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Adaptive Direction Control for UAV Full-Duplex Relay Networks Using Multiple Directional Antennas

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ABSTRACT We consider a UAV (Unmanned Aerial Vehicle) relay network whereby each UAV senses data and forwards it to dedicated ground stations by means of multi-hop relaying. In particular, we focus on a UAV relay network with a simple yet realistic linear topology for which we propose an adaptive direction control scheme to achieve a high throughput performance. In the proposed scheme, each UAV, equipped with multiple directional antennas, selects either the Decode-and-Forward (DF) *straight relaying method* or the *orthogonal relaying method*, for full-duplex data transfer, i.e., data is transmitted and received simultaneously on the same frequency, but at different antennas. The originality of our proposed method is to make each UAV rotate relatively to the position of its neighbouring UAVs, in order to optimize its antenna radiation direction, according to the selected relaying method. The key advantage of the proposed method is that signal direction can be controlled without the need of heavy adaptive signal processing as in conventional beamforming techniques. In order to clarify the decision parameters for selecting a relaying method, we first evaluate the throughput performance of the two-hop relay network under the severe interference conditions of UAV networks, and next, propose a procedure for selecting a multihop relaying method. Numerical experiments show that the proposed scheme enables to achieve a high throughput performance, with low computational costs.

INDEX TERMS Directional antennas, relay networks, unmanned aerial vehicles, wireless networks.

I. INTRODUCTION

Wireless networks based on UAVs (Unmanned Aerial Vehicles) have been attracting a lot of attention and various kinds of applications have been investigated so far, such as environmental monitoring [1], [2], disaster management [3], wireless sensor networks [4]–[6], flying base stations [7]–[10] and FANETs (flying ad hoc networks) [11]. Recently, there has been a particular interest in developing *UAV relay networks*,

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where sensor data collected by UAVs are delivered to dedicated ground stations. In such networks, there are two types of wireless links, i.e., *air-to-air links* between UAVs [12] and *air-to-ground links* or *ground-to-air links* between UAVs and ground stations [13], [14].

On the other hand, in terrestrial wireless networks including mobile ad hoc networks and wireless sensor networks, many data transmission and routing techniques have been studied so far, mostly to achieve high throughput and coverage performance. For instance, routing techniques for MIMO (Multiple-Input, Multiple Output)-based wireless ad

hoc networks have been proposed in [15], [16]. Such techniques may be applied to the UAV relay network. However, due to UAV-specific constraints in terms of battery and weight payload limitations, advanced signal processing techniques such as MIMO antennas are hardly applicable in a UAV relay network. This crucial issue is pointed out in, e.g., reference [17] which, in order to reduce the hardware size and cost for realizing beamforming, proposed to use a polarized antenna array to maximize the energy efficiency of a three node source-relay-destination system, in the case of half-duplex relaying. Therefore, it is crucial to design simplified processing and networking techniques that are tailored to the specific requirements of UAV networks, in order to achieve a high throughput performance.

In this paper, we propose a low-complexity, low-burden data relaying scheme based on adaptive UAV direction control, for a UAV relay network where multiple UAVs relay their sensed data to a fixed ground station through multi-hop links. The key feature of the proposed method is to equip each UAV with simple multiple directional antennas and to exploit full-duplex relaying, with the goal of enhancing the achievable throughput of UAV relay networks. By contrast to half-duplex, full-duplex relaying [18] with directional antennas enables to fully utilize network resources, as packets can be transmitted and received simultaneously on the same frequency, through different antennas. Let us recall that a directional antenna emits power with higher antenna gain in a specific direction, while an omni-directional antenna radiates the signal power towards all directions. This antenna directivity is usually controlled by adaptively adjusting antenna weights by means of signal processing techniques such as beamforming [19]. These techniques, however, require large computational complexities that are inadequate for UAV equipments. Therefore, we instead utilize low cost analog antenna devices such as microstrip patch antennas [20], and propose to adjust their radiating directions by rotating the UAVs themselves, according to their relative positions to their neighboring UAVs and/or ground station. Then, we propose a fully distributed multi-hop relaying method that aims at achieving a good throughput level without requiring computational capabilities to solve optimization problems at any of the UAV nodes. Namely, each UAV relay node along the path simply selects a Decode-and-Forward (DF) relaying method between the *straight relaying method* and the *orthogonal relaying method*, according to the relative positions of its neighboring UAVs, based on a decision table that is set during the initial path establishment phase.

It is worth noting that this proposed adaptive UAV direction control technique lends itself naturally to the specific operations of UAVs, whose positions/rotations can be controlled rather easily, while the cost of advanced signal processing is hardly bearable by individual UAVs. Hence, to clarify the decision parameters for selecting the best relaying method, we first evaluate the throughput performance of a simple two-hop relay network. Based on this preliminary design, we finally propose the full procedure for selecting the best

relaying method in terms of throughput, in the multi-hop UAV network. Numerical results show the efficiency of the proposed method against performance benchmarks.

The remainder of this paper is organized as follows. In Sect. II, we present the relevant State-of-the-Art literature on related issues. In Sect. III, we describe the system model for the UAV relay network. In Sect. IV, we investigate the performance of the two-hop relay network, the simplest case of the relay network. From the results obtained in Sect. IV, we propose the direction control scheme in Sect. V, and evaluate its performance with numerical experiments. In Sect. VI, we conclude the paper and give directions for future work.

II. RELATED WORKS

UAV networks with directional antennas have been considered in the literature. In [21], [22], directional antennas were exploited in air-to-ground links. In [21], directional antennas were used to confine interference on UAV-to-BS (Base Station) channels and blockage probabilities were analyzed. In [22], UAVs were deployed as flying BSs, and a joint altitude and beamwidth optimization problem was studied. In [23]–[26], directional antennas were used in air-to-air links. In [23], the capacity of FANETs with directional antennas was analyzed. In [24], [25], MAC (Medium Access Control) protocols were studied in FANETs with directional antennas. In [26], UAV mesh networks based on millimeter-wave wireless LANs were considered. In the situation where relative positions among UAVs are changed, beam management and self-healing mechanisms were proposed. In [27], [28], the authors aimed at maximizing the throughput performance by considering trajectory optimization and power allocation. By contrast, our proposed scheme in this paper is based on a simple but drastic idea, namely, rotating UAVs according to their relative positions among each other. Although this seems a natural approach especially when UAV helicopters are used, to the best of the authors' knowledge, there have been no prior works making use of this idea.

