A RAY TRACING METHOD FOR RADIO WAVE PROPAGATION PREDICTION ON SELECTED LOCATIONS OF SUN-U CAMPUS

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ABSTRACT

Radio propagation prediction is a crucial step to determine the propagation characteristics of any arbitrary installation for the implementation of a mobile radio system. In this paper, a ray tracing approach using image method is adopted to perform radio propagation predictions in two selected areas of Sun-U Campus, namely an empty hallway located on the second floor in the School of Computer Technology (SCT), and its adjacent academic staff rooms. The values of electrical parameter such as dielectric constant (relative permittivity) of different materials are altered assuming the walls that separate each academic staff room are made of rubber, glass, plasterboard, and concrete. How this variation affects radio wave propagation prediction is discussed while the main propagation mechanisms traveling along the empty hallway are reported. In addition, the reasons for an appropriate interval between two sampling points along a transmitter-receiver route are also illustrated and explained.

Keywords: radio wave propagation, ray tracing, relative dielectric constant

INTRODUCTION

Sunway University, Malaysia recently (in the month of February 2011) made available Sun-U wireless access (Sun-U WLAN) to all staff members and students using their own devices like smartphones and notebooks throughout the whole university campus. To gain wireless access, staff members and students will just have to search for and connect to “Sun-U WLAN” WiFi network and enter their regular network (PC) login credentials. This news comes in timely because with the proliferation of notebooks and smartphones in the university campus, easy access to the internet will both enhance students’ learning experiences and make staff’s work more productive. More importantly, in this age of information and communication technology (ICT), easy wireless access is particularly crucial for constantly bringing new excitement into learning and communication. As a matter of fact, telecommunications, wireless applications, and mobile devices, among others, are fundamentally reshaping the way information is obtained and the ways people learn and communicate with each other.

It is a well-known fact that wireless reception in buildings has often been spotty, with poor voice quality and slow data rates. This is because radio signal, especially at the high frequency bands commonly used for the third-generation (3G) cellular and wireless LAN communications, do not penetrate building walls well (Ortiz, 2008).

To understand fundamentally what affects wireless reception in buildings, a close examination of the relevant propagation mechanisms is required. In principle, there are four basic propagation mechanisms that impact propagation in a mobile communication system, namely, reflection, transmission, diffraction, and scattering (Lim, 2010). Based on the physics of these propagation mechanisms, path loss can be predicted for large-scale propagation models using ray optics with the assumption that the operation frequency is high or wavelength is small compared with the typical size of objects in the environment. For radio waves of 2.4 GHz (that of wireless LAN), ray optics is valid for objects such as hallway and the walls/partitions that separate each academic staff room.

There is a growing need to predict signal levels for short propagation paths in the range of 2 – 100 m (Holloway, Perini, DeLyser, & Allen, 1997). This prediction needs arises because for such short propagation paths, accurate behaviour of reflecting waves from the surrounding objects like building walls (that are made up of different materials) plays a crucial role in signal prediction. Hence, the research findings for short paths propagation can benefit applications like microcellular personal communications services (PCS) deployments in malls and airports. Besides, it can also contribute to the successful design and implementation of business campuses utilizing wireless private branch exchanges (PBX’s) and wireless local-area networks (LAN’s). Not only that, vehicular communications through urban canyons to nearby relays will also benefit from the research findings of short paths propagation prediction.

LITERATURE REVIEW

An examination of the major research in radio propagation in cellular mobile telephone systems shows that theoretical studies, numerical simulations and field measurements have always been closely intertwined. Published research findings of these works are available mostly from 1980s onwards although the topic of indoor radio propagation channel can be dated all the way back to 1959 (Hashemi, 1993). It has been found that any realistic propagation model should take into account a variety of factors and its parameters should be validated through actual field measurements rather than simplified theory.

Although published work on the topic of indoor radio propagation has appeared as early as 1959, it wasn’t until the early 1980s that the first wave of research in indoor propagation began to take place. Rappaport (1996) in his book has credited Cox at AT&T Bell Laboratories and Alexander at British Telecom as the first to carefully study indoor path loss in and around a large number of homes and office buildings.

Indoor radio propagation is governed by the same propagation mechanisms as outdoor, except that their conditions are much more variable. One similarity can be found among the propagation models between indoor and outdoor propagations, i.e., both theoretical and measurement-based path loss models show that the average received signal decreases logarithmically with distance. This phenomenon is called large-scale path loss where signal attenuation is caused by the geometry of objects in the propagation environments.

