless communication system. For example, the researches done by Rasekh et al. [13], Jacob et al. [9], and Ghaddar et al. [10] focus on higher frequency bands instead of classical microwave bands. The research of Rasekh et al. is more focused on the impact of diffraction and rough surface scattering on over-all channel response at 60 GHz, while Jacob et al. investigated the diffraction effect occurring on the edge of different objects at 60 and 300 GHz. Their results show that ray tracing algorithm is applicable not only to UHF, but also to the millimetre band. Along the same line of interest, past researches were also conducted to examine the depolarization effects due to scattering on walls in the 5 GHz band [14] and the viability of site shielding forced by obstacles [15]. The reported findings contribute towards radio systems planning.

In this study, ray tracing and UTD were utilized to carry out simulations on structures of specific shape and material. Two buildings were selected, namely, Moore Hall's façade on the campus of University of Hawaii at Manoa and the shophouses along the street of Lebuh Kimberley, Pinang, Malaysia, as shown in Figures 1 and 2.

Figure 1. Moore Hall's façade [7].

Figure 2. Lebuh Kimberley on Google Street View.

The first scenario was completed using the same façade structure and measurement as in paper [7], with the permission from the authors. The simulation frequency is 2.4 GHz corresponding to the measurement data. As for scenario 2, in Malaysia and some other Southeast Asia countries, heritage shophouses present a unique townscape in historical areas such as George Town and Melaka. Despite the emerging of tourism, many locals are still living in these houses which were built over hundred years ago, for both commercial and residential purposes. Malaysia shophouses have covered walkways known as "five-foot way" to provide continuous public pathways in extreme weathers. It is a good idea to investigate wave propagation in densely populated areas like this, so the residents as well as visitors can benefit. The simulation frequencies are 2.4 GHz, 5.8 GHz, and 60 GHz, respectively.

2. MOORE HALL'S FAÇADE

Figure 3 shows the top view of Moore Hall's façade. The façade, with complex periodic structures, can be approximated by either a flat surface or knife edges in simulation. The former way is practically common in ray tracing software, although it may not be very accurate. To find the reduction in accuracy of total path gain, we first conducted a ray tracing simulation assuming that the building façade is flat by a flat smooth surface. The distance between the transmitter/receiver and wall was 3.038 m. The heights of the transmitter and receiver are 2.0828 m. The relative permittivity (εr) and conductivity (σ) are $\varepsilon r = 2.0$ and $\sigma = 0.0001$ S/m for the building façade and $\varepsilon r = 7$ and $\sigma = 0.0001$ S/m for the ground [7]. Then, simulation was carried out at several meters from the façade to calculate line-of-sight (LoS) field, wall-reflected and ground-reflected fields. LoS propagation is the simplest type of propagation. The fields radiated by antennas of finite dimensions are spherical waves [14]. Assuming that there is a receiver placed z meter from the transmitter, and $E(r0) = E_0 * e^{j\phi_0}$ is the field at reference point $r0$, Equation (1) is used to calculate the LoS field at z meter from the transmitter:

$$E^i(z) = \frac{r0}{z} * E_0 * e^{j\phi_0} * e^{-j\beta z} * \frac{\lambda}{4\pi}, \quad \text{where} \quad \beta = \frac{2\pi f}{c} \quad \text{and} \quad \lambda = \frac{c}{f} \tag{1}$$

