Coverage Estimation Using Probabilistic Line-of-Sight Model for Unmanned Aerial Vehicle Communication

Ankita K. Patel and Radhika D. Joshi

Abstract Aerial platforms have recently gained significant popularity for the rapid development of relief networks in emergencies. These platforms are capable to deliver essential wireless communication for various applications such as public safety, natural disasters, or adding coverage to existing terrestrial networks. A reliable prediction of coverage resulting from an aerial base station is important to provide essential air-to-ground wireless services for disaster-affected areas. Line-of-sight (LoS) is an essential component of air-to-ground wireless channels, particularly useful for radio planning and coverage prediction. The performance of an air-to-ground link can be evaluated on three key parameters: elevation angle, communication range, and altitude between the aerial base station and ground receiver. In this paper, we proposed an elevation-dependent line-of-sight model to estimate the area coverage of an aerial base station. The proposed model is derived from statistical parameters of building distribution, defined by the International Telecommunication Union for four urban environments: urban, suburban, dense urban, and high-rise urban. Coverage of aerial base station is estimated from building blockage probability which is formulated as a weighted function of the developed LoS model. Estimated coverage is simulated for elevation angle and communication range between UAV and ground receiver for low altitudes up to 500 m. We restricted UAV altitude up to 500 m due to the limitation on flying altitude by regulating authorities. Our results contribute to identifying the optimum elevation angle and communication range between UAV and ground receiver for line-of-sight communication. Based on the results, we deduced that the optimum elevation angle to attain 100% coverage is between 60 and 80° for all urban environments. We observed a significant reduction in the communication range with declination in UAV altitude, to attain the same amount of coverage for urban, dense urban, and high-rise urban environments. For

A. K. Patel (✉)
Pune Institute of Computer Technology, Pune, India
e-mail: ankitaketan@gmail.com

R. D. Joshi
College of Engineering, Pune, India
e-mail: rdj.extc@coep.ac.in

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suburban, altitude is not playing a significant role in the range of communication to achieve area coverage.

Keywords Aerial base station · Building blockage probability · Communication range · Coverage estimation · Line-of-sight probability · UAV

1 Introduction

In recent years Unmanned Aerial vehicles (UAV) discover many applications in surveillance and rescue, military, delivery of goods, telecommunication, precision farming, wildlife monitoring, and many more [1]. UAV can be used as a relay or an aerial base station (ABS) to support in realisation a wireless recovery network for a natural disaster where the existing network is destroyed. Homeland Security Bureau in the USA deployed this concept as a communication architecture for system recovery [2]. The ABSOLUTE [3] project is another example of emergency supplementary network deployment funded by the European Commission.

In an emergency condition, ABS can be deployed quickly, with the minimum manpower requirement. The important requirement for these applications is to provide adequate coverage over a known radius for emergency response. The most unique feature that distinguishes UAV communication from the conventional system is the likelihood of establishing a line-of-sight (LoS) link for air-to-ground communication. The availability of a line of sight has a large effect on wireless channel performance. It is particularly useful for radio network planning and area coverage. The line-of-sight probability is mainly dependent on UAV altitude, elevation angle, environment (urban or rural), and communication range with the ground user.

For an emergency, the number of deployed ABS could be limited. This fact mandates the full exploitation of the deployed ABS by estimating the performance of the radio channel. This leads us to develop an analytical model to estimate the area coverage for ABS that can be useful for low-altitude UAV communication. We developed an elevation-dependent low altitude probabilistic LoS model based on statistical parameters of urban scenarios defined by the International Telecommunication Union (ITU). This model will help in RF planning for an aerial network without having any site-specific information. In a disaster condition where infrastructure is destroyed, it is unlikely to avail city map. In this case, the proposed model can be used for RF planning of a city based on statistical parameters of the urban environment. The estimation of the area coverage for ABS was obtained from the blocking probability of LoS ray for various urban conditions. A simple algorithm is used to obtain blocking probability from the proposed LoS model. Performance of estimated area coverage is analyzed for elevation angle, UAV altitude, and coverage range.

The structure of the paper is as follows. In Sect. 2 we reviewed the techniques proposed in the literature for channel modelling and performance evaluation of links. Section 3 discusses the propagation modelling approach of line-of-sight probability for urban environments. Section 4 is dedicated to area coverage estimation from the developed model. Simulation results of the area coverage are described in Sect. 5. Section 6 is for concluding remarks.

