Corner-3D: a RF Simulator for UAV Mobility in Smart Cities

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ABSTRACT

Communication between human-made devices keeps changing. The evolution of the society is tightly linked to the technological and communication development. Today's IoT momentum is fuelling an unstoppable advancement in the communication research field. The emerging communication paradigms outcome of that, represent one of the key enablers of UAVs diffusion in both industrial and leisure applications. Thanks to using cases as infrastructure inspection, surveillance, and rescue, UAVs are quickly becoming one of the pillars of future smart cities. Despite their huge potential, a lot of research and testing is still to be done to fully exploit them. In particular, accurately modeling UAV communications is among the hardest challenges the research community has not properly faced, yet. In this paper, we present CORNER-3D, a lightweight simulator to model the path loss suffered by UAV-to-UAV communications in an urban scenario.

CCS CONCEPTS

• **Networks** → **Network simulations**; • **Computing methodologies** → *Model verification and validation*; Modeling methodologies.

KEYWORDS

Simulation, propagation, path loss, NS-3, UAV

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1 INTRODUCTION

Today's society is quickly and steadily becoming more and more connected. Moreover, with the spreading diffusion of IoT devices, ubiquitous computing, and autonomous mobility, Smart Cities are close to be a reality. The growing number of new-born applications and human needs are generating a huge amount of data traffic. Despite the improvements in terms of computing resources of mobile devices, they are not always able to handle the enormous application-driven computational and network load. Thus, offloading services is becoming of key importance.

Given their diffusion and their ubiquitous nature, UAVs (Unmanned Aerial Vehicles) are rapidly becoming a crucial component in the future Smart Cities. Thus, the increasing need for safety regulations. Not only the industrial applications are quickly doubling, but the hype around UAVs is also fuelling furious research from multiple Communities. The challenges, indeed, span from purely control theory formulation (faced by the Robotics Community) to systems design (Mobile Systems), up to RF communication (Computer Networks and Signal Processing Communities). In spite of their steadily increasing adoption, Unmanned Aerial Vehicles are still quite potentially harmful. Therefore, the need for exhaustive testing is quickly becoming a key asset in order to prevent injuries.

While a great body of work has been done trying to model RF communications between terrestrial vehicles ([2], [15], [23]), the literature is still missing a reference simulator to accurately model Radio Frequency communications between flying UAVs. The challenges that arise in modeling Unmanned Aerial Vehicles communications are multiple, starting from the unbounded, constraint-free mobility intrinsic of UAVs. With the freedom that characterizes UAVs comes the need for accounting a third dimension: the height.

With this work, we propose CORNER-3D, a lightweight model to predict the path loss by the given road map of the urban scenario. CORNER-3D can determine the positional relationship with reference to the location of the potentially communicating UAVs and the distribution of the surrounding obstacles in the simulation environment. The radiation characteristics and properties of the antenna are crucial. Our work leverages those to provide a more accurate understanding and prediction of the connection path between the UAVs. Moreover, CORNER-3D well balances the trade off between the calculation complexity and the accuracy of the prediction. In this paper, we present the simulation results and provide a comprehensive analysis of CORNER and CORNER-3D. We indicate the applicability of CORNER-3D in the flat model, and we provide valuable insights on the impact of height difference between UAVs when calculating path loss.

The remainder of the paper is organized as follows. In Section 2 we present the system design of the path loss prediction model in detail. The simulation results are given by CORNER-3D under NS-3 environment and the analysis of the results are described in Section 3. We discuss the related work and potential future directions in Section 4. Finally, we draw our conclusions and provide extra reasoning in Section 5.

2 SYSTEM DESIGN

In this section, we elaborate and explain the models we built. Furthermore, we compare and analyze the similarities and the differences with other models introduced by previous studies.

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2.1 Flat Propagation Model in Urban Scenarios

Opposite to the open and empty geographical environment on the rural areas, the complex road and topological map of urban areas pose serious challenges to the estimation and prediction of the radio wave propagation. The path loss is estimated by the ray-tracing deterministic N ray model [5]. Considering the trade-off between the computational complexity and the accuracy of the prediction, the "Two Ray" *(N = 2)* model is applied in the computation of path loss (PL) in this paper. As a result of that, the "Two Ray" model can only be used when the positional relationship between the transmitter and the receiver is in line of sight (LOS). Regarding the propagation model, CORNER-3D leverages on the scheme CORNER from Eugenio Giordano et al.[10]. Reference to the local road topology and the obstacles characteristics in the urban scenarios, such as buildings, CORNER applied the path loss (PL) formulas introduced in [21]. In their flat propagation model, the location relationship between two nodes (transmitter and receiver) includes the following three possibilities: line of sight (LOS), on the two adjacent sides of an obstacle without line of sight (NLOS1), and along the two different parallel streets without line of sight (NLOS2).