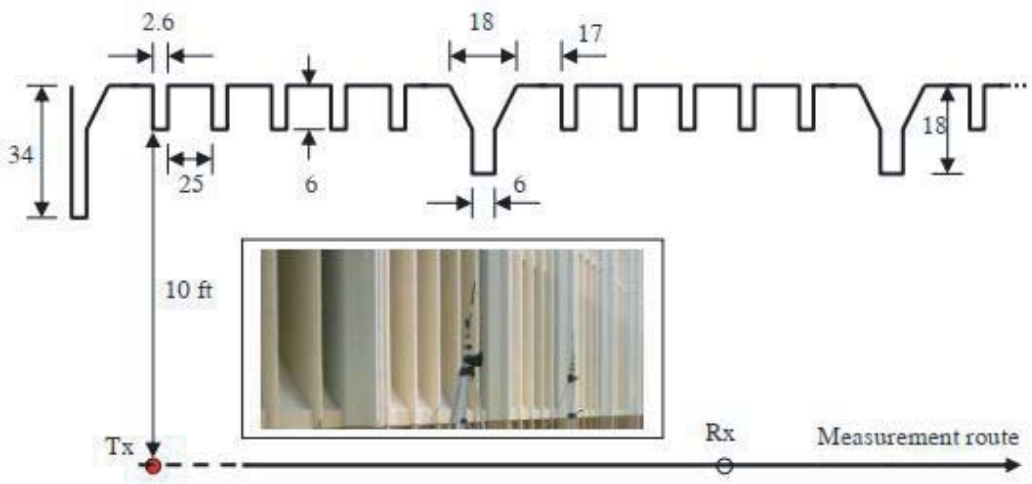

Figure 3. Top view of Moore Hall's façade (not to scale) at the University of Hawaii at Manoa campus, all the values are in inches except indicated [7].

The wall-reflected field with a total ray path of Z meter can be calculated with perpendicular (horizontal) polarization reflection coefficients using Equation (2):

$$E_{r(wall)} = E^r_{\perp}(Z) = E^i(Z) * \Gamma_{\perp}, \quad \text{where} \quad \Gamma_{\perp} = \frac{\cos(\theta_i) - \sqrt{\varepsilon_r}\cos(\theta_t)}{\cos(\theta_i) + \sqrt{\varepsilon_r}\cos(\theta_t)} \tag{2}$$

To calculate the ground-reflected field, parallel (vertical) polarization reflection coefficients are used in Equation (3):

$$E_{r(ground)} = E^r_{\parallel}(Z) = E^i(Z) * \Gamma_{\parallel}, \quad \text{where} \quad \Gamma_{\parallel} = \frac{\cos(\theta_t) - \sqrt{\varepsilon_r}\cos(\theta_i)}{\cos(\theta_t) + \sqrt{\varepsilon_r}\cos(\theta_i)} \tag{3}$$

Finally, the total field can be calculated by summing up each individual field.

To compare with flat surface approximation, the total path gain was then calculated based on knife edge approximation. First, the dimension of Moore Hall's façade (Figure 3) was converted from foot and inch to meter. Then, the periodic structures on the façade were simplified as knife edges at the centre of the slabs for easier building modelling. Figure 4 shows a simplified version of the façade after simplification. Codes were written to describe the architectural elements characterizing the façade.

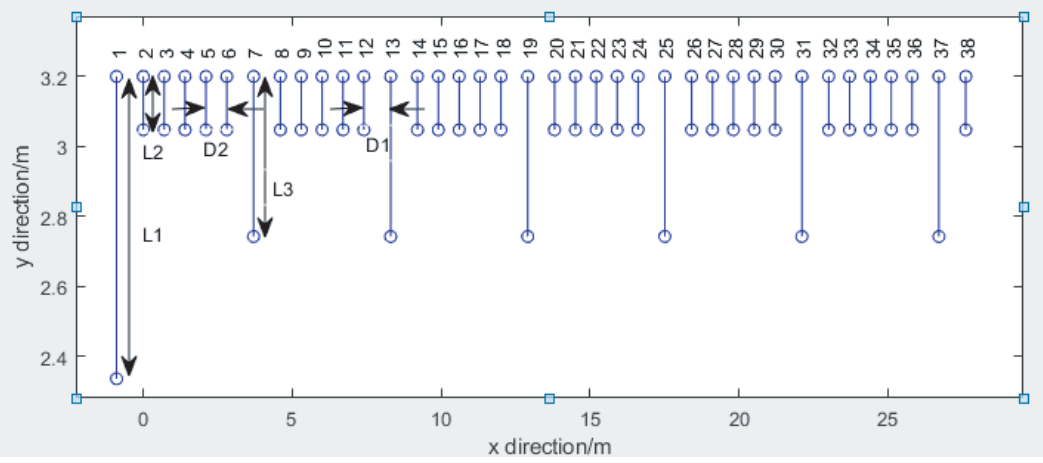

Figure 4. Simplified top view of Moore Hall's façade.

