Joint Configuration of Transmission Direction and Altitude in UAV-based Two-Way Communication

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Abstract

When considering unidirectional communication for unmanned aerial vehicles (UAVs) as flying Base Stations (BSs), either uplink or downlink, the system is limited through the co-channel interference that takes place over line-of-sight (LoS) links. This paper considers two-way communication and takes advantage of the fact that the interference among the ground devices takes place through non-line-of-sight (NLoS) links. UAVs can be deployed at the high altitudes to have larger coverage, while the two-way communication allows to configure the transmission direction. Using these two levers, we show how the system throughput can be maximized for a given deployment of the ground devices.

Index Terms

Unmanned aerial vehicles, UAV two-way communication, interference spin.

I. INTRODUCTION

A number of recent works have considered the use of Unmanned aerial vehicles (UAVs) as flying Base Stations (BSs) to provide data services to ground users, see [1] and the references therein. Compared to a traditional terrestrial BS, UAV can provide higher capacity since line-of-sight (LoS) wireless communication link can be easily established in UAV-ground channel [2]. Moreover, multiple UAVs are considered to enhance coverage as well as throughput with the increasing demand of densely deployment for UAVs [3]. Despite the benefits, there are also

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a number of challenges, such as cell partition according to user distribution, UAVs’ altitudes adjustment and interference management, etc. Furthermore, while the LoS link UAV-ground is beneficial for the useful signal, it should be noted that, when one-way communication (either uplink or downlink) is considered, the co-channel interference always comes through the LoS link as well.

Authors in [4] used evolutionary algorithms in order to find the optimal placement of UAVs to help terrestrial stations to provide wireless services in disaster relief scenarios. Results in [4] shows that increasing the number of UAVs will inevitably lead to interference due to overlapping areas. In [3], in order to maximize the downlink coverage, the authors proposed an efficient deployment method, using circle packing theory, for multiple UAVs while ensuring that the coverage areas of UAVs do not overlap. Authors in [5] considered uplink transmission from UAVs to ground BSs. A communication block is defined for a UAV if it cannot find a BS or there are other BSs stations in its main lobe serving other UAVs, and hence suffer from strong co-channel interference. This blocking probability is minimized by adjusting the UAV’s altitude and/or beamwidth. Hence, in general, UAVs with the directional antennas can have a larger coverage to serve more ground users at the relatively higher altitudes but at the cost of more path loss and interference. The works described above are focused on one-way communication scenario, either uplink or downlink. The method that is commonly used to mitigate co-channel interference is to avoid overlapping areas through altitude control [3] or joint control of the directional antenna’s beamwidth as well as altitude [5].

In this paper, we consider a two-way communication scenario and mitigate the co-channel interference by using the transmission direction as an additional degree of freedom. Our study reveals that adapting the transmission directions for multiple UAV-user links can reduce the co-channel interference, which means that the UAVs can be deployed at relatively high altitudes, thereby enlarging their coverage. Furthermore, the altitudes can also be adjusted according to the topology of ground users, thus improving the system-level throughput.

Consider deployment of two UAVs to serve two cells, see Fig. 1. Note that, here we define a cell to be a spatial region of a fixed size in which the users are deployed randomly, rather than the region that is under a coverage of a specific UAV. The two cells on Fig. 1(a) are asymmetric in a sense that the device/user population in the Cell_1 is much larger compared to the one in Cell_2. Due to this, in the low-altitude deployment from Fig. 1(a), the communication resources of UAV_2 will be poorly used if each of the users in Cell_2 is only intermittently active. This
The adjustment of the transmission direction has been introduced in [6] under the name of interference spin. This concept is here enriched by adjusting the UAV altitude, resulting in improvements in system throughput.
II. SYSTEM MODEL

We consider dual UAVs, as aerial BSs, are deployed to serve two circle cells, Cell\textsubscript{1} and Cell\textsubscript{2}, with the same radius \(d_0\) and the distance between centers of two cells is denoted as \(D\).