2.2 CORNER-3D Propagation Model

CORNER[10] mainly focuses on the communication and propagation between vehicles, without accounting for the effects introduced by the third dimension, the height. When it comes to urban scenarios, considering the altitude, the difference of the height between the transmitter, receiver, and obstacles, leads to a more complicated and changeable detection in the positional relationship. To mitigate the complexity, we propose CORNER-3D. CORNER-3D simulates and predicts the path loss (PL) of vehicles. In addition, it provides a possible simulation and prediction of the PL for the unmanned aerial vehicle (UAV) RF communication in the urban area. In this way, CORNER-3D propagation model will no longer be limited to the applications, such as traffic information collection and exchange. In fact, CORNER-3D will also suit for disaster monitoring, emergency rescue, operations, etc.

Instead of using QUALNET[19], as done by the authors of CORNER, we provide the simulation results leveraging NS-3 [1]. QUALNET provides a complete graphical user interface and is used by Scalable Network Technologies (SNT) with the GloMoSim as the base, which makes QUALNET commonly used in many network simulations. However, it is a commercial software without a free trial or education version in the market. At the same time, with the respect to open source software, such as NS-3, the user base is smaller, and thee are fewer resources and more limitations to using QUALNET. Moreover, NS-3 embeds a number of functional libraries and models for mobility and propagation, which is easy to modify and better suit our goals. The UAV communicates according to the IEEE802.11b standard. The traffic of the network follows Poisson process with the size of the packet 1024 Bytes, 100 packets per second. During the simulation, the nodes are set up as constant position mobility. The obstacles in the simulation environment are the commercial type of building with stone blocks wall type. This is a material type provided by the ns3::Building class in Mobility model.

CORNER-3D utilizes the formulas of PL calculation proved in [21] during the simulation (presented in section 2.2.4). Since the formulas calculate the PL between the transmitter and the receiver with the same height in a flat propagation model. CORNER-3D classifies the positional relationships of the transmitter and the receiver first, then adds the third dimension to precisely calculate the actual distance in space. The carrier frequency of the antenna we used in the simulation is 2.4GHz. In order to be closer to the actual road conditions, then the road map built for the geographical environment includes two-way lane and considering the sidewalk. All road map parameters are in meters for the unit. The road width (RW) is generated by the simulator following the formula:

$$RW = (NL \times 2 \times LW) + 10 \tag{1}$$

$$NL = random(1, 4)$$

NL is the number of lanes per direction. It is a randomly generated integer between 1 and 4 with equal probability. We assume all the roads are two-way lanes. Thus, NL is multiplied by two. Lane Width (LW) is the nominal, or base, value of the lane width [12], and it is set to a constant value of 3.6m. Moreover, we add 10m to consider the sidewalk [10].

The procedure we followed to implement the UAV mobility and communication in CORNER-3D can be summarized in the following steps:

- Positional relationships classification:
  - According to the flat propagation model, identification and classification of the positional relationship category on the plane.
  - Further detection of the location relationship of the UAVs when they are under NLOS1 and NLOS2 categories in flat model. Using Fresnel theory and Fresnel zone with the consideration of height, classify that whether they form the line of sight (LOS) in the space.
- Update of the transmitter position:
  - To build the LOS relationship and then apply the theory of antenna communication, we move the transmitter to the closest street junction point to the receiver to build the LOS relationship when the UAVs cannot form the LOS relation in both flat the 3D propagation model.
- Building the conditions for antennas communication:
  - According to the parameters of the antennas used in the UAVs calculation to obtain the effective radiation range.
  - Calculation of the effective overlapping area within the radiation range of the on-board UAV antennas.
- CORNER-3D path loss calculation:
  - Usage of the real distance under the original, or virtual LOS path to calculate the path loss between the transmitter and receiver if they have the conditions for communication.