Many papers regarding terrestrial wireless multihop networks with directional antennas have been published so far [29]–[31]. It is worth noting that our proposed scheme is also applicable to such terrestrial networks. However, the major differences of our proposal with regard to multihop networks with static ground sensors with directional antennas can be listed as follows:

- 1) As the altitude of UAV networks increases, multipath effects on air-to-air links are diminished, thereby resulting into the free-space LOS model [12]. This means that, at a sufficient altitude, wireless signals are propagated far away from their transmitters, thereby causing serious interference among UAVs. Hence, the proposed scheme is designed to handle such severe interference levels on UAV-UAV links, as well as on UAV self-interferences.
- 2) As detailed in Sect. I, UAV networks are by nature more cost- and battery-limited than terrestrial networks, which is the reason why the UAVs in the

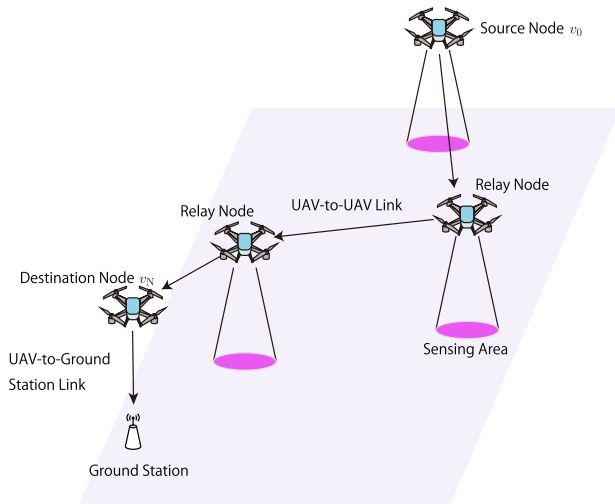


FIGURE 1. UAV relay network.

proposed method are not equipped with adaptive signal processing capabilities. In the case of terrestrial networks, [30], [31] have proposed to rotate beam directions, which can be implemented through beamforming. Our proposed scheme makes use of the mechanical feature of UAVs by making them rotate themselves, instead of rotating the beam direction through heavy signal processing. Furthermore, different signal processing techniques have been proposed to cancel self-interference [32]. We propose to combat UAV self-interference through simple yet efficient relay selection, instead of using signal processing-based cancellation techniques.

III. SYSTEM MODEL

Fig. 1 shows a UAV relay network, which comprises $N + 1$ UAVs v_n ($n = 0, 1, \dots, N$) forming a linear topology. Hereafter, we refer to a UAV as a *node*, simply. Each node has sensors and collects data by the sensors, and the collected data are delivered to the ground station by means of multihop relaying. There are three types of nodes, namely node v_0 with one neighboring node, node v_N connected to the ground station, and nodes v_n ($n = 1, 2, \dots, N - 1$) connected to two nodes, referred to as *source node*, *destination node*, and *relay nodes*, respectively. We assume that all nodes are placed at the same height and do not consider data transmission between the destination node and the ground station.

In our proposed scheme, each node has multiple directional antennas as shown in Fig. 2. Although a larger number of directional antennas increase the flexibility of data relaying algorithms, each node would be burdened with a heavier load. Considering this trade-off, we hence assume each node to be equipped with four antenna elements arranged symmetrically as shown in Fig. 2(c). Note that in the cases of two and three antennas, all pairs of antennas have the same angle between their directions (i.e., π in the case of two antennas, and $2\pi/3$

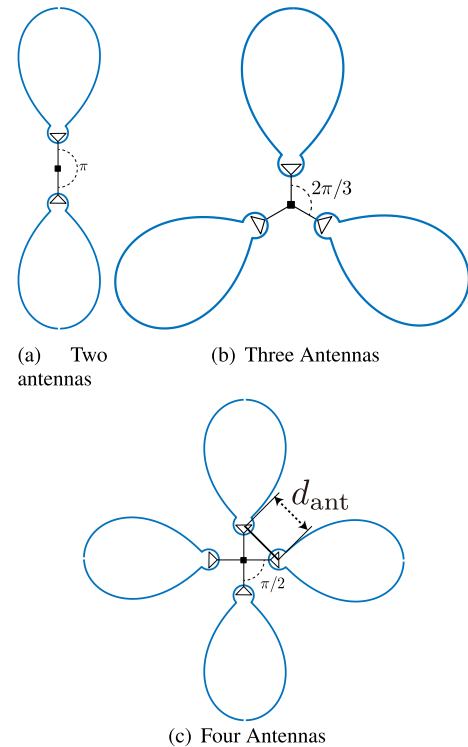


FIGURE 2. Arrangement of multiple directional antennas.

in the case of three antennas). On the other hand, there are two different angles ($\pi/2$ and π) in the case of 4 antennas. We will propose two different relaying methods in Sect. IV, based on this property.

We set the distance d_{ant} between two nearest antenna elements to $d_{\text{ant}} = 0.3$ [m]. Each antenna element has a cosine-shaped radiation pattern with a constant sidelobe level [33], where antenna gain $G(\theta)$ of azimuth angle θ is given by

$$G(\theta) = \begin{cases} C \cos^k(\theta) & \text{if } \cos^k(\theta) \geq f_{\text{SL}} \\ C f_{\text{SL}} & \text{otherwise,} \end{cases}$$

where C is a constant determined by the beamwidth and f_{SL} denotes the sidelobe level. Parameter k is computed by the *half-power beamwidth* θ_{BW} as

$$\cos^k\left(\frac{\theta_{\text{BW}}}{2}\right) = \frac{1}{\sqrt{2}}.$$

Fig. 3 shows the antenna radiation patterns for $\theta_{\text{BW}} = \pi/6, \pi/4, \pi/3$, and $\pi/2$ [rad].

