Evaluating Propagation Models for Communications with Low and Ultra-Low Altitude Platforms in Skyscraper Environments

Irem Bor-Yaliniz, *Student Member, IEEE,* Sebastian S. Szyszkowicz, *Member, IEEE,*,
Halim Yanikomeroglu *Senior Member, IEEE*

***Abstract*—Unmanned aerial vehicles (drones) have recently received significant attention for civilian applications due to their agility in delivering various services or providing capacity as mobile base stations. However, air-to-ground propagation characteristics are not well studied in these skyscraper environments. According to some existing models, line-of-sight (LoS) communication with low-altitude platforms (LAPs) can be achieved at significantly higher altitudes than rooftop level, but this results in high propagation loss due to the increased distance. Alternatively, ultra-low-altitude platforms (ULAPs) operating at near- or below-rooftop altitudes could be deployed, and the channel could be evaluated using geographical building data to determine the presence of LoS. In this study, we evaluate one of the widely used air-to-ground channel models that depends on the probability of LoS (the probabilistic model), and two other channel models that rely on the evaluation of the LoS condition, which can be obtained from the city maps (deterministic models). We modify an ITU channel model to model propagation for both LAPs and ULAPs with the adjustment of a single parameter, while the existing models are only valid either for LAPs or ULAPs. Comparing with ray-tracing simulations, we show that the modified deterministic model most closely follows the predicted propagation pattern.**

***Index Terms*—Drone communications, channel modelling, ray-tracing, urban propagation, line-of-sight.**

I. Introduction

Low-altitude unmanned aerial vehicle platforms (LAPs), i.e., drones, can provide crucial services to civilians, from ubiquitous cellular coverage to emergency aid delivery [1], [2]. However, operational safety and cost are major concerns, which delay the deployment of such services in populated areas. On the other hand, future wireless networks should enable drone operations by providing reliable control for beyond line-of-sight (LoS) and extending the range of drones.

Communications with drones can serve two purposes: First, the communication link can be used to control the operation of the drone [3]. Second, a drone-base-station (drone-BS) can provide wireless ground coverage in *drone-assisted cellular communications* [1]. Drone-based communications in dense urban environments are particularly important, because the first realizations of 5G-and-beyond wireless networks are expected to be in areas with dense population.

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The authors are with the Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada. (e-mail: {irembor, sz, halim}@sce.carleton.ca).

There are few propagation models in urban environments for LAPs [4]–[8]. Among these models, only [8] considers high-rise dense urban environments, with buildings of 60 m height on average. However, metropolitan areas often consist of even higher buildings, with an average building height of 100 m, which can be defined as a *skyscraper environment*. In such environments, there is a conflicting requirement when flying LAPs at higher altitudes (which improves the LoS link opportunities with the ground), but at the cost of higher link pathloss. Therefore, placing drones near or below rooftop level becomes an option.

Existing studies do not take into account that a LAP[1] can be lower than a high-rise building, which changes the propagation model significantly. Because the operational altitude can vary significantly from tens of meters to tens of kilometres, we would like to describe the LAPs lower than 200 m as *ultra-low-altitude* platforms (ULAPs), where 200 m represents near-rooftop level of many skyscrapers. For instance, if the drone is operated at higher altitudes than rooftops, the dominant reason for path loss is the reflection and diffraction around the roof-edges [8], [9]. However, if the drone is operated at altitudes lower than the majority of the rooftops, street canyon propagation models can be more appropriate.

In this paper, we introduce *skyscraper urban environments* and conduct ray-tracing simulations to investigate their propagation characteristics, and compare these results with three propagation models: a probabilistic model that uses a LoS probability to adjust propagation loss, and two deterministic models that determine the presence of LoS based on building geometry, and switch between different propagation models for LoS and non-LoS (NLoS) paths. Furthermore, we show that the amount of diffraction, which is one of the main factors causing different propagation characteristics between altitudes strictly below and significantly higher than rooftops, can be modelled by adjusting a parameter of the ITU model in [9]. Then this adjusted model can be utilized for both LAPs and ULAPs, the original model being good only for ULAPs. We show that the deterministic channel models outperform the probabilistic one, mainly due to more accurate determination of LoS or NLoS, especially at lower altitudes. The root-mean square error (RMSE) results show that the modified ITU model provides more accurate results for both LoS and NLoS links for both LAPs and ULAPs, compared to other models.