2.2.1 *Positional relationships classification.*

The process to estimate the positional relationship classification starts with the detection in the flat model. Figure.1 presents two UAVs: the transmitter (Tx) and receiver (Rx) fulfill into the line of sight (LOS). The UAVs are lying on the same road segment, or at least in the angular view of each other. We start the detection

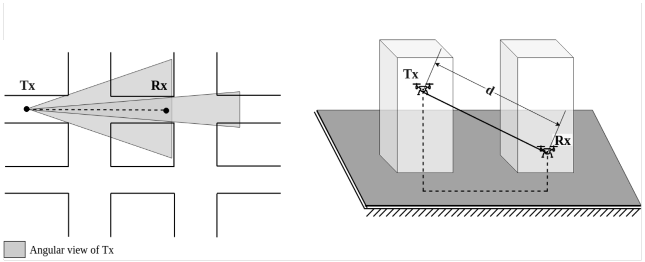

Figure 1: Graphical example: UAVs in LOS positional relationship when they are on the same road segment or within the angular field of view of each other.

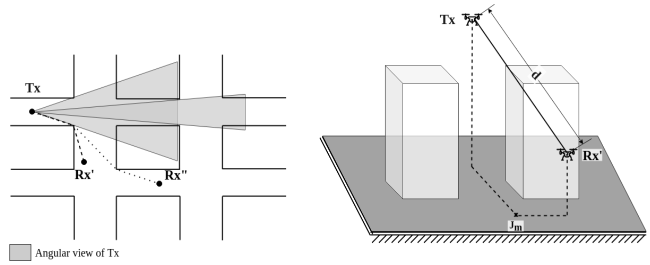

Figure 2: Graphical example: UAVs form NLOS positional relationship when they locate on the two adjacent sides of obstacles.

of positional relationships from the flat model aims to reduce the complexity of calculations and analysis. Separating LOS in flat first, because the detection of the spatial positional relationship following does not only depend on the calculation of the distance between the UAVs, but also on the complex positional relationship with respect to the obstacles. For instance, two UAVs are under no line of sight (NLOS) relationship in the flat model showed in Figure.2. However, accounting for the height difference between the UAVs and the obstacles, there is still the possibility of constituting the LOS relationship. In order to determine whether the two UAVs can transmit information in the space with obstacles, we need to draw support from the Fresnel zone, which is depicted as the long elliptical space between the antennas in Figure.3. The center of the circle on all sections of the ellipsoidal region falls on the line connecting the transmitter and the receiver. The equation to calculate the Fresnel zone radius of each section at the boundary is [25],

$$F_n = \sqrt{\frac{n \times \lambda \times d_1 \times d_2}{d_1 + d_2}} \tag{2}$$

where F_n is the nth Fresnel zone radius, d_1 is the distance from section boundary to one end, d_2 is the distance from the section boundary to the other end, and λ is the wavelength of the radio signal. When n = 1, F_1 is the radius in the first Fresnel zone. In the first Fresnel zone, the electromagnetic waves of different paths have the same effect on the receiving antenna. When the electromagnetic waves pass through the first Fresnel zone, the signal at the receiver is the strongest. In the remainder of this paper, we will only discuss the situation in the first Fresnel zone. In order to ensure the quality of the communication, the recommended blockage of the obstacles is up to 20%. If the intrusion of obstacles exceeds the 20% of the first Fresnel zone, we regard it as that the obstacle blocks the communication between the two UAVs. In such a scenario, the relationship between the UAVs is, therefore, NLOS.

2.2.2 *Update of transmitter position.*

After the classification of positional relationships, we account for the situations where the UAVs are under the NLOS assumption. To build an obstacle-free path for the antennas on the UAV, it is a necessary step to update the position of the UAVs. In this paper, we will update the position of transmitter UAV to the closest street junction to the receiver UAVs, as presented in Figure.4. The transmitter (Tx) moves to position Tx', which is directly above the junction J_m with the same height of the original transmitter for NLOS1. When in the NLOS2 situation, the transmitter (Tx) moves to Tx", directly above the street junction J_p. We use the PL formula in [21] to calculate path loss from the original position of the transmitter to the target point in the junction without changing the height. The equation of the power at the updated position is:

$$P_{Upd} = P_{Tx} - PL_{Upd-J} \tag{3}$$

where P_{Tx} is the power transmitted by Tx antenna, and PL_{Upd-J} is the path loss from the transmitter position to the updated one (street junctions: J_m or J_p). At this point, we have completed the construction of the LOS positional relationship between the UAVs.