A set \(N = \{1, 2...N\}\) of \(N\) users are assumed to be uniformly distributed in each cell with Poisson probabilistic activation during a transmission frame. That is, Cell\textsubscript{1} and Cell\textsubscript{2} respectively include \(K_1=\text{Pois}(\lambda_1) \in N\) and \(K_2=\text{Pois}(\lambda_2) \in N\) active ground users, where \(\lambda_1 \in N, \lambda_2 \in N\) denote the densities of active user in two cells. A new transmission frame starts when the whole set active users have already been served. In the two-dimensional (2D) horizontal plane, we deploy two UAVs at the centers of two cells, respectively. The three-dimensional (3D) coordinates of UAV\textsubscript{1} and UAV\textsubscript{2} can be denoted by, respectively, \(s_1 = (x_0, y_0, h_1)\) and \(s_2 = (x'_0, y'_0, h_2)\). The coordinate of ground user \(G_j, j \in K = \{1, 2, ..., 2N\}\) can be denoted as \(w_j = (x_j, y_j, 0)\). Transmit powers of UAV and ground users are denoted as \(P_u\) and \(P_g\), respectively.

All devices operate in half-duplex mode. Both UAVs use the same frequency band, normalized to 1 Hz and each UAV-user operates in time division duplex (TDD) mode. Load-balanced two-way communication takes place in two successive time slots: the first slot is used in one direction, either downlink or uplink, and the successive slot in the opposite direction.

At the start of each transmission frame, the topology of active ground users can be known by a cloud center, e.g., a macro BS, and then the optimal transmission parameters can be calculated and sent to UAVs as well as ground users \(\text{[7]}\). Compared to data transmission time, the parameter calculation time can be ignored in each transmission frame. The whole system consists of two two-way links: link \(L_1\) with UAV\textsubscript{1} and link \(L_2\) with UAV\textsubscript{2}. All links are slot-synchronous.

We consider the directional antenna for each UAV and the antenna gain of UAV\textsubscript{1}, for example, seen by \(G_j\) is approximately by \(\text{[3]}\):

\[
g(d_{1j}) = \begin{cases} \frac{g_0}{\Phi_B}, & d_{1j} = \| s_1 - w_j \| \leq h_1/\cos\Phi_B; \\ 0, & \text{otherwise}. \end{cases} \tag{1}
\]

where \(g_0 = \frac{30000}{2^2} \times \left(\frac{\pi}{180}\right)^2 \approx 2.2846\) and \(\Phi_B \in (0, \frac{\pi}{2})\) denotes antenna’s half beamwidth \(\text{[5]}\). The term \(d_{1j}\) denotes the distance between UAV\textsubscript{1} and ground user \(j\) in Cell\textsubscript{1}. The omnidirectional antenna is assumed for each ground user with unit gain \(g_0\).

\(^1\)The actual distribution is binomial distribution. We approximate it using Poisson distribution as the number of users is sufficiently large and the active probability for each user is sufficiently small.
The UAV-ground channel model is considered as LoS link while the ground-ground channel model is a NLoS link due to obstacles on the ground. For ease of illustrating our work, large-scale fading with path loss and shadow fading is considered for two kinds of channels, and the fading channels are assumed to be constant in each time slots but vary between different slots. This is sufficient to support our concept, but the work can be extended to other fading models as well. The received signal power of $G_j$ from UAV$_1$ is given by \[2\]:

$$P_{1j}(d_{1j}) = \frac{P_{u \rightarrow g}(d_{1j})}{\psi_{\text{LoS}}}(\frac{4\pi f_c}{c}d_{1j})^{-n_{\text{LoS}}}$$

where $n_{\text{LoS}} = 2$ is path loss exponent for LoS propagation, $f_c$ is the carrier frequency and $c$ is the speed of light. $\psi_{\text{LoS}} \sim N(\mu_{\text{LoS}}, \sigma_{\text{LoS}}^2)$ is shadow fading with normal distribution for LoS link.