For estimating these large-scale effects, a common practice is to express the average large-scale path loss as a function of separation distance between the transmitter and receiver with a path loss exponent, *n*, i.e., path loss $\propto d^n$. Different values of *n* can be obtained for different propagation scenarios such as outdoor and indoor environments, including the heavy multipath indoor cases like a stairwell (Lim et al., 2009). Since different spectrum bands have unique propagation characteristics and require the appropriate propagation models, the values of *n* are frequency dependent for both outdoor and indoor propagation environments. In practice, these *n* values are usually computed from actual measured data, using linear regression such that the difference between the measured and the estimated path losses is minimized over a wide range of measurement locations and transmitter-receiver separations.

A number of propagation models have been developed to predict signal strength in indoor environments, such as the log-distance path loss model, the Ericsson Multiple Breakpoint model (Akerberg, 1998), and the Attenuation Factor model (Honcharenko & Bertoni, 1993). Interestingly, these indoor path loss models have all been empirical models that were developed based on the measured average losses in various in-building environments. One advantage with the empirical approach is that it inherently accounts for all propagation factors, both known and unknown by actual field measurements. Yet, an empirical model is valid only to similar environments where the model is developed.

The accuracy of propagation prediction involves several aspects such as the accuracy of locations and sizes of buildings as well as an accurate knowledge of the electric parameters of walls and other objects involved. Trees, large posts, traffic, and even pedestrians in outdoor scenarios and furniture in indoor cases can all influence the propagation prediction results.

The published value of materials like relative dielectric constant ε_r is frequency dependent and may vary a lot from one to the other. For instance, bricks may be fabricated from different materials, and window glass may be metalized and hence very reflective. Also, because of the very high value of ε_r for water (e.g. 70 for sea water and 81 for distilled water), the water content of materials such as brick, concrete, and ground has a major effect on their dielectric constant. Common values of ε_r that have been reported for various materials of interest (Bertoni, 2000) are excerpted and listed in Table 1.

Table 1. The Values of Relative Dielectric Constants for some Common Materials

Material	Relative Dielectric Constant (ε_r)
Glass	3.8-8
Wood	1.5-2.1
Gypsum board	2.8
Chip board	2.9
Dry brick	4
Dry concrete	4-6
Aerated concrete	2-3
Limestone	7.5
Marble	11.6
Ground	7-30
Fresh water	81
Seawater	81
Snow	1.2-1.5
Ice	3.2

METHODOLOGY

The ray tracing using image method provides a simple and accurate way for determining the ray trajectory between a transmitter (Tx) and a receiver (Rx) (Iskander & Yun, 2002). The image method utilizes the images of the transmit antenna location relative to all the surfaces of the environment. The coordinate of all the images is calculated and afterwards rays are traced towards these images. First and second order reflections can be calculated very efficiently without sending rays to all directions. The drawback of this method is that calculation time grows exponentially when the order of the calculated reflections is increased. Within the scope of this work, however, the image method is an ideal approach for determining the main propagation mechanisms. Figure 1 presents a simple reflection surface to illustrate the basic idea of how the image method works.

For the scenario in Figure 1, LOS (line-of-sight) is the path between the Tx and the Rx. To calculate the reflection from the surface, the image of Tx with respect to the surface is identified and is denoted as Tx’. Note that the distance from Tx to the surface and the distance from Tx’ to the same surface are equal ($d_1 = d_2$). Next, by connecting Tx’ and Rx, the intersection point on the surface (P) is the reflection point where reflection occurs. For multiple reflections, multiple images with respect to the relevant surfaces will be determined in a similar way and the corresponding ray paths can then be obtained.