The location and dimension of the edges are the most important features since they are the sources of diffraction. The simplified periodic structure would be used to calculate the diffracted field from the façade to replace $E_{r(wall)}$ in the flat surface approximation while E_i and $E_{r(ground)}$ would be kept the same.

After determining the dimension, ray tracing diagrams were plotted to graphically display the exact ray paths following Snell's Law of reflection and diffraction. As shown in Figure 4, edges #7, #13, #19, #25, and #31 are wider than their neighbours. The resultant shadowing effects eliminated diffraction at some shorter edges. It was observed that, at edges #14, #20, #26, #27, #32, #33, #34, and #38, the incident rays were blocked. The shadowed edges would be excluded from diffraction field calculation. Figure 5 shows the blocking to incident ray. Not only incident rays from the transmitter, but also diffracted rays from the edges could be blocked by the wider edges. Figure 6 shows a possible situation when a diffracted ray from an edge could be blocked by a wider edge nearby. Program was written to check whether the diffracted ray had any intersection with any edge, so the blocked diffracted rays were ignored in total diffracted field calculation.

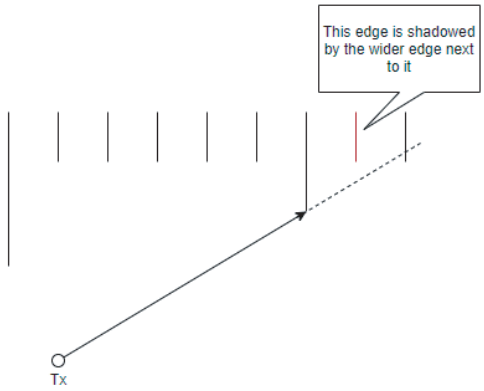

Figure 5. The shadowing effect to an incident ray.

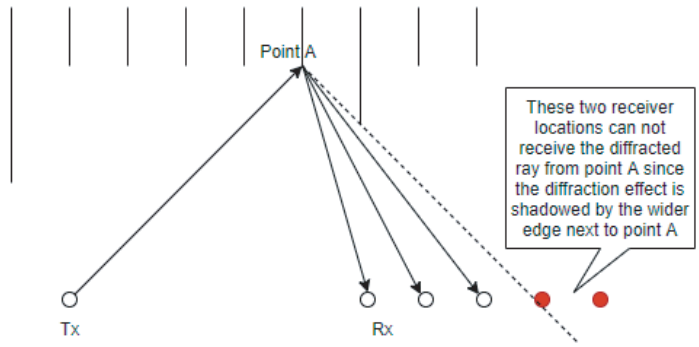

Figure 6. The shadowing effect to a diffracted ray.

If it could be verified that a diffracted ray path from the transmitter to the receiver was not blocked, the corresponding received diffracted field would be calculated by Equation (4). The diffraction coefficient D is calculated with a MATLAB program written by Balanis [16]. Distances s and s' are labeled in Figure 7.

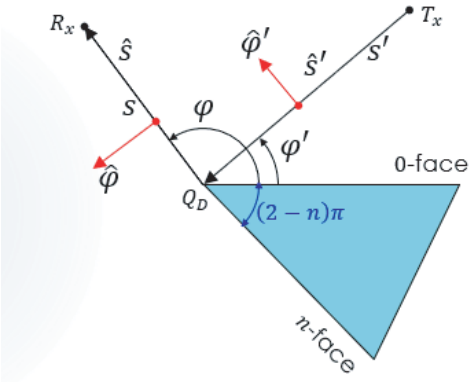

Figure 7. Incident and diffracted ray.

