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# Towards a Comprehensive Ray-Tracing Modeling of an Urban City With Open-Trench Drains for Mobile Communications

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**ABSTRACT** This paper investigates the impacts that open-trench drains make on the accuracy of radio propagation prediction in an urban city environment. Compared with conventional prediction styles that assume the ground to be flat, in this paper, we have considered for the first time the real scenario in many Asian cities to make open-trench drains inclusive in radio propagation modeling. The aims of this paper are twofold. First, to scrutinize one narrow L-shaped structure, modeled after an open-trench drain, by means of comparing ray-tracing simulation results with the actual field measurement results at 2.4 and 5.8 GHz. Second, to compare one city model built without and with the inclusion of open-trench drains for running ray-tracing simulation in yielding radio propagation prediction results. The findings from this paper are especially beneficial to the improvement of mobile communications in extraordinary environments such as open-trench drains, caves, coal mines, underground passageway, and others. Besides, they provide a unique insight into how the presence of the open-trench drains may affect radio wave propagation in an urban city environment.

**INDEX TERMS** Propagation prediction, urban city, ray-tracing, drain, radio propagation.

## I. INTRODUCTION

Propagation prediction and modeling has long played an instrumental and crucial role in the successful designs and implementation of wireless communication systems [1]. As technology advances day by day, wireless and mobile communications are in demand not only in habitable environment, but they are progressively expected in almost any and every setting, including challenging ones such as coal mining and tunnels [2]–[4], open-trench drains [5]–[7], and caves environments [8]–[11]. For this reason, the needs to understand various geometries for accurate propagation modeling have become more apparent, because they contribute towards effective prediction of radio coverage in emerging propagation environments. As a matter of fact, the more we know about a specific environment, the better we can do deterministic propagation modeling, which is seen becoming a prominent propagation prediction method considering the rising of future wireless systems that adopt MIMO transmission schemes as well as mm-wave frequencies [12]. Degli-Esposti [12] went on to answer a definite yes to a fundamental question, “can a better knowledge of the multi-dimensional characteristics of the radio channel help in the design, deployment and optimization of future wireless systems?”, with solid reasons given to back the answer.

A survey of the current propagation modeling tools reveals that ray-tracing has been a backbone of many of these tools because it is less dependent on computer memory and can solve three dimensional problems on modern desktop computers. When ray-tracing is concerned, the ascertainment of the types of rays propagating from a point source to a field point in an urban setting is not a trivial task but has been a hot research topic since the 1990’s [13]. As an example, in [14], site-specific models that are based on two-ray models were developed for real-time prediction of the received power from waves propagating through urban street canyons. These models are used to predict small-area average received power for radio communication in urban environment.

Conventionally, when propagation modeling is conducted for an urban city environment, the ground surface is oftentimes treated as flat when the surface profile undulates moderately. This is especially common across various current commercial propagation prediction tools, which treat the ground surface as flat whenever possible, because doing so will simplify the whole propagation modeling process. Only in cases when the ground surface is upfront not flat, such as hill-like terrain, will special efforts be made to model the ground surface as it is in order to retain the precision results of propagation prediction [15]. In fact, one pioneering work on terrain modeling can be traced back to as early as 1970, when efforts were made to calculate the probability of occurrence of distinct multipath propagation of pulse signals at VHF and UHF bands over irregular terrain [16]. In [17], an overview of the concepts and results for 3D digital terrain-based wave propagation models was presented.

Along a similar line of interest, in this work we have switched our focus to consider for the first time the real scenarios in many Asian cities to make open-trench drain inclusive in radio propagation modeling. The main motivation of this work is to study the impacts open-trench drains make on the precision of radio propagation prediction in an urban city environment when there exist ''holes'' on the ground surface – a scenario not seen in many western countries as the drainage systems in those countries are primarily covered and below ground. Fig. 1 depicts two examples of open-trench drain, in which one is relatively wider and another one narrower. These photos are taken from the city of Palembang, Indonesia.