2.2.3 *Conditions for antennas communication.*

In this work, we will use a dipole antenna placed on a quadcopter. The dipole antenna is the simplest and most widely used antenna in radio communication. Figure.5 shows the plane pattern of the dipole antenna, the two blue lines indicate where the gain decreases 3-dB from the maximum gain value. The 3-dB beamwidth of the dipole antenna is around 77.7 degrees. That is also known as the half-power beamwidth (HPBW) in Figure.6. After the updating position of the transmitter to build a LOS path, we use the HPBW to determine the communication of UAVs in all categories classified

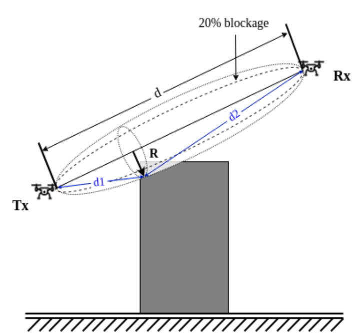

Figure 3: Positional relationship classification using Fresnel zone in 3D. When the intrusion of obstacles exceeds 20% of Fresnel zone, direct communication will be severely damaged and cut off. R is the radius of the Fresnel zone directly above the obstacle.

from the previous steps. Figure.6 shows that two antennas on the UAV build an obstacle-free path in the free space. Figure. 6 (a) shows that the UAVs are not in the radiation range of each other. When their half-power radiation range is overlap as Figure.6 (b), it means that the two UAVs are within the communication range of each other, the calculation of PL is meaningful.

2.2.4 CORNER-3D path loss calculation.

To calculate the path loss, we refer to the formulas presented in [21]. Those are used to calculate the flat PL for transmitter UAV during its position updating process. PL_{Upd-Tx} is the path loss (PL) when the UAVs are under LOS assumption, the transmitter does not need to update its position. PL_{Upd-Jm} is the PL when the UAVs are under the NLOS1 assumption and the transmitter moves towards the street junction J_m as the updated position. PL_{Upd-Jp} is for the PL when the UAVs are under NLOS2 assumption and the transmitter moves towards to the street junction J_p, respectively. The street junctions are as described in section 2.2.2 and as presented in Figure.4.

$$PL_{Upd-Tx} = 0 \tag{4}$$

$$PL_{Upd-Jm} = 20\log(10^{\frac{\lambda}{4\pi d}}) \tag{5}$$

$$PL_{Upd-Jp} = 10\log(10^{\frac{PL_D}{10}} + 10^{\frac{PL_R}{10}}) \tag{6}$$

Finally, under the LOS positional relationship, applying the formula in [21]. We obtain the PL from the transmitter UAV to the receiver UAV, $PL_{CORNER-3D}$, where PL_{Upd-J} is the PL from the position of transmitter UAV to the updated position obtained from formulas (4), (5) and (6); D is the distance between updated position and receiver in space.

$$PL_{CORNER-3D} = PL_{Upd-J} + 20\log(10^{\frac{\lambda}{4\pi D}}) \tag{7}$$

$$D = \sqrt{(x_{Rx} - x_{Upd})^2 + (y_{Rx} - y_{Upd})^2 + (z_{Rx} - z_{Upd})^2)}$$

The power strength of the receiver UAV location P_{Rx} is present as (8) :

$$\begin{aligned} P_{Rx} &= P_{Tx} - PL_{CORNER-3D} \\ &= P_{Tx} - PL_{Upd-J} - 20\log(10^{\frac{\lambda}{4\pi D}}) \end{aligned} \tag{8}$$

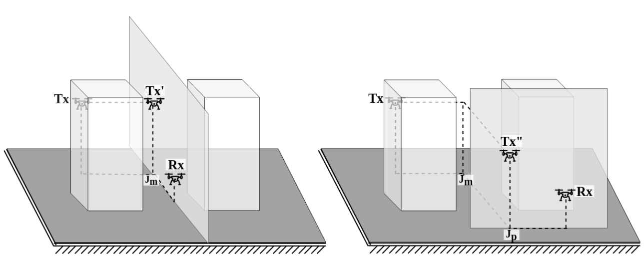

Figure 4: Graphical examples: virtual location of the Tx after position updating. Tx' is the updated location when UAVs are under NLOS1 positional relationship originally in COENER-3D, updated Tx' is directly above the street junction J_m. Tx" is the updated location when UAVs are under NLOS2 positional relationship originally in CORNER-3D, updated Tx" is directly above the street junction J_p.

