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Stochastic-Based Optical Line-of-Sight Probability Model for UAV-Assisted Communication Systems

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***Abstract*—A stochastic model for predicting the Optical Line-of-Sight (O-LoS) probability of links between terrestrial terminals and Unmanned Aerial Vehicles (UAVs) is proposed. The model is based on statistical distributions of inter-building distances and building heights characterizing the area of interest, and explicitly accounts for the terrestrial terminal height. Validation against ray-tracing simulations conducted over central London, for multiple terminal heights, shows excellent agreement across all cases. Additionally, when compared with existing reference models, the proposed approach significantly reduces the gap with ray-tracing results.**

I. Introduction

Interest in Unmanned Aerial Vehicles (UAVs) for communication systems is rapidly growing [1]. When deployed as aerial Base Stations (BSs), UAVs can support connectivity of existing wireless networks – such as cellular and broadband systems – by enabling a three-dimensional (3D) heterogeneous architecture that seamlessly integrates terrestrial and non-terrestrial communications [2]. UAV-assisted applications span a wide range of scenarios, such as providing additional capacity to hotspot areas without extra infrastructure, as well as covering hard-to-reach regions, such as rural or disaster-affected areas. Moreover, Internet of Things (IoT) scenarios represent a key use case for UAV-assisted communication systems, with the UAVs acting as relay nodes to support low-power devices struggling to communicate over long ranges ([3],[4]).

In all the above-mentioned scenarios, the main advantage of using a flying BS lies in its adaptability to avoid clutter-based obstacles and establish a higher likelihood of Line-of-Sight (LoS) links with either street-level User Equipment (UE) or terrestrial 5G BS (e.g., installed on lampposts or building façades), thereby enabling alternative high-data-rate wireless backhaul in congested areas ([5],[6]). This is particularly critical when exploiting millimeter-wave (mmW) capabilities, which suffer from poor obstacle penetration.

Consequently, accurate channel modelling for communications between UAVs and ground terminals comes with a reliable estimation of the LoS probability, which primarily depends on the terrestrial terminal height, the link elevation angle, and the urban morphology. Several models have been proposed in the past for the prediction of the LoS probability for Air-to-Ground (A2G) paths. Some of them ([7] – [11]) focus on the so-called Optical LoS (O-LoS), defined as an unobstructed straight path between transmitter and receiver, while others ([12],[13]) consider the Fresnel LoS (F-LoS), which requires the first Fresnel ellipsoid to be unobstructed, thus avoiding diffraction effects.

Common denominator of the referenced O-LoS models is the definition of a stochastically generated environment with evenly spaced buildings, defined based on the three morphological parameters (α, β, γ) introduced in [7]: α (dimensionless) represents the ratio of built-up to total land area, β (buildings/km^2) is the mean buildings density, and γ (m) is a scale parameter describing the most probable building height, with the vertical extent assumed to follow a Rayleigh distribution. For practical reasons, [7] provides representative (α, β, γ) values for four selected environments – Suburban, Urban, Dense Urban and Urban High-Rise – which are hereinafter referred to *ITU scenarios* or $(\alpha, \beta, \gamma)_{ITU}$.

More specifically, the ITU-R Rec. P.1410-6 [7] provides a methodology to estimate the probability of an O-LoS path between two points in urban environments – hereinafter referred to simply as P_{LoS}. However, such an approach does not account for building width, W (m), and spacing, V (m). By contrast, these parameters are included in the model proposed by Holis in [9], which derived a closed-form formulation for P_{LoS} by fitting Ray-Tracing (RT) simulations over stochastic environments generated based on $(\alpha, \beta, \gamma)_{ITU}$. However, this model is limited only to the ITU scenarios and is valid only for street-level UEs, as it does not explicitly depend on the terrestrial terminal height.

To address these limitations, this work proposes a stochastic-based methodology for estimating P_{LoS}, applicable to arbitrary cluttered environments – given the availability of environmental statistics (as described in Section II.A) – and dependent on the terrestrial terminal height, thus enabling applicability across different use cases.

II. Model Description

This section describes the proposed model, along with the definition and the method for computing the inputs it requires.

A. Model Inputs

The proposed model requires inputs both describing the link geometry and the environment.

The terrestrial terminal is defined by its height, h_{tx} (m), while the UAV is described by the link elevation angle, θ (deg), defined with respect to the local horizon.