(a) (b)

**FIGURE 1. Pictures showing two examples of open-trench drain that can be widely seen in Asian cities. (a) A wider drain. (b) A narrower drain.**

Open-trench drains, such as the ones shown in Fig. 1, can be easily spotted in multifold Asian cities as they make up a significant portion of the urban structures in this part of the world. Though common, the width and depth of these structures differ from place to place even within the same city. The pioneering work on this topic has first appeared in year 2012, which shows that open-trench drains constitute auxiliary channels for radio waves to propagate [5]. The chief difference of this paper from the previous works in this area is that now we are modeling for the first time the real scenario of making open-trench drains inclusive in radio propagation prediction for an urban city, which will be particularly relevant to Asian cities. Towards this end we have modeled one selected site from an urban city environment that contains open-trench drain structures with a specific setup of the transmitter-receiver (Tx-Rx) trajectory at 900 MHz, a band at which GSM operates. Aside from that, another highlight of this paper is that we present a fundamental study of the key propagation mechanisms inside a narrow L-shaped structure using ray-tracing image method approach. This narrow L-shaped structure is modeled after a narrow L-shaped open-trench drain. The study of this narrow L-shaped structure is the first of its kind, and is expected to find its applications beyond the scope of open-trench drains, but in an extension of a wide variety of other scenarios, such as coal mining and tunnel environments, caves conditions, and/or other scenarios that involve very narrow passageway.

## II. A NARROW L-SHAPED STRUCTURE

The urban street canyon has been one of the most widely studied topics in radio propagation modeling because this scenario is deemed very important to receive good coverage in view of the high density of people [18]. Unlike urban street canyon, which is relatively wider, we now extend our work to cover narrow passageway that has not been adequately studied in the past. Specifically, in this paper, we employ ray-tracing of image method to scrutinize one L-shaped structure of a very narrow width. This L-shaped structure is different from those commonly considered in urban environments because its width is very narrow even when compared to the urban street canyon. The dimensions of this structure are shown in Fig. 2, together with an indication of the positions of the Tx and Rx, and the transmitter's images.

As illustrated in Fig. 2, the first Rx location is located 0.9 m away from the Tx, with subsequent Rx locations spaced 0.3 m apart along the receiver route of 61 m in total length, of which 38.4 m constitutes the line-of-sight (*LoS*) portion while the next 22.6 m makes up the non-line-of-sight (*NLoS*) portion. The depth of this structure is 1.52 m, whereas the Tx and Rx are both 1.25 m tall. Since both the Tx and Rx share the same height, effectively we are treating this problem as a two dimensional one, hence simplifying the point at issue.

Intuitively, when one looks at the L-shaped structure in Fig. 2, one will think that reflection makes up one simple propagation mechanism for the entire structure. And yet in reality, the solution is not as straightforward and simple as it might have appeared. In [19], we have presented the preliminary ray-tracing simulation results for this structure at 2.4 GHz to find the relevant ray trajectories, and showed that the above intuition is true only for the *LoS* section. In the *NLoS* section, however, the rays have to undergo a high order of reflections before finally reaching the Rx loca-

