Outage Probability of UAV Communications in the Presence of Interference

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Abstract—Unlike terrestrial communications, unmanned aerial vehicle (UAV) communications have some advantages such as line-of-sight (LoS) environment and flexible mobility. However, the interference will be still inevitable. In this paper, we analyze the effect of the interference on the UAV communications by considering the LoS probability and different channel fading for LoS and non-line-of-sight (NLoS) links, which are affected by the elevation angle of the communication link. We then derive a closed-form outage probability in the presence of an interfering node for all the possible scenarios and environments of main and interference links. After discussing the impacts of transmitting and interfering node parameters on the outage probability, we show the existence of the optimal height of the UAV that minimizes the outage probability. We also show the NLoS environment can be better than the LoS environment if the average received power of the interference is more dominant than that of the transmitting signal in UAV communications.

Index Terms—Unmanned aerial vehicle, interfering node, air-to-air channel, line-of-sight probability, outage probability

I. INTRODUCTION

As the unmanned aerial vehicle (UAV) technology develops, reliable UAV communications have become necessary. However, since UAV communications are different from conventional terrestrial communications, it is hard to apply the technology used in terrestrial communications to UAV communications [1]. Especially, unlike terrestrial communications, UAV communications can have line-of-sight (LoS) environments between a UAV and a ground device, and between UAVs. When the main link is in a LoS environment, the received main signal power will increase due to better channel fading and lower path loss exponent compared to a non-line-of-sight (NLoS) environment. It also means that in the presence of an interfering node, the interfering signal can be received with larger power as the interfering link can also be in a LoS environment [2].

UAV communications have been studied in the literature, mostly focused on the optimal positioning and trajectory of the UAV. The height of the UAV affects the communication performance in different ways. As the height increases, the UAV forms the LoS link with higher probability, which is modeled by the LoS probability in [3], but the distance to the receiver at the ground increases as well. By considering this relation, the optimal height of the UAV in terms of the communication coverage in the air-to-ground (A2G) channel is presented in [4], and for the case of using an UAV as a relay, the optimal height and position of UAVs have also been presented in [5]. The work [6] jointly optimized UAV trajectory and power control to minimize the outage probability without considering the LoS probability. However, all of those works analyzed and optimized for the UAV communications in the absence of an interfering node. Since the interference is an inevitable factor in the current and future networks, the impact of the interference on the UAV communications needs to be investigated carefully.

Recently, the interference has been considered in some works for the optimal positioning and trajectory of the UAV. The optimal deployment of the UAV has been presented to maximize the communication coverage in [7], [8]. The user scheduling and UAV trajectory have been jointly optimized with maximizing the minimum average rate without considering the LoS probability in [9], and the UAV trajectory is also optimized jointly with device-UAV association and uplink power to minimize the total transmit power according to the number of update times in [10]. However, all of those prior works considered limited UAV communication scenarios or environments. Specifically, only the path loss is used for channels without fading in [8]–[10], or the fact that the LoS probability can be different according to the locations of the UAV was not considered in [7].

Therefore, in this paper, we analyze the effect of the interference on the UAV communications by considering both the LoS and NLoS links and channel fading. The probability of forming the LoS link is defined by the elevation angle between a UAV and a ground device, and the path loss exponent and the Rician factor are also determined differently by the elevation angle. The main contribution of this paper can be summarized as follows:

- we consider all the scenarios of main (i.e., from a transmitter to a receiver) and interference (i.e., from an interfering node to a receiver) links in UAV communications, which includes ground-to-air (G2A), ground-to-air

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ground (G2G), A2G, and air-to-air (A2A) channels for the main and interfering links;
• we derive a closed-form outage probability in the presence of interfering node for all the scenarios by considering the LoS probability and different channel fading for LoS and NLoS links; and
• we analyze how the heights of transmitting or interfering node and link distances affect the outage probability through numerical results.

II. SYSTEM MODEL

In this section, we describe the network model and the channel model for UAV communications.