[1]LAPs are platforms flying lower than 10 km

II. Urban Environments

From the perspective of drone communications, urban environments can be classified based on the average height of the buildings:

1) **High-rise Urban:** Consists of buildings with several floors ($\leq$ 30 m).
2) **Very High-rise Urban:** Consists of densely located buildings with several tens of floors (between 30 and 100 m).
3) **Skyscraper Urban:** Consists of densely located skyscrapers ($\geq$ 100 m).

While the first two cases are introduced by [10], we propose the last case for the first time in the UAV literature to describe communications with drones in metropolitan cores such as Hong Kong (521 skyscrapers), New York (771 skyscrapers), and Tokyo (276 skyscrapers) [11]. The particulars of this environment are the extreme heights of the buildings, the high population density, and the deep street canyons, and represent a unique propagation scenario.

Many humanitarian or civil applications of drones in urban areas, such as cargo or emergency-aid delivery, already require ULAPs [2]. Additionally, ULAPs serving as drone-BSs can be especially useful for skyscraper urban environments, where increasing LAP altitude does not necessarily provide more coverage [1]. Note that any application of a drone would require a very reliable communication link to ensure safety of the operation beyond LoS.

There is a lack of models for drone communication channels in urban environments because of two reasons: First, civilian drones are still very recent. Second, drone operations in highly populated areas are strictly prohibited, which currently makes it impossible to obtain channel measurements. Therefore, we have conducted ray-tracing simulations and considered them as a benchmark to evaluate the existing channel models.

III. Channel Models for Low and Ultra-Low Altitude Platforms

The existing models for air-to-ground propagation are valid for LAP altitudes much higher than the rooftops of the buildings in the considered urban setting. For instance, urban areas with buildings of 4 to 6 floors, which corresponds to a typical European city or campus area, are considered in [4]–[6]. These models do not represent the street canyon propagation characteristics of skyscraper environments in terms of presence of LoS, reflection, and diffraction mechanisms, because the altitude of the drone is much higher than the buildings.

A. Probabilistic Model

Recently, an air-to-ground channel model based on [9] was presented in [8]. The average path loss is calculated based on the combination of the following two effects:

1) Free-space loss is modelled via the Friis equation, which can be written as follows for a user[2] located at (x, y) and the drone at (x_D, y_D, h):

$$L_f(h, r) = 20 \log\left(\frac{4\pi f_c}{c}\right) + 20 \log\left(\sqrt{h^2 + r^2}\right), \quad (1)$$

where h is the altitude of the drone, and $r = \sqrt{(x_D - x)^2 + (y_D - y)^2}$ is the horizontal distance between the drone and the user.

2) Channel variation due to diffraction and reflection off environmental obstacles may result in an additional loss. If the terrestrial user and drone have a LoS link, the amount of excessive loss is less, compared to a NLoS connection:

$$L_e(h, r) = \begin{cases} \eta_{LoS}, & \text{if LoS}, \quad (2a) \\ \eta_{NLoS}, & \text{if NLoS}, \quad (2b) \end{cases}$$

where η_{LoS} and η_{NLoS} are the amount of excessive loss for a LoS and a NLoS link, respectively. A *probabilistic model* (PM) is developed in [8] based on the following probability of LoS:

$$P(h, r) = \frac{1}{1 + a \exp\left(-b\left(\arctan\left(\frac{h}{r}\right) - a\right)\right)}, \quad (3)$$

where a and b are constant values depending on the environment. Then the excessive loss can be written as

$$L_e(h, r) = P(h, r)\eta_{\text{LoS}} + (1 - P(h, r))\eta_{\text{NLoS}}. \quad (4)$$

The loss of the air-to-ground link is then

$$L(h, r) = L_f(h, r) + L_e(h, r). \quad (5)$$

B. Basic Deterministic Model

Building geometry can be used to determine LoS and NLoS regions, which also simplifies the model by eliminating the need to calculate $P(h, r)$. Hence, the channel models that use city maps become more *deterministic models*: If a point is known to be LoS or NLoS, this information can be used to switch to the corresponding option in (2). This is the *basic deterministic model* (BDM).

