An Analytical Model of Microcellular Propagation in Urban Canyons

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***Abstract*— The fast growth of cellular coverage demand for multimedia services based on wireless communication requires an increasing use of microcells to guarantee the satisfactory connectivity. In urban environments, especially in old town centres, the application of this solution is heavily limited by difficulties concerning coverage prediction and planning. The purpose of this paper is the investigation, development and testing of an analytical propagation model based on 2D ray–tracing approach for path loss prediction. Formulas are derived taking into account multiple reflections along street walls as well as diffractions at street corners, while ground reflections are neglected. Validation of the model has been carried out by using a data set collected during a measurement campaign in Genoa's old town centre.**

***Index Terms*— UMTS, microcell, reflection, diffraction, canyon effect, street junctions.**

I. Introduction

The rapid increase of mobile communications users and the growth of demand for multimedia services available at mobile terminals have been a formidable incentive to develop a third generation mobile communication technology like UMTS.

The need to provide global access and to manage efficient delivery of different multimedia streams led to the choice of WCDMA as access technique to the radio channel. This choice involves a sophisticated and complex power control mechanism to optimize transmission and to avoid the so called near–far problem [1]. For these reasons it is necessary, on one hand, to extensively use microcells placed in suitable locations, for example in areas which could not be reached otherwise by radio signals due to urban environment structure and ground conformation, and, on the other hand, to integrate them with macrocells in order to guarantee the best tradeoff to provide an acceptable cellular coverage.

Coverage planning is done by studying radio propagation phenomena and by consequently developing a propagation model able to describe channel features. Several propagation models for both microcellular and macrocellular environments can be found in the literature [2], [3]. In microcellular environments these propagation models are often based on the ray–tracing approach leading to accurate path loss prediction, but they require extensive simulations and need great computational resources [4]–[6].

The purpose of this paper is to describe a new theoretical approach to the study of signal propagation in urban microcellular environments, based upon the two fundamental phenomena involved: reflection and diffraction. Through this approach it is possible to derive analytical formulas to predict path loss in these environments.

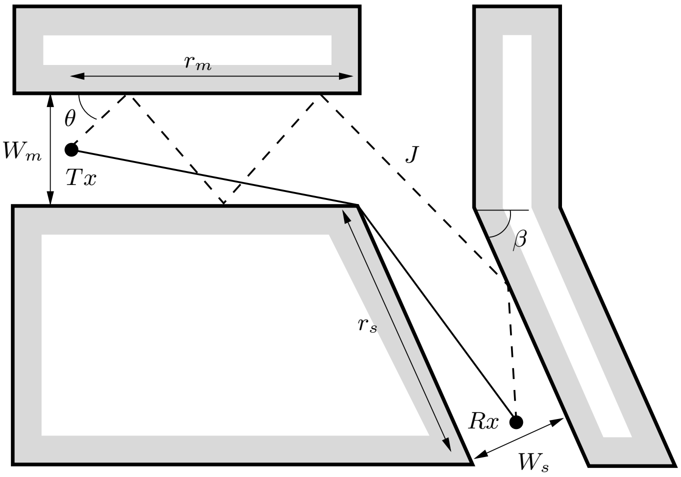

Fig. 1. Model geometry showing the reflected ray with the minimum number of reflections (dashed line) and the direct diffracted ray (solid line). Tx is the transmitter position at distance r_m from junction J while Rx is the receiver position at distance r_s from J. θ is the angle of incidence of reflected ray. Junction angle β is not in the original model (consider it fixed equal to 90°) but has been added to allow a model improvement. For $\beta < \frac{\pi}{2}$ favourable junctions are achieved, while $\beta > \frac{\pi}{2}$ generates unfavourable junctions.

In Section II the investigated propagation model is discussed while Section III describes some modifications applied to the original model to improve the prediction quality. In Section IV the data collected in a measurement campaign are described and an interpretation of the results is presented.