A. Terrestrial & Aerial Network Models

We consider a UAV network, which has a UAV, a ground device (e.g., ground control station or base station), and an interfering node. In this network, there can be three types of communications: UAV to UAV, UAV to ground device (or ground device to UAV), and ground device to ground device. The interfering node can be either on the ground or in the air, and we consider one interfering node.\(^1\)

When a transmitter (Tx), located at \((x_m, y_m, z_m)\), communicates to a receiver (Rx), located at \((0, 0, z_o)\) in the presence of interfering node at \((x, y, z)\), signal-to-interference ratio (SIR) is given by

\[
g(\theta_m, \theta_i) = \frac{h_m e^{-\alpha_m(\theta_m)} P_m}{h_i e^{-\alpha_i(\theta_i)} P_i} = \frac{h_m \beta_m(\theta_m)}{h_i \beta_i(\theta_i)}
\]

where \(\beta_m(\theta_m)\) and \(\beta_i(\theta_i)\) are respectively given by

\[
\beta_m(\theta_m) = e^{-\alpha_m(\theta_m)} P_m, \quad \beta_i(\theta_i) = e^{-\alpha_i(\theta_i)} P_i.
\]

\(^1\)Note that when the multiple interfering nodes are considered, the communication performance such as the outage probability has the similar trend as only dominant interfering node is considered and it is generally determined by the dominant interfering node at the low outage region [11].

Here, \(h_m\) and \(h_i\) are the fading gains of the main link (i.e., the channel between Tx and Rx) and the interference link (i.e., the channel between interfering node and Rx), respectively; \(\ell_m = \sqrt{x_m^2 + y_m^2 + (z_m - z_o)^2}\) and \(\ell_i = \sqrt{x_i^2 + y_i^2 + (z_i - z_o)^2}\) are the distances of main link and interference link, respectively; \(P_m\) and \(P_i\) are the transmission power of the transmitter and the interfering node, respectively; and \(\alpha_m(\theta_m)\) and \(\alpha_i(\theta_i)\) are the path loss exponents of main link and interference link, respectively. In [11], most parameters are determined by \(\theta_m\) and \(\theta_i\), which are the elevation angles between Tx and Rx and between Rx and the interfering node, respectively, which are given by

\[
\theta_i = \arctan\left(\frac{d_i^{(y)}}{d_i^{(x)}}\right), \quad \forall i = \{m, I\}
\]

where \(d_i^{(x)} = \sqrt{x_i^2 + y_i^2}\) is the horizontal distance and \(d_i^{(y)} = \sqrt{(z_i - z_o)^2}\) is the vertical distance of the main link \((i = m)\) or the interference link \((i = I)\).

B. Channel Model

As shown in Fig. 1 there are three types of the channels in the UAV networks: the A2G channel (from UAV to a ground device), the A2A channel (from UAV to UAV), and the G2G channel (from a ground device to a ground device). The G2G channel is the same channel of a terrestrial network, which is generally modeled as NLoS environments with Rayleigh fading in urban area. The G2A channel and the A2G channel have the same characteristics. Hence, we describe characteristics of the A2G and A2A channels in this subsection.

The A2G and A2A channels can have LoS or NLoS environments depending on the height of the UAV and its surrounding environments such as buildings. The elevation angle \(\theta_i\) \((\theta_m\) or \(\theta_i\)) is considered for the A2G (or G2A) channel, while ignored for G2G or A2A channel and assumed to be \(\theta = 0\) or \(\pi\) for those two cases. In the following, we first describe the channel components, affected by \(\theta_i\), and then provide the models for A2G and A2A channels.

1) Components affected by elevation angle \(\theta_i\): The elevation angle \(\theta_i\) affects the probability of forming LoS, the path loss exponent, and the Rician factor as described below.

• The LoS probability is given by [3]

\[
p_{\text{LoS}}(\theta_i) = \frac{1}{1 + a_1 \exp\left\{-b_1 (\theta_i - a_2)\right\}}
\]

where \(a_1\) and \(b_1\) are environment parameters, determined by the building density and height.

• The path loss exponent is determined by \(\theta_i\) as [5]

\[
\alpha(\theta_i) = a_2 p_{\text{LoS}}(\theta_i) + b_2
\]

where \(a_2 = \frac{\alpha(0)}{\pi} - p_{\text{LoS}}(0) \approx \alpha(0) - \frac{\alpha(0)}{\pi} \approx \alpha(0)\) and \(b_2 = \alpha(0) - a_2 p_{\text{LoS}}(0) \approx \alpha(0)\).

