Partnership and Data Forwarding Model for Data Acquisition in UAV-aided Sensor Networks

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***Abstract*—This paper explores a cooperative partnership and data forwarding model in wireless sensor networks using unmanned aerial vehicle (UAV) with the goal of enhancing the data collection efforts. A UAV-based data acquisition architecture is presented to suppress the limitations of the traditional wireless sensor network. For this, we introduce a flexible and fast approach to collect data by taking into consideration the mobility of the mobile sink (UAV) and sensor nodes in the network. In other words, leveraging the mobility of the UAV and the location of sensor nodes, we adopt a novel frame selection technique that classifies sensor nodes into different frames. Then we present a cooperative partnership model that allows sensor nodes in the network to individually pair with their peers and thus transmitting data simultaneously. We also aim to alleviate the packet loss originated from certain sensor nodes located in the rear edge-side of the UAV's coverage area. This situation happens when the UAV is moving in the forward direction while collecting data. Thus, to alleviate these packet losses while guaranteeing a higher success rate of packet reception ratio, we propose a novel data forwarding scheme to closely integrate with the aforementioned partnership model. We conduct simulations to verify our proposed framework, and results show huge performance gain is obtained over the traditional data collection technique.**

Keywords: clustering, consumer application, data acquisition, medium access control (MAC), network throughput, unmanned aerial vehicle (UAV), wireless sensor network (WSN).

I. Introduction

In recent years, we have witnessed a rapidly growing interest of leveraging unmanned vehicles to boost various development and production efforts. Ranging from manufacturing life cycle to filming industries and to civilian applications, autonomous robots are ubiquitously deployed to serve and accomplish a number of specific missions. In wireless communications, for instance, enabled by the advances in computing, communication, and sensing as well as the miniaturization of devices, consumer drones and unmanned aerial vehicles (UAVs) have been receiving significant attention in the not only research community but also in civilian applications. In fact, unmanned aerial vehicle (UAV) has been recognized as a promising carrier and viable technology to enhance the data collection performance [1]. In certain mission critical applications such as public safety network or resilient disaster network, a faster and reliable communication architecture is significant in order to provide a rapid response and network recovery, and as a result detailed information about the catastrophic area can be well articulated. For this, rescuing efforts and disaster recovery can be properly issued, thereby helping disaster victims with the first-aid assistants and responses in terms of connectivity.

Traditionally, we have been reported that accessing the disaster area was difficult and sluggish for the first responders due to a huge damage in terms of infrastructure and existing utilities. Besides, concrete information about a magnitude of the affected area is by far very unclear since a lot of things need to be managed and most importantly some area are still dangerous for human being to get into. To solve the mentioned problems, a number of studies from both academia and industries are taking further steps leveraging the existing technologies and looking into new applications using UAV [2].

To enhance the data gathering efforts and to collect time-sensitive information in such situation, sensor nodes are distributed in the area either randomly or uniformly. A network of the distributed nodes is built to handle data processing and computing. Moreover, since the concrete information about the affected area is very critical and time sensitive, a network of sensor nodes has to be resilient and robust, and thus a reliable and rapid communication architecture is necessary [3], [4]. For this, leveraging the rapid deployment of an unmanned aerial vehicle (UAV), we introduce a novel data gathering technique in UAV-assisted wireless sensor networks utilizing a correlation between partnership and data forwarding model.

In the state of the art of wireless data acquisition system, effective data collection efforts have become a great deal of challenges due to an increase in the number of joint nodes. Accordingly, to overcome a large number of sensor nodes that might degrade a system performance, an enormous number of research studies have been well investigated on the way. One of the major works going on in this area is multiple access scheme or MAC protocols [5]. In fact, multiple access scheme has been recognized as one of key enabled mechanism to tackle these challenges. Having said that, immense studies on enhancing a MAC protocol for sensor networks have been widely considered. In particular, a study in [6] has conducted a survey on various multiple access protocols in different network conditions. H. Xie *et al.,* in [7] have confirmed that novel and efficient MAC protocols could not only increase the received payload but also ensure a good Quality of Service (QoS) in a network. In this regards, to improve the MAC performance in UAV ad-hoc networks, authors in [8] introduce full-duplex radios and multi-packet reception capability. Meanwhile, one of our recent studies on enhancing MAC protocols in aerial sensor networks has leveraged a directional beam forming antenna along with a spatial reuse technique to enable a simultaneous data transmission in multiple UAVs [9].

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From the perspective of a spatial diversity, the authors in [10] have presented a new medium access control (MAC) mechanism to enhance spectrum efficiency and reduce energy consumption in the network. Their findings show that a spatial reuse mechanism offers a great improvement on the network performance. Besides, a cooperative MAC protocol presented in [11] has confirmed that it is quite promising to adopt a spatial diversity solution in cooperative data transmission scenarios. As the UAV is used to to collect data in sensor networks, it is important to keep maintaining a stable packet delivery of data transmission and network coverage. In this regards, M. Dong *et al.,* in [12] proposed a new data gathering algorithm, leveraging both the UAV and mobile agents (MAs) to autonomously collect and process data in wireless sensor networks. To enable an efficiency of collecting data, the UAV dispatches MAs to the network to collect data from sensor nodes. For this, a larger network coverage area and high connectivity can be maintained. However, there is always a trade-off between a high connectivity and network performance of data transmission. While the high connectivity and coverage are properly taken care as in [12], the authors failed to tackle an access scheme on many levels. As a result, the performance of packet reception will become unstable when the network becomes denser. Indeed, although the problems of data acquisition are well addressed in the literature, the need for more efficient scheme still persists due to an exponential growth of the number of sensor nodes in the network [13].