II. Propagation model

The model used in this study is taken from [7], where the results obtained with the analytical formulas developed are compared with the experimental data sets taken in New York [8] and Tokyo [9]. However, only the formulas developed in [7] to evaluate the path loss along the side street have been used in our case study.

The model geometry and parameters are shown in Fig. 1. The model is based upon the following simplifying hypotheses:

1) all surfaces are assumed to be flat and smooth;
2) streets are assumed to be straight with uniform width, crossing perpendicularly (this last hypothesis will be eliminated);

3) reflections cause constant loss (this hypothesis will be eliminated);
4) only the path with the minimum number of reflections is considered;
5) only the direct diffraction component is considered (solid line in Fig. 1);
6) Tx and Rx are assumed to be positioned in the middle of the streets

where the first two are commonly called urban street grid hypotheses.

The first three hypotheses simplify the reflection calculation because the information about incidence angles is not used, thus making the reflection coefficients evaluation no more necessary, as opposed to what usually happens in real ray–tracing approaches.

The third and the perpendicular junction hypothesis will be discussed and then eliminated in Section III-B.

Considering the reflection component, the path with the minimum number of reflections is the dominant one: referring to the geometry shown in Fig. 1 (assume $\beta = 90°$ now), the minimum number of reflections N_{min} is obtained as

$$N_{min} = \left\lfloor 2\sqrt{\frac{r_m r_s}{W_m W_s}} \right\rfloor \tag{1}$$

Should the signal with N_{min} reflections not reach the receiver, this latter would probably be reached by other rays with a greater number of reflections and the following analytical formula would underestimate the attenuation.

The attenuation for the reflection component is given by

$$PL_R = 10 \log \left(\frac{\lambda}{4\pi(r_m + r_s)} \right)^2 + N_{min} L_r \tag{2}$$

where L_r represents the attenuation for each reflection, the term $r_m + r_s$ is an approximation of the total path covered by the ray and λ is the wavelength at the operating frequency.

Considering the diffraction component, the dominant contribution is given by the direct diffracted signal from Tx to Rx. Using the Fresnel–Kirchhoff theory [10], the diffracted field at the receiver can be expressed as

$$E(Rx) = \frac{jA}{2\lambda} \iint_{\Omega} \frac{e^{-jk(r+s)}}{rs} \left(\cos(n, r) - \cos(n, s)\right) \mathrm{d}\Omega \tag{3}$$

where

- A is the electric field amplitude at 1 meter from Tx
- Ω is the aperture at street junction
- k is the wave number
- r, s are the distances of Tx and Rx from street junction.

Using the concept of Fresnel zones [7] and the approximations reported in the next set of equations (4), that are valid in most of the microcellular environments, (3) can be simplified down to the result shown in (5), describing the attenuation of the diffracted component PL_D [7].

$$\begin{aligned} r &\cong r_m \gg W_m \\ r &\cong r_s \gg W_s \\ \cos(n, r) &\cong 0 \\ \cos(n, s) &\cong -1 \end{aligned} \tag{4}$$

$$PL_D = 20 \log \left(\frac{\lambda}{4\pi r_{m,s}} \right) + 10 \log \left(\frac{\lambda r_{m,s}}{4 r_{s,m}^2} \right), \; r_{m,s} < r_{s,m} \tag{5}$$

In (5) the inequality $r_{m,s} < r_{s,m}$ means:

$$\begin{aligned} r_{m,s} = r_m, \; r_{s,m} = r_s \quad &\text{if} \quad r_m < r_s \\ r_{m,s} = r_s, \; r_{s,m} = r_m \quad &\text{if} \quad r_m > r_s \end{aligned}$$

Finally, considering both the reflection and diffraction contributions, the resulting expression for the path loss along a side street, expressed in dB, is given by

$$PL_{side} = 10 \log \left[\left(\frac{\lambda}{4\pi} \right)^2 \frac{\lambda}{4 r_{m,s} r_{s,m}^2} + \left(\frac{\lambda}{4\pi(r_m + r_s)} \right)^2 10^{\frac{L_r N_{min}}{10}} \right], \quad r_{m,s} < r_{s,m} \tag{6}$$

where the first term in square brackets takes into account the diffraction contributions while the second one represents the reflection contributions.

