Leveraging UAV Rotation To Increase Phase Coherency in Distributed Transmit Beamforming

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***Abstract*—Distributed transmit beamforming (DTBF) can allow a swarm of unmanned aerial vehicles (UAVs) to send a common message to a distant target. DTBF among N nodes can provide N^2 times the received power compared to a single node and can reduce interference by confining the signal in a certain direction. However, DTBF requires time, frequency, and phase synchronization. Here, we focus on the issue of phase incoherence at the distributed transmit nodes from two sources—different local oscillators (LOs) and hovering position movement—and how to counteract their impact at the receiver via local decisions, namely, rotation. To investigate how the UAV body and its rotation can affect phase coherency, we conduct controlled in-field experiments where we control the phase offset at two distributed antennas and measure the received signal level at four antenna positions on a drone for various rotation angles. We show that significant improvements can be achieved at the receiver through rotation. We also show that there exists an optimal combination of UAV rotation angle and antenna position on the drone to mitigate the effects of phase incoherence among the distributed transmitters. Finally, we demonstrate an interesting trade-off where, due to the heterogeneous nature of the UAV body, rotation angles that yield maximum beamforming gains might not result in the best average (or minimum) beamformed signal level across all possible phase errors at the distributed transmitters.**

I. Introduction

We motivate the use of DTBF in UAV swarms via the search and rescue example illustrated in Fig. 1. In this scenario, a drone swarm covers a large area to search for missing persons. The swarm hovers over the large area, while an anchor UAV near the base camp, acts as a relay. We are interested in the swarm-to-anchor link. Due to the long distance separating the swarm and the anchor drone, the UAV swarm is tasked to beamform the common message signal (*e.g.,* target found) to the anchor drone which in turn will relay back the information to the base. As is the case with any wireless system, there are many challenges to overcome (*e.g.*, carrier frequency offset, timing errors, channel reciprocity). There are, however, two challenges that are unique to achieving transmit beamforming from a UAV swarm: (*i*) Phase offsets due to each drone being equipped with a different local oscillator (LO), and (*ii*) phase errors due to drone hovering position movement.

The different LOs across the swarm will exhibit different offsets from a reference phase and also experience random drifts over time. An example of the phase difference between two distributed software-defined radios (SDRs) including a sudden jump in phase error is shown in Fig. 2(a). Furthermore, the fluctuations in hovering position of each UAV will result in phase errors depending on the wavelength of the signal. An

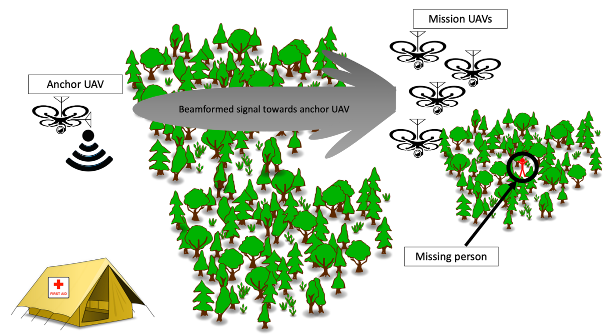


Fig. 1. A scenario where DTBF could help search and rescue missions.

example of the UAV hovering error across multiple experiments at the same position is shown in Fig. 2(b). (For details regarding the experiments that produced these figures, we refer the reader to [1], [2].) As a result of these prevalent issues, a local method at the receiver through which the beamformed signal level can be increased, is desired.

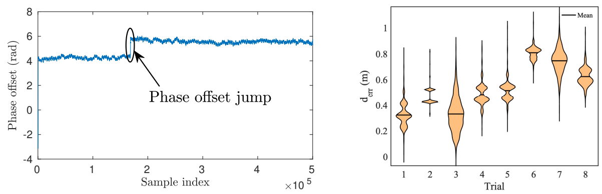
A. Related Work

Distributed beamforming has been the focus of many studies for more than two decades [3]. We focus here on UAV and channel feedback related works. In their AirBeam prototype, [4] experimentally demonstrated distributed beamforming in an air-to-ground channel with the clocking solution achieved via a National Instruments OctoClock cable that was connected to UAVs. In [5], tilted antennas were proposed to achieve beamforming. Recently, the U.S. Air Force has been exploring the automation of DTBF in a UAV swarm [6]. Moreover, to reduce the channel state information (CSI) feedback overhead, an event-triggered DTBF was been proposed in [7], and an adaptive positioning algorithm for the distributed transmit nodes was suggested in [8].

These require explicit feedback to deal with the distributed phase offsets, and with short channel coherence in UAV-based links and the potential of outdated CSI, a local decision method that could reduce the need for CSI feedback and yet result in increased beamformed signal levels is desirable. The proposed method in this work could be valuable in such contexts.