C. Urban Canyon Model

A more sophisticated deterministic model, the urban canyon model (UCM), is investigated in this section. The UCM depends on a model recently released by ITU-R for below-rooftop propagation within street canyons in urban environments, which requires the knowledge on the locations of the BSs and the users, as well as the street widths, shapes, and alignments [10]. This model can also be valid for drone channels when ignoring near-field effects of flight and machinery, such as attenuation due to the drone's body and effects of turbulence, similarly to the approach of the previous air-to-ground models [4]–[6], [8].

[2]The "user" in this study is either the pilot of the drone, or a person on the ground served by a drone-BS.

1) Line-of-Sight Propagation: The median of the LoS pathloss is given by

$$L_{LoS} = L_b + 6 + \begin{cases} 20\log\left(\frac{d}{R_b}\right), & \text{if } d \le R_b, \quad (6a)\\ 40\log\left(\frac{d}{R_b}\right), & \text{if } d > R_b, \quad (6b)\end{cases}$$

where $d = \sqrt{h^2 + r^2}$ is the distance between a user and drone, $R_b \approx \frac{4h_D h_u}{\lambda}$ is the break-point distance, and h_D and h_u are the heights of the drone and the user, respectively.

2) Non-Line-of-Sight Propagation: In addition to L_{LoS}, there are two other components for NLoS propagation in deep urban canyons [10, Chap. 4.1.2]: First, the loss at the corner region is described by

$$L_{corner} = \begin{cases} \frac{L_c}{\log_{10}(1+d_c)}\log_{10}\left(l_{u,c} - \frac{w_d}{2}\right), \\ \text{if } \frac{w_d}{2} + 1 \le l_{u,c} \le \frac{w_d}{2} + 1 + d_c, \quad (7a)\\ L_c, \\ \text{if } l_{u,c} > \frac{w_d}{2} + 1 + d_c, \quad (7b)\end{cases}$$

where $l_{u,c}$ represents the user's distance from the corner, w_d is the width of the streets. Corner loss region, and corner loss are represented by d_c and L_c, respectively. Then, attenuation beyond the corner region is given as

$$L_{att} = \begin{cases} 60\log_{10}\frac{l_{u,c} + l_{d,c}}{l_{u,c} + \frac{w_d}{2} + d_c}, \\ \text{if } l_{u,c} > \frac{w_d}{2} + 1 + d_c, \quad (8a)\\ 0, \\ \text{if } l_{u,c} \le \frac{w_d}{2} + 1 + d_c. \quad (8b)\end{cases}$$

Note that $l_{d,c}$ denotes the drone's distance to the corner region, i.e., the intersection of the drone's street with the street where the user is located. Finally, the path loss for a NLoS link becomes,

$$L_{NLoS} = L_{LoS} + L_{corner} + L_{att}. \quad (9)$$

Note that L_c is a critical parameter in determining the path loss, as it determines the average amount of diffraction, and is given as 20 dB in [9]. We propose to adjust L_c based on the altitude, because loss around the corner decreases with increasing altitude. For instance, if the altitude of a LAP is strictly higher than the rooftop level of the buildings, there will be more diffraction rays contributing to the channel. For ULAPs at altitudes strictly lower than rooftop levels of the buildings, diffraction is less likely to occur, and L_c must be higher than the one in the previous case, which is verified by our experiments in the next section.

IV. Simulations and Discussions

The channel models presented in the preceding sections are evaluated against ray-tracing simulations on a toy map of a skyscraper environment with regular block size of 60 m, street width of 20 m, and buildings with a fixed height of 100 m. The propagation loss of the drone communication link is presented as a heat map in Fig. 1, Fig. 2, and Fig. 3, where $h \in \{50 \text{ m}, 200 \text{ m}, 1000 \text{ m}\}$, respectively. The drone is hovering at $(255, 255, h)$ over the point marked with a black star, which is the center of the intersection. The ray-tracing experiments were conducted using *Wireless InSite*[3]. The parameters of the channel models and ray-tracing experiments are given in Table I.