$$E_d = E_i(Q_D) * D_\perp * A(s', s) * e^{-j\beta s} \tag{4}$$

$$\text{where} \quad E_i(Q_D) = \frac{r_0}{s'} * E_0 * e^{-j\phi_0} * e^{-j\beta s'} * \frac{\lambda}{4\pi} \quad \text{and} \quad A = \sqrt{\frac{s'}{s(s+s')}} \tag{5}$$

Figure 8 compares the wall fields for knife edge and flat surface approximations. In theory, reflection occurs when waves are bounced off a flat smooth surface such as a building wall, or flat ground, or sea surface; whereas diffraction occurs when the waves are bounced off an opening or around a barrier in their path. In the context of our research work, reflection takes place when the wall is assumed to be one flat smooth large surface, but diffraction occurs when actual periodic façade structure is considered, because those are narrow and small. It can be observed from Figure 8 that the wall field from flat surface is around 7 dB stronger than knife edges approximation. There are lots of spikes on the curve from knife edges due to the complex structure, while the reflected field does not have much fluctuation. These differences will have a huge impact on the total estimated field.

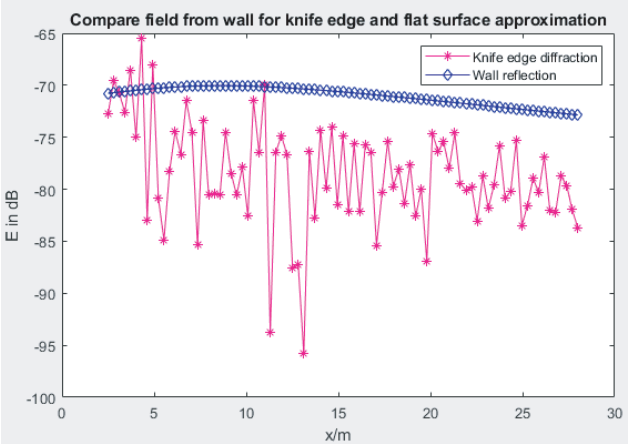

Figure 8. Wall fields for knife edge and flat surface approximations.

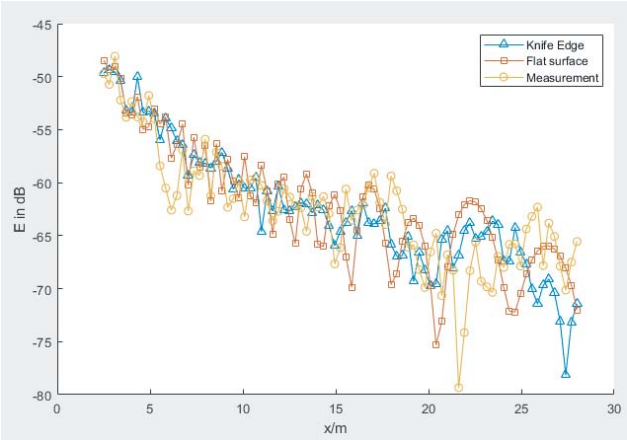

Figure 9. Compare total fields from simulations and measurement.

Finally, the simulation results of total fields were compared with the measurement data. Figure 9 plot the estimated and measured total fields in one graph to show a clearer comparison. To further evaluate the accuracy of prediction, root mean square error (RMSE) of the results was calculated compared to the measurement, which are 3.81 dB for knife edge approximation and 4.36 dB for flat surface approximation. According to the RMSE values, the knife edge approximation gives a better prediction of path gain in electromagnetic propagation simulation, which can also be proven by direct observation. One of the reasons for this is that the flat surface approximation neglects some necessary details in the structure and gives a stronger field than diffraction. Another possible reason could be that the flat surface model underestimates the effect of interference near the complex structure, so the total field curve does not follow the measured value nicely.

3. SHOPHOUSES ALONG STREET LEBUH KIMBERLEY, PINANG, MALAYSIA

First the length and width of the street were measured with Google Maps. Figure 10(a) shows the length of the street. There are 10 units of shophouse over 50 m, so the distance between two pillars' centres is 5 m. The width of the street is 9 m. The transmitter and receiver are placed at the centre of the street, and the distance from the centre line to the pillars is 4.5 m. The dimension of a pillar in typical old shophouses was found on a website [17], where exact measurements were provided. Figure 10(b) labeled the dimension of a single pillar.