2 Related Work

For a UAV communication system, it is important to understand the communication channel thoroughly and to evaluate the QoS parameters for the same. This motivates us to develop a generalized channel model and estimate area coverage from the developed model. In literature, various studies are available either on channel modelling or evaluating the performance of the network. In this study, we have evaluated the performance of the channel based on the developed model.

There is a need for a generalized model which does not rely on sight-specific information to evaluate the performance of the channel. In literature, there is a lack of a generalized RF propagation model which can easily link with RF propagation conditions. Many studies are available on measurement-based channel models given in [4–6], these are site-specific and do not give a generalized approach for channel modelling. Cai et al. [4] modelled a suburban city of Madrid using USRP, whereas Khawaza et al. [5] performed ultrawideband (UWB) measurement using a P410 UWB kit to model the channel. Suburban and urban measurements for three cities are performed by Matolak [6] to model the channel. Geometry-based modelling approaches for line-of-sight modelling are available in [7, 8]. Feng et al. [7] proposed a theoretical modelling approach for the dense urban city. Statistical parameters like building height, building width, street width, street angle distribution, and building coverage are used for modelling. This approach is very specific to geometry considered by the author, not a generalized approach for city modelling. Al Hourani [8] developed the line-of-sight analytical model based on the geographic model of Melbourne city. A path loss model for line-of-sight, non-line of sight, and obstructed line of sight were developed by Feng et al. [9]. This model cannot be generalized as it was based on a single city. Holis and Pechac [10] deduced a generic statistical model for air-to-ground path loss, but this model was obtained for high-altitude platforms. Another generic statistical model approach is given by Al Hourani et al. [11], for low altitude platform above 500 m of the ground. In our study, we considered an altitude below 500 m due to limitations in the flying altitude of UAVs as per guidelines provided by the regulatory authority of India. The proposed work presents a generalized line-of-sight modelling approach for four different urban environments to evaluate the area coverage of aerial base stations.

Previous work has attempted to study the performance of coverage such as Zhao et al. [12] considered the relative distance between multiple UAVs to estimate area coverage for UAV mounted base station for sensor networks. Mozaffari et al. [13] studied the performance of air-to-ground channels based on a single UAV's altitude and coverage radius. On-demand user-based coverage is implemented by Hatiao et al. [14], where ABS can change its position as per the user's movement while maintaining connectivity between UAVs. A 3D layout of ABS is considered by Kalantari et al. [15] to cover a maximum number of users with minimal transmission power. Al Hourani [16], estimated ABS coverage and information rate for air-to-ground links based on the altitude of the UAV. Maurila Matracia et al. [17] present a new stochastic framework for urban and rural areas.

The main contribution of our work is the modelling of line-of-sight probability and estimation of area coverage using ITU-R parameters. This allows rapid estimation of the link performance without relying on site-specific information. This study will help to optimize the key parameters for an aerial base station such as elevation angle, altitude, and communication range.

3 System Model

Aerial platforms deployed at low altitudes are quasi-stationary platforms such as quadcopters, balloons, and helicopters. These are easier to deploy and can go in line with the cellular concept, as low altitude combines superior coverage with a confined cell radius. These platforms are dependent on the end user's application.

3.1 Statistical Propagation Model

Developing an RF model requires an accurate study of the conditions and constraints of the environment. The layout and characteristics of the buildings are some of the most important conditions in an urban environment. The international telecommunication union (ITU) [18] has suggested statistical parameters α_s, β_s and γ_s, that describe the general statistics of a certain area. These parameters are explained below:

- α_s: the ratio of building area covered in a land to the total area of land (dimensionless)
- β_s: mean of the number of buildings per unit area in buildings/km^2
- γ_s: a variable that describes the building height distribution as per Rayleigh probability distribution:

$$P(h) = \frac{h}{\gamma_s} e^{-\frac{h^2}{\gamma_s^2}} \tag{1}$$

where h is the height of the building in meters. By following the steps given in [18] Probability of Line of Sight can be obtained is

$$P(LoS) = \prod_{n=0}^{m} \left[1 - \exp\left\{ -\frac{\left(ht - \frac{\left(n+\frac{1}{2}\right)(ht-hr)}{m+1}\right.}{2\gamma_s^2} \right\} \right] \tag{2}$$