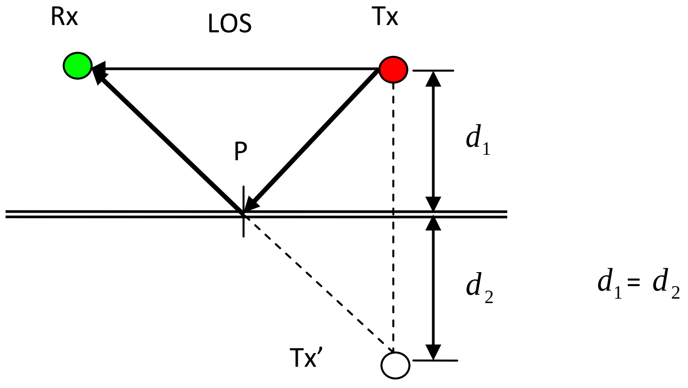

Figure 1. Illustration of the Image-Based Ray Tracing Method

Two locations have been selected from Sun-U campus for ray tracing simulation purpose, namely SCT academic staff rooms and the adjacent hallway. In these two locations, the radio links for ray tracing simulation have been established in a straight line manner, and they are denoted as the paths from Tx 1 to Rx 1, as well as that from Tx 2 to Rx 2. Figure 2 presents the layout of the SCT academic staff rooms and the adjacent hallway, with indication of the locations of the two transmitters (Tx 1 and Tx 2) and receivers (Rx 1 and Rx 2).

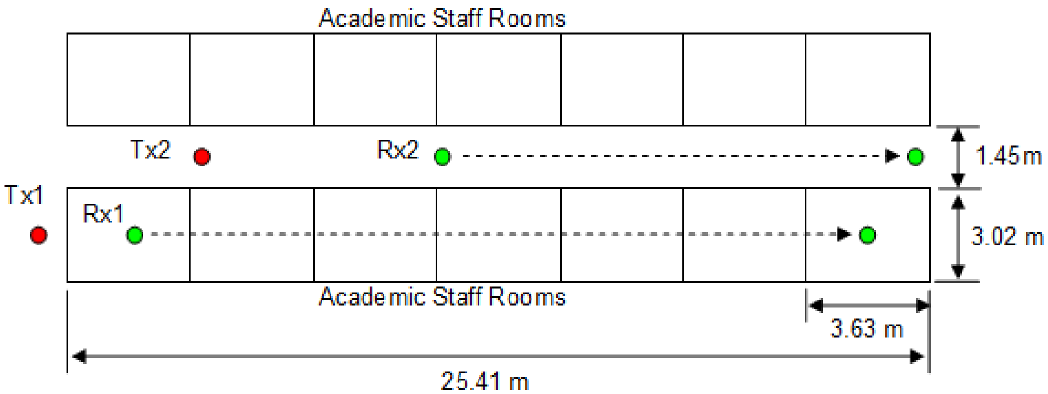

Figure 2. Layout of the SCT Academic Staff Rooms and the Adjacent Empty Hallway (not to scale)

SCT Academic Staff Rooms

Buildings have a huge selection of partitions and obstacles that form not only the internal but also the external structure (Rappaport, 1996). For instance, in an office building environment, soft and hard partitions can be commonly seen. While the former are partitions that may be moved and do not extend to the ceiling, the latter are formed as part of the building structure. On Sun-U campus in particular, the buildings walls and hard partitions are made up of various materials such as bricks, plasterboard, and glass.

It is worth pointing out that one distinct feature about Sun-U campus is that quite a significant number of the building walls are glass walls. This is especially the case for those at or near the foyer like the info center, security center, the Sunway College office (then Manchester Business School's office), Sunway TES, Lancaster University's office, and LeCordon Bleu Institute of Culinary Arts.

The LeCordon Bleu Institute of Culinary Arts for instance, is a modern, newly-completed 2-storey full glass building to house the reception office of the Sunway LeCordon Bleu Institute of Culinary Arts. This paper will examine, via ray tracing simulations, the effects of building walls (that are made up of various materials) on radio propagation path gains across multiple partitions in the SCT academic staff rooms. Figure 3 and Figure 4 show two pictures of the environments concerned.

Figure 3. Picture of the SCT Academic Staff Rooms and the Adjacent Hallway

Figure 4. Picture of the Foyer on Sun-U Campus

Hallway Adjacent to the SCT Academic Staff Rooms

The other objective of this paper is to investigate, again via ray tracing simulation using image method, the main propagation mechanisms travelling along an empty hallway adjacent to the SCT academic staff rooms. This is a different propagation scenario whereby no obstacles are assumed present along the hallway for simulation purpose. Neither was there any movement of people or stuff during the simulation. The goal of this work is to understand how signal travels from one point to another. In other words, the behavior of the EM wave as it makes its way from the transmitter to the receiver at various interval (e.g. 3 m, 1 m, 0.02 m, 0.002 m) is under scrutiny.