In this context, environmental morphology is the dominant driver affecting propagation, being the interaction between electromagnetic waves and clutter elements surrounding the terrestrial terminal the most impactful on P_{LoS}. Specifically, resorting only on qualitative descriptors – such as those associated to the ITU scenarios (e.g., Suburban or Dense Urban) – may be insufficient to capture the complexity of real urban environments. Moreover, although (α, β, γ) can be adapted to

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different areas, the assumption of an equivalent evenly spaced building layout might not hold in practice, especially for historical cities (e.g., London). In addition, the prevalence of street canyons in modern grid-structured cities (e.g., New York) is not captured by the existing (α, β, γ)-based methodologies.

To address these limitations, in this contribution, the environment is stochastically described by three Cumulative Distribution Functions (CDFs), namely D_{b1}, D_{b12}, and H_b (the subscript b denotes "building"), which respectively describe the distance from the terrestrial terminal to the first obstructing building, the inter-building distance between the first and second obstructing buildings, and the building heights distribution. These CDFs are built following the methodology outlined in Section 4 of ITU-R Rep. P.2402-0 [14], further detailed in [15], and briefly summarized below.

A set of randomly-deployed survey points is defined within the area of interest, the latter retained from large-scale digital maps (e.g., OpenStreetMap or LiDAR-derived 3D urban models). For each survey, radial lines are traced over discrete angular directions, with a fixed angular resolution (e.g., 10 degrees). Along each radial direction, the distance from the survey point to the first obstructing buildings, d_{b1} (m), and the distance between the first and second obstructing buildings, d_{b12} (m), are recorded, together with their respective heights, h_{b1} (m) and h_{b2} (m). The outlined procedure is further clarified in Fig. 1.

Repeating this procedure over multiple survey points and directions enables the statistical characterization of inter-building distance and vertical extent, overcoming the assumption of evenly spaced buildings and accounting for potential street-canyon effects.

It is worth noting that only the height distribution of the first obstructing building is used as model input, i.e., $H_b = H_{b1}$, since the height distributions of the first and second buildings are statistically similar when averaged over all directions (under the assumption that building heights are independent from direction and distance from the survey point).

B. Model Formulation

The proposed approach for evaluating P_{LoS} relies on a Monte Carlo simulation, following [15], in which, for each realization, the environment is stochastically generated from the input statistics (see Section II.A) and a ray is launched from the terrestrial terminal and traced – by means of a ray-launching approach – toward the UAV, along θ.

Differently from [15], it is assumed here that only the first two buildings encountered along the ray path can potentially affect P_{LoS}, as the impact of including additional buildings is statistically negligible over a large number of realizations, as assumed in [14]. Although this simplification is particularly reasonable for terrestrial terminals deeply embedded in clutter, e.g., with h_{tx} below the median of H_b, it will be further discussed in the remainder.

Accordingly, for each Monte Carlo realization, the probability that a LoS ray exists between the terrestrial terminal and the UAV, i.e., P_{LoS}, is computed by combining the probabilities that each building along the propagation path lies below the propagation path itself.

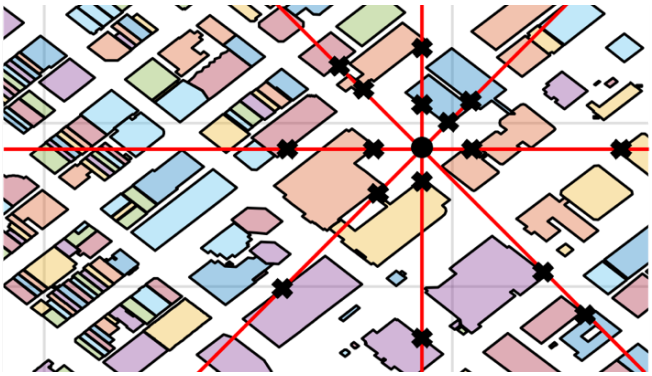


Fig. 1. Example of radial directions (red lines) traced from a survey location (black dot), with intersections with buildings along each radial (black crosses).

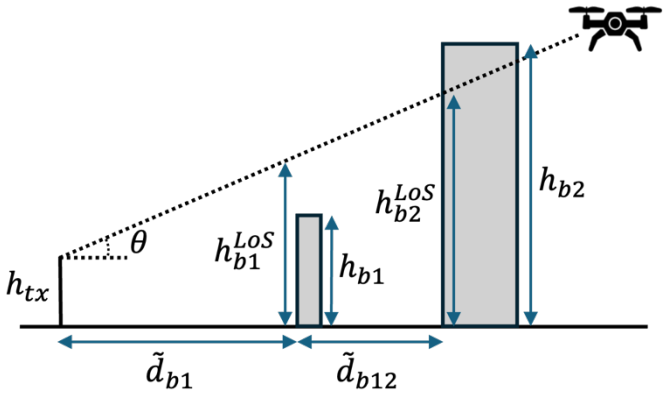


Fig. 2. Simplified scheme of the overall geometry.

