Wireless Propagation in Non Line of Sight Urban Areas using Uniform Theory of Diffraction

Grant A. Ellis
Department of Electrical and Computer Engineering
National University of Singapore

Abstract: This paper describes a three-dimensional electromagnetic propagation model for signal power prediction in a non line of sight urban area located in Singapore. The model, which is implemented using the Ohio State NEC-BSC V4.2 basic scattering code and is based on ray theory and uniform theory of diffraction (UTD) takes into account first-order, second order, and third order effects including triple reflections and diffractions. The simplified propagation model of Raffles Place, the central business district of Singapore, uses more than 360 geometrical structures and is compared with data measured at 937.6 MHz along a drive route at the site. The results from the propagation model produced reasonable agreement with the measurements showing that a simplified model using UTD can be used to simulate the gross features of electromagnetic scatter in an urban area. It is shown that use of penetrable dielectric building walls are also necessary for accurate prediction of radio wave propagation in urban areas under non line of sight conditions. It is also found that third order scattering effects can be dominant in non line of sight situations and may be necessary for accurate predictions.

1 INTRODUCTION

As cellular mobile communications systems become more widely used, there is an increasing need to develop reliable planning tools for base station deployment. Part of this growth is due to frequency reuse whereby the same frequencies are utilized in geographically distinct areas or cells such that signal path loss over distance can be exploited. Frequency reuse provides for significantly greater capacity. One of the drawbacks with frequency reuse however, is the potential for interference between nearby cells. As cells become smaller in size, the use of reliable planning tools becomes even more necessary. In these environments, accurate signal strength prediction plays an important role in controlling intercell interference and providing coverage for low-power handheld units. The use of reliable planning tools means that the use of expensive and time-consuming measurements in the field can be minimized. These tools can also provide a cost effective means of anticipating problems at the early stages of base station deployment and of optimizing parameters such as antenna location and orientation.

Several techniques have been developed [1-6] for analysis of multipath and other propagation effects in macrocellular and microcellular environments. In several of these approaches, ray tracing or launching techniques are combined with GTD/UTD (Geometrical Theory of Diffraction /Uniform Theory of Diffraction) to analytically determine the sum of all incident, reflected, and diffracted fields at the receiver location. The use of GTD/UTD is appropriate, since the frequencies used in mobile communications (e.g. > 900 MHz) are usually high enough such that the assumption that the features of most building structures are much larger than the wavelength used becomes valid. In [2], a computer based propagation model is used to obtain a time delay representation of the received signal. In [3, 4], a multislit waveguide with randomly distributed gaps between the sides of buildings is considered as a model of straight streets under line of sight conditions. In [5], a ray launching technique is used to detect the intersection of a ray with an object and the diffracted and reflected rays are then computed. This process is repeated until a maximum number of reflections is exceeded. In [6], 2D FDTD is corrected to account for spherical wave spreading and applied to a simple outdoor environment. Each building in the model consists of a perfectly conducting core with a dielectric coating.

In this paper, a particular urban area was selected, a three-dimensional model was created and the propagation characteristics were simulated using NEC-BSC V4.2 (Numerical Electromagnetic Code-Basic Scattering Code) [7]. The model presented includes contributions to the received signal from all possible propagation paths, including ground and wall reflections from diffracted and specularly reflected signals both in the LOS (Line of Sight) and NLOS (Non Line of Sight) regions using GTD/UTD. This code is structured such that all of one type of scattered

1054-4887

field or interaction is computed at one time to increase efficiency. Buildings having an arbitrary layout can be modeled even if the streets are not rectilinear and the buildings walls on each side of the streets are not coplanar.

The purpose of this research is to investigate how accurately UTD could predict electromagnetic scattering in a non line of sight urban environment using a simplified model consisting of plates and curved surfaces. In order to evaluate the limitations of the model, predictions from the model considering 1st, 2nd, and 3rd order scattering mechanisms were compared to CW test data measurements from a private cellular provider. This paper is organized as follows: Section 2 describes the urban propagation model, Section 3 compares the measured vs. predicted results, and Section 4 summarizes the results and provides some directions for future research.

2 URBAN PROPAGATION MODEL

The goal of this investigation was to determine how well UTD could be used to predict electromagnetic scattering in a heavily urbanized environment using a simplified model of the site. Raffles Place, the central business district of Singapore was chosen as an appropriate site for this study due to its high building density. Other reasons for choosing Raffles Place were:

1. The building layout does not lie completely in a rectangular grid. This allows for investigations to be carried out in an area without a rectangular grid layout and having a somewhat random building orientation.
2. Drive routes can be investigated which are mainly non-line-of-sight (NLOS).
3. The building heights in this area range from 5 to 282 meters. The effects of diffraction from the edges of rooftops and sides of buildings can be investigated.