(a) (b)

Figure 10. (a) Street Lebuh Kimberley, Pinang, Malaysia with measurement on Google Maps. (b) The dimension of a pillar from an old shophouse façade [17].

The pillars along the street form a periodic structure as seen along the street. Hence, diffraction effects from these pillars could be evaluated as a whole in wave propagation prediction. Unlike the Moore Hall's façade, the pillars of shophouses did not cause shadowing effect to each other, and the shape of the pillars was focused on instead. The pillars along the street were simplified as flat surface, knife edge structure, and square pillars, respectively, as shown in Figure 11. The simulation results from different approximations would be compared to show the effects of simplification. Considering the pillars as square structure was the closest way to approximate the actual scenario, but it took longer time to model the structure and determine the field strength at both edges of a pillar, which increased the computational cost. The flat surface approximation was the simplest but most different from the real structure since all the details along the street were neglected. The knife edge approximation was between the two, which took the distribution of pillars into consideration but ignored the shape of the structures. It was assumed that the square pillar approximation gave the closest results to the measurement data, so the results from other simulations would have something as a reference. The dielectric constant used in the simulation was 7.5 [18], since the pillars were made of limestone. The dielectric constant of the ground is 7, and the conductivity σ was assumed to be 0 S/m.

Same as in the previous section, simulations were executed for different approximations using Equations (1) to (4). Figures 12(a), 12(b), and 12(c) plot the individual and total fields at 2.4 GHz based on different approximations. Figure 13 plots the total fields in one graph. It is worthwhile to mention that from 40 m to 50 m, the reference field (square pillar line in Figure 13) drops to a relatively low level compared to other parts of the street. In flat surface approximation which replaces the field from the pillars with reflection from a flat wall, the drop between 40 m and 50 m is not as visible as in knife edge approximation. The RMSE is 5.4575 dB for flat surface and 3.8492 dB for knife edge compared with square pillar results, proving that the knife edge approximation is more accurate than flat surface approximation. Also, from Figure 13, it can be observed that the knife edge approximation follows the reference data better.

In order to provide a clearer display for comparing the wall fields from different approximations, Figure 14 plots the fields from the pillars (wall) only. Diffracted fields are around 8 dB lower than the reflected field, which is in good agreement with the first scenario where the diffracted field is 7 dB lower than reflected field. A conclusion can be drawn that approximating a complex structured façade by a flat surface tends to give a stronger field than diffraction, which is the dominant propagation mechanism on the original façade.

Besides 2.4 GHz, simulation was carried out at higher frequencies (5.8 GHz and 60 GHz) for the three approximations, as shown in Figures 14 and 15. 60 GHz was selected since it is a typical frequency