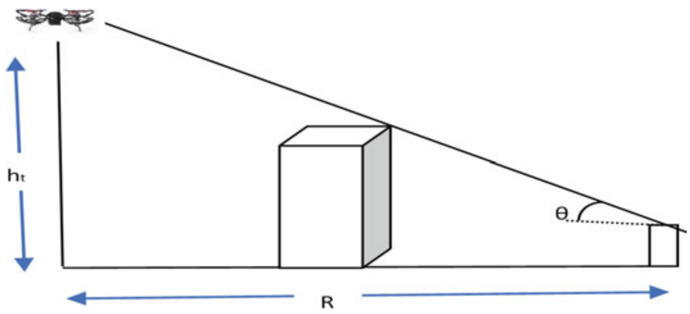


Fig. 1 The geometry of line-of-sight scenario for air to ground link

where $m = floor(R\sqrt{\alpha_s \beta_s} - 1)$ and R is the distance between transmitter and receiver as depicted in Fig. 1; ht and hr are transmitter and receiver heights, respectively. Receiver height hr is much lower as compared to UAV altitude ht and building heights; then the ground distance R can be written as ht/tan(θ); where θ is the elevation angle as shown in Fig. 1. The resulting plot of the P(LoS) series will be smooth for the large values of ht and can be defined as a continuous function of θ. Four different environments; suburban, urban, dense urban, and high-rise urban are selected for simulation of P(LoS).

For simulation, buildings are randomly generated using statistical parameters, in a 1 × 1 km area with a resolution of 1 m. The statistical parameters; α_s is (0.1, 0.3, 0.5, 0.5), β_s is (750, 500, 300, 300) and γ_s is (8, 15, 20, 50) for suburban, urban, dense urban and high-rise urban environment, respectively. The entire area is divided into small grids. The calculations were made for azimuthal angles between 0 and 360° of altitude up to 500 m. The LoS probability for a specific elevation angle is calculated as a median of data obtained from an azimuthal angle. The simulation was performed for an entire range of elevation angles from 0 to 89° for four simulation environments.

3.2 Modeling Line of Sight Probability

The simulation results show the LoS probability between UAV and ground receiver. The elevation angle between 60 and 90° is more realistic for UAV applications for all the environments to ensure 100% line-of-sight communication. We observed that trend shown in Fig. 2 can be approximated as a simple S curve equation. The LoS probability is modelled as a simple S curve equation of the following form:

$$P_{LoS} = \frac{1}{a_3 + e^{-(-a_1 + a_2(\theta - a_4))}} \tag{3}$$

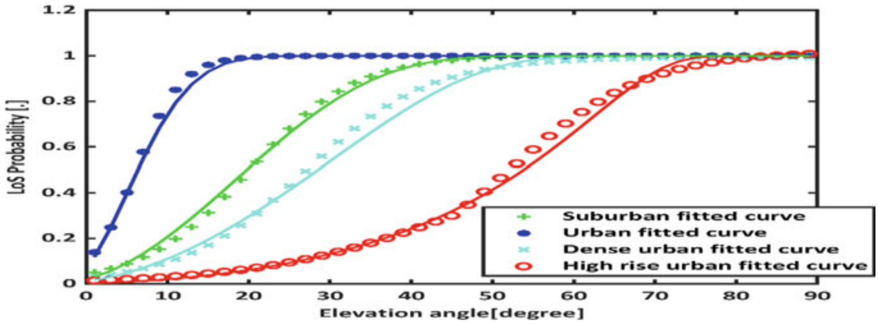


Fig. 2 Calculated line-of-sight probability, with their related curve fitting for suburban, urban, dense urban and high-rise urban environments

Table 1 Parameters of LoS probability calculation

Environment	a_1	a_2	a_3	a_4
Suburban	2.1778	0.3557	1	0
Urban	3.0734	0.1565	0.9989	0.158
Dense urban	3.4912	0.1304	1.007	0.3344
High-rise urban (0–45°)	4.2234	0.0815	1.5747	0.114
High-rise urban (45–90°)	4.7313	0.1209	0.9801	13.144

where a_1, a_2, a_3, and a_4 the empirical parameters given in Table 1 are obtained from the least-square curve fitting method. These results are compared with the model given in [19], where a shadowing model of roadside buildings is explored. Link blockage probability is defined as a function of azimuthal and elevation angle. Several test cases use from both models and they give similar results. Figure 2 shows that our model follows the calculated LoS modelling for all four environments. For high-rise building distribution, parameters are calculated separately for angles below and above 45°.