• The Rician factor is determined by \(\theta_i\) as [5]

\[
K(\theta_i) = a_3 \exp(b_3 \theta_i)
\]

where \(a_3 = K(0)\) and \(b_3 = \frac{2}{\pi} \ln\left(\frac{K(0)}{K(\pi)}\right)\).

Fig. 1. System model when UAVs are the communication devices. There are four types of channels: ground-to-ground (G2G), ground-to-air (G2A), air-to-ground (A2G), and air-to-air (A2A) channels. The blue lines represent the main links and the red dotted lines represent the interference links, and \(\theta_{m0}\) and \(\theta_1\) are the elevation angles of main link and interference link, respectively.
\[ p^{(LL)}_o(\Theta, D) = 1 - Q \left( \frac{2K_n(\theta_m)\beta_m(\theta_m)}{\beta_m(\theta_m) + \gamma_i\beta_i(\theta_i)} \right) + \frac{\gamma_i\beta_i(\theta_i)}{\beta_m(\theta_m) + \gamma_i\beta_i(\theta_i)} \times \exp \left( - \frac{K_n(\theta_m)\beta_m(\theta_m) + \gamma_i\beta_i(\theta_i)}{\beta_m(\theta_m) + \gamma_i\beta_i(\theta_i)} \right) I_0 \left( \frac{2\beta_m(\theta_m)}{\beta_m(\theta_m) + \gamma_i\beta_i(\theta_i)} \right) \] (13)

Note that from (4)-(6), we can see that \[ p_o(\theta_i) \] and \[ K(\theta_i) \]
are increasing functions of \[ \theta_i \] and \[ \alpha(\theta_i) \] is a decreasing function of \[ \theta_i \], so the received power increases when \[ \theta_i \] increases.

2) Air-to-Ground (A2G) channel: When the main link and the interference link are both A2G channels, \[ h_m \] and \[ h_l \] can be in either LoS or NLoS environments. We consider that the channel fading is Rician fading for LoS environments and Rayleigh fading for NLoS environments. Therefore, the distribution of the channel fading, \( h_i, i \in \{m, l\} \), is given by
\[
f_{h_i}(h) = \begin{cases} f_{L_i}(h) & \text{for LoS case} \\ f_{N_i}(h) & \text{for NLoS case} \end{cases}
\]
where \( f_{L_i}(h) \) and \( f_{N_i}(h) \) are noncentral Chi-squared and exponential distribution, respectively, and given by
\[
f_{L_i}(h) = \frac{1}{\mathcal{H}_L} \frac{K(\theta_i)}{\mathcal{H}_L} \exp \left( -K(\theta_i) - \frac{1 + K(\theta_i)}{\mathcal{H}_L} h \right) I_0 \left( 2 \sqrt{K(\theta_i)h} \right)
\]
\[
f_{N_i}(h) = \frac{1}{\mathcal{H}_N} \exp \left( -\frac{h}{\mathcal{H}_N} \right) = \exp(-h).
\]
Here, \( I_0(\cdot) \) is the modified Bessel function of the first kind with order zero, and \( \mathcal{H}_L = 2 + 2K(\theta_i) \) and \( \mathcal{H}_N = 1 \) are the means of LoS and NLoS channel fading gain, respectively.

3) Air-to-Air (A2A) channel: In A2A channel, the channel will be in LoS environments and \( \theta_i = \frac{\pi}{2} \), so the distribution of the channel fading, \( h_i, i \in \{m, l\} \), is given by
\[
f_{h_i}(h) = \frac{1}{2} \exp \left( -K(h) - \frac{h}{2} \right) I_0 \left( 2\sqrt{K(\theta_i)}h \right)
\]
(11)

where \( K_o = K(\frac{\pi}{2}) \). Unlike the A2G channel, the Rician factor \( K_o \) and the path loss exponent \( \alpha \) of A2A channel are not affected by \( \theta_i \).