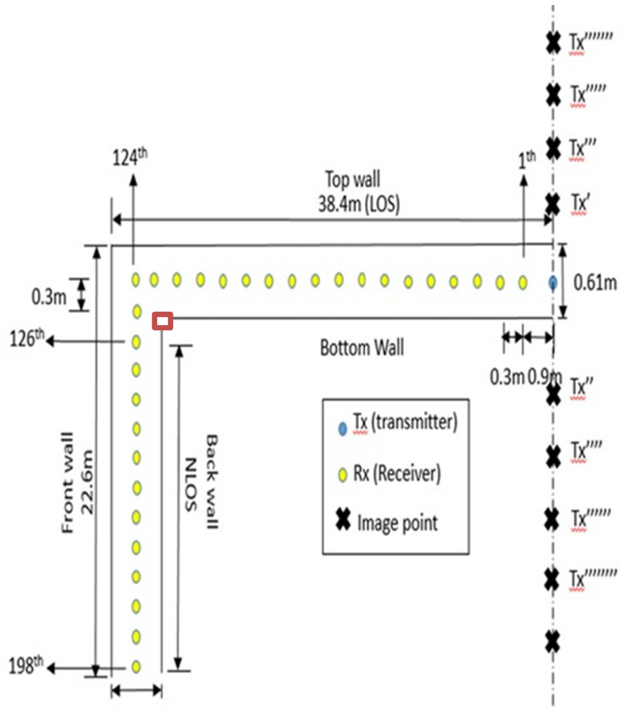


**FIGURE 2.** Top view of the narrow L-shaped structure with the locations of the Tx, Tx's images, and Rx indicated (dimension is in meters, not to scale).

tions, hence making this process a complicated one. Take for instance, at Rx location 126$^{th}$, the rays have to undergo a minimum order of eighth reflections to reach its destination, i.e. 1$^{st}$ order bottom wall – 2$^{nd}$ order top wall – 3$^{rd}$ order bottom wall – 4$^{th}$ order top wall – 5$^{th}$ order front wall – 6$^{th}$ order back wall – 7$^{th}$ order front wall – 8$^{th}$ order back wall. Another possible ray's path for this 126$^{th}$ Rx location is when the ray starts reflecting from the top wall, i.e. 1$^{st}$ order top wall – 2$^{nd}$ order bottom wall – 3$^{rd}$ order top wall – 4$^{th}$ order front wall – 5$^{th}$ order back wall – 6$^{th}$ order front wall – 7$^{th}$ order back wall – 8$^{th}$ order front wall- 9$^{th}$ order back wall. When the Rx moves gradually further and further away from the Tx, e.g. at Rx location 198$^{th}$, the order of walls reflection increased drastically to a minimum order of 104, hence making this simple geometry a complex one to solve technically.

In view of the high order of reflections that the rays have to undergo to reach each specific Rx location in the *NLoS* section of the structure, and considering the fact that the final signal strength of such high order reflected rays will be weak and gradually imperceptible, other alternative propagation mechanism should be explored. Based on our experiences with field measurement and ray-tracing simulation in various indoor and outdoor environments [20], [21], we recognize one probable propagation mechanism that will play a key role especially in the *NLoS* section of the structure, which is corner diffraction. This corner diffraction is indicated by a small red square box in Fig. 2, and we showed that the diffracted rays are present all throughout the *LoS* and *NLoS* sections of the structure, as illustrated in Fig. 3.

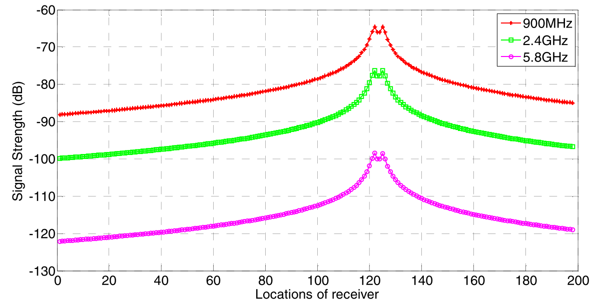


**FIGURE 3.** The corner diffracted rays propagating inside the narrow L-shaped structure at three different frequencies.

As can be observed from Fig. 3, there are two peak values of the diffracted rays that can be seen at Rx locations 123$^{rd}$ and 125$^{th}$, because at these two Rx locations, they are the closest to the corner of the said structure in which diffraction occurs, hence the peak values. This pattern holds true for 900 MHz, 2.4 and 5.8 GHz. Having now identified the relevant propagation mechanisms for this structure, we next further our analysis to compare our ray-tracing simulation results with two sets of previously-collected field measurement results from this structure at 2.4 and 5.8 GHz [6]. These comparisons are shown in Fig. 4 and Fig. 5 respectively.