4 Coverage Estimation

An accurate coverage estimation can be achieved by determining an optical line of sight in an area where a building and terrain database is available. Building blockage probability is the estimate to obtain an optical line of sight between the UAV transmitter (Tx) and receiver (Rx). Building blockage probability states that each building lying between UAV and receiver is below the line-of-sight ray as shown in Fig. 3. Coverage will depend on the distance between transmitter and receiver and buildings which do not obstruct LoS ray. Coverage can be estimated from building blockage probability using an algorithm as described in [18], which is based on parameters α_s

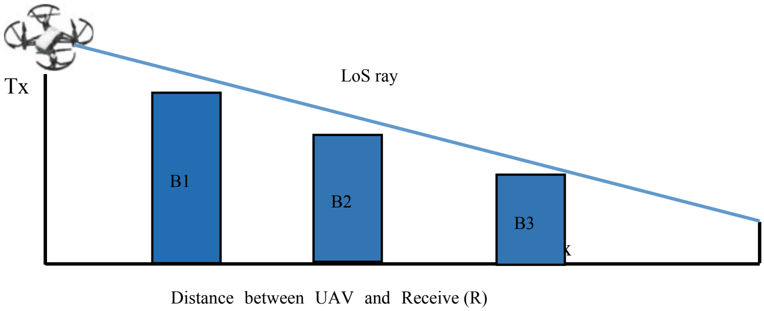


Fig. 3 Building geometry for LoS ray between transmitter and receiver

and β_s. The first step is to calculate the number of buildings between the UAV and ground receiver with the help of parameters α_s, β_s, and LoS probability defined in Sect. 3.

4.1 Steps to Estimate Coverage and Building Blockage Probability

Step 1: Calculate the number of buildings between UAV and receiver.

To obtain the number of buildings between transmitter and receiver, a ray will be pass-through $\sqrt{\beta_s}$ buildings, arranged in a rectangular grid. Only a fraction of α_s land will be covered. The expected number of building pass through per kilometre are:

$$b = \sqrt{\alpha_s \beta_s} \tag{4}$$

If R is the distance between transmitter and receiver then the number of the building between UAV and receiver are

$$B_{ur} = R\sqrt{\alpha_s \beta_s} \tag{5}$$

Step 2: Obtain the distance of each building from a transmitter.

All the buildings are evenly spaced between transmitter and receiver. The distance between two buildings is:

$$d_b = R/B_{ur} \tag{6}$$

The distance of each building from the transmitter is:

$$d_x = (x + 1)d_b \tag{7}$$

where x is the count of buildings between Tx and Rx and x is given by {0, 1- - $(B_{ur} - 1)$}.

Step 3: Obtain building blockage probability which describes that LoS ray will be present at xth building is given by

$$P_b = \prod_{0}^{B_{ur}-1} P_{LoS} d_x \tag{8}$$

Step 4: Estimate area coverage from building blockage probability:

$$C = \frac{P_b}{{B_{ur}}^2} \tag{9}$$

Area coverage for a given scenario is estimated from an above-mentioned algorithm, LoS probability given in Eq. 3 and statistical parameters α_s, β_s. Estimated coverage is mainly dependent on three parameters UAV altitude, elevation angle, and communication range. Simulation is performed to evaluate the effect of these three parameters on estimated coverage.

5 Simulation and Results

Simulation is performed for four environments: suburban, urban, dense urban and high-rise urban. For a simulation area of 1 × 1 km is considered with randomly generated buildings as per statistical parameters defined in [18]. Table 2 shows the parameters considered for simulation.