III. Model improvement

A. Diffraction

It can be seen, analyzing data, that prediction provided by the above model in the part of side streets far from the junction is not as good as in the part near the junction. Because only diffraction is meaningful in this part of side streets [7], [11], performances could be improved by changing the method used to calculate diffraction contributions. Therefore, the model has been modified by using the uniform theory of diffraction (UTD) formulas in place of the Fresnel–Kirchhoff theory, without increasing the complexity.

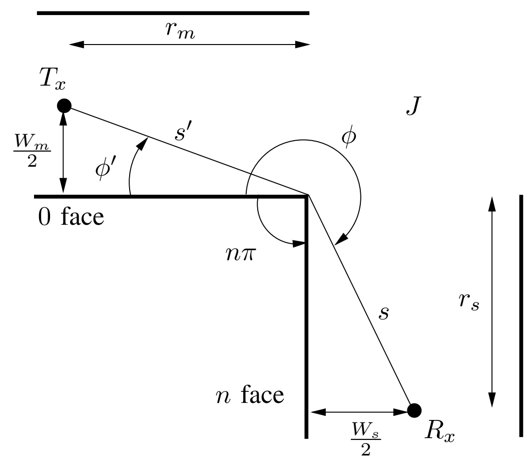

Fig. 2. Geometry of corner at junction for application of UTD theory.

To apply UTD formulas, the corner at the junction is modeled as a wedge, as seen in Fig. 2, where s' and s are the transmitter and receiver distances from the corner and ϕ' and ϕ are the angles of incidence and diffraction measured from the 0 face: s' and ϕ' are fixed while s and ϕ vary with receiver position.

A critical issue in applying the UTD model to experimental scenarios is how the main parameters involved in (7)–(10), i.e. signal polarization and wedge characteristics, are chosen. In the experiments carried out to validate the model, the signal was transmitted by a vertically polarized antenna and the wedge material was typically concrete or stone. However, it turns out that these parameters are not suitable to take into account all the propagation aspects neglected by the simplified model. In fact, the scenario depicted in Fig. 1 implies that the receiver is reached not only by the direct diffracted ray and by the N_{min}–reflections ray, but also by a number of higher order diffracted and reflected components that interfere with each other. It turns out that a better compliance between the proposed model and the experimental data is obtained if (7)–(10) are evaluated for horizontally polarized signals and perfectly conducting wedge. Such a choice seems to allow the model to take into account, at some extent, the higher order effects not explicitly modeled. In particular, a perfect conductor does not attenuate the diffracted ray, which can therefore collect, in a sense, the higher order contributions.

Hence, equations (7)–(10) are UTD formulas calculated for polarization parallel to the plane of incidence and perfect conductor [12]: SF_{tc} is the attenuation factor for waves from transmitter to the corner, SF_{cr} is the attenuation factor for waves from corner to the receiver and D is the scalar diffraction coefficient.

$$SF_{tc} = \frac{e^{-jks'}}{s'} \tag{7}$$

$$SF_{cr} = \sqrt{\frac{s'}{s(s+s')}}\, e^{-jks} \tag{8}$$

$$\begin{aligned} D = \frac{e^{-j\pi/4 \sin(\pi/n)}}{n\sqrt{2\pi k}} & \left[\frac{1}{\cos(\pi/n) - \cos\left(\frac{\phi-\phi'}{n}\right)} \right. \\ & \left. + \frac{1}{\cos(\pi/n) - \cos\left(\frac{\phi+\phi'}{n}\right)} \right] \end{aligned} \tag{9}$$

The diffracted field strength $|E_d|$ at the receiver is then

$$|E_d| = |E_0| \cdot |SF_{cr} \cdot SF_{tc} \cdot D| \tag{10}$$

where $|E_0|$ is the emitted field strength.