TABLE I: Simulation parameters for ray-tracing and channel models.

Parameter	Value
Conductivity of walls	150×10^{-4} S/m
Conductivity of ground	5×10^{-4} S/m
Permittivity of walls	15 (relative)
Permittivity of ground	5.72 (relative)
Thickness (walls and ground)	0.3 m
Building height (h_B)	100 m
Building width	60 m
Street width (w_d)	20 m
Simulation grid step	5 m
Carrier frequency (f_c)	2.5 GHz
Receiver height	1 m
Drone altitude	$h \in \{50 \text{ m}, 200 \text{ m}, 1000 \text{ m}\}$
L_c (urban)	$L_c \in \{30 \text{ dB}, 20 \text{ dB}, 5 \text{ dB}\}$
d_c (urban)	30 m [10]
η_{LoS} (high-rise)	2.3 dB [8]
η_{NLoS} (high-rise)	34 dB [8]

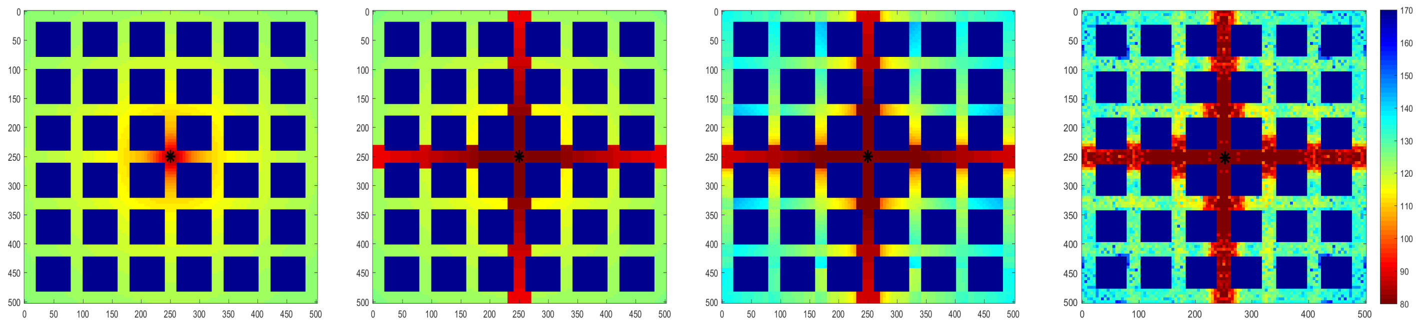
For the PM, a circular propagation pattern can be observed in Fig. 1a, 2a and 3a, because the probability of having a LoS connection only depends on distance and altitude, as given in (3). Therefore, the PM is more suitable for altitudes much higher than rooftop, as in the case of Fig. 3a, because the propagation is dominated by free-space loss as $h \gg r$. In other words, (5) is dominated by $L_f(h,r)$ as $L_e(h,r)$ approaches η_{LoS}, and errors in the LoS probability becomes less significant. This situation can also be observed in Fig. 4, and as h increases the PM resembles the linear regression line of the ray-tracing data.

Fig. 1b, 2b, and 3b show the propagation pattern of the BDM model. For h= 50 m and 200 m, there is no LoS connection, except on the drone's streets. However, at $h =$ 1000 m, LoS regions appear in other streets as well.

The deterministic models perform better in predicting ray-tracing simulations in Fig. 1 and Fig. 3 compared to Fig 2. In particular, the UCM can capture weak-diffraction ($h = 50$ m) and strong-diffraction ($h = 1000$ m) cases by adjusting L_c in (7b) successfully, which is supported by the RMSE values in Table II. Note that the UCM has the best overall RMSE, meaning the RMSE for LoS and NLoS combined at these altitudes. On the other hand, its RMSE at 200 m altitude is comparable to that is other methods. When the altitude increases to 200 m in Fig. 2 and Fig. 4b the ray-tracing results starts to differ from Fig. 2c, because the near-rooftop diffraction cannot be captured with the UCM.