For clarity, let h_{bi}^{LoS}(m) be the cumulative height of the ray evaluated at building i $(i = 1,2)$. Moreover, let $X(x)\colon \mathbb{R}^+ \to [0,1]$ denote a generic CDF, and $Y = X^{-1}(y_i)\colon [0,1] \to \mathbb{R}^+$ its inverse, where $y_i \sim U(0,1)$ is the i-th random scalar.

Accordingly, referring to Fig. 2, P_{LoS} can be evaluated as:

$$P_{LoS} = P(h_{b1} < h_{b1}^{LoS}) \cdot P(h_{b2} < h_{b2}^{LoS}) = \\ = H_b(h_{b1}^{LoS}) \cdot H_b(h_{b2}^{LoS}) \quad (1)$$

where the cumulative heights h_{b1}^{LoS} and h_{b2}^{LoS} can be obtained as:

$$h_1^{LoS} = h_{tx} + \tilde{d}_{b1} \cdot tan\,\theta = h_{tx} + D_{b1}^{-1}(y_1) \cdot tan\,\theta \quad (2)$$

and

$$h_2^{LoS} = h_1^{LoS} + \tilde{d}_{b12} \cdot tan\,\theta = h_1^{LoS} + D_{b12}^{-1}(y_2) \cdot tan\,\theta. \quad (3)$$

In (2) and (3), the terms $\tilde{d}_{b1}$(m) and $\tilde{d}_{b12}$ (m), represent the distance between the terrestrial terminal and the first obstructing building, and the distance between the first and the second obstructing buildings, respectively, both obtained via random inverse sampling from the corresponding input CDFs (see rightmost terms of the equations). For clarity, an example of the overall geometry is illustrated in Fig. 2, showing a propagation path obstructed only by the second building, h_{b2}.

It is worth noting that multiple Monte Carlo realizations are required to obtain long-term statistical stability of the results, thus averaged over both survey locations and azimuthal directions. In principle, the number of realizations, N, should

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be chosen such that additional realizations produce only marginal statistical variation: based on the authors' experience [15], N between $5 \cdot 10^4$ and 10^5 is sufficient.

Despite these large numbers, the computations in (1)-(3) involve only inverse sampling of the input CDFs and are therefore executed almost instantaneously. Consequently, a complete simulation for a given terminal height, covering the elevation range from 0 to 90 degrees with reasonably small angular step (e.g., 1 degree), requires only a few minutes on a standard PC.

III. Model Validation

Experiments are always preferable for model validation. However, in this context, conducting an extensive campaign to properly sample a large, typically dense urban area at different terminal heights and link elevations is extremely challenging, particularly due to privacy and security concerns in sensitive areas, such as airports, government buildings and stadiums. To address this, RT tools have been employed in the last decade as a reliable alternative for model validation.

Consequently, an RT campaign was set up to validate the model outlined in Section III.B, following a methodology similar to the one illustrated in [8],[9]. Unlike [8] and [9], however, this work uses a real 3D map of the site rather than a stochastically generated environment with evenly spaced buildings based on specific (α, β, γ) values.

Simulations were performed using MATLAB® RT over the central district of London (see Fig. 3), which shows $(\alpha, \beta, \gamma)_{LON} = (0.5, 397.6, 24.3)$. Input statistics were derived from the map following the methodology in Section II.A. For the sake of brevity, they are omitted here, but can be found in ([14]-[15]).

A total of $N_{tx} = 100$ terrestrial terminals (transmitters) are randomly located over the 3D map, each at a height h_{tx}. For each transmitter (tx), a set of airborne receivers (UAVs) is defined at a slant distance of $r = 1$ km, with azimuth angles $\phi \in \Phi = \{0,10,\ldots,350\}$ deg, and elevations $\theta \in \Theta = \{0,10,\ldots,90\}$ deg. For each transmitter-receiver pair, a LoS indicator, $l(tx, r, \phi, \theta) \in \{0,1\}$, is evaluated, where $l = 1$ means that a direct path exists, $l = 0$ otherwise. The LoS probability, as function of h_{tx} and θ, is then computed by averaging l over all the tx locations and azimuthal directions:

$$P_{LoS}(h_{tx}, \theta) = \frac{1}{N_{tx}|\Phi|} \sum_{t=1}^{N_{tx}} \sum_{\phi \in \Phi} l(tx, r, \phi, \theta) \qquad (4)$$

where $|\Phi|$ represents the cardinality of the set Φ.