According to [11], the attenuation of the diffracted components is given by

$$L_{UTD} = 20 \log\left(\frac{\lambda}{4\pi}\frac{|E_d|}{|E_0|}\right) \tag{11}$$

Hence the final equation of the model becomes

$$\begin{aligned} PL_{side} = 10 \log & \left[\left(\frac{\lambda}{4\pi}\right)^2 |SF_{tc} \cdot SF_{cr} \cdot D|^2 + \right. \\ & \left. + \left(\frac{\lambda}{4\pi(r_m + r_s)}\right)^2 10^{\frac{L_r N_{min}}{10}} \right] \end{aligned} \tag{12}$$

where the first term in square brackets is the attenuation due to diffraction and it results from (11) simplified using (10).

B. *Reflection*

An improvement to the model concerning reflection will be described now: a more general formulation for number of reflections calculus will be shown. This improvement allows to remove the strict hypotheses of perpendicular junctions and constant loss per reflection so it gives the model a more general form.

Referring to Fig. 1 (where now β can vary), total number of reflections N is given by (13), where the new parameter β is used to model the angle between side street and main street at junction J.

$$N = c_1 \tan(\theta) + c_2 \tan(|\beta - \theta|) \tag{13}$$

where

$$c_1 = r_m/W_m \quad c_2 = r_s/W_s \quad \theta \in (0, \frac{\pi}{2}) \quad \beta \in (0, \pi)$$

Absolute value is necessary to take into account favourable junctions, $\beta < \frac{\pi}{2}$ (that is side streets that have the same direction of signal propagation), and unfavourable ones, $\beta > \frac{\pi}{2}$ (that is side streets that have a direction that is against signal propagation).

We want to find θ_{min} that gives the minimum of (13), that is N_{min}.

$$\begin{aligned} N_{\text{min}} = & \frac{-c_1 \pm \left(c_1 c_2 \tan^2(\beta) + c_1 c_2\right)^{\frac{1}{2}}}{\tan(\beta)} + c_2 \tan \left[\beta + \right. \\ & \left. - \arctan\left(\frac{-c_1 \pm \left(c_1 c_2 \tan^2(\beta) + c_1 c_2\right)^{\frac{1}{2}}}{c_1 \tan(b)}\right) \right] \end{aligned} \tag{14}$$

For $0 < \beta < \frac{\pi}{2}$ the minimum number of reflections is given by (14) evaluated with plus sign.

Assume now $\beta > \frac{\pi}{2}$. In this case we have to add the condition $\theta > \beta - \frac{\pi}{2}$ to assure that the ray goes through the side street and is not reflected away and N_{min} is given by (14) evaluated with minus sign.

Finally if $\beta = \frac{\pi}{2}$ we obtain again the original value of N_{min} of Eq. (1).

Another model improvement about the calculus of reflection contributions has been made by dropping the constant loss per reflection hypothesis and modeling L_r, expressed in dB, according to the incidence angle

$$L_r = 10 \log\left(\left|\frac{\cos(\alpha) - (\epsilon_c/\epsilon_0 - \sin(\alpha)^2)^{\frac{1}{2}}}{\cos(\alpha) + (\epsilon_c/\epsilon_0 - \sin(\alpha)^2)^{\frac{1}{2}}}\right|\right) \tag{15}$$

where the argument of the logarithm is the reflection coefficient for a wave with a polarization parallel to the plane of incidence, α is the incidence angle, ϵ_c is the characteristic permittivity, ϵ_0 is the vacuum permittivity and f is the operating frequency.

IV. Measurements and Considerations

In order to validate the path loss of (6) and the accuracy improvements given by (12) and by equations stated in Section III-B, a measurement campaign has been carried out to collect data in a real microcellular environment.