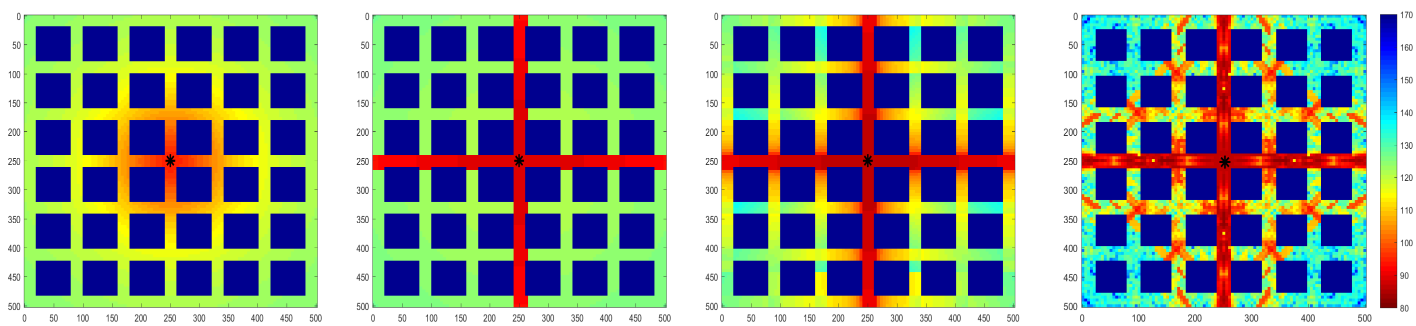
In summary, PM has significant error for lower altitudes, making this model a better option for LAPs rather than ULAPs. The BDM, which is also the simplest model, performs almost the same as the UCM for LoS; however, it has worse performance for NLoS at 1000m. The UCM has the best

[3]http://www.remcom.com/wireless-insite



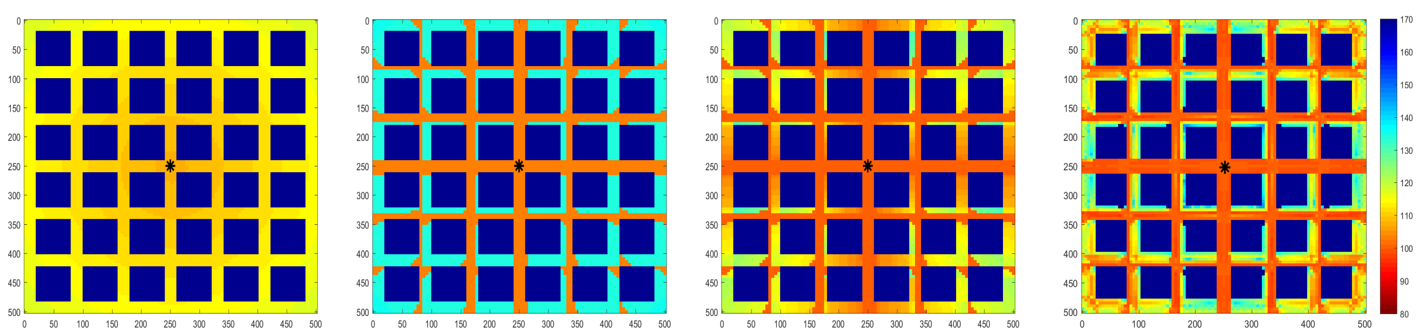
(a) Probabilistic model in [8]. (b) Basic deterministic model (2). (c) Model in [10] ($L_c = 30\ dB$). (d) Ray-tracing experiment.

Fig. 1: Propagation patterns for a drone-BS at 50 m altitude.