In the UAV relay network, each node is fixedly placed at a position and rotates according to relative positions of nodes. In order to fully utilize network resources, we consider the *full-duplex relaying* model, as shown in Fig. 4. While either a transmitter antenna or a receiver antenna is used at a time in the *half-duplex relaying* model, both the transmitter antenna and the receiver antenna are used simultaneously. Although full-duplex relaying enhances link utilization, the self-interference from the transmitter antenna

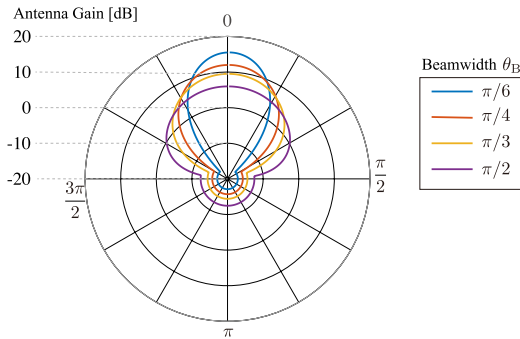


FIGURE 3. Antenna radiation pattern.

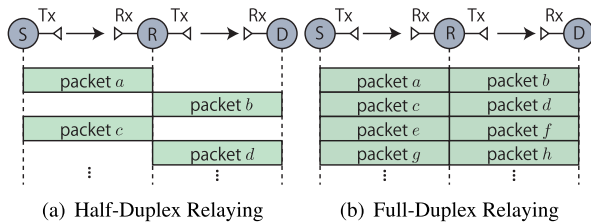


FIGURE 4. Half-duplex and Full-duplex relaying. “Tx” and “Rx” represent transmitter and receiver antennas, respectively.

to the receiver antenna may largely degrade the signal-to-interference plus noise ratio (SINR). Suppose that a signal is transmitted from v_i and received at v_j ($i, j = 1, 2, \dots, N, i \neq j$). We represent the received power of the signal by $p_{i,j}$, which includes the effects of transmit power, antenna transmit and receive beam gains and path-loss (see Eqs. (2), (3), (5), (6), and (8)).

Let γ_n ($n = 1, 2, \dots, N$) denote the SINR at node v_n , respectively. γ_n is given by

$$\gamma_n = \begin{cases} \frac{P_{n-1,n}}{\sum_{\substack{j=0 \\ j \neq n-1}}^{N-1} p_{j,n} + p_{\text{self}} + w} & n = 1, 2, \dots, N - 1 \\ \frac{P_{n-1,n}}{\sum_{j=0}^{N-2} p_{j,n} + w} & n = N, \end{cases}$$

where p_{self} and w represent the self-interference and the power of the Additive White Gaussian Noise (AWGN), respectively. In order to calculate received powers over air-to-air links or self-interference links, we consider only the direct path. Note that air-to-air LOS links can be modeled by a Rician fading channel [12]. We assume that the power $p(\delta)$ received at a receiver antenna separated from a transmitter antenna by distance δ is given by the Friis free-space equation [34]:

$$p(\delta) = \frac{P_{\text{TX}} G_{\text{TX}} G_{\text{RX}} \lambda^2}{(4\pi)^2 \delta^2}, \quad (1)$$

where P_{TX} , G_{TX} , G_{RX} , λ denote the transmission power, the transmitter antenna gain, the receiver antenna gain, and the wavelength of the signal, respectively.

In the UAV relay network, each node is required to maintain a routing table as well as the positions of its neighboring nodes. In the network, data packets are transferred through two phases: a *control phase* and a *data exchange phase*. In the control phase, the ground station firstly searches relay nodes by relaying control packets. Because each UAV node has no knowledge about its neighboring nodes initially, control packets are transmitted to several directions instead of using a simple flooding algorithm. When a UAV node receives a control packet, it replies its position to the ground station on the reverse direction. After collecting positions of the UAV nodes, the ground station establishes a path along the UAV nodes and advertises a routing table and positions of neighboring nodes to each relay node. Each relay node then determines its direction according to the proposed scheme explained in the following sections. In the data exchange phase, data packets are delivered on the established path.

We consider a *quasi-static* routing strategy in the proposed scheme, i.e., the data exchange phase has a significantly longer duration compared to the control phase. This means that this control information will not be required to be exchanged frequently. Hence, the incurred overhead can be assumed to be limited. It is worth noting that an excessively longer data exchange phase deteriorates the performance of the proposed scheme because wind disturbance might fluctuate the positions of the relay nodes. In section V-C, the throughput robustness to the disturbance is evaluated.

IV. PRELIMINARY STUDY FOR UAV RELAY NETWORKS

A. TWO-HOP RELAY NETWORK

We first evaluate the performance of the two-hop relay network, which corresponds to $N = 2$. Fig. 5 shows the configuration of this network, where L represents the distance between source and destination nodes, and d represents the distance of the relay node from the line between the source and the destination nodes. We assume that $d < L$. Parameter α ($0 < \alpha < 1$) represents the relative position of the relay node between the source and destination nodes.

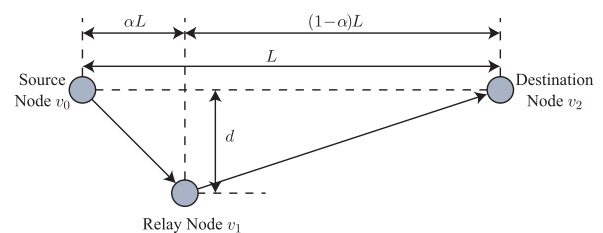


FIGURE 5. Two-hop relay network.