III. OUTAGE PROBABILITY ANALYSIS

In this section, we analyze the outage probability by considering various environments of main and interference links. For given the elevation angle set \( \Theta = (\theta_m, \theta_l) \) and the link distance set \( D = (\ell_m, \ell_l) \) of main and interference links, the outage probability is defined as
\[
p_o(\Theta, D) = \mathbb{P} \left[ \gamma(\theta_m, \theta_l) < \gamma_l \right]
\]
(11)

where \( \gamma_l \) is the target SIR, which can be defined by \( \gamma_l = 2^{\frac{R_l}{W}} - 1 \) for the target rate \( R_l \) and the bandwidth \( W \).

We consider the interference limited environment, and the derived outage probabilities are given in the following theorem.

Theorem 1: For given \( \Theta = (\theta_m, \theta_l) \) and \( D = (\ell_m, \ell_l) \), the outage probability \( p_o(\Theta, D) \) can be presented as
\[
p_o(\Theta, D) = p_o(\theta_m, \theta_l)p_o(\ell_m, \ell_l)^{(LL)}(\Theta, D)
\]
\[
+ p_o(\theta_m)(1 - p_l(\theta_l))p_o^{(LN)}(\Theta, D)
\]
\[
+ (1 - p_o(\theta_m))p_l(\theta_l)p_o^{(NL)}(\Theta, D)
\]
\[
+ (1 - p_o(\theta_m))(1 - p_l(\theta_l))p_o^{(NN)}(\Theta, D)
\]
(12)

where \( p_o^{(\ell_m, \ell_l)}(\Theta, D) \) is the outage probability with the environment of the main link \( \ell_m \) and that of the interference link \( \ell_l \). The environment \( \ell_i \) can be either LoS (i.e., \( \ell_i = L \)) or NLoS (i.e., \( \ell_i = N \)), and \( p_o^{(\ell_m, \ell_l)}(\Theta, D) \) for four cases of \( \ell_i = L \) or \( \ell_i = N \) are given as follows:

1) Case 1 \( (\ell_m = L \text{ and } \ell_l = L) \): \( p_o^{(LL)}(\Theta, D) \) is given by (13).

2) Case 2 \( (\ell_m = L \text{ and } \ell_l = N) \): \( p_o^{(LN)}(\Theta, D) \) is given by
\[
p_o^{(LN)}(\Theta, D) = \gamma_l \beta_l(\theta_l)
\]
\[
\times \exp \left( -\frac{2K_m(\theta_m)\beta_m(\theta_m)}{2\beta_m(\theta_m) + \gamma_l\beta_l(\theta_l)} \right) I_0 \left( 2\sqrt{K_m(\theta_m)\beta_m(\theta_m)} \right).
\]
(14)

3) Case 3 \( (\ell_m = N \text{ and } \ell_l = L) \): \( p_o^{(NL)}(\Theta, D) \) is given by
\[
p_o^{(NL)}(\Theta, D) = 1 - \frac{\beta_m(\theta_m)}{2\beta_m(\theta_m) + \beta_m(\theta_m)}
\]
\[
\times \exp \left( -\frac{2\gamma_l\beta_l(\theta_l)}{2\gamma_l\beta_l(\theta_l) + \beta_m(\theta_m)} \right).
\]
(15)

4) Case 4 \( (\ell_m = N \text{ and } \ell_l = N) \): \( p_o^{(NN)}(\Theta, D) \) is given by
\[
p_o^{(NN)}(\Theta, D) = \gamma_l \beta_l(\theta_l)
\]
\[
\beta_m(\theta_m) + \gamma_l\beta_l(\theta_l).
\]
(16)