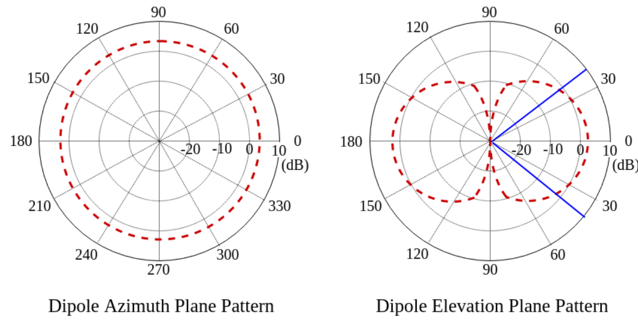

Figure 5: Plane patterns of dipole antenna in azimuth and elevation.

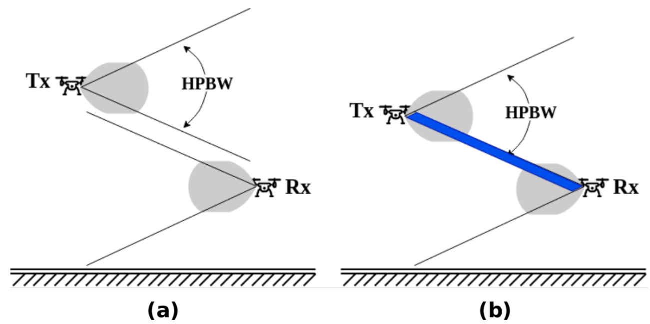

Figure 6: Radiation range of dipole antenna on UAVs limited by the half-power beamwidth (HPBW). When there is an overlap between the radiation ranges, blue area in (b), the radio propagation and communication is valid.

3 EVALUATION

In this paper, we mainly focus on the results from NS-3 simulation. However, instead of providing the connectivity and routing of the network, we initialized the simulation environment as the urban road map and then predicted the PL under discrete-time. The simulator randomly generates the locations of the transmitter UAV and the receiver UAV in the range of the urban map, detects the positional relationship between them. After that, the simulator calculates the path loss (PL) using Corner-3D according to the positional relationship in the current screenshot. We leave as future work, a study of a proper model for the simulation and calculation of the UAV's flight and radio propagation in continuous time, which the positional relationship between UAVs can be updated in the real-time, together with the prediction and the summary of the effects caused by the UAVs mobility. In the end, attempt to use the actual UAVs to measure the PL then compared with our simulation and prediction results. In the initialization of the simulation, the location of UAVs, the number of lanes, the width of the streets, and the size (including the width and the height) of the obstacles, are all randomly generated to be as realistic as possible. Since there is a big number of variables established during the initialization, we set part of the parameters as constants for the purpose of reducing the complexity of the calculation. According to the information provided by the Interstate Highway standards for the U.S. Interstate

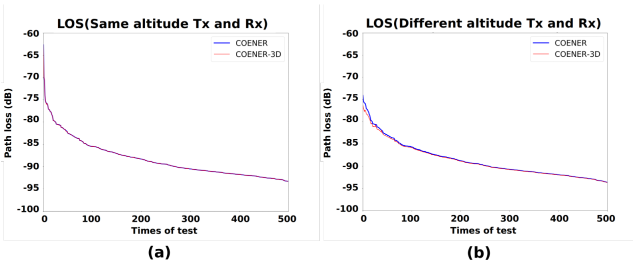

Figure 7: NS-3 simulation results comparison between CORNER and CORNER-3D (under 500 times of simulation): in complete LOS positional relationship when Tx and Rx are at the same altitude and the different altitude, respectively.

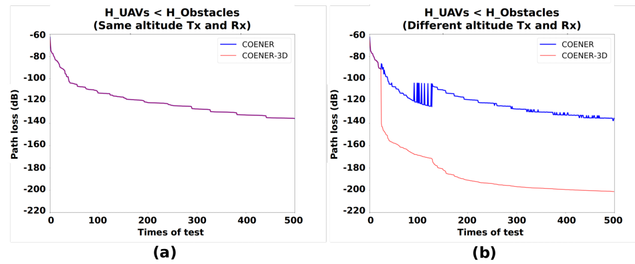

Figure 8: NS-3 simulation results comparison between CORNER and CORNER-3D (under 500 times of simulation): in complete NLOS positional relationship when Tx and Rx are at the same altitude and the different altitude, respectively.