We consider the *straight relaying* and *orthogonal relaying* methods as shown in Fig. 6. In both relaying methods, we make use of the DF strategy. In the straight relaying method, two antenna elements directed to their opposite directions are used as transmitter and receiver antennas. By using

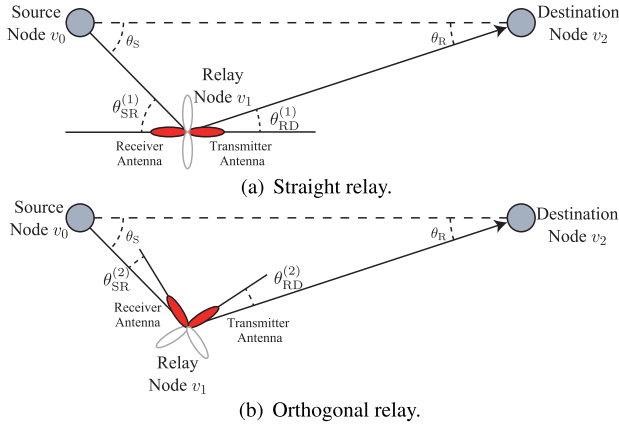


FIGURE 6. Two relaying methods for the relay node.

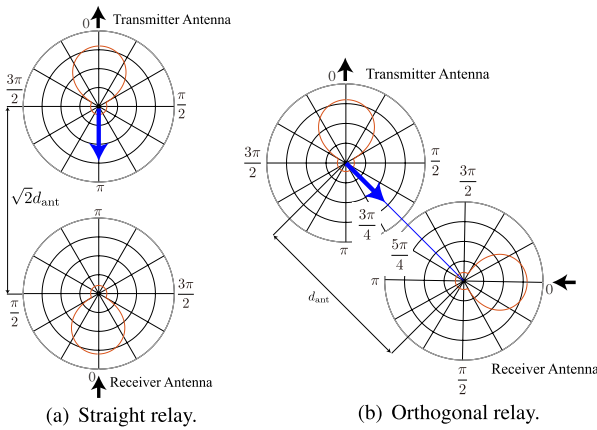


FIGURE 7. Self-interference in straight relaying and orthogonal relaying methods. Blue arrows indicate self-interference.

angles $\theta_{SR}^{(1)}$ and $\theta_{RD}^{(1)}$ in Fig. 6, $p_{0,1}$ and $p_{1,2}$ are given by

$$p_{0,1} = \frac{P_{TX}G(0)G(\theta_{SR}^{(1)})\lambda^2}{(4\pi)^2L_{SR}^2}, \quad (2)$$

$$p_{1,2} = \frac{P_{TX}G(\theta_{RD}^{(1)})G(0)\lambda^2}{(4\pi)^2L_{RD}^2}, \quad (3)$$

where $G(\theta)$ represents the antenna gain as a function of the azimuth angle θ . We set $\theta = 0$ for the transmitter antenna of the source node and the receiver antenna of the destination node. L_{SR} and L_{RD} denote the distance between v_1 and v_2 and the distance between v_2 and v_3 , respectively. From Fig. 5, we obtain L_{SR} and L_{RD} as

$$L_{SR} = \sqrt{\alpha^2 L^2 + d^2}, \quad L_{RD} = \sqrt{(1-\alpha)^2 L^2 + d^2}.$$

Since the transmitter and receiver antennas are directed to opposite directions in the straight relaying method as shown in Fig. 7, p_{self} is given by

$$p_{self} = \frac{P_{TX}G^2(\pi)\lambda^2}{(4\pi)^2(\sqrt{2}d_{ant})^2} = \frac{P_{TX}G^2(\pi)\lambda^2}{32\pi^2 d_{ant}^2}. \quad (4)$$

In the orthogonal relay method, two antenna elements directed to their orthogonal directions are used as the transmitter and the receiver antennas. By using angles $\theta_{SR}^{(2)}$ and $\theta_{RD}^{(2)}$

in Fig. 6(b), $p_{0,1}$ and $p_{1,2}$ are given by

$$p_{0,1} = \frac{P_{TX}G(0)G(\theta_{SR}^{(2)})\lambda^2}{(4\pi)^2L_{SR}^2}, \quad (5)$$

$$p_{1,2} = \frac{P_{TX}G(\theta_{RD}^{(2)})G(0)\lambda^2}{(4\pi)^2L_{RD}^2}. \quad (6)$$

Since the directions of the transmitter and receiver antennas are orthogonal in the *orthogonal relaying* method as shown in Fig. 7(b), we can write p_{self} is given by

$$\begin{aligned} p_{self} &= \frac{P_{TX}G(3\pi/4)G(5\pi/4)\lambda^2}{(4\pi)^2 d_{ant}^2} \\ &= \frac{P_{TX}G^2(3\pi/4)\lambda^2}{(4\pi)^2 d_{ant}^2}, \end{aligned} \quad (7)$$

where we utilize the symmetry of the antenna gain, i.e. $G(3\pi/4) = G(5\pi/4)$. Note that $G(\pi) = G(3\pi/4)$ when the antenna radiation pattern in Fig. 3 is used. Therefore, p_{self} in the straight relaying method is lower than that in the orthogonal relaying method. This is because the distance between the transmitter antenna and the receiver antenna is larger in the straight relaying method.

In both relaying methods, $p_{0,2}$ is given by

$$\begin{aligned} p_{0,2} &= \frac{P_{TX}G(\theta_S)G(\theta_R)\lambda^2}{(4\pi)^2 L^2}, \\ \theta_S &= \cos^{-1} \frac{\alpha L}{\sqrt{\alpha^2 L^2 + d^2}}, \\ \theta_R &= \cos^{-1} \frac{(1-\alpha)L}{\sqrt{(1-\alpha)^2 L^2 + d^2}}. \end{aligned} \quad (8)$$

Based on *Shannon's channel capacity*, we define the achievable throughput R between the source and the destination nodes as

$$R = \min_{n \in \{1,2\}} \{B \log_2(1 + \gamma_n)\}, \quad (9)$$

where B [Hz] denotes the transmission bandwidth. From (9), the throughput performance is obtained by selecting the minimum transmission rate between the transmission rates on links (v_0, v_1) and (v_1, v_2) . Let $R_{str}(d, L, \alpha)$ and $R_{ort}(d, L, \alpha)$ denote the throughputs of the straight relaying method and the orthogonal relaying method for parameters d, L , and α , respectively. The optimal throughput $R_{opt}(d, L, \alpha)$ is obtained by

$$R_{opt}(d, L, \alpha) = \max\{R_{str}(d, L, \alpha), R_{ort}(d, L, \alpha)\}. \quad (10)$$

From Eqs. (9) and (10), the optimal throughput is obtained by maximizing terms that include minimizations. Therefore, it is difficult to derive a close-form solution of the optimal throughput performance even in the simplest two-hop network and it can only be found through exhaustive search. Therefore, in the next subsection, we numerically compute the throughput performance.