Proof: The outage probability is obtained as (12) using the law of total probability. We derive \( p_o^{(\ell_m, \ell_l)}(\Theta, D) \) for the above four cases as follows. For Case 1, \( K_m(\theta_m) \neq 0 \) and \( K_l(\theta_l) \neq 0 \) as both main and interference links are in LoS environments, and \( p_o^{(\ell_m, \ell_l)}(\Theta, D) \) can be obtained using (8) as
\[
p_o^{(LL)}(\Theta, D) = \int_0^\infty \int_0^\infty \frac{h_m(h)}{h_m(h)} f_{h_i}(g) dg dh
\]
\[
= 1 - \frac{1}{2} \int_0^\infty Q \left( \sqrt{2K_m(\theta_m)}, \frac{\beta_m(\theta_m)}{\beta_m(\theta_m)} \right) I_0 \left( 2\sqrt{K_m(\theta_m)\beta_m(\theta_m)} \right) \times \exp \left( -K_l(\theta_l) - \frac{g}{2} \right) I_0 \left( 2\sqrt{K_l(\theta_l)\beta_m(\theta_m)} \right) \]
(17)
(a) is from the cumulative distribution function (CDF) of the noncentral Chi-squared distribution, and the integral term can be presented as
\[
\int_0^\infty \exp \left( -c^2 x \right) I_0 \left( d \sqrt{2x} \right) Q \left( e, f \sqrt{2x} \right) \, dx
\]
\[
= \frac{1}{c^2} \left\{ \exp \left( \frac{d^2}{2c^2} \right) Q \left( \sqrt{\frac{ce}{c^2 + f^2}}, \frac{df}{c\sqrt{c^2 + f^2}} \right) - \frac{f^2}{c^2 + f^2} \exp \left( - \frac{d^2 - c^2 e^2}{2(c^2 + f^2)} \right) I_0 \left( \frac{de}{c^2 + f^2} \right) \right\}
\]
(18)
where \( c = \sqrt{0.5} \), \( d = \sqrt{K_1(\theta_1)} \), \( e = \sqrt{2K_m(\theta_m)} \), and \( f = \sqrt{\frac{\gamma_1\beta_1(\theta_1)}{2\beta_m(\theta_m)}} \) from [14] eq. (46). By using (18) in (17), \( p_o^{(L-L)}(\Theta, D) \) is presented as (13).

In Case 2, \( K_m(\theta_m) \neq 0 \) and \( K_1(\theta_1) = 0 \) as the interference link is in NLoS environment, and \( p_o^{(L-N)}(\Theta, D) \) is obtained using (8) and (9) as
\[
p_o^{(L-N)}(\Theta, D) = \int_0^\infty \int_0^\infty f_{h_m}(h) dh f_{h_1}(g) \, dg
\]
\[
= 1 - \int_0^\infty \left\{ \exp \left( -c^2 x \right) \right\} \, dx
\]
\[
= \frac{1}{c^2} \left\{ 1 - \frac{f^2}{c^2 + f^2} \exp \left( - \frac{d^2 - c^2 e^2}{2(c^2 + f^2)} \right) \right\}
\]
(19)
In (19), the integral term can be presented as
\[
\int_0^\infty \exp \left( -c^2 x \right) I_0 \left( d \sqrt{2x} \right) Q \left( e, f \sqrt{2x} \right) \, dx
\]
\[
= \frac{1}{c^2} \left\{ 1 - \frac{f^2}{c^2 + f^2} \exp \left( - \frac{d^2 - c^2 e^2}{2(c^2 + f^2)} \right) \right\}
\]
(20)
where \( c = 1 \), \( e = \sqrt{2K_m(\theta_m)} \), and \( f = \sqrt{\frac{\gamma_1\beta_1(\theta_1)}{2\beta_m(\theta_m)}} \) from [14] eq. (40). By using (20) in (19), \( p_o^{(L-N)}(\Theta, D) \) is presented as (13).

In Case 3, \( K_m(\theta_m) = 0 \) and \( K_1(\theta_1) \neq 0 \) as the main link is in NLoS environment, and \( p_o^{(N-L)}(\Theta, D) \) is given by
\[
p_o^{(N-L)}(\Theta, D) = \int_0^\infty \int_0^\infty f_{h_m}(h) dh f_{h_1}(g) \, dg
\]
\[
\equiv 1 - \frac{1}{2} \int_0^\infty I_0 \left( \sqrt{2K_1(\theta_1)} g \right) \exp \left( - \gamma_1\beta_1(\theta_1) g \beta_m(\theta_m) \right) \, dg
\]
(21)
In (21), (a) is from the CDF of the exponential distribution and the integral term can be presented as
\[
\int_0^\infty \exp \left( -c^2 x \right) I_0 \left( d \sqrt{2x} \right) \, dx = \frac{1}{c^2} \exp \left( \frac{d^2}{2c^2} \right)
\]
(22)
where \( c = \sqrt{\frac{1}{2} + \frac{\gamma_1\beta_1(\theta_1)}{\beta_m(\theta_m)}} \) and \( d = \sqrt{K_1(\theta_1)} \) from [14] eq. (9). By using (22) in (21), \( p_o^{(N-L)}(\Theta, D) \) is presented as (15).