Figure 1 shows a three-dimensional view of the geographical layout of Raffles Place used in the UTD model with the drive route shown. The drive route begins along Cecil Street and follows onto Collyer Quay up to Fullerton Square then turns left onto Battery Road where it ends on Chulia Street. The area covered is about 500 m by 500 m and the length of the drive route is 1.12 km. The data predicted along this route is compared with the measured drive data collected by MobileOne, a private cellular network provider in Singapore. In all field measurements, GPS was used to record the location of the measured signal power along the route. The following input model parameters are required in the NEC-BSC UTD code [7]:

1. Coordinates of the plates, curved surfaces, and other structures necessary to simulate building exterior and roofs.
2. Estimate of the electrical permittivity, conductivity, and thickness of the building exteriors.
3. Transmitter and receiver locations.
4. Transmitter and receiver antenna patterns.
5. Operating frequency used.
6. Types and order of UTD interactions to be included in the simulation.

The coordinates of the building exteriors were extracted from an aerial map by using an overlay having a fixed origin selected on the map. The corners of the buildings were measured relative to this origin. Most building shapes were modeled using only plates, which were assumed to be flat surfaces having average electrical permittivity and conductivity. Structures having low curvature sections were modeled using multiple plates to form a piecewise linear approximation of that section. When the radius of curvature of the structure was substantial, cylinders or truncated cones were used. Elliptic cylinders were also used to model some building structures.

The ground plane was simulated using a single homogeneous half space of a relative dielectric permittivity $\varepsilon_r = 10$ and conductivity $\sigma = 0.001$ S/m, which can be considered reasonable for a typical ground. Preliminary studies suggest that the predicted signal power near the ground is somewhat insensitive to the ground dielectric constant and conductivity. The seawater surface was also included in the model and was modeled as a dielectric coated plate with a relative permittivity of $\varepsilon_r = 80$ and electrical conductivity $\sigma = 4$ S/m.

The model database used in the UTD propagation model consists of 360 plates and 5 cylinders to represent the 64 buildings and other structures located at Raffles place. The number of plates in the model could easily exceed 500 if the entire area is to be accurately modeled. However, following the assumption that effects from structures like trees, lamp posts, telephone boxes, Mass Rapid Transit station buildings, etc can be ignored, these structure were not included in the model [8]. Every attempt was made to define the model in more detail in areas where it was illuminated strongest by the antenna. Because of the wide variation in building heights, the detailed description in the model is not limited to the area local to the transmitter. Since the model used omnidirectional antennas for the transmitter and receiver, the entire area including but not limited to the region between the transmit antenna and the receiver field point was modeled. As a result of the above, the number of plates required for modeling was quite large to account for all the possible ray paths.

The building exteriors were modeled as dielectric plates to approximate materials, such as glass windows, absorbing panels, concrete, etc. Research is still underway to produce useful approximations for the thickness, permittivities and conductivities of these dielectric layers [8]. The choice of a good approximation for the electrical properties is of utmost importance, since the Fresnel reflection coefficients depend on these values. These coefficients dictate the reflection coefficient of the materials influencing the modeled results.

The buildings located at Raffles Place were constructed using a variety of materials, such as concrete, glass, and steel. It is difficult to identify the electromagnetic properties of each individual building exterior and it is assumed that all the building walls have electrical property values averaged over those of glass and concrete. The building walls were modeled using plates and cylinders coated with dielectric on one side to simulate the building exterior and a perfect electric conductor on the other. The material properties were chosen as $\varepsilon_r = 15$, $\sigma = 7$ S/m, and thickness = 0.5 meter [9, 10]. The accuracy of the model is limited by the lack of accurate building and street databases and the approximation of building exteriors to be "smooth" flat surfaces having an average relative permittivity and conductivity.

Both the transmitter and receiver antennas were simulated using vertically polarized half-wave dipoles. The transmitter input power was 32.4 dBm. The transmitter dipole antenna was placed 3 m above the machine room on the rooftop of Ocean Building, a building of about 120 m in height. The receiver was placed 2 m above the ground to simulate mounting of a vertical monopole on top of a car. The measured data was taken at intervals of between 28 - 59 m using a GPS based measurement system. The simulated data is sampled in 20 m intervals with and without spatial averaging. All UTD scattering mechanisms were selected during the simulation. The NEC-BSC UTD code however, allows for the individual scattering terms to be selected to investigate their behavior along the route.

3 COMPARISON OF THE MEASURED VS. PREDICTED RESULTS

Three sets of simulation cases were considered. The first simulation case considers only the 1st and 2nd order interaction terms listed in Table 1. The second simulation case considers up to and including the 3rd order interactions. The additional 3rd order interaction terms are listed in Table 2. For these first two cases, the building walls only reflect and diffract the radio waves using the material dielectric properties given. The third simulation case considers 1st, 2nd, and 3rd order interactions listed in Tables 1 and 2 using penetrable dielectric plates as building walls. For this case, radio waves are both reflected and transmitted through the plates to simulate propagation through building structures.