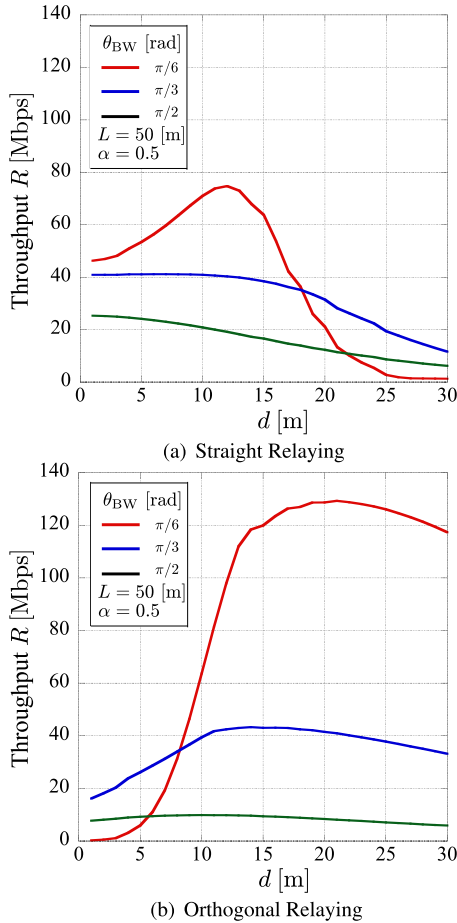


FIGURE 8. Throughput performance of straight relaying and orthogonal relaying methods for $L = 50$ [m] and $\alpha = 0.5$.

B. THROUGHPUT PERFORMANCE OF TWO-HOP RELAY NETWORKS

In this preliminary study, we evaluate the throughput performance of the two-hop relay network by setting $P_{TX} = 0$ [dBm] and $B = 20$ [MHz]. We set the noise power $w = -60.8$ [dBm], unless otherwise stated. An appropriate design of the transmission power P_{TX} is an important technical issue because it affects the battery power of UAVs as well as the throughput performance. In order to assess the battery power, however, a comprehensive study is required because it depends on several factors such as weight payload, wind, etc. [35]. Therefore, in this paper, we do not consider the design problem of the transmission power. Relay node v_2 's direction is adjusted such that $\theta_{SR}^{(1)} = \theta_{RD}^{(1)}$ and $\theta_{SR}^{(2)} = \theta_{RD}^{(2)}$. Figs. 8(a) and 8(b) show the throughput versus distance d in the straight and orthogonal relaying methods, respectively. When $d < 15$ and $\theta_{BW} = \pi/3, \pi/6$, we observe that the throughput increases with d . The reason is that increasing d mitigates the so-called *overreach interference* from v_0 to v_2 , i.e., $p_{0,2}$, and as a result, improves γ_2 . Namely, because all wireless signals are transmitted on the same frequency band, v_2 receives wireless signals not only from v_1 (i.e. the desired

signal) but also from v_0 (i.e., overreach interference). From Fig. 6, however, because θ_S and θ_R increase with d , larger d mitigates the overreach interference especially for narrower beamwidth (i.e. $\theta_{BW} = \pi/6$).

We also observe that the orthogonal relaying method achieves a higher throughput than the straight relaying method for $d > 10$ and $\theta_{BW} = \pi/3, \pi/6$. This break point will be referred to as a *switching point*, hereafter. One possible strategy for adaptive direction control is hence to change relaying methods at the switching point.

Fig. 9 shows the throughput performance vs. normalized distance d/L for $\alpha = 0.5$ and $\theta_{BW} = \pi/6$. The tendency of Fig. 9 shows that, at first, straight-line configuration is optimal as this enables the best beam alignments with respect to both the source and destination nodes, while limiting the self-interference at the same time, but as the relay node moves away, the best transmit/receive beam angles approach the orthogonal configuration and it becomes more crucial to align towards the directions of source and destination nodes, despite the increased level of self-interference of the orthogonal configuration as compared to the straight-line configuration. We observe that the switching points for different L occur approximately at the normalized distance, i.e., at $d/L \approx 0.22$. We also observe a similar trend for different α . This means that we can select a relaying method solely based on α and d/L , which hence represent network configuration parameters as they reflect well the nodes' relations.

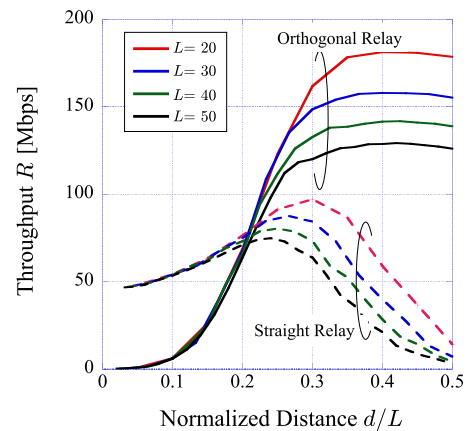


FIGURE 9. Throughput R vs. normalized distance d/L for $\alpha = 0.5$ and $\theta_{BW} = \pi/6$.

In the above numerical results, we assume a large difference between the transmission power and the noise power, i.e., $P_{TX} - w = 60.8$ [dB]. Chen et al. [36] also consider a similar situation where P_{TX} and w are set to $P_{TX} = 10$ [dBm] and $w = -100$ [dBm], respectively. However, we note that the above tendency is observed for a higher noise power. Fig. 10 shows the throughput performance vs. normalized distance d/L for $w = -50.8$ [dBm]. Although the higher noise power degrades the throughput performance, we observe that Figs. 9 and 10 have a similar trend. Therefore, the switching point can be determined by α and d/L .