RESULTS

SCT Academic Staff Rooms

The received signal strength arising from a specific transmitter placed at a certain place will vary with locations within any given building. As a signal passes through walls that are made up of various materials, different levels of signal attenuation result. The exact nature of this signal variation depends primarily on the shape and construction of the building as well as the geometry of the radio link. To depict the variation resulting from a signal passing through walls made up of four different types of materials, Figure 5 is plotted for the case when Tx 1 is put on one end of the SCT academic building while Rx 1 is moved across the SCT academic staff rooms (see Figure 2) in a straight line manner. The four materials under scrutiny are rubber wall, glass wall, plasterboard wall, and concrete wall. Of all these four types of different walls, plasterboard wall is the one that reflects the true condition in the existing building.

In addition to these four simulations of distinct walls, line-of-sight (LOS) ray is also plotted assuming there are no walls blocking the transmitter-receiver path as the signal fades away after leaving the point source. This additional simulation will serve as a general guideline to compare how signal will attenuate passing through walls made up of different materials. In Figure 5, the five scenarios described earlier carry different values of relative dielectric constant. In free space (LOS scenario), dielectric constant has a value of 1. Whereas for the four different walls, the relative dielectric constants are: rubber wall, ε_r = 2.5; glass wall, ε_r = 5; plasterboard wall, ε_r = 6; and finally, concrete wall, ε_r = 9. Table 2 records all these aforementioned values.

Table 2. Values of Relative Dielectric Constant of Various Walls

Wall	Relative Dielectric Constant (ε_r)
Rubber	2.5
Glass	5
Plasterboard	6
Concrete	9

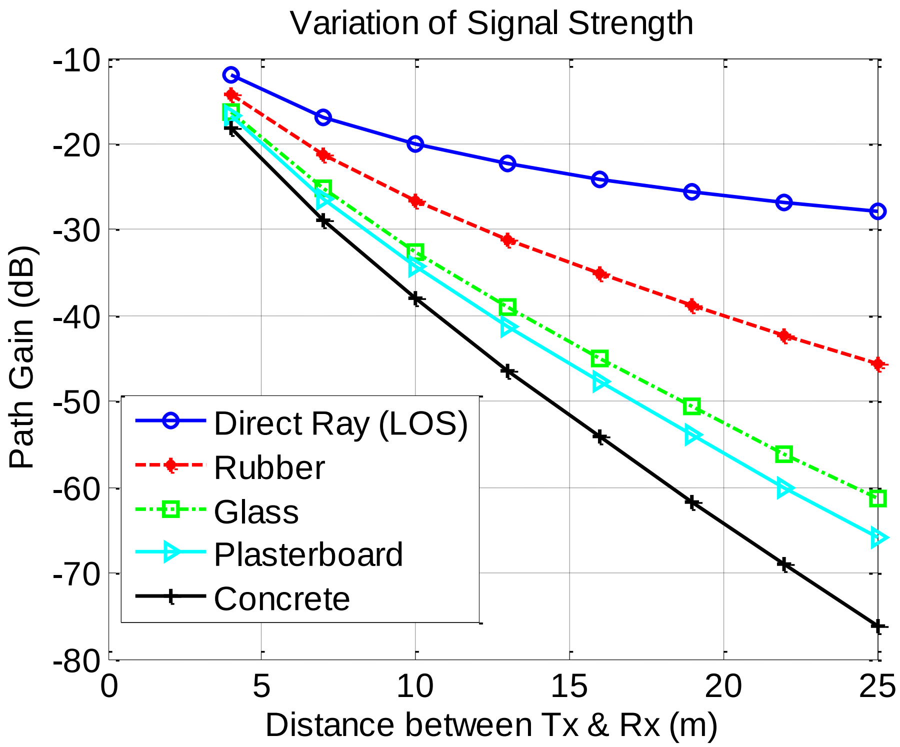

Figure 5. Signal Attenuation across the SCT Academic Staff Rooms (Wall Transmission Effects)

In Figure 5, the rays are plotted by considering only the transmitted ray (a single transmission coefficient for each ray) passing through the wall separating each of the SCT academic staff rooms. When only a single ray is considered in the simulation, be it a direct ray, reflected ray, or transmitted ray, the curve will appear smooth unless a mixture of the rays (e.g. direct + reflected ray; or reflected + reflected rays) are shown.