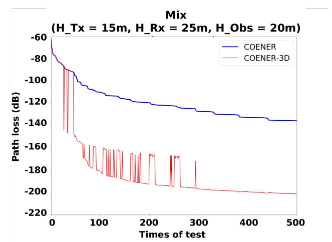

Figure 9: NS-3 simulation results comparison between CORNER and CORNER-3D (under 500 times of simulation): in randomly positional relationship between Tx and Rx.

Highway System [26] and the Federal Bundesstraße Interurban network in Germany, the lane width (LW) is defined as 12-foot (3.7m) and 3.5m, respectively. Therefore, we set the value LW of equation (2) as 3.6m. In Europe, the limitation on flight altitude of UAVs is 500 feet (152 m). Hence, in our simulation, the flight height of UAVs ranges from 0 to 50m. CORNER-3D is based on urban scenarios. Since cities have several blocks, large commercial buildings, and residential areas instead of single buildings. Therefore, in the setting of obstacles, the size is closer to a piece of connection area than a single house. The width of the obstacles is between 50m to 100m and the height ranges from 10m to 50m.

3.1 Comparison between CORNER and CORNER-3D

According to the system initialization in [10], the height for antennas both transmitter and receiver are set at a low height around 1.5m. Figure.7 presents the difference of path loss (PL) between [10] and CORNER-3D when applying CORNER-3D under different positional relationships between the UAVs. Figure.7 shows the UAVs maintain the flying under the line of sight situation. We can appreciate the transmitter UAV and receiver UAV fly at the same altitude. When that happens, the two lines representing the path loss calculation are almost coincident during the entire simulation. Regarding the plot in Figure.7 (b), low PL value corresponding to relatively close distance between the two UAVs. Here, the PL values are clearly different because of the difference in height that is accounted for CORNER-3D when calculating the distance between UAVs. It is worth mentioning that, as the distance increases, the influence of height misalignment becomes smaller, as the two lines start overlapping.

Even though CORNER-3D did not use the complex formulas presented in [21] under NLOS2 category, the adaption of the transmitter's position applied in the CORNER-3D is reliable according to the results from Figure.8. Figure.8 presents the simulation results for the CORNER and CORNER-3D where the UAVs are fully lower than the obstacles. When UAVs are flying at the same altitude, there is no obvious difference in the PL results between CORNER and CORNER-3D as shown in Figure.8 (a). Whereas, in Figure.8 (b), we can notice a significant difference between the path loss values calculated by CORNER and CORNER-3D. Again, thus, it is due to the influence of the height difference between the UAVs on the distance calculation. In fact, that results in the different signal strengths for the antennas at different angles in the radiation range.

In Figure. 9, we plot the path loss results with random positional relationships between two UAVs. The red line (CORNER-3D) has a very particular trend. The sharp jumps are due to the fact that under the 3D-regime, the original NLOS positional relationship may change, NLOS1 and NLOS2 may become LOS, and NLOS2 may also form a NLOS1 relationship. Therefore, even though the PL shows similar value at different locations in CORNER, the PL in CORNER-3D can be significantly different.

3.2 PL distribution of the propagation in CORNER-3D

Figure.10 shows the PL distribution obtained using CORNER-3D with the UAVs placed in an ideal grid urban scenario. The simulating scenario is a $200m \times 200m \times 50m (L \times W \times H)$ space, where the transmitter UAV is placed at (0,0,15). There is a difference in width between the horizontal roads and the vertical roads, Roads along the same direction have equal width. The receiver UAV is randomly placed in the simulated scenario. We use a top view in Figure.10 (a) to visually represent the distribution of the path loss at the frequency of 2.4 GHz. The gray squares represent the obstacles. It is worth mentioning that, in the range of distance of about 20m from the transmitter UAV, as we can appreciate from the blank area in Figure.10 (b), we did not get any value of signal attenuation for the simulation. This is because the half-power beamwidth of the dipole antenna is about 78 degrees and in the blank area, the half-power

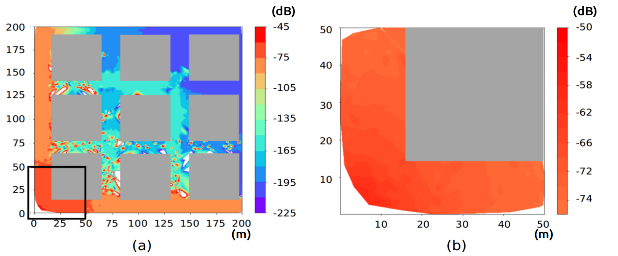

Figure 10: Example of path loss distribution and signal attenuation using CORNER-3D for a source placed in the left bottom, the axis origin point and the random location of receiver.

beamwidth regions of the two UAVs do not overlap. Hence, the UAVs cannot communicate, and the PL cannot be calculated.