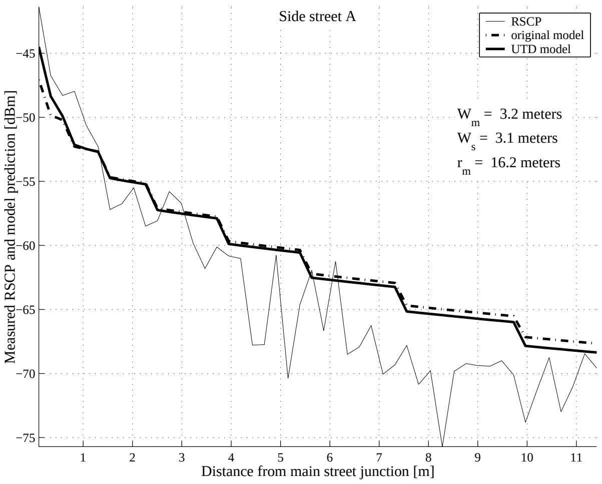

Fig. 3. Measured RSCP (thin solid line), original model prediction (dash–dotted line) and UTD model prediction (thick solid line) in side street A.

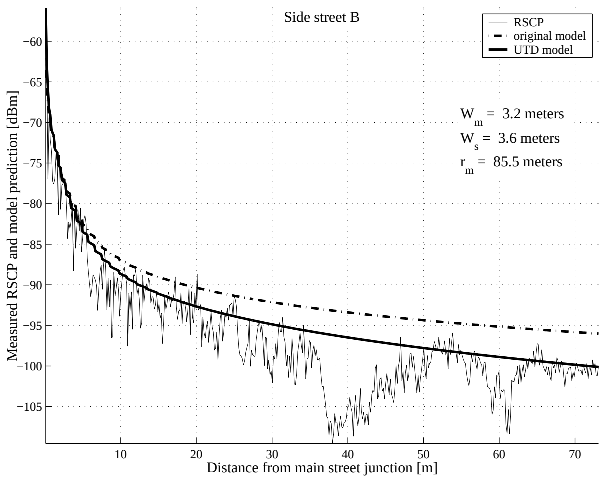

Fig. 4. Measured RSCP (thin solid line), original model prediction (dash–dotted line) and UTD model prediction (thick solid line) in side street B.

The measurement campaign has been set in Genoa's old town centre, where the urban structure makes it necessary to use microcells to guarantee a suitable coverage. The selection of the analyzed streets has been made as much as possible consistent with the model hypotheses.

In old town centres, street widths range approximatively between 2 and 6 meters and the buildings along the streets are tall (3 to 7 floors): this configuration is an extreme case of urban canyon and is the typical environment where microcell propagation takes place. Measurements have been made using the following tools and parameters:

- vertically polarized transmitting antenna with 7 dBi gain placed in the middle of the street, 3.5 meters high;
- UMTS transmitter with output power set at 20 dBm and carrier frequency set at 2.1626 GHz;
- PC and UMTS scanner equipped with an omnidirectional receiving antenna moved in the middle of the streets, 1.5 meters high;
- measured data: CPICH RSCP (Received Signal Code Power on Common Pilot Channel), that is the received power on one code measured on the pilot bits of the Primary CPICH, after despreading [1], sampling rate: 25 samples/sec;

A. Diffraction improvement

In the first tests we assumed that junctions are perpendicular and the loss due to a single reflection has a constant value of -2 dB, while the values of other parameters, such as main street width W_m, side street width W_s and transmitter distance r_m from junction J, are listed in each figure: in this cases we evaluated only the effects yielded by diffraction calculus improvement.

In side streets it has been observed (see also [7]) that the received power is dominated by the reflected components when the receiver is near to junction J. However, these components drop much faster than the diffracted components as the receiver moves away from the junction, where the diffraction becomes therefore the main propagation effect.

Fig. 3 refers to a side street, named A, that is very short, about 11 meters long, therefore the main contribution is carried by reflected signals: this is clearly shown by the step–like shape of the prediction that agrees with measured signals. Furthermore, changing the way diffraction is calculated yields little changes in the prediction, as it is clearly visible comparing the thick solid line and the dash–dotted one of Fig. 3.