Additionally, to show the wall reflection effects that result from a mixture of different rays, Figure 6 is plotted using the total rays travelling along the empty hallway next to the SCT academic staff rooms, which consists of direct ray, left-wall singly-reflected ray, right-wall singly-reflected ray, left-wall doubly-reflected ray, and right-wall doubly-reflected ray. Four cases of the total rays are plotted in Figure 6, which illustrates the different reflection effects from the four distinct types of walls, namely, rubber, glass, plasterboard and concrete walls.

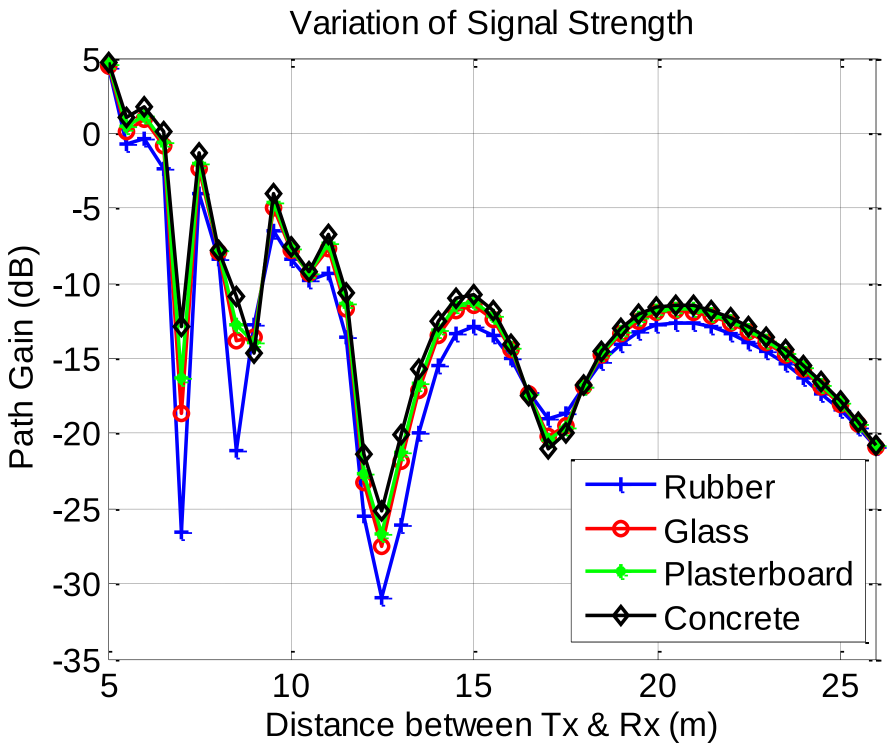

Figure 6. Signal Attenuation next to the SCT Academic Staff Rooms (Wall Reflection Effects)

Hallway Adjacent to the SCT Academic Staff Rooms

In this section, a different scenario is presented, which is different from the signal attenuation across the SCT academic staff rooms described earlier. In Figure 5, only one ray is examined at any given time. But for this section (similar to Figure 6), up to several orders of rays are examined all together at one time. This includes both the LOS ray as well as the reflected rays of different orders from both the left and right walls.

These surrounding walls are assumed as rubber wall (relative dielectric constant, ε_r = 2.5) for the simulations in Figures 7, 8, 9, and 10, respectively. Since different wall materials will cause different reflection coefficient values, which in turn will result in some changes of the analysis results, only a single wall material is selected for the simulations to analyze the effects of the interval between two sampling points.

For this work, the Tx and Rx are moved to sit along an empty hallway adjacent to the SCT academic staff rooms. In particular, Tx 2 and Rx 2 are put at the center of the empty hallway, with Rx 2 being moved away gradually from the Tx in a straight line manner, as illustrated in Figure 2 earlier. The results of the signal attenuation along this empty hallway along the receiver route are plotted in Figure 7, at an interval of 0.02 m.

In addition to Figure 7, Figure 8 is plotted with the interval between any two sampling points along the receiver route increased from 0.02 m to 3 m. Other parameters remain unchanged. In Figure 9, however, the interval is reduced to 1 m, which is a value between 0.02 m and 3 m. On top of that, Figure 10 is also plotted to investigate the signal behaviour when the interval is further reduced to a small number, 0.002 m.