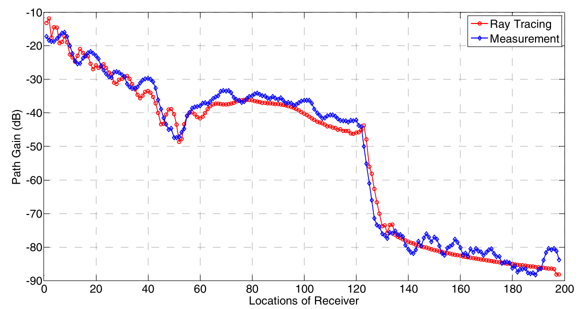


**FIGURE 4.** Measurement and ray-tracing simulation results of the narrow L-shaped structure at 2.4 GHz.

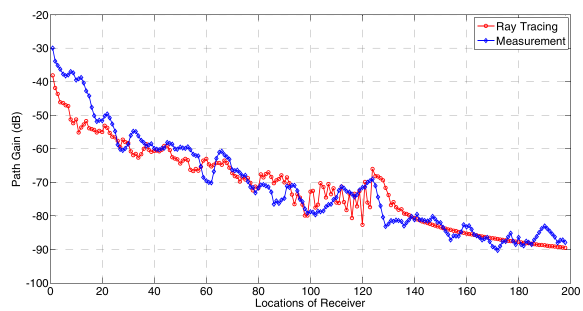


**FIGURE 5.** Measurement and ray-tracing simulation results of the narrow L-shaped structure at 5.8 GHz.

As can be observed from Fig. 4 and Fig. 5, there is a good agreement between the field measurement results and the ray-tracing simulation results. Specifically, at 2.4 GHz, the difference between the measurement and simulation results is slight with a mean error of 0.99 dB and a standard deviation of 2.89 dB. On the other hand, at 5.8 GHz, it has recorded a mean error of 0.99 dB and a standard deviation of 4.65 dB. These mean error and standard deviation values are comparable to other published values for urban scenarios [22]. At both frequencies, in the *LoS* section, the total simulated rays are the sum of the direct ray, ground-reflected ray, corner-diffracted ray, and the walls-reflected rays (up to 10 order reflections when the results converged). As for the *NLoS* section, corner-diffracted ray become the primary contributory ray in this section of the structure. In both cases, the used reflection coefficients are Fresnel reflection coefficients, while the used diffraction coefficients are the Uniform Theory of Diffraction (UTD). The signal formulation of the diffracted field can be written as follows:

$$E_d = \frac{e^{-j\beta s'}}{s'}\sqrt{\frac{s'}{s(s'+s)}}e^{-j\beta s}D_{||,\perp}\left(\frac{\lambda}{4\pi}\right) \quad (1)$$

where $s'$ is the distance along the incident ray path from the source to the diffraction point, $s$ is the distance along the diffracted ray path from the diffraction point to the observation point, $\sqrt{\frac{s'}{s(s'+s)}}$ is the spreading factor, and $D_{||,\perp}$ is the diffraction coefficients for soft and hard polarizations. Subsequently, the received power in decibels (dB) can be obtained from equation (2):

$$P = 20\log_{10}|E_D| \quad (2)$$

When plotting the simulation results in Fig. 4 and Fig. 5, the values of the relative dielectric constant and the conductivity used are 30 and 0.0001 at 2.4 GHz (for earth wet condition), and 7 and 0.0001 at 5.8 GHz (for earth dry condition). When water is present inside the structure, a different value of the relative dielectric constant should be used, i.e. 81 for water. Additional simulation results show that when water is present inside the open-trench drain structure, the ground-reflected ray from the water surface is stronger by comparison to the scenario when the structure is dry.

## III. URBAN CITY WITHOUT AND WITH OPEN-TRENCH DRAINS

Several site surveys took place on Google Map when choosing a suitable area to be modeled. The primary criterion of choosing is to locate a site where the alignment of buildings is pertinent with open-trench drains surrounding the buildings, as are often the real scenarios. Once a suitable site is identified, an interactive full 3D ray-tracing software package that has been developed by the Hawaii Center for Advanced Communications (HCAC) is utilized for radio propagation prediction for two conditions, namely, when the open-trench drains are absent, and present. In this ray-tracing software that has been developed by HCAC, the basic geometric entity is a plate, and the primitive geometric objects are triangles. A plate is a flat polygon that can represent a wall, a rooftop, or a piece of terrain and it is commonly represented by a single triangle or several triangles. The input file to the ray tracing engine is a description of the model, the electric parameter, and the antennas. In this work, the input files are the city models created with and without the open-trench drains.