4 RELATED WORK

In the past decade, Unmanned Aerial Vehicles (UAVs) have gradually become more and more used in wireless network routing and Internet of Things research due to their unique independence and flexibility. However, failures with flying UAVs may be extremely dangerous. Thus, the need for modeling their communication in advance. Jan-Erik Berg [3] proposed a simple recursive method by using the street crossing angles and the linear sections of the streets to calculate the path loss of microcells in the streets. It provides the basic mathematical model of CORNER and CORNER-3D, however, the author did not provide the relevant simulations or the comparisons with actual measurements. In [4], the authors compared the performance of original Walfisch-Ikegami propagation model [24], Hybrid COST 231 Walfisch-Ikegami model [6], Walfisch-Bertoni model [9], and ten ray model [11] in path loss calculation. Except for the COST 231 Walfisch-Ikegami model, other models have very obvious errors. And the computational complexity of all the models proposed in the article is relatively high. With the advent and rapid development of 5G technology, Shu Sun et al [22] applied two large-scale propagation PL model into 5G urban scenarios, the alpha-beta-gamma (ABG) model and the close-in (CI) free space reference distance model. These two models have a wide range of applicable frequencies but require a large number of parameters, and the calculation formulas are extremely complicated. The calculation of path loss is one of the simple methods to predict radio propagation. It would be possible to obtain a more accurate path loss using ray-tracing to compute and predict the 3D propagation model. In [8], The authors used beam orientation of antenna to build a new propagation shadowing model. Dereje W. Kifl et al [13] compared delay spread prediction for different height of antenna by ray tracing, The study in [16] provided fast 3D deterministic predictions in a large-scale urban area, respectively. Even though, the inevitable and the most obvious defect of ray-tracing is its computational complexity.

In this paper, we used NS-3 to simulate and present our results. The mobility initialization in NS-3 does not support 3D communication originally. Therefore, we need to modify part of the libraries to adapt our needs in the 3D simulation. Paulo Alexandre Regis et al [17] implemented the 3D mobility simulation of UAVs in NS-3 as well. However, their paper mainly focuses on the direction and distance of the random walk of the UAVs rather than the communication and propagation aspect. In [7], a communication tool based on OPNET [18], OPAR is introduced. Compared with the model we proposed, OPAR can provide an accurate path loss considering the different types of obstacles, for instance, foliage, buildings, and ground. However, their research is still in the process of building a network architecture and does not provide relevant data results to confirm the reliability of the simulation or actual application. Many of the existing works are simulations that focus on the UAV wireless network architectures, network topology, and network stability. For example, the mobility of UAVs in the space provides great convenience for information collection. In [20]Zoheb Shaikh et al proposed a flexible and robust communication architecture; AVENS[14] evaluates and selects the development and the applicability of network protocols, codes, and systems. These studies pose the basis and will provide support and reference for our future research when we evaluate our simulation on real UAVs in the wild.

5 FINAL REMARKS

In this paper, we proposed CORNER-3D, a new propagation model for 3D path loss calculation in urban scenarios with obstacles. CORNER-3D separates the relatively simple positional relationship (LOS) between the UAVs by means of the first flat model and the stereoscopic model. CORNER-3D further classifies it into LOS or NLOS (in the 3D space) by using the relevant properties of the antenna. After classifying the positional relationship of the UAVs, the calculation of the PL is performed using the simple formulas provided by [21]. Through verification of the simulation results, CORNER-3D can accurately predict the connection between UAVs. It can be applied to both flat and stereoscopic environments. The simulation results provided by CORNER-3D are path loss predictions under the specific positional relationship of UAVs in a discretized time window. We leave as a future work the modeling of the UAVs motion in continuous time. Moreover, we plan to optimize our model to provide real-time results for changes in location. On top of that, we intend to account for shadowing and fading in order to improve the applicability and accuracy of the model.

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