In Case 4, \( K_m(\theta_m) = 0 \) and \( K_1(\theta_1) = 0 \) as the main and the interference links are both in NLoS environments, and \( p_o^{(N-N)}(\Theta, D) \) is given by
\[
p_o^{(N-N)}(\Theta, D) = \int_0^\infty \int_0^\infty f_{h_m}(h) dh f_{h_1}(g) \, dg
\]
\[
\equiv 1 - \frac{1}{2} \int_0^\infty I_0 \left( \sqrt{2K_1(\theta_1)} g \right) \exp \left( - \gamma_1\beta_1(\theta_1) g \beta_m(\theta_m) \right) \, dg
\]
(23)
By simple calculation in (23), \( p_o^{(N-N)}(\Theta, D) \) is obtained as (16).
From (26), we obtain the first derivatives of \( p_o^{(L,L)}(v) \) and \( p_o^{(N,N)}(v) \) according to \( v \), respectively, as

\[
\frac{\partial p_o^{(L,L)}(v)}{\partial v} = \left( p_o^{(N,N)}(v) - 1 \right) \exp \left( -\frac{A(v)^2 + B(v)^2}{2} \right) B(v) \\
\times \left\{ I_1(A(v)B(v)) \frac{\partial A(v)}{\partial v} - I_0(A(v)B(v)) \frac{\partial B(v)}{\partial v} \right\} \\
+ p_o^{(N,N)}(v) \exp \left( -\frac{A(v)^2 + B(v)^2}{2} \right) A(v) \\
\times \left\{ I_1(A(v)B(v)) \frac{\partial B(v)}{\partial v} - I_0(A(v)B(v)) \frac{\partial A(v)}{\partial v} \right\} \\
+ \frac{\partial p_o^{(N,N)}(v)}{\partial v} \exp \left( -\frac{(A(v))^2 + B(v)^2}{2} \right) I_0(A(v)B(v)) < 0 \quad (27)
\]

\[
\frac{\partial p_o^{(N,N)}(v)}{\partial v} = -\frac{\gamma_t}{(v + \gamma_t)^2} < 0. \quad (28)
\]

In (27) and (28), the inequalities are obtained since \( \exp(v) \geq 1 \), \( I_o(v) \geq 1 \), \( A(v) \geq 0 \), \( B(v) \geq 0 \), \( I_1(v) \geq 0 \), \( \frac{\partial B(v)}{\partial v} \leq 0 \), and \( 0 \leq p_o^{(N,N)}(v) \leq 1 \). Hence, \( p_o^{(L,L)}(v) \) and \( p_o^{(N,N)}(v) \) are monotonically decreasing functions of \( v \).

If \( v = 0 \), from (28) and (27), we have

\[
\frac{\partial p_o^{(N,N)}(0)}{\partial v} < \frac{\partial p_o^{(L,L)}(0)}{\partial v} \quad (29)
\]

since \( \frac{\partial p_o^{(N,N)}(0)}{\partial v} = -\frac{1}{\gamma_t} \), \( \frac{\partial p_o^{(L,L)}(0)}{\partial v} = \frac{\partial p_o^{(N,N)}(0)}{\partial v} \exp \left( -\frac{B(0)^2}{2} \right) \), and \( p_o^{(N,N)}(0) = p_o^{(L,L)}(0) = 1 \). Hence, for small \( \epsilon \), we have

\[
p_o^{(N,N)}(\epsilon) < p_o^{(L,L)}(\epsilon). \quad (30)
\]

If \( v \) approaches \( \infty \), \( B(v) \to 0 \), \( \lim_{v \to \infty} p_o^{(L,L)}(v) = \lim_{v \to \infty} p_o^{(N,N)}(v) = 0 \), and from (28) and (27), we have

\[
\frac{\partial p_o^{(N,N)}(v)}{\partial v} \to -\frac{\gamma_t}{(v + \gamma_t)^2}, \\
\frac{\partial p_o^{(L,L)}(v)}{\partial v} \to \frac{\partial p_o^{(N,N)}(v)}{\partial v} \exp \left( -\frac{A(v)^2}{2} \right). \quad (31)
\]