As a trial, we have reported the preliminary results of using this software for a selected town in Kajang, Malaysia at 2.4 GHz to examine the impacts open-trench drains make on propagation prediction [23]. In this paper, we have further selected a different site from the city of Semenyih in Malaysia, for running simulations at 900 MHz, a band at which GSM operates in this region of the world. Fig. 6 shows the selected site as seen on Google Maps, a 150 m × 150 m area from the city of Semenyih [24]. Supplementary to Fig. 6, Fig. 7 and Fig. 8 present the modeled sites built without and with the open-trench structures inserted.

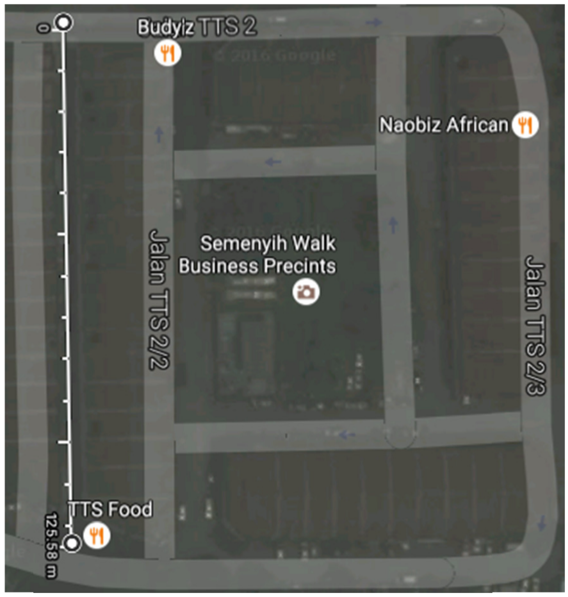


**FIGURE 6. The selected site from the city of Semenyih as seen on Google Maps.**

In Fig. 7, a city model without the existence of open-trench drains is presented. This model does not portray the real scenario in the city, but was created as a contrast to Fig. 8, where open-trench drains have been included in the city model adjacent to the four buildings. The inclusion of the open-trench drains in Fig. 8 mimics the real scenario of the selected city. On Google Earth, the "measure distance" tool available in it was utilized to estimate the dimensions of the buildings to the best accuracy possible. All four buildings are 20 m in width and 11 m in height, with various lengths of the buildings indicated accordingly in Fig. 7 for buildings A, B, C, and D. As for the open-trench drains, they are all 1 m in width and 1.5 m in depth. Specifically, the open-trench drain next to Building A is spaced 1 m away from the edge of the building's wall; but the ones surrounding Buildings B and C are spaced 0.25 m away from the buildings' walls. As for Building D, the adjacent open-trench drain is spaced 1 m away from the wall along the width of the building and 0.25 m away from the wall along the length of the building. Fig. 9 demonstrates these differences. Estimate values are fed to the

