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Reliable transmissions in AWSNs by using O-BESPAR hybrid antenna

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ABSTRACT

An AWSN composed of bird-sized Unmanned Aerial Vehicles (UAVs) equipped with sensors and wireless radio, enables low cost high granularity three-dimensional sensing of the physical world. The sensed data is relayed in real-time over a multi-hop wireless communication network to ground stations. In this paper, we investigate the use of a hybrid antenna to accomplish efficient neighbor discovery and reliable communication in AWSNs. We propose the design of a hybrid Omni Bidirectional ESPAR (O-BESPAR) antenna, which combines the complimentary features of an isotropic omni radio (360° coverage) and directional ESPAR antennas (beamforming and reduced interference). Control and data messages are transmitted separately over the omni and directional modules of the antenna, respectively. Moreover, a communication protocol is presented to perform neighbor UAVs discovery and beam steering. We present results from an extensive set of simulations. We consider three different real-world AWSN application scenarios and employ empirical aerial link characterization to demonstrate that the proposed antenna design and protocol reduces the packet loss rate and end to end delay by up to 54% and 49% respectively, and increases the goodput by up to 33%, as compared to a single omni or ESPAR antenna.

1. Introduction

In recent years, mobile sensors have been successfully adopted for terrestrial and ocean monitoring. The next logical step in their evolution is to enable mobile sensors to explore the aerial dimension, i.e., engineering Unmanned Aerial Vehicles (UAVs) with sensors and wireless radios to form an Aerial Wireless Sensor Network (AWSN). The idea of equipping a UAV with sensors is not new. In fact, most UAVs have in-built sensors such as accelerometers and gyroscopes, which measure various parameters related to the vehicle's motion to assist with autonomous flying. UAVs have been fitted with additional sensors such as cameras for collecting data about the physical environment. The sensed data is relayed to a ground station by equipping the UAV with a 802.11 or Zigbee radio. Even though this enables real-time collection of data, the area that can be monitored is limited to the range of the wireless radio. However, if the MAVs can communicate with each other wirelessly and create a multi-hop aerial network, then the sensed information can be relayed back to a distant base station in real-time. Such an aerial network would significantly extend the coverage range, thus enabling access to remote areas. It is thus no surprise that AWSNs are being increasingly used in a variety of applications such as precision agriculture [1], environmental monitoring [2] and search and rescue operations in dangerous areas [3].

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On surface, this kind of network may appear to be very similar to ad-hoc networks, extensively studied by the networking community. However, one of the major distinction of AWSNs is the dynamism and timescale where the vehicles may connect/disconnect with each other for a very short duration of time. Given the short connection opportunities, it is critical that a UAV can quickly detect the presence of another UAV in its communication range (i.e. neighbor discovery) so as to maximize the duration for which data can be transferred [4]. Moreover, in a typical AWSN [5], the node density can be fairly high, leading to excessive interference, thus affecting the network throughput. The inter-node interference can also impact the neighbor discovery mechanism (e.g., data packets may collide with control packets intended for neighbor discovery), which in turn can further reduce the overall network throughput. Another unique property of AWSNs is that the nodes can move in all three dimensions. It has been shown that the difference in the altitude of the UAVs can have a significant effect on the signal strength variability between transmitter–receiver pairs for omni-directional radios, due to the relative monopole antenna orientation.

In this paper, we explore the idea of using directional antennas to overcome the aforementioned challenges. By radiating greater power in one or more directions, such antennas are known to reduce interference from unwanted sources and subsequently increase throughput. In particular, we seek to build upon the popular Electronically Steerable Passive Array Radiator (ESPAR) antenna [6] for a number of reasons. First, it can achieve directional transmission by beamforming so that the signal is transmitted exactly within the beam width, thus limiting interference. The antenna has a single active element at the center and is surrounded by six reactively loaded parasitic elements. Through changing the reactances of the elements, a signal beam which points to the specified direction and relevant nulls can be formed. This creates a larger radiation intensity in the desired direction, thus extending the range over which the signal is transmitted. Second, the small form factor (120 mm diameter and 61.5 mm height for a seven-element ESPAR) [7] and low-power operation, make it well-suited for mounting on a UAV. Third, is its ability to create desired transmit radiation patterns in real-time [8], which is particularly important for the dynamism inherent in an AWSN. Finally, it has also been shown that ESPAR can generate 360° continuous beam and null steering, which makes it suitable for the 3D flight of the UAVs.

However, incorporating the ESPAR antenna in an AWSN presents several non-trivial challenges. Although an ESPAR antenna is capable of generating multiple lobes in different directions, the gain in each direction reduces as compared with a single directional ESPAR [9]. Also such an antenna causes unnecessary interference as it transmits in multiple directions. Therefore, for this work, we consider a single directional ESPAR antenna. Neighbor discovery with a single beam directional ESPAR can incur significant delays. This is because, scanning the entire neighborhood of a node can only be achieved by sweeping the directional beam in 360 degrees. Note that, the beams of both neighboring UAVs need to be aligned with each other for neighbor discovery to be successful. Despite, the quick operation of the ESPAR antenna, this process can use up precious seconds (excluding the delay incurred for exchanging handshaking messages, once the beams are aligned), which could otherwise be used for data transfer. In the worst case, a data exchange opportunity may be completely lost if the two beams are unable to encounter each other during the scanning process. Moreover, the presence of a single directional antenna only permits a UAV to communicate with a single neighbor at any given time. Also note that the ESPAR antenna cannot reach the neighbor UAV that is right above or under the antenna due to the nulls. However, according to the state-of-art path planning algorithms of UAVs [10–12], the flight trajectories of UAVs are not crossed or overlapped in order to avoid the collision and maximize the sensing coverage. Moreover, we assume the flight altitude of UAVs is within twice the half-power beam width of ESPAR antenna.

To address these issues, in this paper, we leverage the complimentary properties of omni-directional (360° coverage) and directional antennas (discussed earlier) and propose the design of a hybrid antenna. In particular, we propose to use the isotropic omni antenna as a control channel to quickly achieve neighbor discovery, and two directional antennas as the data channel to achieve greater throughput and reduced interference. As such, we refer to our proposed hybrid design as Omni Bi-directional ESPAR (O-BESPAR) antenna. The two independent directional beams permit a node to transmit and receive simultaneously, hence the name bi-directional. We also propose a communication protocol that incorporates an efficient neighbor discovery mechanism which not only allows UAVs to discover each other rapidly but also enables quick alignment of directional beams to maximize the data transfer opportunities. According to our communication protocol, sender UAV broadcasts control messages through the omni module in order to exchange location information with receiver. After both beams are steered to each other, the data transmission commences over the directional module. However, the transmission range of the omni antenna is much smaller than the directional ESPAR module. As such, if no neighbor is found by the broadcast of the omni module, the communication protocol will use the directional module to perform bi-directional beam sweeping. Each beam covers 180 degrees so that the scanning delay is minimized.

In summary, the following are our specific contributions:

- To the best of our knowledge, this is the first paper to propose an omni and bi-directional hybrid antenna structure.
- We propose a communication protocol that achieves efficient neighbor discovery for the proposed hybrid antenna. We exclusively use the omni antenna as a control plane for neighbor discovery. The two directional beams are only invoked as a backup mechanism during neighbor discovery to address the disparity in the communication range of the omni and directional antennas. These beams are primarily used as the data plane for reducing interference and achieving increased throughput.
- We conduct extensive simulations to analyze the performance of the proposed O-BESPAR antenna and communication protocol. In our experiments we consider three different scenarios which reflect real-world use cases for AWSNs and also