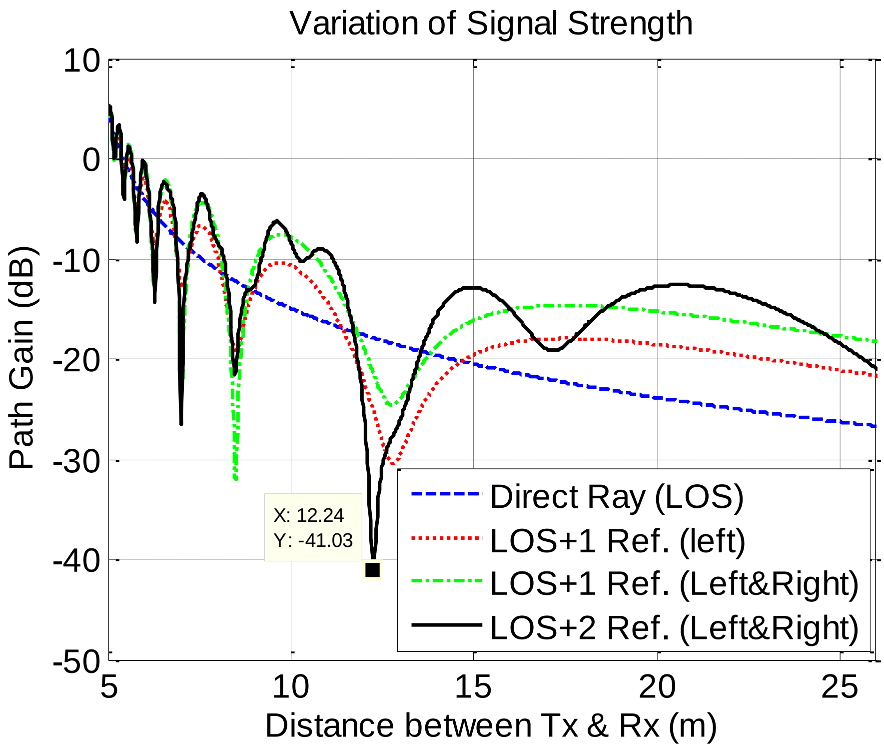

Figure 7. Signal Attenuation along the empty hallway (Interval = 0.02 m)