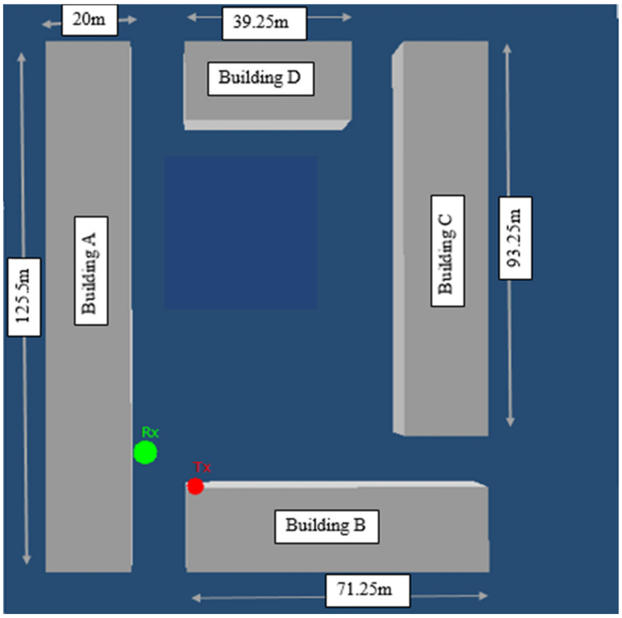


**FIGURE 7.** The city model without open-trench drains (not to scale).

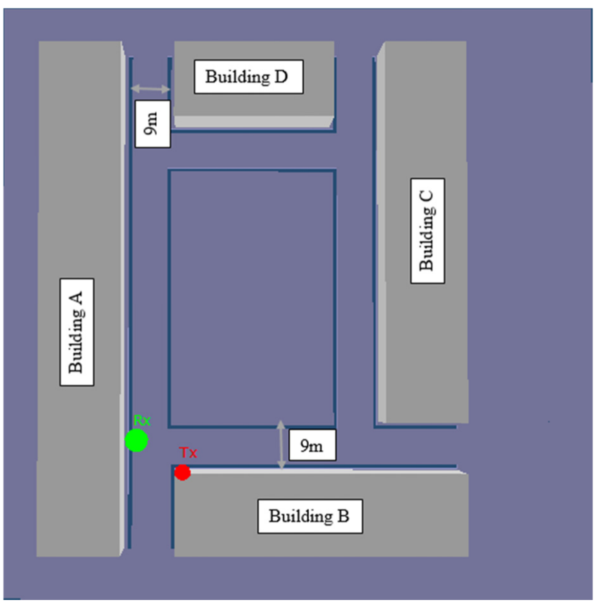


**FIGURE 8.** The city model with open-trench drains (not to scale).

ray-tracing software for the values of the relative dielectric constant ($\varepsilon_r$) and the conductivity ($\sigma$) of the buildings and the open-trench drains at 4.44 and 0.0001 S/m respectively, for bricks.

## IV. THE EFFECT OF OPEN-TRENCH DRAINS

Having set the layout of the modeled city without and with the existence of the open-trench drains, in this section, we present the propagation prediction results of one selected scenario. In this scenario, the Tx is positioned on the left corner of the rooftop of Building B at a height of 12.5 m. On the other hand, the Rx, which mimics the movement of a person talking

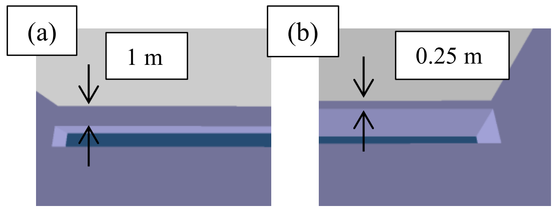


**FIGURE 9.** Zoomed-in view of the open-trench drains surrounding various buildings. (a) 1 m away from the wall. (b) 0.25 m away from the wall (not to scale).

on a mobile phone at an average height of 1.65 m, moves along in a straight line adjacent to the open-trench drain next to Building A. Specifically, the Rx is 1.25 m away from the edge of the open-trench drain and 3.25 m away from the wall of Building A. The Rx moves for a total distance of 100 m at a regular interval of 0.5 m. In total, there are 201 points of power gain (dB). Fig. 10 depicts the locations of the Tx and Rx, as well as the Rx trajectory path; while Fig. 11 shows the difference in power gain along the Rx trajectory path between the two aforementioned scenarios.