Side street analyzed in Fig. 4 is longer than side street A. In the prediction curve, the contribution due to reflected signals and to the diffracted ones are clearly visible in the initial and in the final part of the side street, respectively. In general, the reflected contribution is dominant in the first 15–25 meters, depending on street characteristics, while in the remaining part only diffraction is significant. In cases where reflection is the most important effect, the two formulas lead to similar predictions (step–like shape).

In general, original model predictions well agree with measured data for perpendicular junctions; however, where diffraction becomes the dominant effect, predictions degrade faster than using UTD. This is probably due to the not perfect match between street characteristics and the simplifying hypotheses used to develop the model: in particular narrow streets, like the ones in our scenario, have a very complex structure and this originates several higher order contributions not included in the original model. On the contrary, UTD formulas, evaluated using parallel polarization and perfect conductor, seem to better predict the global signal behaviour.

B. Reflection improvement

In this section, measurements made in side streets that cross main streets not perpendicularly are compared with the model: it now includes all the improvements, that is diffraction is evaluated using UTD formulas, the number of reflections depends on the insertion angle at the junction and the loss per reflection is chosen according to the incidence angle.

In Fig. 5 the transmitting antenna is very far from the junction, $r_m = 161$ meters, and so fast power decreasing, due to reflection contributes, is not so clear as in the other

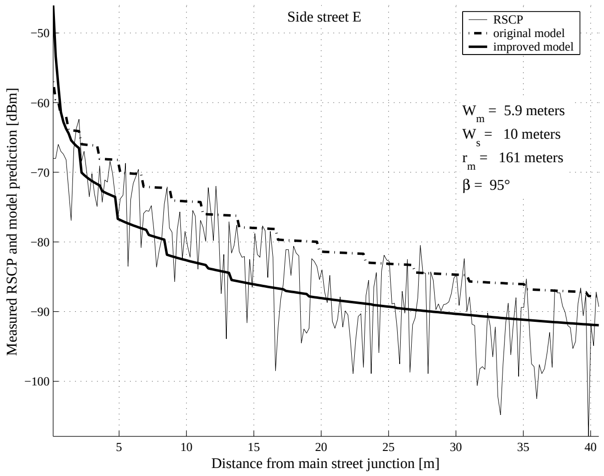

Fig. 5. Measured RSCP (thin solid line), original model prediction (dash–dotted line) and improved model prediction (thick solid line) in side street E.

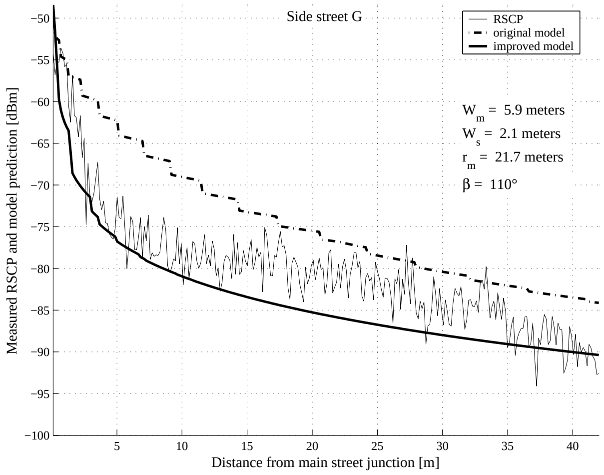

Fig. 6. Measured RSCP (thin solid line), original model prediction (dash–dotted line) and improved model prediction (thick solid line) in side street G. First 10 meters show the important improvement of the model that well agree with data.

examples; this is probably also due to side street width because this is one of the little examples of quite wide street in the old city centre. The insertion angle is little unfavourable. In the range 10–20 the model little underestimates received power, while model and recorded data agree well in the other parts of the street.

Fig. 6 shows how the improvements done about reflection are important. This propagation effect is important, in this case, mainly in the first 10 meters: received power decreases very quickly in this part of street and the improved model, thanks to the variable loss and the calculus of the incidence angle, models this behaviour agreeing very well with recorded data.