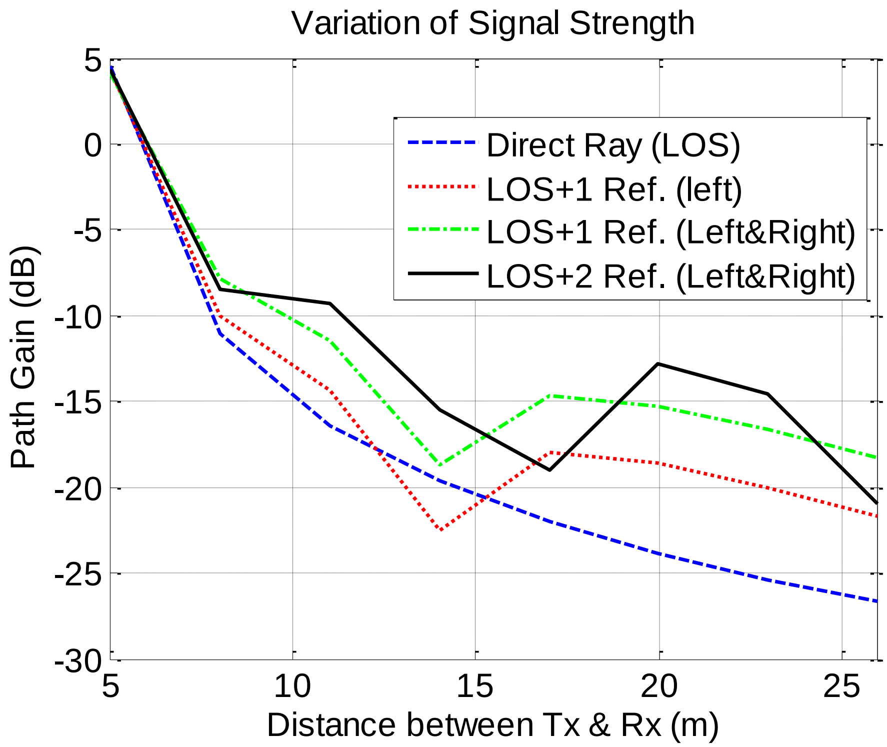

Figure 8. When the Interval is increased to 3 m

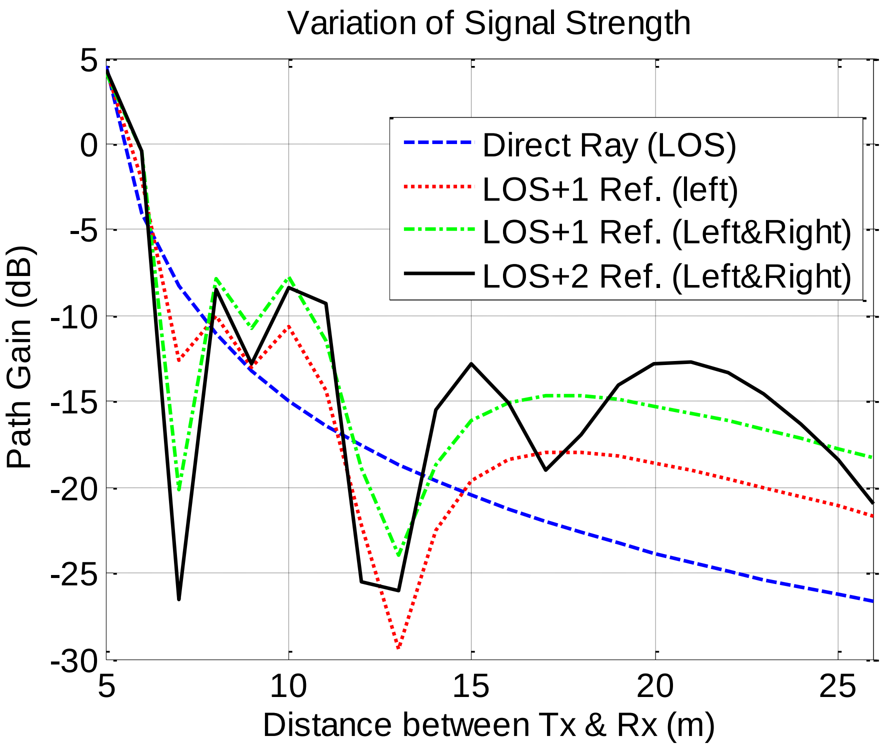

Figure 9. When the Interval is reduced from 3 m to 1 m

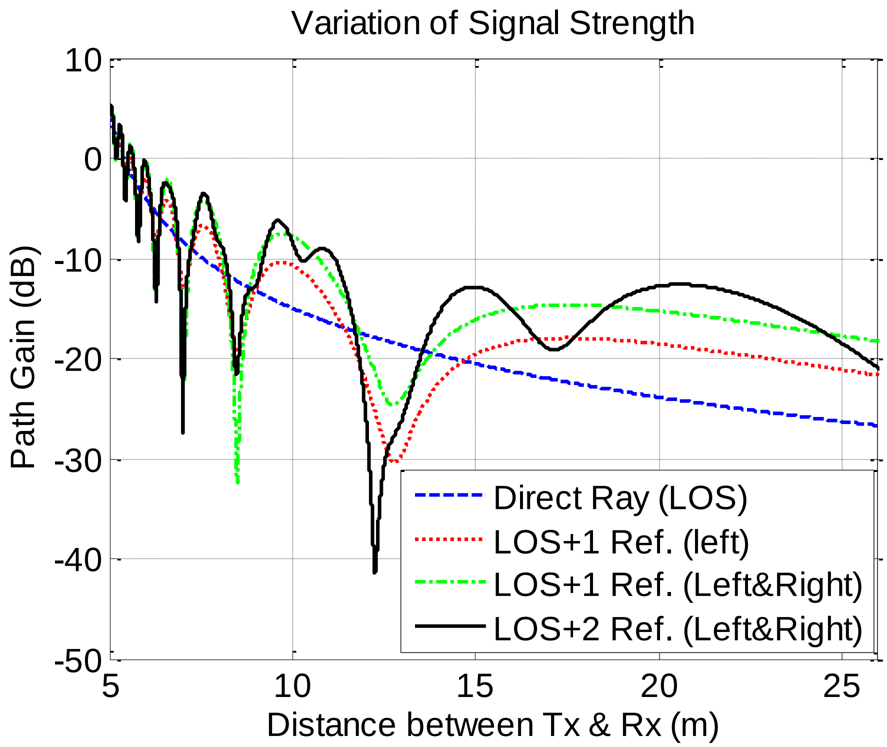

Figure 10. When the Interval is further reduced to 0.002 m

DISCUSSION

SCT Academic Staff Rooms

It can be observed from Figure 5 that the signal attenuation for the LOS case is the smallest, with signal dropping from -12.4 dB to -27.96 dB, or a total attenuation of 15.56 dB. However, in the absence of the LOS ray, when there are walls standing in the way between Tx 1 and Rx 1, the signal attenuation becomes greater as the value of the relative dielectric constant of the material of the wall increases. This can be seen in Figure 5 that shows that signal attenuation for rubber wall, glass wall, plaster board wall, and concrete wall are 31.42 dB, 45.18 dB, 49.05 dB, and 58.06 dB respectively. The difference of the total signal attenuation between the LOS case and the concrete wall is 42.50 dB.