B. Reasoning and Contributions

In our previous work [9], we showed that the UAV body can increase polarization mixing and result in significant reductions in cross-polarization discrimination (XPD). This



(a) (b)

Fig. 2. (a) Phase difference between two distributed SDRs. (b) Violin plots show the estimated distributions of position error for repeated trials of a fixed UAV hovering location.

finding means that the UAV body alters the phase of the incident electromagnetic wave. The main idea of this work is to leverage that finding to increase phase coherency and result in a more aligned combination of received (beamformed transmission) signals.

In this work, we study the impact of the UAV body and its rotation on phase coherency in distributed beamforming applications. We quantify what we term *rotational gain* and show that regardless of the antenna placement, the UAV's heterogeneous body structure can be used to increase the level of the beamformed received signal simply by rotating the receiver drone relative to the transmitters, without the need for explicit phase feedback. Additionally, we show that as the phase offsets between transmitting nodes change, the optimal rotational angle for a given antenna position changes as well. Lastly, we explore the trade-offs of this rotation strategy, specifically that rotation angles that result in the strongest possible received signal do not always have the highest value, on average.

The paper is organized as follows. The DTBF model and experiments that investigate using the UAV body to increase phase coherency are presented in Section II, and our conclusions are presented in Section III.

II. Improving Beamforming Gain Through UAV Body Rotation

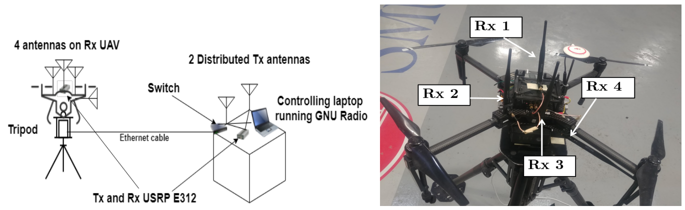
We first briefly present the model for a distributed transmit beamforming system with phase errors. Then, we discuss our experiment setup and findings.

A. DTBF System Model

The received, beamformed power, P_r , at the receiver (anchor UAV) when N transmitting UAVs employ conjugate-based beamforming (*i.e.*, each UAV uses w_i^* where w_i is the channel fading coefficient) is [10]:

$$P_r = || \sum_{i=1}^{N} w_i e^{-j\Theta_i} ||^2 \quad (1)$$

Here, the phase error term $\Theta_i = \phi_{er}(i) + \phi_{lo}(i) + \phi_o(i)$ includes, respectively, hovering phase error, the LO phase error, and the nominal phase offset which is given by $\phi_o(i) = \frac{2\pi d_o(i)}{\lambda}$ where $d_o(i)$ is the distance from the i^{th} swarm UAV to the anchor UAV, and λ is the carrier wavelength. Through controlled experiments, we show how to combat the negative effects of these errors via local decisions by the UAV in the form of rotation and antenna selection.



(a) (b)

Fig. 3. (a) Experiment setup illustration. (b) The four UAV-mounted antennas.

B. Experiment Setup

We now investigate how UAV rotation can help counteract the impact of phase offsets experienced by the distributed transmit nodes. Four different antenna positions on the UAV body are analyzed. We use two USRP E312s for the experiments: one USRP, which acts as the transmitter is connected to two spatially-distributed transmitter (Tx) antennas that are 10 inches apart; while the other USRP is mounted on the drone body and connected to four antennas. The receiver (Rx) UAV is attached to a tripod, which is adjusted to approximately the same height of the distributed transmit antennas. The Tx-Rx separation distance is 10 ft. Fig. 3(a) illustrates the experimental setup, and Fig. 3(b) shows the Rx UAV with the four antenna positions. The UAV-mounted antenna positions were chosen according to prior research efforts [2], [9].

GNU Radio is used to create two sinusoids $m_1(t)$ and $m_2(t)$, where $m_2(t) = e^{j\phi_{ind}} m_1(t)$ and ϕ_{ind} is the artificially-induced and controlled phase offset that we use to emulate a real distributed system that has random offsets. Specifically, this induced phase is equivalent to the difference in phase between the two distributed nodes, *i.e.,* $\phi_{ind} = \Theta_1 - \Theta_2$, where Θ_i is the phase error term in (1). The message signal is used to modulate a carrier at a frequency of 2.48 GHz (channel 14 in IEEE 802.11), which is transmitted using two identical VERT2450 omnidirectional dipole antennas. The same antennas types are used at the transmitter and receiver. The process is automated and controlled via GNU Radio. The collection of measurements lasts for 3 seconds per Rx combination. The induced phase offset values are done in $\pi/9$ intervals and span $-\pi$ to $+\pi$. For comparison, a measurement is also taken for a transmission from a single antenna (no beamforming). For each induced phase offset, the drone is rotated in $45°$ increments from $0°$ to $360°$.