Figure 2 shows a comparison between the predicted signal powers resulting from the first two simulation cases (1st and 2nd order interactions only, and 1st, 2nd and 3rd order interactions) and the measured fields. The 1st and 2nd order interaction terms listed in Table 1 result in a total of 5015 ray paths along the drive route. Table 2 lists the 3rd order interaction terms resulting in an additional 42850 ray paths. The curve showing all 1st, 2nd and 3rd order interactions appears to give better agreement with the measured field data.

The greatest discrepancy between the measured and predicted data for cases 1 and 2 occurs over the 0.2 km stretch located immediately before point D near Fullerton Square (Figure 1). The predicted results for the case of up to 3rd order interactions underestimate the measured data by more than 20 dB. This is difficult to explain using the model because there are no nearby structures located in this area on which the rays can get scattered. Along the drive route to the right of Collyer Quay is an open area immediately adjacent to Marina Bay. One possible explanation for the discrepancy between the measured and predicted data is the lack of radio wave propagation through buildings since modern office-building interiors are composed of mostly air. Studies have shown that radio waves may penetrate into buildings with only between 9-11 dB attenuation at 900 MHz [11]. Our model was modified to allow the building walls to be penetrable by radio waves such that the total attenuation through the building structures is between 12-15 dB. The properties of the building walls were changed to ε_r = 15, σ = 0.0023 S/m, and thickness = 1 m and were simulated as penetrable dielectric plates. Shown in Figure 2 is the measured vs. predicted signal power along the drive route in Figure 1 using penetrable walls. The correspondence between measured and predicted power is much better than for the cases where the building walls only provide reflection and diffraction. It can be observed that use of penetrable building walls results in 11 dB less variation in the predicted field along the drive route than for the case of 3rd order scatter only. Table 3 lists the RMS error and standard deviation for each simulation case.

Additional observations can be made from the measured vs. predicted signal power results shown in Figure 2. At location A on Cecil Street, the peak in the measured received field may be attributed to 3rd order interactions since this peak cannot be seen in the 2nd order results. For instance, in the prediction, a 3rd order reflection occurs between the Singapore Land Tower building, the OUB Center, and a second reflection from the Singapore Land Tower (Figure 3). Multiple interactions between the Ocean Building and the Ocean Towers also occur before the ray arrives at the receiver location.

At location B, the measured signal power is at the lowest level along the drive route and the number of 2nd and 3rd order ray paths appears to be minimum. At location B the only contribution to the signal power at the receiver location appears to be from the diffraction from the rooftop of the Ocean building. This location is also the point closest to the transmitter along the drive route.

At location C, the predicted results that include up to 2nd order interactions only indicate a drop of nearly 50 dB in the received signal strength due to obscuration by an overpass located along the route. For the predicted results that include 3rd order interactions, the effect of the overpass is minimal. The measured signal power also indicates essentially no effect due to the overpass. The effects of the 3rd order interactions appear to be dominant directly under and immediately beyond the overpass. Multiple rays that originate at the transmitter location may be diffracted from the rooftop edge on top of the Ocean Building and then diffract and reflect from the north side of the John Hancock building. These rays are then reflected from the sides of both the Union Overseas Shopping Center and a restaurant and then finally are reflected from the side of the Hitachi Center (see Figure 4) to the receiver location immediately beyond the overpass location.

Probably the most interesting observation in the measured and predicted data is shown at location D. Here, the measured and predicted signal powers are at their maximum value over the entire route. Location D is in front of the Singapore Land Tower on Battery Road. The received signal power is about 12 dB above the average signal power along the entire route. At this location, the transmit antenna on the Ocean Building is obstructed by several buildings. The received signal appears to come from several ray paths that first begin as reflections from the OUB Center and UOB Plaza and then are reflected from the Singapore Land Tower and Standard Chartered buildings to the receiver location. This area of Battery Road appears to behave like a parallel-plate waveguide so that the rays from several locations are guided into a relatively narrow street bounded by the Singapore Land Tower on one side and Standard Chartered Bank and May Bank on the other side (see Figure 5).

At the end of the route and furthest from the transmitter on Battery street (location E) is the location of the largest discrepancy between the 2nd and 3rd order predicted data. The measured signal power in the area around location E however, is nearly constant. The predicted data however, shows almost a 50 dB variation for the 1st and 2nd order interactions and nearly 27 dB of variation for the case of up to 3rd order interactions. The predicted data shows a 2nd order interaction that is the result of a specular reflection from the City House building and then diffraction between the edges of the Exchange Building and Golden Shoe Car Park (Figure 6) to the receiver location. The measured power increase is only about 1 dB at this location. Rays reflected from the Republic Plaza and the UOB Plaza channel into this area resulting in a peak in the received signal power. Like the results shown at location D, this area may behave like a parallel-plate waveguide where multiple reflections occur between UOB Plaza on one side and the Sinsov building on the other side across Battery Street.