Hallway Adjacent to the SCT Academic Staff Rooms

From Figure 7, which shows the signal attenuation along the empty hallway depicted in Figure 3, it can be noticed that when multiple reflections are included in the simulations, fading occurs due to multipath propagation.

In this scenario, first and second orders of reflections from both the left and right walls are considered in the simulation using ray tracing of image method. The two surrounding walls act as reflectors for the empty hallway where the transmitter and the line segment (between Tx 2 and Rx 2 in Figure 2) are located. Since the walls surround both Tx 2 and Rx 2, multiple paths are created for which a transmitted signal can traverse. As a consequence, the receiver sees the superposition of multiple copies of the transmitted signal, each traversing a different path. Each of these signals (direct ray, left-wall-reflected rays, and right-wall-reflected rays) experiences differences in attenuation, delay and phase shift while traveling from the transmitter to the receiver.

Hence, at the receiver, constructive and destructive interference occurs that amplifies and attenuates the signal power respectively. Strong destructive interference (deep fade) occurs at location 12.24 m along the receiver path. As for the simulation results that involve only the direct ray, signal attenuates gradually from 4.32 dB to -26.67 dB as it moves away bit by bit from the transmitter (or a total of 30.99 dB in signal attenuation).

Judging from Figure 7 to Figure 10, it was observed that the interval between two sampling points of any given transmitter-receiver path should be carefully chosen so that the signal can be interpreted precisely. From the four intervals that range from 0.002 m to 3 m (0.002 m, 0.02 m, 1 m, and 3 m), it was observed that 0.02 m is the ideal choice in this scenario as the answers converge at this interval. A further reduction to 0.002 m brings not much difference to the ray tracing simulation results, since Figure 10 and Figure 7 are almost identical. But when the sampling interval is set at a high number, such as 3 m in this scenario, the results obtained are a general one, with no show of deep fading along the receiver route. These results might not reflect the true condition of the signals' actual behaviour.

CONCLUSION

In this paper, a ray tracing using image method has been adopted to run simulations for radio propagation predictions at two selected locations on Sun-U Campus at 2.4 GHz. From this work, it was shown that multiple reflections from the surrounding walls along an empty hallway produce many paths by which the signal can propagate from the transmitter to the receiver. This propagation phenomenon whereby a signal travels from a transmitter to a receiver through multiple paths (rays) is called multipath.

The effects of multipath can be good, and/or bad, depending on the applications. For instance, for narrowband systems, the sum of phasors that causes fading is a bad effect that might result in temporary failure of communication. Likewise for wideband systems, multipath that might cause inter-symbol interference is also a bad effect. Nevertheless, for multiple-input multiple-output (MIMO) system, multipath is desired because it can lead to multiple parallel channels. To analyze the multipath effects accurately, the interval between any two sampling points along the transmitter-receiver route ought to be chosen carefully. Explicitly, the interval cannot be set to an unreasonably high number (two consecutive sampling points are separated too far from one another); otherwise it might result in an inaccurate interpretation of the results obtained.

For ray tracing simulations across the SCT academic staff rooms, the received signal shows a systematic decrease with distance, but with a varying amount of total signal attenuation, that in turn depends on the materials of the associated wall/partition. The simulations and analysis from this work shows that signal attenuation rises as the value of the relative dielectric constant of the material of the wall increases. In other words, a signal can penetrate rubber wall more easily with less attenuation than it does concrete wall.

In a nutshell, the findings of this work have added more insights to short propagation paths that have seen steady rising of its accurate prediction needs especially in recent years. One may conclude that radio waves propagation within a building is strongly influenced not only by the layout of the buildings but by the construction materials as well. In the present scenario of SCT academic staff offices, the plaster board partition exhibits a gradual signal loss totaling to 49.05 dB over a distance of 25 m along a transmitter-receiver route at 2.4 GHz.

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