Similar to \[2\], assuming channel reciprocity, the received signal powers of UAV$_1$ and the ground user $G_j$ from $G_j$ can be respectively given by

$$P_{j1}(d_{j1}) = \frac{P_{g \rightarrow u}(d_{j1})}{\psi_{\text{LoS}}}(\frac{4\pi f_c}{c}d_{j1})^{-n_{\text{LoS}}}$$

$$P_{jj'}(d_{jj'}) = \frac{P_{g \rightarrow g}(d_{jj'})}{\psi_{\text{NLoS}}}(\frac{4\pi f_c}{c}d_{jj'})^{-n_{\text{NLoS}}}$$

where $j' \in K$ and $j' \neq j$, $n_{\text{NLoS}} = 4$ is path loss exponent for NLoS propagation. $\psi_{\text{NLoS}} \sim N(\mu_{\text{NLoS}}, \sigma_{\text{NLoS}}^2)$ is shadow fading with normal distribution for NLoS link.

In this paper, we consider that each UAV can be deployed at two specific altitudes: either a low altitude $H_l = d_0/\tan(\Phi_B) + h_0$ or a high altitude $H_h = (d_0 + D)/\tan(\Phi_B)$, where $h_0 \geq 0$ is set to make sure that the UAV with low altitude will not fall into antenna main lobe of the other UAV with the high altitude, thus the interference between UAVs can be ignored.

### III. SYSTEM THROUGHPUT AND OPTIMAL CONFIGURATION

#### A. Two-way sum-rate

The interference spin or, for short, spin of link $L_1$ can be defined as \[6\]: $p_1 = 0$ if downlink takes place in the odd slot and uplink takes place in the even slot; $p_1 = 1$ vice versa. Furthermore, the relative spin, to illustrate the interference between two-way links $L_1$ and $L_2$, can be defined as $r = p_1 \oplus p_2$, where $\oplus$ is an XOR operator. In summary, $r=1$ means two links use different communication directions while $r=0$ means they use the same direction.

With this, the received signal-to-interference-and-noise-ratio (SINR) for any link can be expressed as the function of $r$. We consider two co-channel links: $L_1$ with UAV$_1$ and $G_j$; $L_2$ with UAV$_2$ and $G_{j'}$. According to geometry, we have $h_1 \leq d_{1j} \leq h_1/\cos\Phi_B$, $h_2 \leq d_{2j} \leq h_2/\cos\Phi_B$. 

Consider the the co-channel users \( G_j \) and \( G_{j'} \) that are located in different cells as shown in Fig. 2. The received signal in link \( L_1 \) at \( G_j \) from \( \text{UAV}_1 \) experiences co-channel interference from \( \text{UAV}_2 \) only when \( \text{UAV}_2 \) is deployed at a high altitude and the relative spin is \( r = 0 \). On the other hand, interference from the co-channel user \( G_{j'} \) is present when \( r = 1 \). Thus, in this scenario, the received SINR of downlink at \( G_j \) from \( \text{UAV}_1 \) is given as

\[
\text{SINR}_{u,g,d}^1 = \frac{P_{j1}(d_{1j})}{rP_{j',j}(d_{j'j}) + t(h_2)(1-r)P_{2j}(d_{2j}) + \sigma^2}
\geq \frac{P_{j1}(h_1/\cos\Phi_B)}{rP_{j',j}(d_{\text{min}}) + t(h_2)(1-r)P_{2j}(h_2) + \sigma^2} \triangleq \text{SINR}_{u,g}^1(r, h_1, h_2) \quad (5)
\]

where \( \sigma^2 \) denotes the power of additive white Gaussian (AWGN) and \( d_{\text{min}} = 2d_0/N \) is approximated as the minimal distance between ground users by simply assuming that users are deployed with equidistant intervals. The binary indicator \( t = 1 \) means \( \text{UAV} \) is deployed at the \( H_h \) while \( t = 0 \) means \( \text{UAV} \) is deployed at the \( H_l \), and it can be expressed as

\[
t(h) = \frac{h - H_l}{H_h - H_l} = \begin{cases} 1, & h = H_h; \\ 0, & h = H_l. \end{cases}
\quad (6)
\]