4 CONCLUSION

In this paper, a simplified model using UTD with ray tracing and consisting of 360 plates and 5 cylinders was used to predict high-frequency electromagnetic wave propagation in an urban environment. Taking into account single, double, and third order UTD terms interacting between building walls and corners, the gross features of the electromagnetic response were accurately predicted. The three-dimensional model was developed using arbitrary building layouts modeled using simple structures constructed using plates to represent flat surfaces and cylinders for curved surfaces.

Several sets of UTD simulations were performed and the resulting predicted signal powers were compared with measurements along the drive route located in Raffles Place, the central business district of Singapore. Comparisons between the predictions and measurements suggest that:

1. When there is no line of sight (NLOS), diffraction cannot be neglected. The effects of diffraction from the edges of the rooftop appeared to be significant at the transmitter location. 1st and 2nd order interactions alone may not be sufficient for accurate predictions. Inclusion of higher order scattering is important for the accurate prediction of the scattering in NLOS situations. Inclusion of 3rd order interactions also result in 9 dB less variation than 2nd order interactions in the predicted signal power along the drive route.

2. For NLOS cases, the fields at the receiver location often result from scattering on structures local to the receiver location. These fields may also result from reflections from large structures or surfaces far away from the receiver location. This can result in propagation paths that may not be intuitively obvious. These higher order scattering terms (3rd order and above) may require a larger model to account for all possible ray paths.

3. Lack of sufficient structures in the propagation model and inaccuracies in antenna positions, route locations, may introduce errors into the predicted signal powers. Another source of potential error is scattering from cars, trucks, or other vehicles located near the receiver and not included in the model. It was also assumed that the dielectric constant and conductivity of the building exteriors throughout the model was constant. These simplifications introduce extra error.

4. UTD can also produce artifacts in the predicted fields. At some locations considering up to 2nd order interactions only result in artifacts not observed in the measured data. At those locations, the 3rd order scatter is dominant over the 1st and 2nd order scatter effects.

5. At two locations along the drive route, it was found that the peak in the received signal power might be the result of a parallel-plate waveguide effect caused by multiple reflections between adjacent buildings separated by a street or road.

6. Effects of radio wave propagation through building walls and structures are necessary in resolving differences between measured and predicted data under NLOS conditions. Use of penetrable building walls in the model reduces the RMS error in the prediction by 13 dB.

Future work may include incorporation of higher order (e.g. 4th order) interaction terms in the propagation study. This may be useful for the prediction of the signal power near Fullerton Square. The dielectric properties of the building exteriors are also very important and may have a large effect on the magnitudes of reflections from buildings. Future work includes additional modeling of propagation through buildings. Analysis of these effects will be helpful in resolving differences between measured and predicted signal power data. Also of interest are the cross-polarized fields scattered in non line of sight locations, for the study of polarization diversity antenna schemes.

ACKNOWLEDGMENTS

The author wishes to thank the following for their contributions:

1. MobileOne for providing the CW drive test measurement data.
2. Building and Construction Authority of Singapore for providing a detailed map of Raffles Place.
3. To my student, Cheong Si Neng for the Raffles Place model.
4. Ronald J. Marhefka at The Ohio State University Electroscience Laboratory for strong support and help in using the NECBSC code.

REFERENCES

[1] F. Ikegami, T. Takeuchi, S. Yoshida, "Theoretical prediction of mean field strength for urban mobile radio", *IEEE Trans. on Ant. and Prop.* Vol. 39, No. 3, pp. 299-302, March 1991.

[2] J. P. Rossi, J.C. Bic, A. J. Levy, Y. Gabillet, M. Rosen, " A ray launching method for radio-mobile propagation in urban area", *IEEE Ant. and Prop. Symp.,* Vol. 3, pp. 1540-1543, June 1991.

[3] N. Blaunstein, M. Levin, "Propagation Loss in the Urban Environment with Rectangular Grid-Plan Streets", *10th International Conference on Antennas and Propagation*, pp. 2.178-2.181, 14-17 April 1997.

[4] N. Blaunstein, R. Giladi, and M. Levin, "Characteristics' Prediction in Urban and Suburban Environments", *IEEE Trans. Veh. Tech.*, Vol. 47, No. 1., pp. 225-234, Feb. 1998.

[5] S. Y. Tan, H. S. Tan, " Propagation model for microcellular communications applied to path loss measurements in Ottawa city streets", *IEEE Trans. on Veh. Tech.,* Vol. 44, No.2, pp. 313- 317, May 1995.

[6] J. Schuster and R. Luebbers, "Comparison of GTD and FDTD Predictions for UHF Radio Wave Propagation in a Simple Outdoor Urban Environment," *IEEE APS Int. Symp. Dig*., Montreal, Canada, Vol. 3. pp. 2022-2025, July 1997.

[7] R. J. Marhefka, J.W. Silvestro, "Near-zone basic scattering code, User's manual with space station applications" Technical Report 716199-13, March 1989.