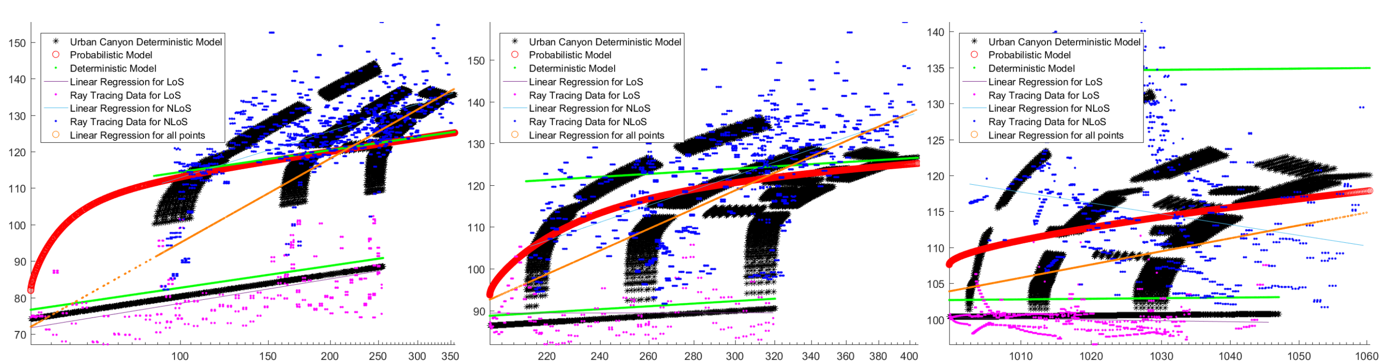
(a) Probabilistic model in [8]. (b) Basic deterministic model (2). (c) Model in [10] ($L_c = \ 20dB$). (d) Ray-tracing experiment.

Fig. 2: Propagation patterns for a drone-BS at 200 m altitude.



(a) Probabilistic model in [8]. (b) Basic deterministic model (2). (c) Model in [10] ($L_c = 5\ dB$.) (d) Ray-tracing experiment.

Fig. 3: Propagation patterns for a drone-BS at 1000 m altitude.



(a) Propagation data at 50 m. (b) Propagation data at 200 m. (c) Propagation data at 1000 m.

Fig. 4: Propagation data at different altitudes compared with ray-tracing simulation results.

TABLE II: RMSE of propagation models for building heights h_B of 60 m and 100 m.

Model	Altitude \ $\mathbf{h_B}$	RMSE for LoS 60 m	RMSE for LoS 100 m	RMSE for NLoS 60 m	RMSE for NLoS 100 m	Combined RMSE 60 m	Combined RMSE 100 m
Probabilistic (PM)	50 m	34.27	34.24	10.15	10.33	16.97	17.04
	200 m	24.00	24.10	15.93	11.98	16.35	13.72
	1000 m	11.20	11.97	10.41	8.85	10.31	9.73
Basic Deterministic (BDM)	50 m	8.01	7.99	9.98	10.14	9.24	9.36
	200 m	3.05	5.68	19.56	13.01	16.36	11.17
	1000 m	2.41	3.37	16.60	21.47	7.66	15.03
Urban Canyon (UCM)	50 m	7.12	7.11	9.04	8.82	8.40	8.19
	200 m	2.52	5.72	18.13	13.88	15.45	12.25
	1000 m	2.24	1.95	13.56	12.49	6.53	9.07

performance for altitudes lower or higher than rooftops, but it does not perform well for altitudes around rooftops. The relative height of the drone and surrounding buildings has a significant effect on the propagation characteristics, which must be considered when controlling drones, or providing coverage with drone-BSs.

V. Conclusion

Measurement campaigns to collect propagation data in the skyscraper drone environment are not currently possible due to regulatory restrictions of flying drones that have enough capability (payload weight) to perform channel measurements in populated areas at the moment. There exists a dilemma whether it is possible to guarantee safe drone operations due to lack of channel models, and it is difficult to improve channel models due to safety concerns. Therefore, we have conducted ray-tracing experiments in skyscraper environments for LAPs and ULAPs, and compared various channel models with the simulation results. We observed that “deterministic” models were a better match to ray-tracing data both in the visual patterns, and in the error calculations. We conclude that, regardless of the channel model used, the channel model for drones in skyscraper environments should be aware of the line-of-sight condition, which can be obtained from building geometry and map data. The ground coverage by a single drone, or multiple drones, can then be evaluated much more accurately.

The models discussed in this article are based on experiments conducted with terrestrial base stations [9], [10]. Whether drone-specific communication issues will be solved by designing drones properly [1] or they will need to be mitigated by secondary techniques such as signal processing remains as an open question. Our study aims at changing the game by introducing the help of city maps and line-of-sight evaluation to increase the precision of the communication channel models. That is an acceptable assumption for cities, where the maps are known, and the main blockage is buildings, rather than vegetation.

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