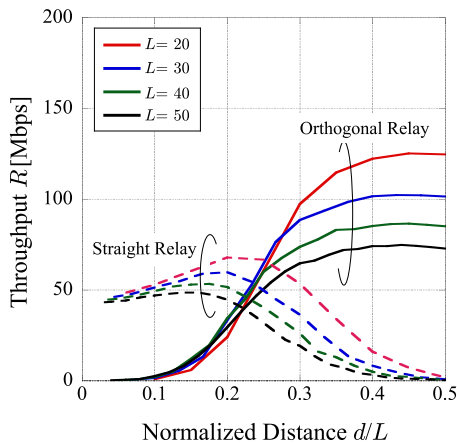


FIGURE 10. Throughput R vs. normalized distance d/L for $\alpha = 0.5$, $\theta_{BW} = \pi/6$, and $w = -50.8$ [dBm].

V. ADAPTIVE DIRECTION CONTROL

A. DECISION TABLE FOR DIRECTION CONTROL

Based on the results obtained in the previous section, we propose a direction control scheme for multi-hop UAV relay networks. Fig. 11 shows the network configuration, where L_n and d_n ($n = 1, 2, \dots, N - 1$) denote the distance between v_{n-1} and v_{n+1} and the distance of v_n from the line between v_{n-1} and v_{n+1} , respectively. α_n ($0 < \alpha_n < 1$) represents the relative position of v_n between v_{n-1} and v_{n+1} .

Let $l_{i,j}$ ($i, j = 1, 2, \dots, n, i \neq j$) denote the line between v_i and v_j . As shown in Fig. 12, we define $\theta_n^{(R)}$ ($n = 1, 2, \dots, N$) as the angle between the direction of the receiver antenna in v_n and line $l_{n-1,n}$, and $\theta_n^{(T)}$ ($n = 0, 1, \dots, N - 1$) as the angle between the direction of the transmitter antenna in v_n and line $l_{n,n+1}$.

In the proposed direction control scheme, each node has a *decision table* $T = \{\tau(\alpha^{(i)}, \delta^{(j)}) \in \{0, 1\} \mid i = 1, 2, \dots, N_a, j = 1, 2, \dots, N_d\}$, where there are $N_a \times N_d$ entries. Value 0 or 1 is assigned to entry $\tau(\alpha^{(i)}, \delta^{(j)})$, based on the throughput performance of two-hop relay networks. Let $R_{str}(\alpha^{(i)}, \delta^{(j)})$ and $R_{ort}(\alpha^{(i)}, \delta^{(j)})$ denote the achievable throughput of the straight relaying method and of the orthogonal relaying method, respectively, given the relative position $\alpha^{(i)}$ and the normalized distance $\delta^{(j)}$. We define sets \mathcal{A} and \mathcal{D} as $\mathcal{A} = \{\alpha^{(i)} \mid i = 1, 2, \dots, N_a\}$ and $\mathcal{D} = \{\delta^{(j)} \mid j = 1, 2, \dots, N_d\}$,

respectively. The decision table is set to $\tau(\alpha^{(i)}, \delta^{(j)}) = 0$ if $R_{str}(\alpha^{(i)}, \delta^{(j)}) > R_{ort}(\alpha^{(i)}, \delta^{(j)})$, $\tau(\alpha^{(i)}, \delta^{(j)}) = 1$, otherwise. When $\tau(\alpha^{(i)}, \delta^{(j)}) = 0$, the straight relaying method is selected, and when $\tau(\alpha^{(i)}, \delta^{(j)}) = 1$, the orthogonal relaying method is selected. Fig. 13 shows an example of decision tables, where black pixels and white pixels correspond to entries with $\tau(\alpha^{(i)}, \delta^{(j)}) = 0$ and $\tau(\alpha^{(i)}, \delta^{(j)}) = 1$, respectively.

We assume that each node knows the position of their neighboring nodes by means of GPS. After all nodes are deployed on a two-dimensional plane in the air, their directions and relaying methods are determined as follows. Node v_0 chooses an antenna element as its transmitter antenna and sets $\theta_0^{(T)} = 0$. Node v_N chooses an antenna element as its receiver antenna and sets $\theta_N^{(R)} = 0$. Next, node v_n ($n = 0, 1, \dots, N - 1$) calculates α_n and $\delta_n = d_n/L_n$, and finds the nearest entry $\tau(\hat{\alpha}, \hat{\delta}) \in \mathcal{T}$ to (α_n, δ_n) , where $(\hat{\alpha}, \hat{\delta})$ is obtained by

$$\hat{\alpha} = \arg \min_{\alpha^{(i)} \in \mathcal{A}} |\alpha^{(i)} - \alpha_n|, \quad \hat{\delta} = \arg \min_{\delta^{(j)} \in \mathcal{D}} |\delta^{(j)} - \delta_n|. \quad (11)$$

Node v_n then decides its relaying method according to $\tau(\hat{\alpha}, \hat{\delta})$. Namely, v_n selects the straight relaying method if $\tau(\hat{\alpha}, \hat{\delta}) = 0$, and the orthogonal relaying method otherwise. The decision table is computed in advance and is set at each relay node in the initial path establishment phase. Each relay node can decide its relaying method only by searching the decision table. As no optimization is processed by relay nodes, the proposed scheme does not incur high computational costs. Specifically, relay node v_n ($n = 1, 2, \dots, N - 1$) needs to have information on positions of v_n and neighboring two nodes v_{n-1} and v_{n+1} and its decision table. Suppose that the coordinate for each position is represented with N_{real} bytes. Because a decision table has $N_a \times N_d$ entries with binary numbers, the complexity required for computing this table at each relay node is given by $O(6N_{real} + N_a N_d) = O(\max\{N_{real}, N_a N_d\})$. On the other hand, because relay node v_n just selects an entry in the decision table based on given α_n and δ_n , the time complexity of v_n solely depends on the computational complexities to calculate α_n and δ_n , which are given by simple operations.