[8] M. F. Catedra, J. Perez, F. Saez de Adana, and O. Gutierrez, "Efficient ray-tracing techniques for three-dimensional analyses of propagation in mobile ommunications: application to picocell and microcell scenarios", *IEEE Antennas and Prop. Magazine*, Vol. 40, No. 2, pp. 15-28, April 1998.

[9] S-C Kim, B. J. Guarino Jr., T. M. Willis III, V. Erceg, S. J. Fortune, R. A. Valenzuela, L. W. Thomas, J. Ling, and J. D. Moore, "Radio propagation measurements and prediction using three-dimensional ray tracing in urban environments at 908MHz and 1.9GHz", *IEEE Trans. on Veh. Tech.,* Vol. 48, No. 3, pp. 931- 946, May 1999.

[10] O. Landron, M. J. Feuerstein, and T. S. Rappaport, "In Situ Microwave Reflection Coefficient Measurements for Smooth and Rough Exterior Wall Surfaces", in Proc. 43rd *IEEE Veh. Technol. Conf.*, pp. 77- 80, 1993.

[11] A. M. D. Turmani, A. F. de Toledo, "Modeling of radio transmissions into and within multistory buildings at 900, 1800, and 2300 MHz", *IEE Proc.* I, 140, (6), pp. 462-470, 1993.

Grant A. Ellis was born in Portland, OR in 1960. He received the B.S. and M.S. degrees in electrical engineering from Washington State University, Pullman, WA, in 1983 and 1986, respectively, and the Ph.D. degree in electrical engineering from the University of Washington, Seattle, in 1995. From 1983 to 1985 he was a staff engineer with the Boeing Aerospace Company, and from 1987 to 1998 he was a principal engineer with the Boeing Defense and Space Group. He was an assistant professor of electrical engineering with the National University of Singapore from 1998 to 2001. He is presently a member of the research staff of HRL Laboratories in Malibu. His current research interests are in microwave circuit design including monolithic MIC design, active antenna design, and propagation analysis.

Dr. Ellis is a member of Tau Beta Pi, Eta Kappa Nu, ACES, and the IEEE.