For simplicity and similar to (5), in the following text we adopt the lower bounds on SINRs [5]. For the received signal of uplink at \( \text{UAV}_1 \) from \( G_j \), it suffers from interference from the co-channel user \( G_{j'} \) only when \( \text{UAV}_1 \) is deployed at the high altitude and \( r = 1 \). The received SINR at \( \text{UAV}_1 \) is:

\[
\text{SINR}_{g,u,d}^1 = \frac{P_{j1}(d_{1j})}{t(h_1)(1-r)P_{j',1}d_{j'1} + \sigma^2} \geq \frac{P_{j1}(h_1/\cos\Phi_B)}{t(h_1)(1-r)P_{j',1}(h_1) + \sigma^2} \triangleq \text{SINR}_{g,u}^1(r, h_1) \quad (7)
\]

When the co-channel users are located in the same cells as shown in Fig. 1, the received signal in downlink at \( G_j \) from \( \text{UAV}_1 \) always gets co-channel interference from \( \text{UAV}_2 \) when the two links use the same direction \( r = 0 \). Furthermore, it still gets interference from the co-channel user \( G_{j'} \) when \( r = 1 \). It is analogous for the received signal in uplink. Then, the lower bounds on the SINR in this scenario are given, respectively, by:

\[
\text{SINR}_{u,g,d}^1(r, h_1, h_2) = \frac{P_{j1}(h_1/\cos\Phi_B)}{rP_{j',j}(d_{\text{min}}) + (1-r)P_{2j}(h_2) + \sigma^2} \quad (8)
\]

\[
\text{SINR}_{g,u,d}^1(r, h_1) = \frac{P_{j1}(h_1/\cos\Phi_B)}{(1-r)P_{j',1}(h_1) + \sigma^2} \quad (9)
\]
The SINRs for link $L_2$: $\text{SINR}_{ug,d}^2$, $\text{SINR}_{gu,d}^2$, $\text{SINR}_{ug,s}^2$, $\text{SINR}_{gu,s}^2$ can be derived in a similar way. Then, the maximum achievable co-channel two-way sum-rate for co-channel links $L_1$ and $L_2$ in two scenarios can be expressed, respectively, as:

$$R_d^{(c)}(r, h_1, h_2) = \log_2 \left( 1 + \text{SINR}_{ug,d}^1 \right) + \log_2 \left( 1 + \text{SINR}_{gu,d}^1 \right) + \log_2 \left( 1 + \text{SINR}_{ug,d}^2 \right)$$

$$R_s^{(c)}(r, h_1, h_2) = \log_2 \left( 1 + \text{SINR}_{ug,s}^1 \right) + \log_2 \left( 1 + \text{SINR}_{gu,s}^1 \right) + \log_2 \left( 1 + \text{SINR}_{ug,s}^2 \right)$$

The users, without co-channel link, can be individually served without co-channel interference, and then the individual two-way sum-rate, in link $L_1$, can be expressed as

$$R^{(i)}(h_1) = \log_2 \left( 1 + \text{SNR}_{ug}^1(h_1) \right) + \log_2 \left( 1 + \text{SNR}_{gu}^1(h_1) \right)$$

where $\text{SNR}_{ug}^1$ and $\text{SNR}_{gu}^1$ can be respectively expressed as $\text{SNR}_{ug}^1(h_1) = \frac{P_{ij}(h_1/\cos\Phi_B)}{\sigma^2}$ and $\text{SNR}_{gu}^1(h_1) = \frac{P_{ij}(h_1/\cos\Phi_B)}{\sigma^2}$.

The individual two-way sum-rate $R^{(i)}(h_2)$ in link $L_2$ can be expressed in a similar way.