In wireless multihop networks, a lot of efforts have been made for maximizing the throughput performance in both centralized and distributed manners. In the

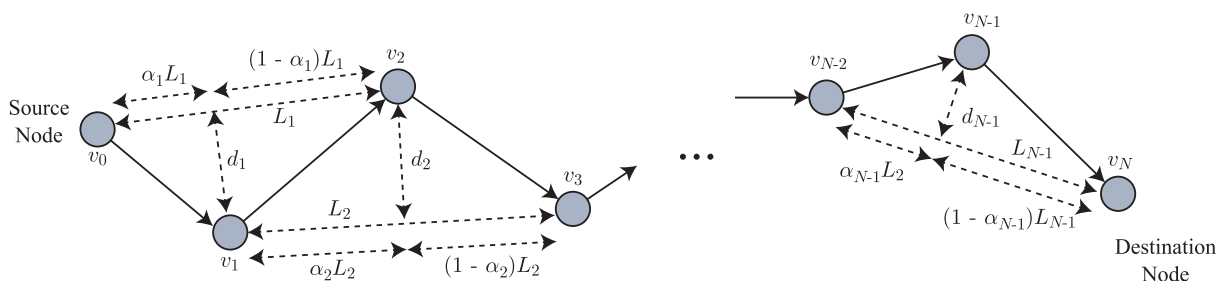


FIGURE 11. A Multi-hop relay network.

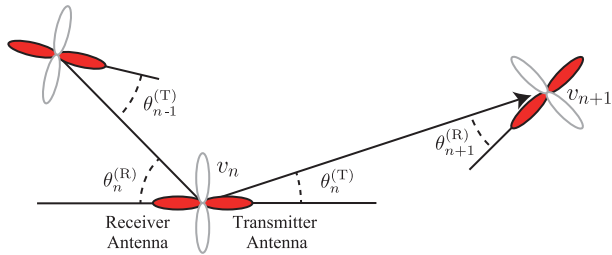


FIGURE 12. Node direction in a multihop relay network.

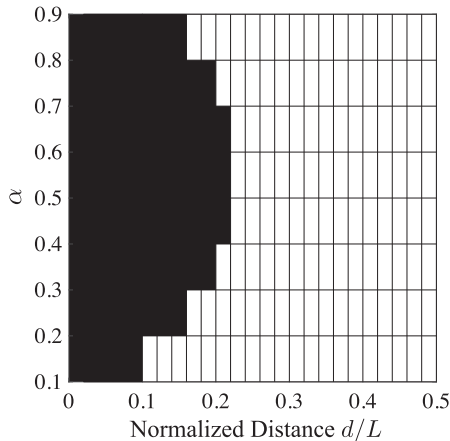


FIGURE 13. An example of decision tables for node direction. Black pixels and white pixels correspond to the straight relaying method and the orthogonal relaying method, respectively.

centralized approach, the throughput maximization problem is formulated as a global optimization problem with full knowledge of channel states and network configuration parameters. On the other hand, in the distributed approach, only local or partial network information is used to optimize the throughput performance. Interested readers may refer to the literature on distributed approaches such as [38]. It is worth noting that our proposed adaptive direction control method can be implemented in a fully distributed manner, as each node selects the appropriate relaying method according to the relative positions of its neighboring nodes.

B. THROUGHPUT PERFORMANCE OF MULTIHOP RELAY NETWORKS

We now evaluate the throughput performance of the proposed scheme through numerical experiments. We consider a 40 × 200 [m²] area and divide it into five small areas, each of size 40 × 40 [m²]. A multihop relay network with N = 5 is obtained by randomly deploying one node in each small area, as shown in Fig. 14. We define the overall achievable throughput T as

$$T = \min_{n \in \{1, 2, \dots, N\}} B \log_2(1 + \gamma_n),$$

where parameters P_{TX}, w, B are set to the same values as in sect. IV-B.

We compare the performance of the proposed scheme with that of a *random direction* scheme, where directions of all nodes are randomly chosen. Note that the proposed scheme

is not compared to conventional beamforming schemes as they require the powerful computational capabilities of adaptive signal processing, which are unavailable in the considered UAV network to comply with its need of a lightweight and low-complexity technology. However, further throughput enhancement is possible by combining the proposed method with other components for data delivery such as the routing and channel assignment schemes that have been proposed so far.

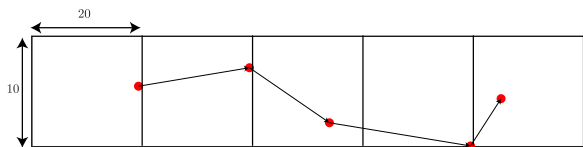
We obtain K = 10⁵ sets of random directions and compute the empirical complementary cumulative distribution function F(x) = Pr(T > x) [39], which is obtained from a set of 10⁵ throughputs. Let T_(k) (k = 1, 2, . . . , K) denote the set of throughputs sorted in increasing order.¹ F(x) is then obtained by

$$F(x) = \begin{cases} 1 & \text{if } x < T_{(1)} \\ \frac{K - k}{K} & \text{if } T_{(k)} \leq x < T_{(k+1)} \\ & (k = 1, 2, \dots, K - 1) \\ 0 & \text{if } x \geq T_{(K)}. \end{cases}$$

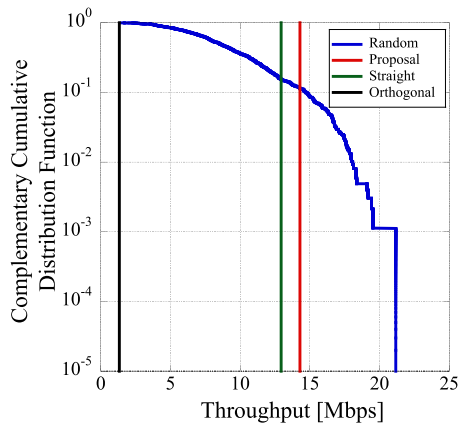
Fig. 14 shows the throughput performance of the random direction scheme and of the proposed scheme for θ_{BW} = π/3 (Fig. 14(b)) and π/6 (Fig. 14(c)).