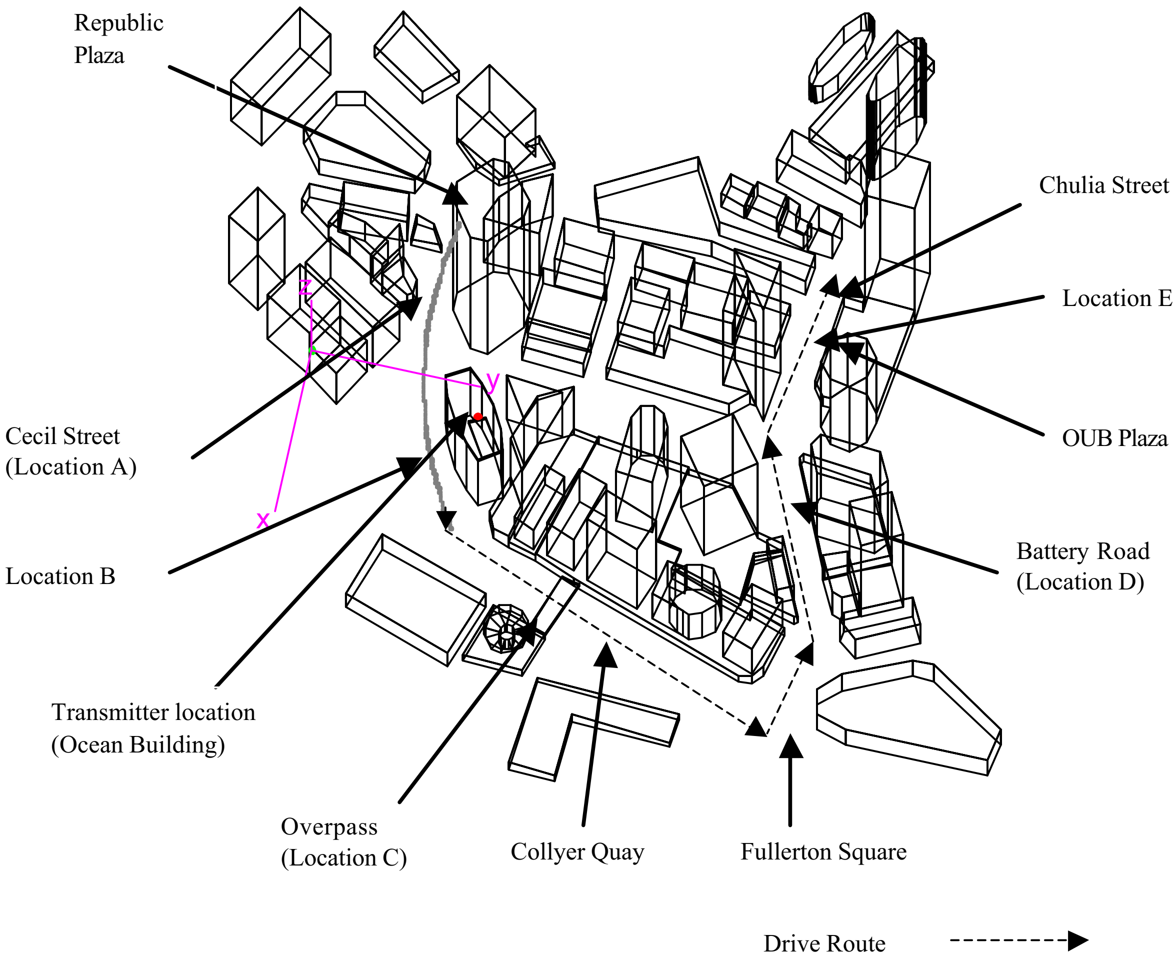

Figure 1. UTD model of Raffles Place and drive route.

Table 1. 1st and 2nd order interactions considered in case 1.

RP	Single Reflection from plates
RPRP	Double reflection from plates
DP	Single edge diffraction
VP	Single corner diffraction
RPDP	Plate Reflection – Edge Diffraction
RPVP	Plate Reflection – Corner Diffraction
DPRP	Edge Diffraction – Plate Reflection
VPRP	Corner Diffraction – Plate Reflection
DPDP	Edge Diffraction – Edge Diffraction
DN	Diffraction from End Cap Rim
RN	Reflection from End Cap
DC	Diffraction from Curved Surface
RC	Reflection from Curved Surface

Table 2. 3rd order interactions considered in case 2.

RPRPRP	Triple reflection from plates
RPRPDP	Double Plate Reflection – Edge Diffraction
RPRPVP	Double Plate Reflection – Corner Diffraction
RPDPRP	Plate Reflection – Edge Diffraction – Plate Reflection
RPVPRP	Plate Reflection – Corner Diffraction – Plate Reflection
DPRPRP	Edge Diffraction – Double Plate Reflection

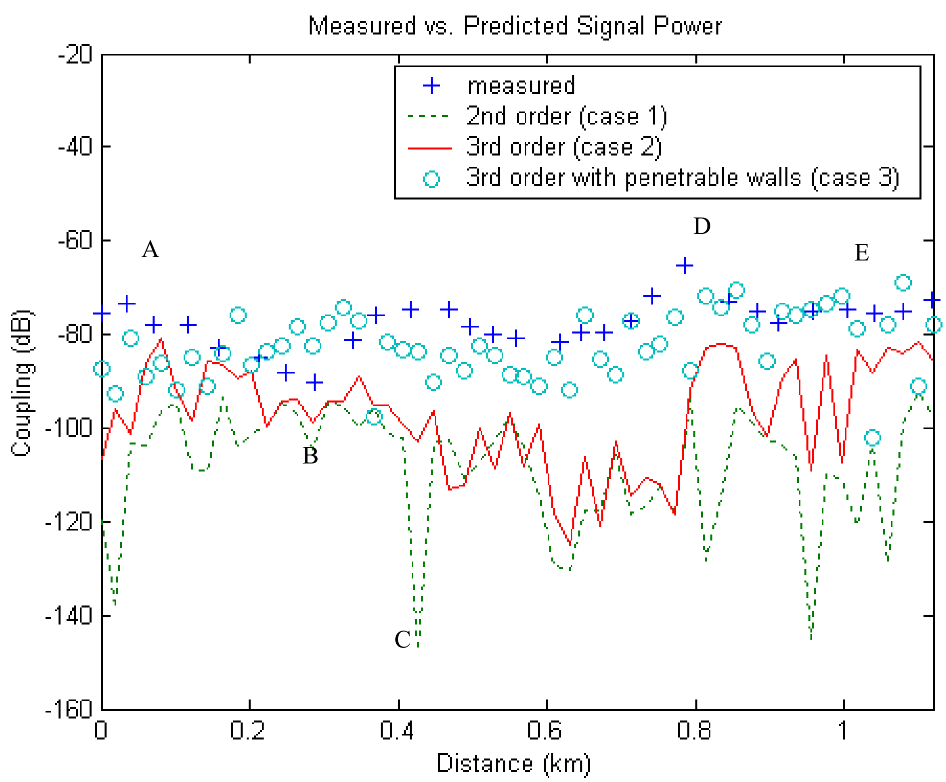

Figure 2. Measured and predicted signal power along drive route.

Table 3. RMS error and standard deviation between measured and predicted power along drive route.