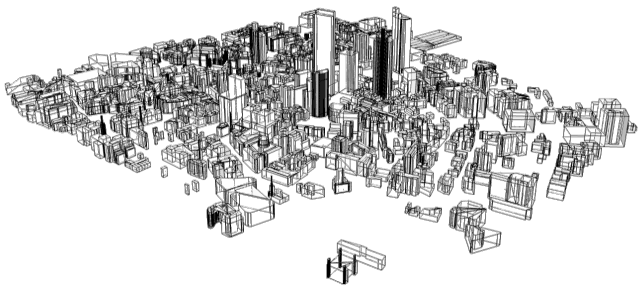


Fig. 3. 3D map of interest (London) used for model validation.

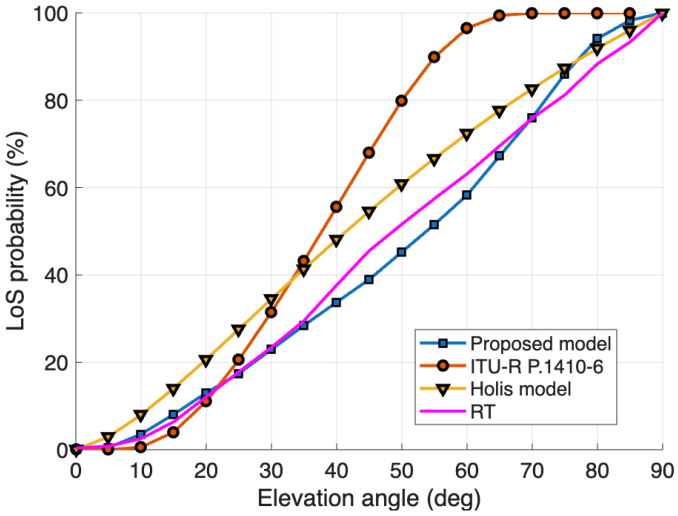


Fig. 4. LoS probability vs. elevation angle for $h_{tx} = 1.5$ m. Comparison between models and RT data. Central district of London.

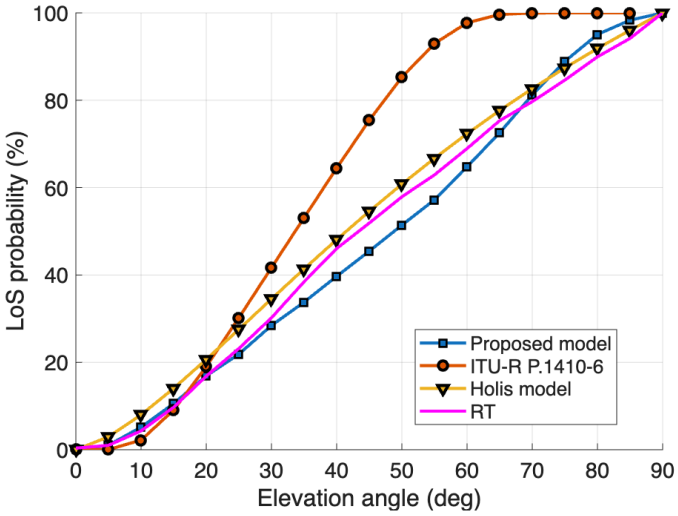


Fig. 5. LoS probability vs. elevation angle for $h_{tx} = 5$ m. Comparison between models and RT data. Central district of London.