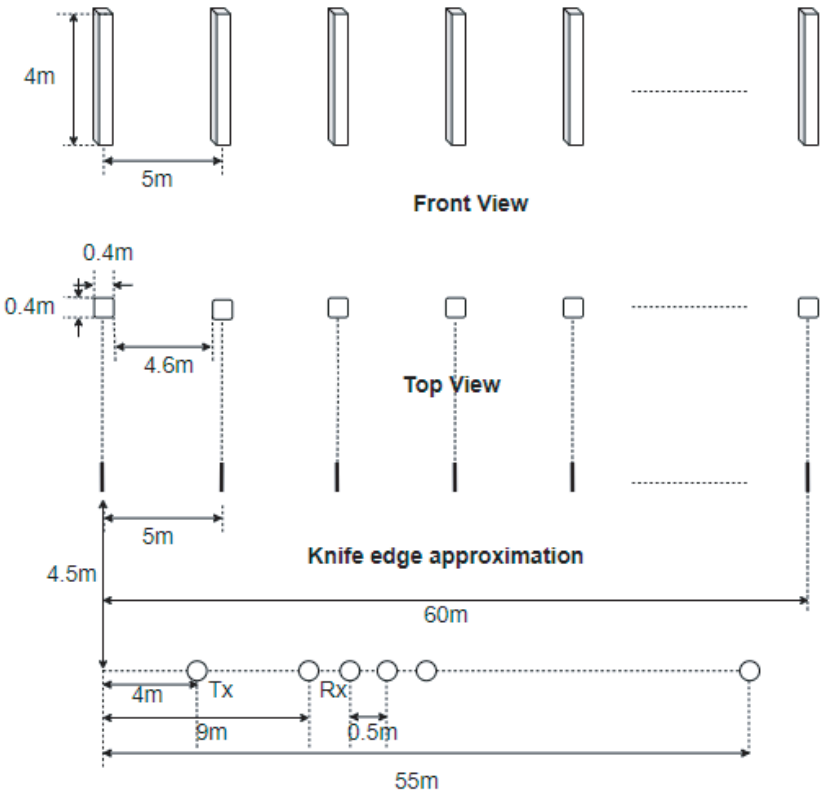

Figure 11. Simplified geometry of pillars along the street.

band in a 5G mobile communication system. With the results obtained from the simulation, the RMSE was calculated and shown in Table 1. It can be observed that at whatever frequencies, the knife edge approximation results are always closer to the reference data, giving a better propagation prediction. The RMSEs of both approximations decrease as the frequency increases, because the amplitude of the field strength drops with increasing frequency. Roughly, the root mean square error can be reduced by $1.5 \sim 3$ dB by shifting to knife edge approximation.

Table 1. Shophouse RMSE at 2.4 GHz, 5.8 and 60 GHz.

RMSE/dB	Knife edge approximation	Flat surface approximation
2.4 GHz	3.8492	5.4575
5.8 GHz	3.2455	5.4091
60 GHz	1.8896	4.6292

By comparing the total fields at 2.4 GHz, 5.8 GHz, and 60 GHz in Figures 13, 15, and 16, it can be observed that signals at higher frequencies have greater attenuation. This phenomenon agrees with what has been expected, because the LoS (free space propagation) field, which is the most significant component in total field, drops with increasing frequency. In addition, when the frequency gets higher, its wavelength gets shorter, so radio wave becomes more likely to be absorbed when meets obstacle and results in decrease in total field. Therefore, millimetre wave does not travel the same distance as lower frequency wave.

The execution time of each MATLAB simulation programs was counted. The time was exclusive

Table 2. The execution time of simulation programs.

Execution time (s)	Knife edge approximation	Flat surface approximation
Moore Hall's Facade	1.3197	0.0456
Shophouse	0.3209	0.0636

statements for clearing workspace, plotting graphs, and calculating errors. According to Table 2, flat surface approximation is more timesaving than knife edge approximation for both scenarios because the execution time varies with complexity of the façade surface. Also, using flat surface can save the preparation time before running a simulation, which is spent on extracting the characteristic structure of the building manually. However, using flat surface will increase root mean square error of the results by 1.5 dB to 3 dB. Hence, there is a trade-off between accuracy and computation time, and it is important to know which one is more critical in a specific practical application. Therefore, if high accuracy is desired, knife edge approximation is preferred over flat surface approximation even though the latter is faster.