Case	Order of interactions included in model	RMS Error	Standard Deviation
1	1st, 2nd	33.0 dB	13.2 dB
2	1st, 2nd, 3rd	22.5 dB	13.1 dB
3	1st, 2nd, 3rd with penetrable walls	9.2 dB	8.1 dB

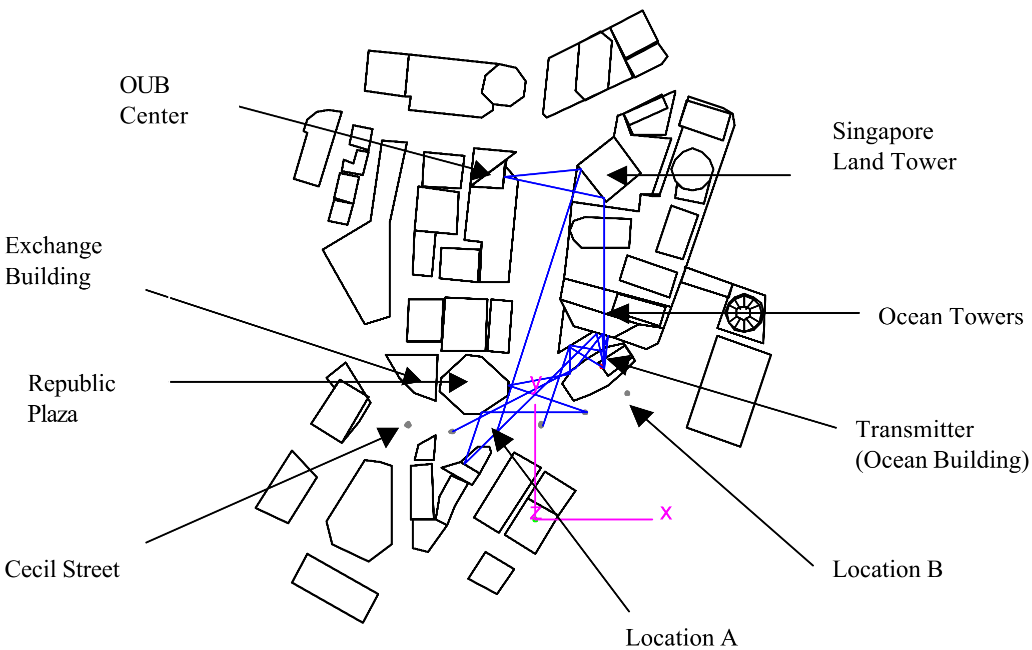

Figure 3. Major Ray Contributions at locations A and B along Cecil Street.

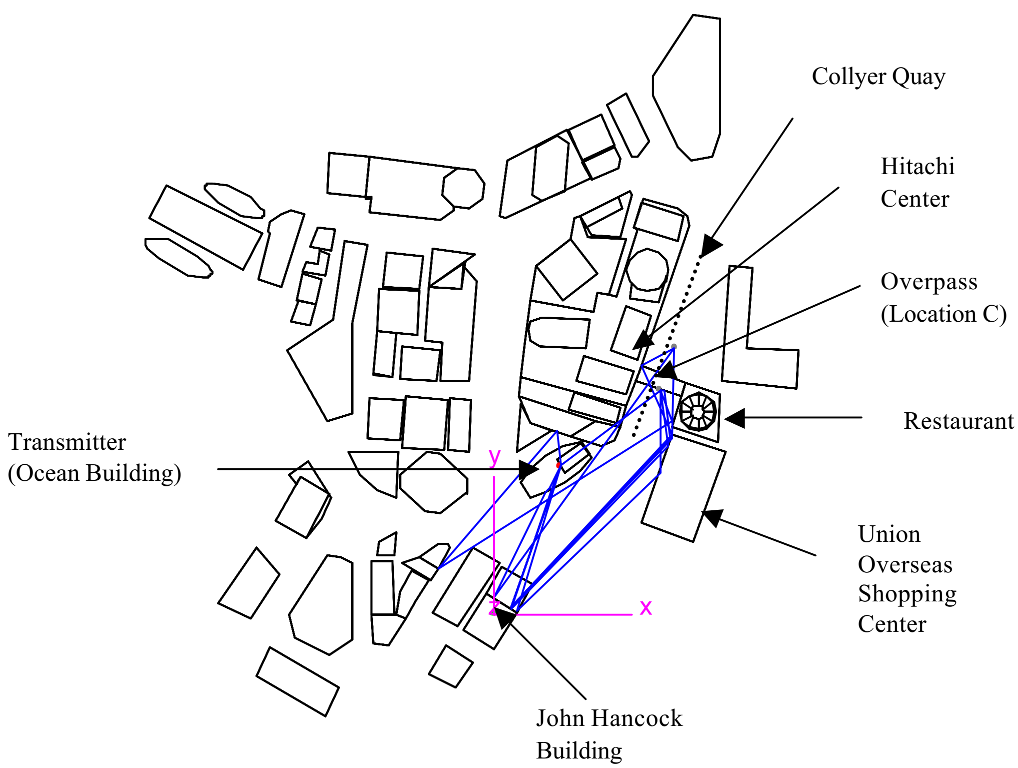

Figure 4. Major Ray contributions at Overpass (Location C).