In these figures, the blue curves correspond to the empirical complementary cumulative distribution function F(x) for θ_B = π/3 and π/6 obtained by the random direction scheme, while the red line indicates the performance of the proposed method. The green and black lines indicate the performance when only the straight relaying and the orthogonal relaying schemes are used at all relay nodes, respectively. Although the proposed scheme cannot achieve the best performance, the figures show that the proposed scheme is a promising approach to achieve higher throughput performance with low-cost computation, as discussed in the previous sections. When θ_{BW} = π/3, the throughput of the proposed scheme is almost equal to the 90-th percentile (i.e., F(x) ≈ 10⁻¹) of the throughput performance of the random direction scheme. Furthermore, when θ_{BW} = π/6, the throughput of the proposed scheme is more than the 99-th percentile (i.e., F(x) ≈ 10⁻²) of the random direction scheme. We also observe that the proposed scheme can achieve a higher throughput performance compared to the straight relaying and the orthogonal relaying schemes especially when θ_B = π/6. This is because, from the discussion for Figs. 8, 9, and 10 in section IV, the proposed scheme can avoid the harmful effects of the severe UAV-to-UAV interferences and UAV self-interferences by strategically adjusting the directions of the relay nodes based on parameters α̂ and δ̂ in the decision table, enabling the selection of the throughput maximizing relaying method.

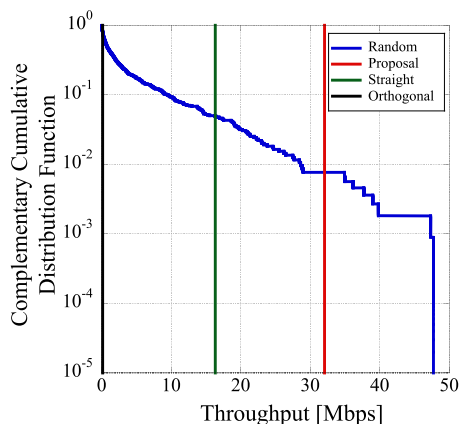
¹ In [39], empirical distribution functions are defined by interpolating linearly between samples. In this paper, however, in order to show throughput values correctly, we do not use the interpolated distribution functions.



(a) Example of Relay Network



(b) Complementary Cumulative Distribution Function of Throughput for $\theta_B = \pi/3$.



(c) Complementary Cumulative Distribution Function of Throughput for $\theta_B = \pi/6$.

FIGURE 14. Throughput performance in random search and proposed system.

C. THROUGHPUT ROBUSTNESS TO DISTURBANCES

In UAV networks, positions and directions of UAVs are fluctuating due to wind disturbance [37]. In order to evaluate the robustness of the proposed scheme against uncertainty of directions, we add a random noise η_n ($n = 0, 1, \dots, N$) to the direction of node v_n , modeled as a Gaussian distribution $\mathcal{N}(0, \sigma^2)$ with mean 0 and variance σ^2 . In relay nodes v_n ($n = 1, 2, \dots, N - 1$), noise η_n may reduce both the receiver antenna gain $G(\theta_n)^{(R)}$ and the transmitter antenna gain $G(\theta_n)^{(T)}$.

We conduct 10^3 experiments for each variance and calculate the average throughput. Fig. 15 shows the average throughput vs. standard deviation σ for $\theta_{BW} = \pi/3$ and $\pi/6$. We observe that the average throughput decreases as σ^2 increases, and that the wider beamwidth ($\theta_{BW} = \pi/3$)

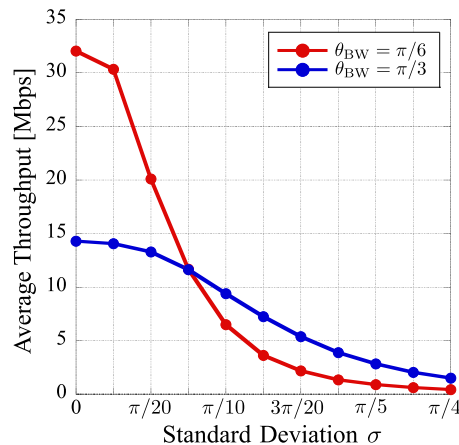


FIGURE 15. Average throughput vs. standard deviation σ .

has a higher robustness against uncertainty. Although this result is intuitively clear, the throughput performance discloses a trade-off relationship between antenna gain and uncertainty, and hence the proposed system should use more stabilized UAVs, which is currently one of the most challenging research topics in control systems [40]–[42].

VI. CONCLUSION

In this work, we have considered the problem of throughput enhancement in a multihop UAV relay network where UAVs forward their sensed data to a ground station, through multihop UAV links. We have proposed a full-duplex relaying scheme making use of multiple directional antennas that enable adaptive UAV direction control scheme to achieve higher throughput performance. The proposed scheme adapts the direction of UAV nodes by simply selecting either the straight relaying method or the orthogonal relaying method. Numerical experiments show that the proposed scheme can achieve a high throughput performance in a distributed manner, without inducing heavy computational costs.

Given the difficulty of the problem in this multihop network setting, we have solely focused on UAV relay networks with linear topologies, and have not considered direction control schemes for mesh topologies. Direction control schemes for mesh topologies are challenging because each node should control its direction by taking into account the interference among multiple paths. This research avenue will be tackled in the future work.

We consider that beamforming techniques are promising techniques in the context of UAV networks, as they enable to adaptively form optimum beamwidth and direction according to the relative positions of UAVs, unlike the proposed scheme, provided that UAVs have sufficient signal processing capabilities. However, various issues pertaining to computational complexity, energy consumption, and hardware size are yet to be solved. In the future work, we will investigate possible UAV relaying schemes using adaptive beamforming, while taking care of the limitations mentioned above.

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