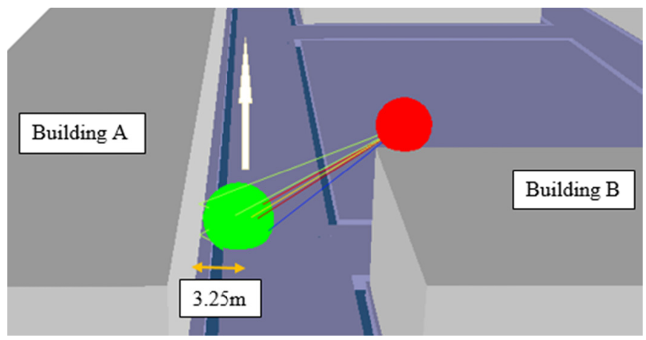


**FIGURE 10.** The Rx mimics the movement of a person moving in a straight line adjacent to the open-trench drain.

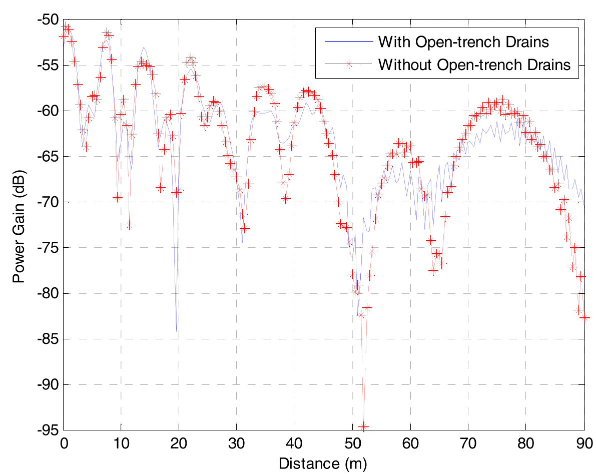


**FIGURE 11.** The power gain along the Rx trajectory path from the two scenarios.

As can be observed from Fig. 11, the power gains obtained from the two scenarios generally follow the same trend, and this is positive because these two scenarios should have the same overall trend as we are in essence examining the same site, except one is with the open-trench drain included. A closer scrutiny of Fig. 11 however, reveals that the presence of the open-trench drain may cause either an increase or decrease in power gain. Take for instance, at a location of 19.5 m along the receiver route, the presence of the open-trench drain has lowered the power gain by approximately 15 dB. This is because at this location, the participating rays that reach the Rx location are different for the two scenarios, as further illustrated by Fig. 12.

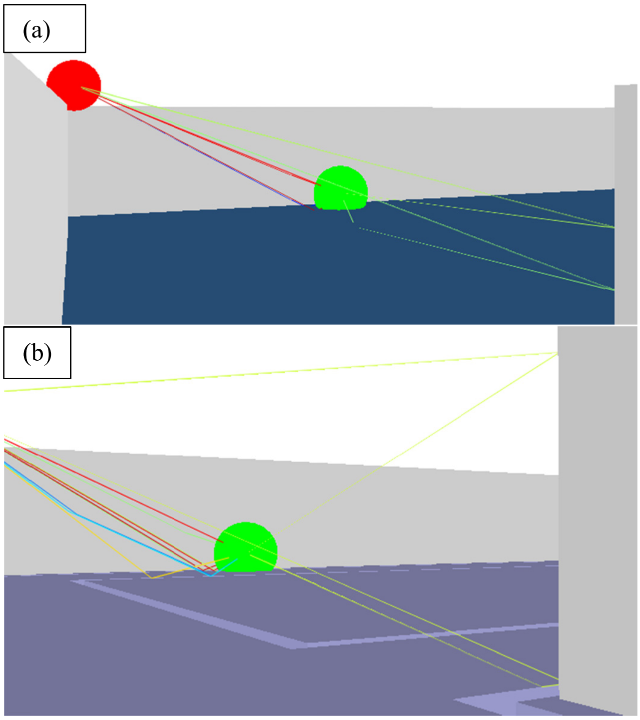


**FIGURE 12. Zoomed-in view of the participating rays that reach the Rx location at 19.5 m (a) without open-trench drains (b) with open-trench drains.**

Two scenarios are portrayed in Fig. 12, each demonstrating the participating rays that reach the Rx location at 19.5 m under each specific condition. In Fig. 12 (a), the one without open-trench drain, the participating rays that reach this Rx location include one edge-diffraction from the wall of Building C and one hybrid ray that is made up of a wall-diffracted ray cum a ground-reflected ray. This combination apparently yield stronger power gain compared to Fig. 12 (b), when open-trench drain is present. In the latter case, the participating rays are similar to the former case except for one change in the hybrid ray. The participating hybrid ray in the latter case is made up of a wall-edge diffracted ray and another diffracted ray from the edge of the open-trench drain near Building C. This double diffraction contributes to lower power gain.