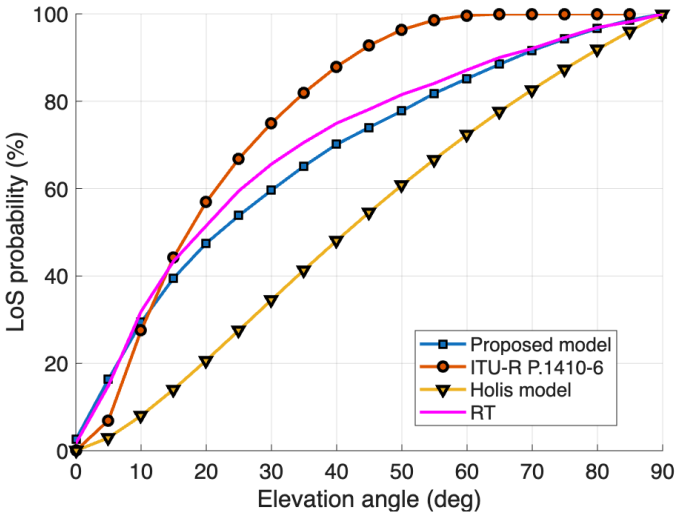


Fig. 6. LoS probability vs. elevation angle for $h_{tx} = 20$ m. Comparison between models and RT data. Central district of London.

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Three use-cases were considered: 1) $h_{tx} = 1.5$ m, representing a street-level UE; 2) $h_{tx} = 5$ m, representing a radio unit mounted on a lamppost; and 3) $h_{tx} = 20$ m, representing a radio unit installed on a building façade.

The corresponding comparisons between the proposed model and RT results, as function of θ, are presented in Fig. 4-Fig. 6, respectively. The results demonstrate a satisfactory agreement between the proposed model and the RT for all cases, confirming its adaptability to different terrestrial terminal heights. As expected, the model results show an increasing trend of P_{LoS} with h_{tx}, for the same elevation angle, reflecting the higher likelihood of direct paths for higher terminals. Furthermore, results reveal that the initial assumption of accounting only for the first two buildings obstructing the propagation path is valid, at least for terminal heights below the average clutter height (24.3 m for the London environment).

For each case, the P_{LoS} predicted by the ITU-R P.1410-6 [7] and Holis [9] models is also reported, both exhibiting lower agreement with the RT for all scenarios, compared to the proposed model. Specifically, the ITU-R model (red curves with circular markers) shows a change in magnitude and slope with increasing h_{tx}, reflecting its explicit dependence on terminal height. However, while the ITU-R predictions closely follow the RT trend up to $\theta \approx 20$ deg in all cases, they significantly overestimate the RT results. This overestimation is likely related to the absence of building width in the ITU-R model, which leads to higher P_{LoS} than the reference. The Holis model (yellow curves with triangular markers) – originally proposed for street-level UEs – aligns well with the proposed approach for cases 1 and 2. However, in case 3 ($h_{tx} = 20$ m), a significant discrepancy emerges, which stems from the Holis model's complete lack of dependency on terminal height. Interestingly, Holis model performs slightly better in case 2 than 1, which may appear counterintuitive given its "street-level" applicability. This behavior is a hint that Holis model is overestimating the RT results and can be attributed to the model's calibration only to the ITU scenarios. As a proof, in this study, the ITU scenario most representative for the London area is the Dense Urban (DU) configuration, $(\alpha, \beta, \gamma)_{ITU,DU} = (0.5, 300, 20)$, which differs from the actual triplet $(\alpha, \beta, \gamma)_{LON} == (0.5, 397.6, 24.3)$ showing lower building density and lower vertical extent, thus a higher P_{LoS}. This stresses the importance of using, whenever applicable, the actual morphological features of the environment, while relying solely on the ITU reference scenarios might be too limiting for real-world applications.

IV. Conclusions

This study proposes a methodology for estimating the probability of O-LoS in ground-to-air propagation paths, to be potentially exploited for the link design of UAV-assisted communication systems. The proposed model relies on a Monte Carlo simulation based on stochastic geometry and featuring an effective ray-launching approach, which explicitly accounts for both the terrestrial terminal height and the link elevation angle, h_{tx} and θ, respectively. Each realization randomly generates the surrounding environment using statistical distributions of building spacing, D_{b1} and D_{b12}, and vertical extent, H_b, for the area of interest, assuming two dominant obstructing buildings for terminals deeply embedded in clutter.

A statistical comparison with RT results obtained for a real urban environment across multiple use-cases demonstrates the good accuracy and reliability of the proposed model. In addition, the proposed model effectively overcomes key limitations of existing reference models in the literature, specifically the ITU-R P.1410-6 and the Holis models, which do not account for building width and terrestrial terminal height, respectively.

Future work includes further investigation on the impact of additional obstructing buildings along the propagation path, especially for scenarios involving high terminal heights, i.e., above the median clutter height, operating at low elevation angles. Moreover, extending the validation of the model to a wider range of urban morphologies – such as grid-structured or residential areas – will be essential to fully assess its accuracy and applicability.

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