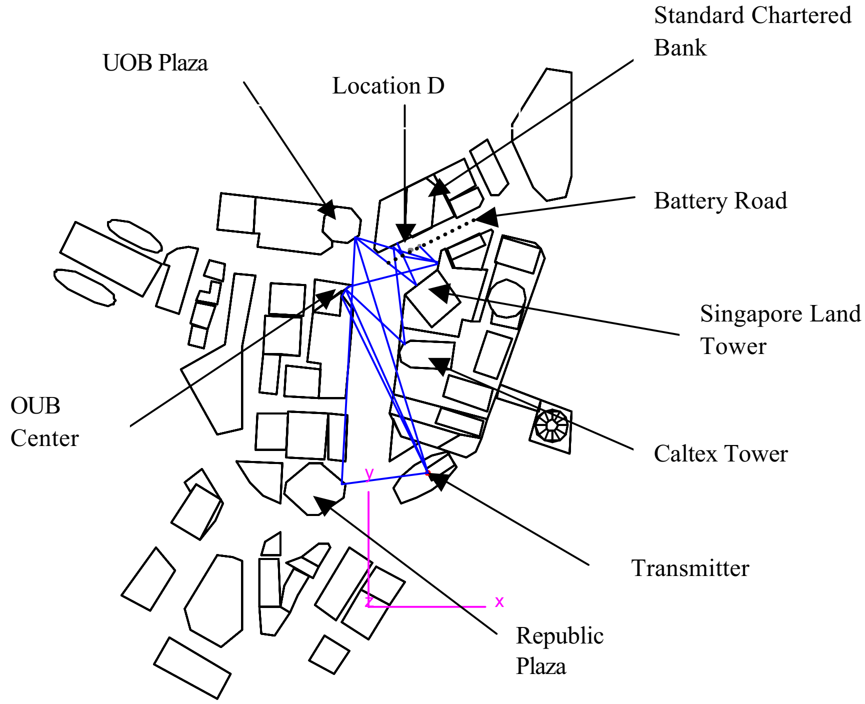

Figure 5. Major Ray Contributions at location D.

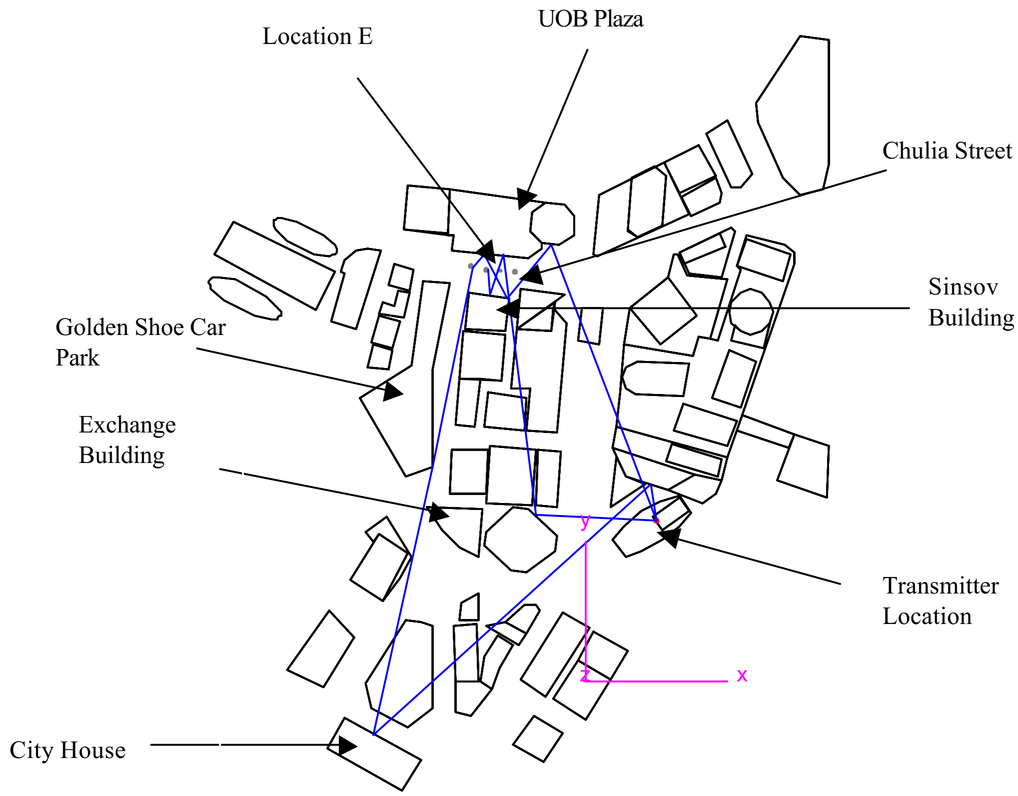

Figure 6. Major Ray contribution at Location E.