C. Results

The received power at the four UAV-mounted receive antennas for a fixed induced phase offset of $0°$ are given in Fig. 4. In the figure, DTBF denotes Distributed Transmit Beamforming while No Beamforming indicates transmission from a single Tx. Based on these results, we make the following observations:

1) Rotational gain: For a fixed antenna position, rotation of the drone can result in an increase in received power. This rotational gain can offset the decrease in beamforming gains

TABLE I
ROTATION GAIN STANDARD DEVIATION (IN DB)

Rx Antenna	Standard Deviation
Rx 1	2.980
Rx 2	3.060
Rx 3	6.060
Rx 4	3.940

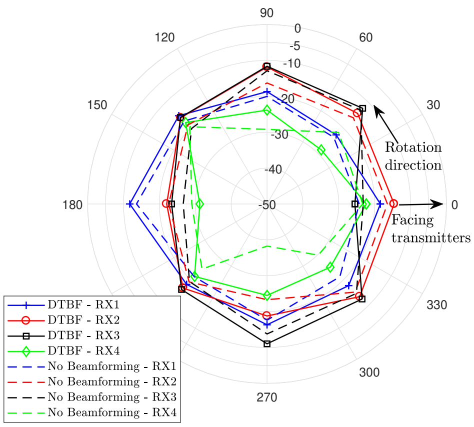


Fig. 4. Measured receive power at the four UAV-mounted receive antennas across all rotation angles and 0° induced phase offset. Solid lines indicate Rx power when DTBF and dashed lines indicate no beamforming.

that might be experienced due to phase offset at the distributed Tx nodes. This rotational gain, compared to 0° (no rotation), can reach up to 6.6 dB for Rx1, 7.4 dB for Rx2, 14.5 dB for Rx3, and 13.9 dB for Rx4. This result shows that by performing local, Rx-based rotation, the received signal power can be significantly improved, and the reductions experienced by phase offsets at the Tx side can be significantly reduced. We can also observe that, for a fixed rotational angle and an induced phase offset, different antenna positions can provide substantial improvements in received power levels (Fig. 4). For example, at 90° rotation, the received power at Rx3 is about 7 dB stronger than that of Rx1. At 45°, the beamformed signal power is 7.5 dB stronger at Rx2 than that of Rx1. Lastly, due to polarization mismatch, the horizontal Rx antenna (Rx4 in Fig. 4) is the worst performing in most cases, regardless of whether DTBF is performed or not. The standard deviation of this rotation gain at 0°-induced phase offset for the four antennas is summarized in Table I. We can see from the table that UAV rotation indeed results in variations in the beamformed power level with the minimum standard deviation belonging to Rx1 (antenna mounted on top of the UAV), and the maximum standard deviation belonging to Rx4, which is the horizontal antenna attached to the leg of the drone.

2) Joint impact of phase offset and drone rotation: In the previous discussion, we fixed the induced phase offset between the distributed Tx nodes and investigated how drone rotation and antenna position affect the beamformed receive power. Here, we analyze how beamforming can be influenced by the joint variation in phase offset and drone rotation. To do so, we visually inspect Fig. 5, where the beamformed receive power for the three vertical antennas at all induced phase offsets and rotation angles is plotted. First, we see that the beamformed signal power changes not only with rotation but also with the (controlled) induced phase offset for a fixed rotation angle. Second, we see that the antenna mounted on top of the drone body (Rx1) exhibits one peak concentrated around 0° phase offset around 180° rotation (Fig. 5(c)), while the other two vertical antennas (Rx2 and Rx3) exhibit two peaks that alternate depending on the UAV rotation angle (Figs. 5(a) and 5(b)).

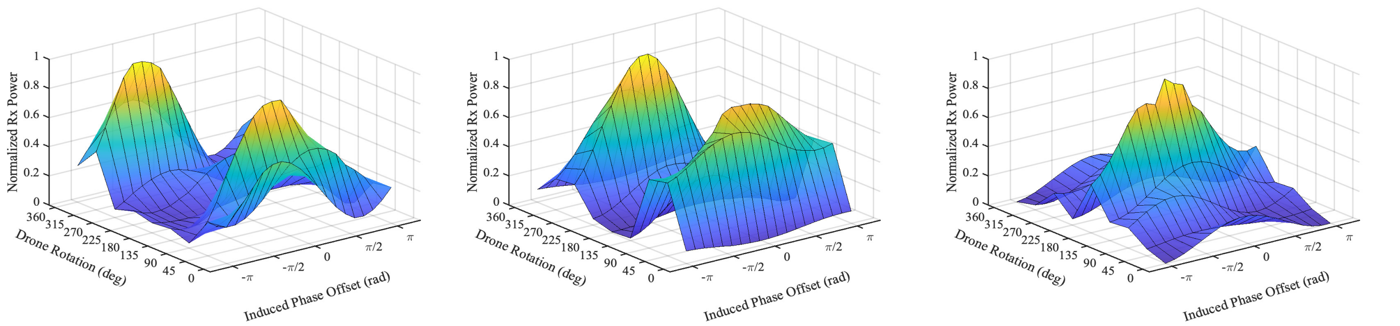
3) Trade-offs in Rotational Gain: Rotation is found to also alter the statistics of the beamformed signal power across different induced phase offsets. For example, in Fig. 5(b) while at 45°, the average of the received signal power across all phase offsets is higher than the average received power at 270°. The maximum power at 270° is higher (around 0.8) than that at 45°, which is only 0.6. The minimum received signal power at 45° is around 0.4, while at 270°, it is 0.1 – a significant reduction solely due to the change in UAV rotation angle and the resulting local reflection/scattering. Depending on the required performance (*e.g.*, higher average and lower minimum vs. higher maximum value) intelligent rotation by the UAV can be designed according to these needs.