Model accuracy in the first 20–25 meters is particularly important in this scenarios for cellular coverage planning. These parts of the streets are critical due to the rapid power decrease: mobile terminals might not be able to create a new active set for handover procedures before the radio link with their serving base station becomes too weak to keep the connection active.

V. Conclusions

In this paper a model [7] to predict signal behaviour in large side streets has been analyzed, improved and validated for the case of narrow side streets in old town centres: a measurement campaign has been conducted to acquire real data in the UMTS band in this microcellular environment.

The model shows appreciable match with real data under the simplifying hypotheses of street grid listed in Sec. II: the comparison between model prediction and real data shows that the model is suitable to analyze propagation in this environment.

The original model [7] has been improved to better model signal behaviour both in the part near junctions and in the far part. If diffraction contribution is calculated using the UTD approach, prediction error is practically halved far from the junctions, without increasing model complexity, as shown in Sec. IV. Model has also been made more adaptable by generalizing the way reflection is calculated: this allows to take into account not perpendicular junctions and to improve model prediction in the first 20–25 of side streets where reflection is the dominant propagation effect and where measured data exhibit a fast power decrease that can be crucial for mobile terminals handover.

References

[1] H. Holma and A. Toskala, *WCDMA for UMTS Radio Access For Third Generation Mobile Communications*, 3rd ed. John Wiley & Sons, 2004.

[2] T. K. Sarkar, Z. Ji, K. Kim, A. Medour, and M. Salazar-Palma, "A survey of various propagation models for mobile communication," *IEEE Antennas Propagat. Mag.*, vol. 45, no. 3, pp. 51–82, June 2003.

[3] D. J. Cichon and T. Kürner, *COST 231 documents*, 1996, ch. 4 Propagation Prediction Models, pp. 115–207.

[4] W. Zhang, "Fast two–dimensional diffraction modeling for site–specific propagation prediction in urban microcellular environments," *IEEE Trans. Veh. Technol.*, vol. 49, no. 2, pp. 428–436, Mar. 2000.

[5] H. Son and N. Myung, "A deterministic ray tube method for microcellular wave propagation prediction model," *IEEE Trans. Antennas Propagat.*, vol. 47, no. 8, pp. 1344–1350, Aug. 1999.

[6] G. E. Athanasiadou, A. R. Nix, and J. P. McGeehan, "A microcellular ray–tracing propagation model and evaluation of its narrow–band and wide–band predictions," *IEEE J. Select. Areas Commun.*, vol. 18, no. 3, pp. 322–335, Mar. 2000.

[7] Q. Sun, S. Y. Tan, and K. C. Teh, "Analytical formulae for path loss prediction in urban street grid microcellular environments," *IEEE Trans. Veh. Technol.*, vol. 54, no. 4, pp. 1251–1258, July 2005.

[8] A. J. Rustako, Jr., N. Amitay, G. J. Owens, and R. S. Roman, "Radio propagation measurements at microwave frequencies for microcellular mobile and personal communications," in *IEEE International Conference on Communications*, Boston, June 1989, pp. 482–486.

[9] Y. Nagata, Y. Furuya, E. Moriyama, M. Mizuno, I. Kamiya, and S. Hattori, "Measurement and modeling of 2 GHz–band out–of–sight radio propagation characteristics under microcellular environments," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, London, Sept. 1991, pp. 341–346.

[10] M. Born and E. Wolf, *Principles of optics*, 6th ed. Pergamon Press Ltd, 1980.

[11] A. G. Kanatas, I. D. Kountouris, G. B. Kostaras, and P. Constantinou, "A UTD propagation model in urban microcellular environments," *IEEE Trans. Veh. Technol.*, vol. 46, no. 1, pp. 185–193, Feb. 1997.

[12] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proceedings of the IEEE*, vol. 62, no. 11, pp. 1448–1461, Nov. 1974.