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An efficient medium access control protocol for WSN-UAV

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ABSTRACT

Recent advances in Unmanned Aerial Vehicle (UAV) technologies have enhanced Wireless Sensor Networks (WSNs) by offering a UAV as a mobile data gathering node. These systems are called WSN-UAV that are well-suited for remote monitoring and emergency applications. Since previous Medium Access Control (MAC) protocols proposed in WSNs are not appropriate in the presence of a UAV, few researches have proposed new MAC protocols to meet WSN-UAV requirements. MAC protocols of WSN-UAV should be extremely efficient and fair due to the time-limited presence of the UAV in the neighborhood of each sensor. However, issues such as high throughput in dense networks, fairness among sensors, and efficiency have not been resolved yet in a satisfactory manner. Moreover, previous works lack analytical evaluation of their protocols. In this paper, we present a novel MAC protocol in WSN-UAV, called Advanced Prioritized MAC (AP-MAC), that can provide high throughput, fairness, and efficiency, especially in dense networks. We also analytically evaluate AP-MAC using a 3-dimensional Markov chain and validate its correctness using simulation. Simulation results under various scenarios confirm that AP-MAC can approximately improve throughput and fairness up to 20% and 25%, respectively, leading to higher efficiency compared with previous work in WSN-UAV systems such as Prioritized Frame Selection (PFS).

1. Introduction

Wireless Sensor Networks (WSNs) have become popular for a wide range of applications (e.g. see [1,2]) which significantly benefit the society. In these applications, sensors, directly or indirectly through other sensors, are connected to a base station or a sink node which gathers the sensed data [3] from sensors. However, these kinds of connections to the sink are not always possible. For instance, if sensors are deployed in an area far from the sink or there is a lack of communication, a fully-connected sensor network may not be possible; in disaster situations, we cannot rely on the previously established infrastructure which may no longer be valid. To solve these problems, some studies such as [4–6] have exploited Unmanned Aerial Vehicles (UAVs) as a mobile sink to gather data from sensors. The new system is called WSN-UAV. WSN-UAVs also strengthen the applicability of WSNs in domains such as environmental monitoring, surveillance and law enforcement, and disaster management [6]. The most noticeable benefits compared with conventional sensor networks are low cost, improved safety for humans, and easy deployment [7]. There are also many applications in WSNs that employ UAVs to extend the range of communication [8], maximize the data communication capability of the network by using vehicles as relay nodes [9], collect data from a wide area network in remote or harsh environment [10], and aid node localization in mobile network [11].

WSN-UAVs are different from mobile WSNs because in mobile WSNs, some nodes or the sink may move [12,13]. In WSN-UAV, sensors have much shorter time to communicate with the UAV, and the UAV cannot stop or slow down very much to collect data from sensors. Therefore, it is crucial for the protocols being designed for these networks to handle this special situation in which at each time instant, some nodes become ready to communicate with the UAV while some other nodes are losing their connection to it. In addition, especially in disaster situations, the number of nodes, their position, and the amount of their data is unpredictable. In this critical, short period of time during which the UAV passes the sensors, they should be able to send their data in an efficient and fair manner to the UAV.

The major challenge in these systems is the MAC protocol as recent studies such as [5,12,14,15] show that traditional MAC protocols (e.g. see [16]), even those designed for mobile sensor networks, are not appropriate for WSN-UAV systems. In addition, despite knowing this fact, previous works on WSN-UAV systems mostly focused on increasing packet delivery ratio and decreasing packet error rate. As two examples, the protocol presented in

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[17] exploits IEEE 802.11 between sensors and the UAV, and uses IEEE 802.16 for the UAV to send data to the sink. As shown by [18], protocols based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) do not perform well in dense networks where there is a large number of transmitting nodes. The Prioritized Frame Selection (PFS) protocol, which was introduced in [18,19], uses CDMA for sensors to send their sensed data to the UAV which outperforms CSMA/CA but it does not consider fair channel access for sensors. Moreover, in [12], it is shown that CDMA is a complex scheme for both sensors and the UAV, and furthermore, CDMA is not suitable for dense WSNs [20]. Results of [20] also state that TDMA is more power efficient than CDMA.

The correct operation of a WSN-UAV also implies considering other constraints such as timing [14] and location awareness (the data gathering algorithm must take into account the relational location of sensors and the UAV) because the UAV moves fast, and at any instant, some sensors are entering the UAV's radio range while some others are leaving that. Hence, in such a short, transient period, sensors have to register themselves with the UAV and send as much data as possible to the UAV in a fair manner. This is the fundamental difference between WSN-UAV and other mobile wireless sensor networks (MWSNs) because in other MWSNs, the sink moves much slower than the UAV or stops at different locations (e.g. dense locations full of transmitting nodes) to collect the available data completely. Therefore in this new case, it is very important to have a fast, reliable and fair MAC and data gathering protocol. By fairness we mean that almost the same amount of data should be gathered from each sensor, the one which is closer to the UAV and also the sensor which is far, to *evenly* sense the environment; otherwise, the sensors closer to the UAV can send much more data, and it makes the results gathered in the network less accurate. Therefore, an efficient and applicable MAC protocol is inevitable. We believe that, in addition to low energy consumption and low packet loss ratio (mentioned by [5,18,19,21]), an appropriate MAC protocol for WSN-UAV systems should be efficient in terms of high network throughput, short delay in channel access, and fairness in data gathering from sensors, and to the best of our knowledge, this is the first MAC protocol in WSN-UAVs with these goals.