Fig. 6 depicts a cross-section of the surface plot of Rx power for the antenna mounted in the middle of the front of the drone (Rx3). This cross-section shows the Rx power as a function of the phase offset, parameterized by the drone rotation angle. This figure clearly illustrates the trade-off between rotation angles. To experience the highest possible Rx power, the receiver drone should rotate to an angle of 270°. However, in achieving a high peak power, the receiver sacrifices stability–the Rx power is much more sensitive to changes in the net phase offset of the system. On the other hand, if the receiver wishes to maximize the lowest possible Rx power, it should rotate to 45°, but in doing so, it sacrifices peak power. These statistical trade-offs are summarized in Table II. Per column, maximums/minimums are highlighted in green/red and **bold**/*italics*, respectively.

Lastly, it is worth noting that the rotation impact can change according to the distributed transmitters topology. For instance, if the transmitters are spatially distributed in a way that spans more than one side of the UAV, then, rotation might be more beneficial to certain transmitters than others. An interesting issue arises where the optimal topology of distributed transmitters can change according to the relative UAV direction. We leave this problem for future work.

III. CONCLUSION

After characterizing the behavior of phase errors due to UAV hovering movement and having different radios, we have experimentally demonstrated that UAV rotation alone can alter phase coherency at UAV-mounted antennas. Specifically, we have shown that by leveraging the heterogeneous structure of the UAV body, rotation can provide significant improvements in the level of beamformed signal power. An additional degree of freedom is investigated by having multiple



(a) (b) (c)

Fig. 5. Received power in a DTBF system for four antennas at different rotation and induced phase-offset angles. Values are normalized to the maximum received power across all antennas measurements. (a) Vertical antenna mounted to the left (Rx2), (b) Vertical antenna mounted in the middle (Rx3), and (c) Vertical antenna mounted at the top of the drone body (Rx1).

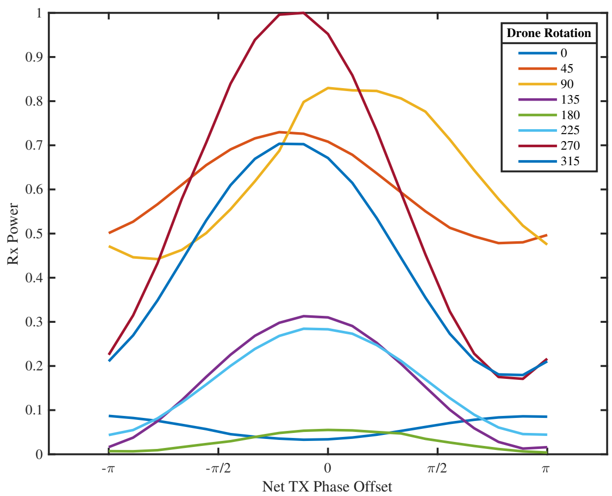


Fig. 6. Cross-section for the received power by Rx3.

TABLE II
RX POWER STATISTICS PER DRONE ROTATION

Rotation	Max	Min	Mean
0	0.087	0.033	0.061
45	0.730	**0.478**	0.597
90	0.830	0.442	**0.630**
135	0.313	0.013	0.156
180	*0.055*	*0.004*	*0.029*
225	0.284	0.044	0.158
270	**1.000**	0.171	0.565
315	0.703	0.180	0.429
360	0.087	0.033	0.061

antenna positions on the UAV, and the results suggest that for a certain phase error at the transmitter, there exists an optimal combination of UAV rotation angle and an antenna position. We have also shown that rotation angles that result in maximum instantaneous power do not necessary guarantee the highest average power across all possible phase offsets, revealing an important design choice to be made to meet certain performance metrics. Next, we aim to leverage our findings to implement and evaluate the performance of a UAV rotation-based beamforming system.

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