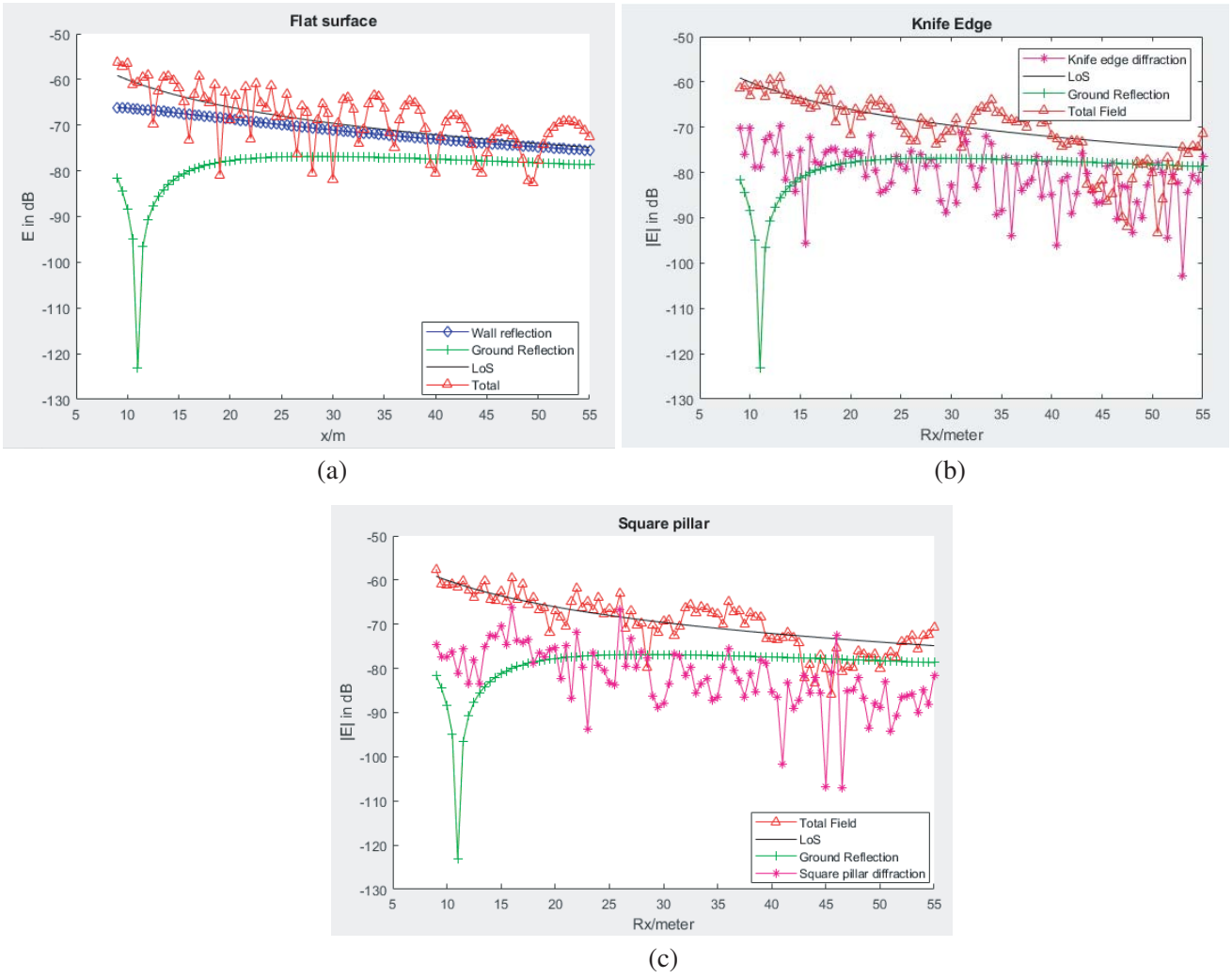

Figure 12. (a) Simulation results for flat surface approximation. (b) Simulation results for knife edge approximation. (c) Simulation results for square pillars approximation.

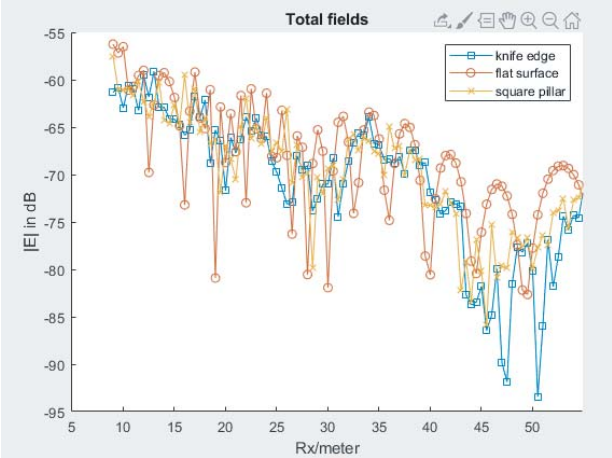

Figure 13. Total fields from different approximations.