The results presented in Figs. 4 and 5, were obtained for the estimation of the area coverage for elevation angle and communication range for four environments. From Fig. 4, it is observed that area coverage is linearly increasing with elevation angle and

Table 2 Simulation parameters

Parameters	Value
Area	1 × 1 km
UAV altitude	100–500 m
Elevation angle	0–90°
Communication range	100 m–1 km
Distance between buildings	20 m

falls after attaining the maximum value. This trend is common in all environments. Based on experimental results, we identified the optimum elevation angle to achieve maximum coverage in the range of 60–80° for altitudes 200, 300, 400 and 500 m for all environments. For an altitude of 100 m, the optimum elevation angle lies between 35 and 65°. The high elevation angle is recorded for high altitude to attain the same amount of area coverage.

Figure 5 shows the estimation of area coverage with a communication range for different altitudes. The maximum altitude considered for the suburban area was 300 m, above this, there is no significant change was observed. This is due to less

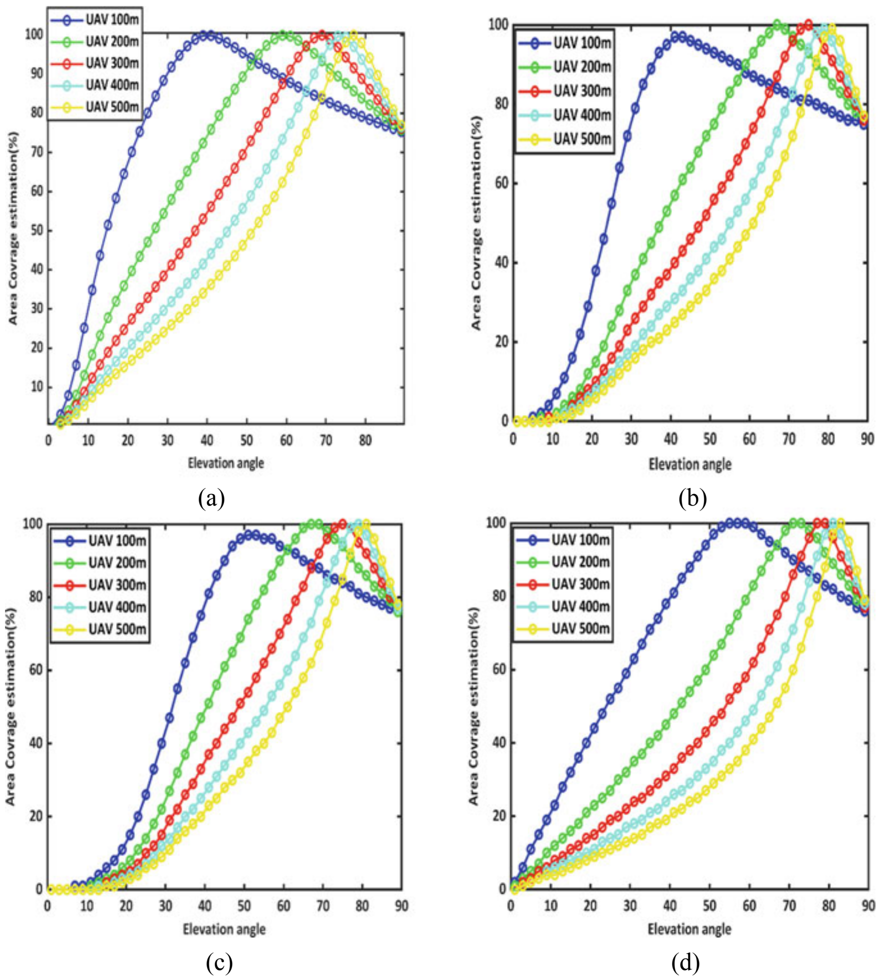
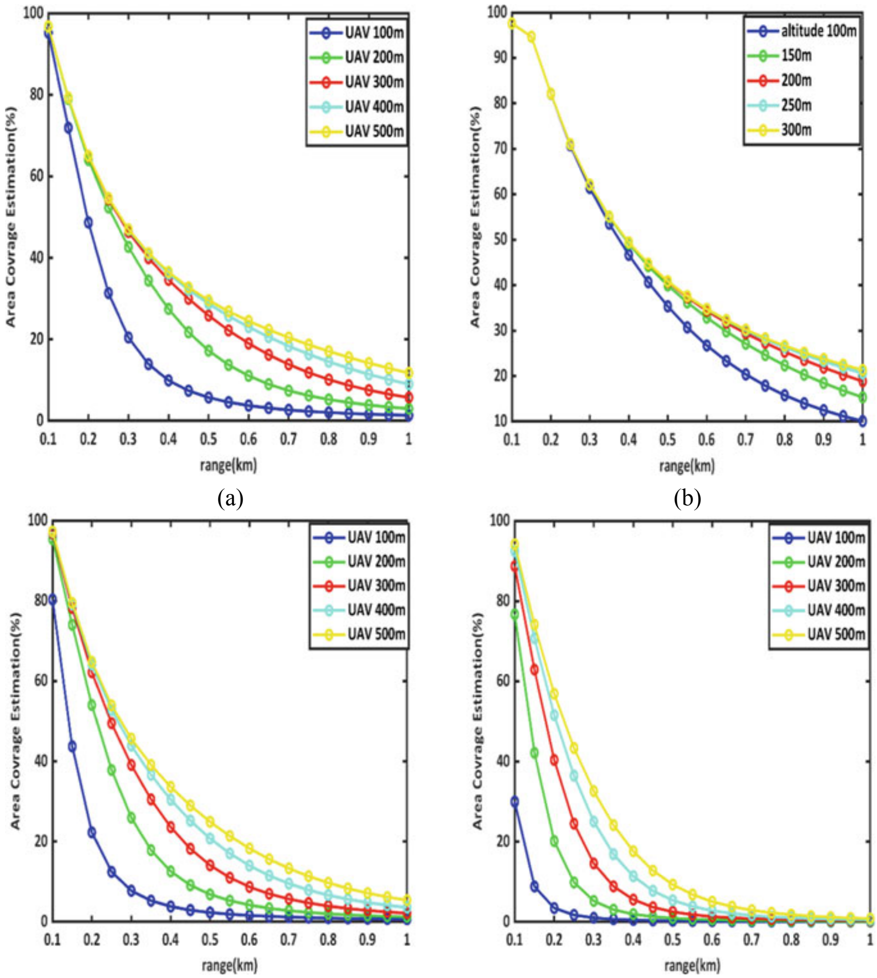