Notwithstanding the foregoing, the presence of the open-trench drains does not always contribute to lower power gain.

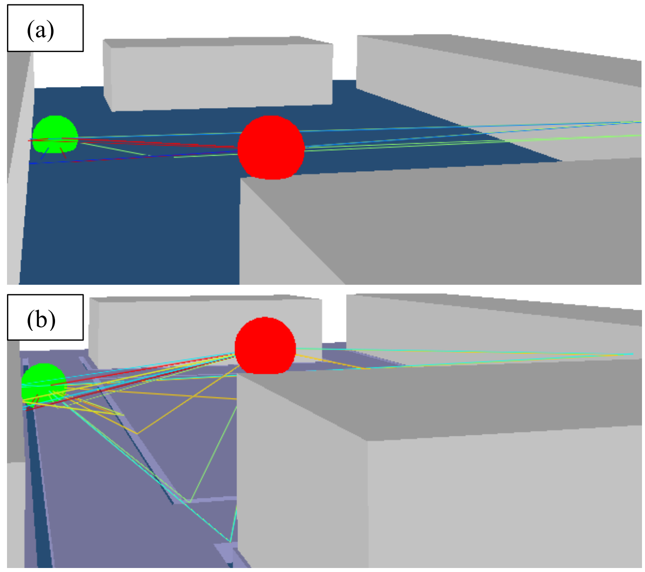


**FIGURE 13. Zoomed-in view of the participating rays that reach the Rx location at 52 m (a) without open-trench drains (b) with open-trench drains.**

In another instance, at the Rx location of 52 m, the case where open-trench drains are present; it has recorded a higher power gain. This is because at this location, there are more participating rays arising from the single drain-edge diffraction that reach the Rx location (a phenomenon not seen in the former case when the open-trench drains are absent). Similar observations can be made for the receiver route between 63 m to 67 m, and between 85 m to 90 m, where the presence of the open-trench drains has contributed to higher power gain. Fig. 13 portrays this phenomenon, where more participating diffracted rays from the open-trench drain's edge are shown.

## V. CONCLUSION

In this paper, we have presented a pertinent topic that is especially relevant to Asian cities, and beyond. To start with, we have selected a narrow L-shaped open-trench drain from which field measurements were conducted at 2.4 and 5.8 GHz and their results compared with ray-tracing simulation results. A satisfactory agreement is reached from these two comparisons. The insights gained from this comparison are particularly useful because unlike urban street canyon scenario that has been more thoroughly explored, we have now extended our understanding on radio propagation in narrow passageway, which can potentially enhance wireless and mobile communications in environments such as open-trench drains, caves, coal mines, underground passageway, and others. In our next step, to venture beyond a single open-trench drain structure, we have modelled one city for two general cases, namely, without and with the existence of open-trench drains. One scenario is presented with a specific set-up of the transmitter and receiver positions, and a ray-tracing scheme is utilized to yield the numerical results for the two general cases at 900 MHz. Our findings suggest that in a city where open-trench drains are present, varying degree of difference in power gain can be expected for the relevant transmitter-receiver trajectory. Therefore, when propagation modeling is conducted, the inclusion of the open-trench drains into the relevant propagation prediction software will contribute towards improved precision and accuracy of the prediction results, which in turn may improve the overall quality of service for wireless and mobile communications. Further work in this area may include showing the influence of open-trench drains on ray-tracing based prediction in a deeply shadowed area.

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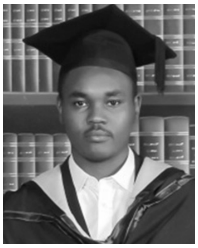

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