In this paper, we present a novel, efficient, and fair MAC protocol called Advanced Prioritized MAC (AP-MAC) in WSN-UAV systems. AP-MAC enables sensors to transmit their sensed data in a TDMA fashion to increase efficiency. Specifically, AP-MAC divides the channel time into fixed-length time intervals each of which consists of four steps. In step 1, the UAV announces its presence to the sensors in its line of sight. In step 2, the sensors which are not registered with the UAV attempt to send a registration frame with their own information. Then, in step 3, the UAV makes a fair and efficient TDMA schedule and sends it to the successfully-registered sensors, and in step 4, the sensors send their data according to the TDMA schedule. Then, another time interval begins. To decrease the registration overhead, we also present a novel random channel access method for step 2 during which transmissions of the sensors may collide. We call this method Advanced Prioritized Random Access (APRA) which reduces collision probability as much as possible. AP-MAC is also empowered by a fair TDMA scheduling method called Advanced Fair Data Acquisition (AFDA); based on the position of each sensor and the amount of remaining data to be uploaded, sensors are given specific priorities such that, on average, a fair share of the channel to sensors is provided.

We also present an analytical model of APRA using a novel 3-dimensional discrete-time Markov chain. On the contrary to the previous works such as [22], to model our presented protocol, we further assume that the collision probability is different in each state of the Markov chain. The model can be used to analytically obtain metrics such as the average registration delay of sensors with the UAV. Then, we evaluate our model using simulation. Results show that the analytical model almost matches the simulation results. Moreover, investigation of AP-MAC under different simulation scenarios for various network parameters illustrates its success in increasing the efficiency of WSN-UAV systems in terms of the aforementioned metrics. Comparison of AP-MAC with previous works also indicates its success in improving throughput, fairness, and registration delay.

The cornerstones of our work are:

1. We present an efficient MAC protocol (AP-MAC) in terms of high network throughput in dense networks using our channel access method called Advanced Prioritized Random Access (APRA).
2. APRA improves latency and collision probability in channel access compared with previous protocols by eliminating unnecessary transmissions and exact timing.
3. AP-MAC attains fairness in data gathering among sensors using another presented method called Advanced Fair Data Acquisition (AFDA); it operates in a TDMA fashion to gather data from network nodes fairly.
4. We analytically evaluate APRA using a novel 3-dimensional discrete-time Markov chain model.

The rest of this paper is organized as follows. Section 2 surveys related work and main challenges, and compares our work with other relevant methods in the literature. Section 3 details the network model, our protocol (AP-MAC), and how AP-MAC operates. The analytical model of APRA is presented in Section 4 and simulation results are presented in Section 5. Finally, Section 6 concludes the paper.

2. Related work

Extensive research has been done on MAC protocols of multi-hop ad hoc, and wireless sensor networks [3,16,23]. However, WSN-UAV systems sound different from existing UAV systems and other mobile WSNs. It has been shown that IEEE 802.11 CSMA/CA is not suitable for the WSN-UAV systems [24] although it has been widely used in Wireless Local Area Networks (WLANs), WSNs, and Vehicular Ad hoc Networks (VANETs) [25–29]. This is due to the following reasons: first, IEEE 802.11 suffers from a longer contention delay in the communication between sensors and the UAV. This delay becomes more significant in a high-density sensor network. The second reason comes from the well-known hidden terminal effect [23] which can easily happen between any two sensors. Using RTS/CTS exchange is time-consuming; as a result, the system performance degrades. The third reason is the high energy consumption brought by the large overhead exchange among sensors and between sensors and the UAV [19].

The IEEE 802.11p protocol was approved for VANETs. Although [30,31] tried to improve the performance of this protocol, it still suffers from long delay in WSN-UAV systems [24]. Although there are some similarities between WSN-UAVs and VANET Vehicle-to-Infrastructure (V2I) communication schemes, the number of nodes in VANETs is much smaller than in WSN-UAVs leading to lower collision probability, the receiving unit in VANETs covers the road width completely, and all nodes have the same link quality to the receiving unit. On the other hand, in WSN-UAVs, sensors located at different locations to the UAV experience different communication durations and link quality. Nodes in VANETs do not worry about power consumption and processing power while these are very critical parameters in the WSN-UAVs. The IEEE 802.11p WAVE protocol also does not use nodes positions as a priority parameter; therefore, it is not fair in WSN-UAVs. In addition, since IEEE 802.11p is a CSMA/CA-based, it is not efficient when the number of nodes increases as in WSNs [24].

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