Fig. 4 Wireless communication coverage estimation with elevation angle between UAV and ground receiver: **a** suburban, **b** urban, **c** dense urban, and **d** high-rise urban



(a) (b) (c) (d)

Fig. 5 Wireless communication coverage estimation with communication range: **a** suburban, **b** urban, **c** dense urban, and **d** high-rise urban

infrastructure density in the area. The higher the building density lower is the communication range. It is observed that maximum communication range can be achieved at higher altitudes. To cover at least 50% of the area, the distance between the UAV and ground receiver should be 500 m. For the suburban scenario, altitude is not having a greater impact on the communication range rather for other environments, altitude plays a significant role. For suburban areas, altitude does not play a significant role while calculating communication range for a certain value of area coverage. Our results help to evaluate the performance of the area coverage for an urban scenario to elevation angle, altitude, and communication range. This can be utilized for the RF planning of disaster-affected areas without prior knowledge of the site.

6 Conclusion

This paper developed a generalized low altitude elevation-dependent LoS propagation model for four different urban environments; urban, suburban, dense urban, and high-rise urban. This model facilitates RF planning of airborne base stations to fulfil connectivity for the disaster-affected area. The proposed technique is based on simple statistical urban parameters, not dependent on the 3D model of the site. For the disaster-affected areas, the proposed model can be used for RF planning of a city, based on statistical parameters without any prior knowledge of the city map. This model showed that line-of-sight between UAV and ground receiver can be expressed as a function of elevation angle. An algorithm is defined to estimate area coverage from the developed model, as a function of building blockage probability. Performance of estimated coverage was evaluated for three important parameters of UAV propagation: elevation angle, communication range, and UAV altitude. A simulation was performed for a low altitude between 100 and 500 m. Results show the optimum elevation angle lies between the range of 60–80° for Low altitude LoS propagation. UAV altitude plays a significant role to evaluate an optimum communication range for more than 50% coverage except for the Suburban environment.

Future work will include the analysis of air-to-ground UAV channels for large-scale and small-scale fading effects at low altitudes and estimate performance parameters for the same.

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