**B. Transmission scheme and average throughput**

Transmission scheme for this UAV-based two-way system will divided into three steps: 1) UAV$_1$ and UAV$_2$ serve users in their corresponding cells until there are no co-channel users in the cells; 2) If two UAVs are both deployed at the low altitudes, e.g., Fig. 1(a), the remaining users in Cell$_1$ are individually served by UAV$_1$; if one of UAVs is deployed at the high altitude, e.g., UAV$_2$ in Fig. 1(b), it can help UAV$_1$ to serve the remaining users in Cell$_1$; 3) If there is still individual user in Cell$_1$ after cooperatively served by UAV$_2$ in Fig. 1(b), then it will be individually served by its corresponding UAV (UAV$_1$). Thus the number of pairs of co-channel users and individual users vary with the UAV altitudes. As explained earlier, three cases of potential optimal UAV altitudes can reach the maximal throughput with different active users in two cells.

Defining $k = K_1 - K_2$, number of pairs of co-channel users in different cells $a_d$, number of pairs of co-channel users in the same cell $a_s$ and number of individual served users $b$ can be
expressed as
\[ a_d^{(+)}(h_1, h_2|k > 0) = K_2 \]  (13)
\[ a_d^{(-)}(h_1, h_2|k \leq 0) = K_2 + k \]  (14)
\[ a_s^{(+)}(h_1, h_2|k > 0) = \begin{cases} 0, & h_1 = H_i, h_2 = H_i \text{ or } h_1 = H_h, h_2 = H_h; \\ k, & h_1 = H_h, h_2 = H_i. \end{cases} \]  (15)
\[ a_s^{(-)}(h_1, h_2|k \leq 0) = \begin{cases} 0, & h_1 = H_i, h_2 = H_i \text{ or } h_1 = H_h, h_2 = H_h; \\ -k, & h_1 = H_h, h_2 = H_i. \end{cases} \]  (16)
\[ b^{(+)}(h_1, h_2|k > 0) = \begin{cases} k, & h_1 = H_i, h_2 = H_i \text{ or } h_1 = H_h, h_2 = H_h; \\ k - 2\lfloor \frac{k}{2} \rfloor, & h_1 = H_i, h_2 = H_i. \end{cases} \]  (17)
\[ b^{(-)}(h_1, h_2|k \leq 0) = \begin{cases} -k, & h_1 = H_i, h_2 = H_i \text{ or } h_1 = H_h, h_2 = H_h; \\ -k - 2\lfloor \frac{k}{2} \rfloor, & h_1 = H_h, h_2 = H_i. \end{cases} \]  (18)

Then, considering Poisson probabilistic activation of ground users, the average throughput of this system can be given by the following proposition.

**Proposition 1:** The average throughput of UAV-based two-way communication system can be expressed as

\[ C(r, h_1, h_2, \lambda_1, \lambda_2) = \sum_{k=1}^{N} P(k, \lambda_1, \lambda_2) \sum_{K_2+k,K_2\in\mathbb{N}} \binom{N}{K_2+k} \binom{N}{K_2} c^{(+)}(r, h_1, h_2|k, K_2) \]
\[ + \sum_{k=-N}^{0} P(k, \lambda_1, \lambda_2) \sum_{K_2+k,K_2\in\mathbb{N}} \binom{N}{K_2+k} \binom{N}{K_2} c^{(-)}(r, h_1, h_2|k, K_2) \]  (19)

where \( r \in \{0, 1\} \) and \( h_1, h_2 \in \{H_h, H_i\} \). \( P(k, \lambda_1, \lambda_2), c^{(+)}(\cdot|k) \) and \( c^{(-)}(\cdot|k) \) are respectively expressed as