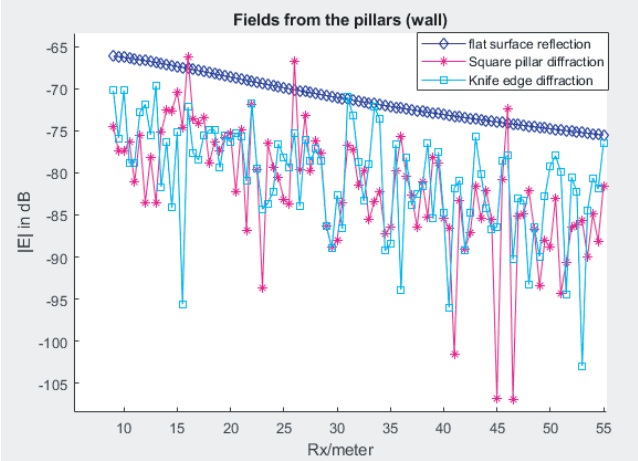

Figure 14. Fields from the pillars (wall).

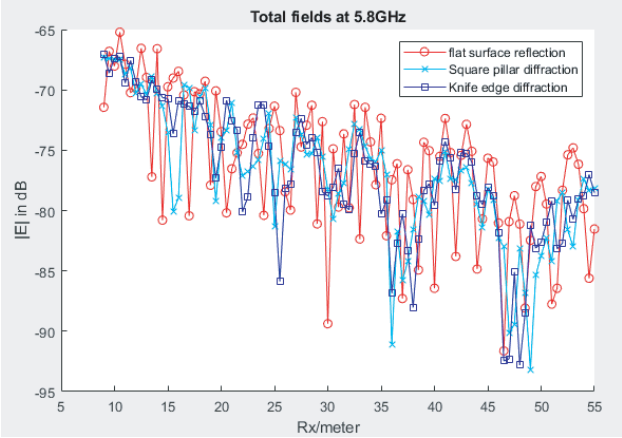

Figure 15. Total fields at 5.8 GHz.

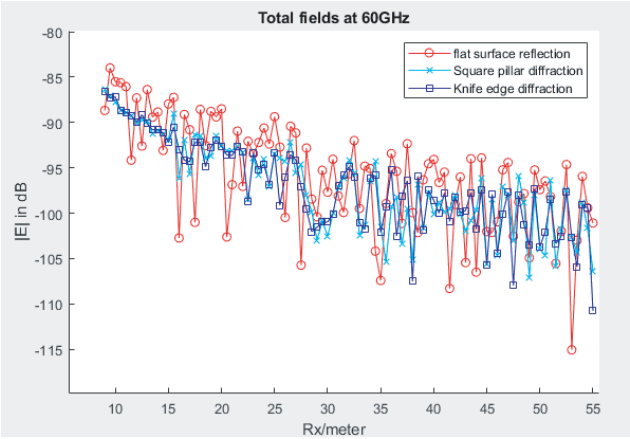

Figure 16. Total fields at 60 GHz.

4. CONCLUSION

In this research, ray tracing simulations for wave propagation at different frequencies were conducted for two scenarios using different approximations. The analysis on the simulation results gave an insight on simulation accuracy which varies with the degree of simplification and the frequency of the signal. The potential to improve the simulation accuracy by 1.5 dB to 3.0 dB is possible with adequate preparation and computation time. The method of characterizing building features as well as simulating multiple path fields can be extended to other environments at various frequencies, guaranteed by its flexibility and versatility. In future works, a measurement campaign could be done for the shophouses scenario. The received power from a transmitter along a route parallel to the street could be measured at fixed intervals, so that a better reference data set could be used for the analysis of the simulation results. This study has the potential to benefit the improvement in accuracy in propagation prediction and support the development of ray tracing propagation prediction software and the design of wireless communication system.

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