From (31), we can see that for large \( v_0 \gg 1 \), \( \frac{\partial p_o^{(L,L)}(v_0)}{\partial v} > \frac{\partial p_o^{(N,N)}(v_0)}{\partial v} \), and we have

\[
p_o^{(L,L)}(v_0) < p_o^{(N,N)}(v_0) \quad (32)
\]

Therefore, from (30), (32), and the fact that \( p_o^{(L,L)}(v) \) and \( p_o^{(N,N)}(v) \) are both monotonically decreasing functions, we can know that there exists unique \( v' \) in \( 0 < v' < \infty \) that makes \( p_o^{(L,L)}(v') = p_o^{(N,N)}(v') \). Therefore, we obtain (24). ■

From Corollary 1 when the main and interference links are in the same environment, NLoS environment can be more preferred if the average received power of interference is much larger than that of transmitting signal (i.e., small \( \frac{\beta_o^{(N,N)}}{\beta_o^{(L,L)}} \)), but for the opposite case (i.e., large \( \frac{\beta_o^{(N,N)}}{\beta_o^{(L,L)}} \)), LoS environment can be better in terms of outage probability.

IV. Numerical Results

In this section, we present the effects of height, parameters, and channel state on the outage probability. Unless otherwise specified, the values of simulation parameters are \( \alpha_1=12.08 \), \( b_1=0.11 \), \( \alpha_2=3.5 \), \( \alpha_3=2 \), \( k_0=1 \), \( k_1=15 \), and \( P_s=10^{-8}W \).

Fig. 2 presents the outage probability \( p_o(\Theta, D) \) as a function of height \( d_m^{(V)} \) with \( d_m^{(H)} = 100m \) for different values of \( \gamma_t \), \( \ell_t \), and \( P_t \). The circle means the optimal height with the lowest outage probability.
the A2G or the G2A channel. From this figure, we can see that generally, longer horizontal distance of interference link (i.e., larger $d_4^{(H)}$) results in lower outage probability. On the other hand, longer vertical distance of interference link (i.e., larger $d_3^{(V)}$) does not always result in lower outage probability. Specifically, when the main link is the A2A channel, the outage probability can be smaller with $d_3^{(V)}$ than with $d_3^{(V)} = 100m$. This is because, as $d_4^{(H)}$ increases, the LoS probability of interference link with $d_3^{(V)} = 50m$ decreases faster than that with $d_3^{(V)} = 100m$.

Fig. 4 presents the outage probabilities $p_0^{(LL)}(\Theta, D)$ and $p_0^{(NN)}(\Theta, D)$ as a function of $\frac{\beta_0(\theta_0)}{\beta_h(\theta_h)}$ with $d_m^{(H)} = 100m$, $d_4^{(V)} = d_3^{(V)} = 70m$, and $\gamma_1 = 2$. From this figure, we can confirm that both outage probabilities are monotonic decreasing functions with $\frac{\beta_0(\theta_0)}{\beta_h(\theta_h)}$. In addition, there exists a cross point of those probabilities at around $\frac{\beta_0(\theta_0)}{\beta_h(\theta_h)} = 1.7$. For smaller $\frac{\beta_0(\theta_0)}{\beta_h(\theta_h)} < 1.7$, $p_0^{(LL)}(\Theta, D)$ is greater than $p_0^{(NN)}(\Theta, D)$, but it becomes opposite for larger $\frac{\beta_0(\theta_0)}{\beta_h(\theta_h)} > 1.7$. This verifies the results in Corollary 1.

V. CONCLUSION

This paper analyzes the impact of the interfering node for reliable UAV communications. After characterizing the channel model affected by the elevation angle of the communication link, we derive the outage probability in a closed form for all possible scenarios of main and interference links. Furthermore, we show the effects of the transmission power, the horizontal and vertical link distances, and the communication scenarios of main and interference links. Specifically, we show the existence of the optimal height of the UAV for different scenarios, which increases as the power of interfering node increases or the interference link distance decreases. We also analytically prove that NLoS environment can be better than LoS environment if the average received power of interference is much larger than that of transmitting signal. The outcomes of our work can provide insights on the optimal deployment of UAV in the presence of interfering node.

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