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A tree-based data collection protocol for optical unmanned aerial vehicle networks☆

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ABSTRACT

In Wireless Sensor Networks (WSNs), sensors are spread over a remote and hardly accessed sensing zone. In this situation, Unmanned Aerial Vehicles (UAVs) allow to facilitate the data gathering from sensors in real time. In the present paper, we consider an optical UAV network that allows the real time data distribution to a base station, based on multiple collection trees and multiple base stations. Each UAV is identified by an optical codeword with adequate structure to reduce the codeword management process implied by the UAV mobility. Using the attributed codewords, each UAV can optically switch the gathered data to reach a base station for processing. Furthermore, we present quality-based attachment and re-attachment procedures allowing to an UAV to attach and re-attach to a tree whether it notices the quality degradation of its link to the collection tree.

1. Introduction

In Wireless Sensor Networks (WSNs), sensors are spread in a remote and hardly accessed sensing area. This fact presents a serious issue when data collection is concerned. Thus, Unmanned Aerial Vehicles (UAVs) will facilitate the data gathering from sensors in real time. UAVs are increasingly used day by day in several domains such as agriculture, fire fighting, disaster sensing, and collecting data [1–3]. In this context, we propose an UAV network architecture using optical inter-UAVs communication links. The use of UAVs with FSO links is needed to deliver large amounts of collected data. Since an UAV can handle multiple information types (simple data, images, video, etc.) depending on the application type. For example, when we consider an agricultural application, an UAV can capture high-resolution images of a field. In the literature, several works discuss the data gathering using UAVs. Yan and Mostofi [4] used a robot (UAV) to visit some fixed points to gather data. Ho et al. [5] improve the total energy consumed in the data gathering by UAVs using an heuristic algorithm. Ho et al. [6] present a UAV route planning in a cluster-based communication topology. Jawhar et al. [7] present a bridging approach for efficient data gathering which is performed using cooperation amongst sensors, advanced coding, data storage techniques, and UAVs path planning. Jawhar et al. [8] describe a framework that considers a mobile UAV which delivers the collected data from sensors deployed in a linear WSN to a sink node. Say et al. [9] propose a data gathering framework in WSNs using UAVs. The proposed approach allows to remove the redundant sensors transmitting data to UAVs which maximizes the data throughput. Kwon and Hailes [10] use UAVs as communication relays and consider UAV dynamic positioning method, to enhance the signal-to-noise ratio (SNR) and the data throughput. Although, the existing works considered UAVs

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to gather data, they do not address several critical aspects allowing to enhance the data collecting process. These aspects are mainly: the real time data gathering, the UAV network connectivity, the identification of collected data sources, and the quality of service (QoS). Whereas the use of FSO links by UAVs is a classic challenge that has already been addressed in the literature [11–13], the exiting works have not treated the mobility aspect which characterizes UAVs, the continuous adaptation of a dynamic topology, and the UAV number available in the network which is generally fewer than the number of collection points. In this paper, that extends our work discussed in [14], we present a data gathering protocol which considers the presented issues. The proposed architecture uses structured codewords and optical inter-UAVs communication links, and it is formed of multiple collection trees and multiple base stations to generalize the studied UAV network in [14]. In the proposed network, each node is uniquely identified by an optical codeword structured in the manner to optimize the codeword management process implied by the UAV mobility. Based on the attributed codewords, each UAV in the network can perform the optical switching process to route the gathered data to a base station for processing. Furthermore, an UAV can initiate a quality based attachment and re-attachment procedures. Indeed, a UAV can attach to a collection tree after the selection of the better received quality vector from its neighbors. After the attachment to a tree, an UAV can decide to initiate a reattachment procedure whether it notices the quality degradation of its attachment link. The re-attachment procedure requires the search of another attachment point in the actual or different tree.

The paper presents these contributions:

- The considered architecture is formed of several collection trees and uses optical inter-UAVs communication links. Each collection tree is composed of UAV nodes that gather data from sensors and a root UAV that routes the gathered data from all the nodes in the tree to a base station for processing.
- Hierarchical and structured codewords uniquely identify UAVs and their traffics. Furthermore, the gathered data is optically switched from an UAV to another in the objective to reach a base station. At each node, the received packets are optically buffered in the Virtual Optical Memory (VOM) [15], which avoids the optical to electronic conversions.
- In the proposed network topology, an UAV can initiate a quality based attachment and re-attachment procedures. Indeed, an UAV can attach to a collection tree after the selection of the better received quality vector from its neighbors if it notices the quality degradation of its attachment link. The re-attachment procedure consists on the search of a new attachment point in the same or different tree.
- A tree management procedure is presented in order to dynamically create a collection tree by initiating a root election procedure and replacing a root node if required.

The rest of the paper is organized as follows. Section 2 presents the considered network architecture. Section 3 presents the UAV model. Optical codewords and the codeword-based UAV identification plan are elaborated in Section 4. The techniques related to routes announcement, nodes attachment, and resources allocation are detailed in Section 5. We present in Section 6 the codeword-based data routing using the optical packet switching. In Section 7, the obtained simulation results are described. Finally, Section 8 concludes the paper.

2. Proposed UAV network architecture

We present in this Section the Inter-UAVs communication advantages when depending on FSO links. As well, we depict the architecture of the proposed three layer UAV network.

2.1. Inter-UAVs FSO communication

In addition to military domain, UAVs have seen an expansion in academic and civilian use. The significant data volume generated by sensor nodes which is carried by UAVs, needs high data rates, which fit FSO communication. Three main FSO link types exist when considering UAVs: UAV-UAV, ground-UAV, and UAV-ground. Communication through FSO links gained an increasingly importance since its distinguished features when compared to the other transmission techniques. Indeed, FSO communications offer a large bandwidth, an easy deployment, a high data throughput, a license free spectrum, and an immunity to electromagnetic interference. However, there are several challenges to be considered when using FSO technology. For instance, environmental conditions (fog, rain, dust..) inducing scattering, loss of sight (LOS) and divergence are inevitable causing the degradation of FSO communications. The LOS issue must be considered in the case of high data rate applications. Chlestil et al. [16] present a method to reduce the LOS issue which consists on the use of spherical and directional emitters having a large divergence beam.

2.2. Proposed network architecture

In this part, we detail the considered UAV architecture which is mainly formed of three layers, as shown in Fig. 1.

- The first layer consists on a network of UAVs that collect data from sensors. The UAVs, which move according to a mobility model, are organized into clusters structured as a tree. In the considered hierarchical architecture, each UAV needs to attach to a parent and can have several child. Each node gets the gathered data coming from its child, possibly aggregates it with its own data and forwards it to its parent. We suppose that each UAV can communicate with cluster heads, UAV neighbors, and collection nodes. The UAVs coordinate and cooperate together to cover all the sensing area.