\[ P(k, \lambda_1, \lambda_2) = e^{-(\lambda_1+\lambda_2)} \frac{(\lambda_1)}{\lambda_2}^{k/2} I_k(2\sqrt{\lambda_1\lambda_2}) \]  (20)
\[ c^{(+)}(r, h_1, h_2|k, K_2) = \frac{a_d^{(+)} R_d^{(c)} + a_s^{(+)} R_s^{(c)} + b^{(+)} R^{(i)}}{2(a_d^{(+)} + a_s^{(+)} + b^{(+)})} \]  (21)
\[ c^{(-)}(r, h_1, h_2|k, K_2) = \frac{a_d^{(-)} R_d^{(c)} + a_s^{(-)} R_s^{(c)} + b^{(-)} R^{(i)}}{2(a_d^{(-)} + a_s^{(-)} + b^{(-)})} \]  (22)

where \( I_k(z) \) is the modified Bessel function of the first kind.
Proof: \( P(k, \lambda_1, \lambda_2) = \mathbb{P}\{K_1 - K_2 = k\} \) is defined as the probability that \( K_1 \) and \( K_2 \) users, with difference \( k \in [-N, N] \) users, are respectively active in Cell_1 and Cell_2. Given the Poisson distributed population of active users, \( \mathbb{P}\{K_1 - K_2 = k\} \), following the Skellam distribution [8], can be given by (20).

Given the difference active users \( k \), the whole active cases should be \( \sum_{K_2+k, K_2 \in \mathbb{N}} \binom{N}{K_2+k} \binom{N}{K_2} \). For each case, that is with given \( K_2 \) as well as \( k \), the average throughput \( c^{(+)}(r, h_1, h_2|k, K_2) \) can be calculated by three parts: sum-rates of the co-channel users in different cells, the co-channel users in the same cell and the individual users. As shown in (21), the numerator denotes the the total two-way sum-rate for all users. The denominator is the number of time slots to serve the whole users. The derivation for \( c^{(-)}(\cdot) \) is the same.

C. Spin and altitude configuration

It can be seen from (19) that the average throughput depends on three key parameters: spin, UAV altitudes and user densities. Defining parameter set \( \eta = \{r, h_1, h_2\} \), as described earlier, we can derive that only three configurations influence the maximal throughput according to different \( \lambda_1 \) and \( \lambda_2 \): \( \eta_1 = \{1, H_l, H_h\} \), \( \eta_2 = \{1, H_h, H_l\} \) and \( \eta_3 = \{0, H_l, H_l\} \).

Then, the optimal configuration can be calculated by

\[
\eta^* = \arg\max_{\eta \in \{\eta_1, \eta_2, \eta_3\}} C(\lambda_1, \lambda_2, \eta)
\]

IV. NUMERICAL RESULTS AND CONCLUSIONS

In the simulations, we consider the two-way communication over \( f_c = 2 \) GHz carrier frequency with equally transmit powers for all devices (\( P_u = P_g = 35 \) dBm) in an urban environment (\( \mu_{\text{LoS}} = 1 \) dB, \( \sigma_{\text{LoS}} = 1 \) dB, \( \mu_{\text{NLoS}} = 30 \) dB, \( \sigma_{\text{NLoS}} = 8 \) dB [2], [3]). Other parameters can be set as: \( \sigma^2 = -120 \) dBm, \( h_0 = 1 \) m, \( d_0 = 100 \) m, \( D = 300 \) m, \( N = 30 \), \( \Phi_B = \pi/3 \). Fig. 3 compares the throughput performance for fixed and proposed optimal configurations of spin and altitudes. Result shows that deploying two UAVs at the low altitudes and using the same direction can reach the highest throughput when two cells have relatively similar user densities. On the other hand, when the user densities in two cells have relatively large difference, the maximal throughput can be achieved by using different directions and deploying them at different altitudes, the one with less actively users in its corresponding cell at high altitude and the other at low altitude. Moreover, Fig. 3 shows the optimal configuration in (23) can maximize throughput across the whole \( \lambda_1 \) with different \( \lambda_2 \).
The main conclusion is that using different transmission directions for UAV-based two-way communication can reduce the co-channel interference as much as possible and UAVs can be deployed at the high altitudes to have a larger coverage. Then, the transmission directions and UAVs’ altitudes can be configured according to a given deployment of the ground users in order to maximize system throughput.

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