Thus, prototyping an efficient approach for data gathering has become a key design choice and it is increasingly important that multiple access issues are explicitly considered, or the packet collisions among sensor nodes will degrade the system performance. As a result, it is practically clueless to consider a huge number of nodes in the network. For this, this paper aims to address a UAV data acquisition problem with an efficient MAC protocol. Towards this goal we present:

- A time-sensitive approach for effective data collection utilizing the unmanned aerial vehicle (UAV). Therefore, while maintaining a high connectivity as well as better coverage area, this work can also achieve a huge performance gain in terms of throughput and delay.
- A cooperative partnership model allowing sensor nodes in the network to be paired into groups. For this, multiple data transmissions can happen simultaneously, thereby leading to a lower latency and an increase throughput.
- A novel data forwarding scheme closely integrated with the partnership model. While guaranteeing a higher success rate of packet reception ratio, we also aim to alleviate packet losses occurring in rear edge-side of the UAV's coverage area when the UAV is moving forward.

The rest of the paper is organized as follows. We describe our proposed network model in section II. Then in section III we present our novel MAC protocol called partnership and data forwarding model. Simulation studies are conducted and numerical results are given in section IV. Conclusion and final remark of this paper are mentioned in section V.

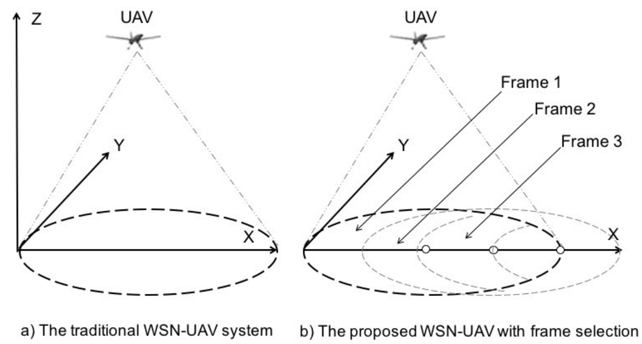

Fig. 1. Illustration of communication network in UAV-aided sensor network

II. The Proposed Network Model

In this section, we introduce our proposed network model for time-sensitive data gathering in wireless sensor network utilizing UAV. Using as an aerial relay, the UAV equipped with smart sensors and antenna for collecting the ambient data. These data are useful for understanding the awareness of the environment or used as input for data manipulation. As given in Figure 1, two communication network architectures are presented: a) the traditional WSN-UAV system and b) the proposed WSN-UAV system with frame selection. The term WSN-UAV, used in the figure, represents a system of wireless sensor network employing the UAV. In other words, sensor nodes collect the ambient data that will be transmitted to the UAV upon receiving the UAV's beacon signal. The area that receives the beacon signal of the UAV at any particular point in time is known as the UAV's coverage area.

In the traditional WSN-UAV system as given in Figure 1-a), a data transmission between the sensor network and the UAV occurs when the nodes receive the UAV's beacon signal. In other words, the sensor nodes temporary store the ambient data after collecting them and will transmit to the UAV when they receive enough signal strength from the UAV. In this conventional system, all sensor nodes inside the UAV's coverage are competing for a channel to transmit data. This kind of data transmission model falls into a problem of many-to-one data infusion. This situation creates a high possibility of packet collisions and re-transmission, thereby increasing time latency between multiple senders and the receiver, the UAV.

In the proposed WSN-UAV system as depicted in Figure 1-b), however, we classify sensor nodes inside the UAV's coverage area into different frames according to their relative positions. As a matter of fact, sensor nodes inside the same UAV's coverage area will not receive the same signal strength from the UAV due to the position differences. For this, sensor nodes belonging to different frames should also have different priority of data transmission in response to the UAV's mobility. In this work, we consider an aircraft type UAV because a specific direction is required for the UAV to collect data in the sensor network. When the UAV moves in the forward direction, it is possible that some sensor nodes in the rear edge-side of the UAV's coverage area might lose their direct communication links to the UAV. Thus, in response to this challenge, sensor nodes inside the UAV's coverage should be assigned into groups and have different priority of data transmission. A detailed description of how sensor nodes can be classified into clusters or frames can be found in [14].

III. Partnership and Data Forwarding Model (PDF)

Due to the fact that one of the primary concerns in wireless data transmission is to properly address a key challenge in medium access control (MAC) protocol, it is important that the issue is well taken into consideration when aiming to enhance the data gathering efforts. As mentioned earlier, novel and efficient MAC protocols could not only increase the received payload of sensor nodes but also ensure a good quality of service (QoS) and fairness in a network. Having said that, we take into account the aforementioned network model and introduce a spatial reuse-based partnership and data forwarding model with the goal of enhancing the data gathering efforts in UAV-assisted wireless sensor network. The proposed framework consists of three correlated models. The former two aims to enable a simultaneous data transmission between sensor nodes in the network, while the latter focuses on alleviating a packet loss in the rear edge-side of the UAV's coverage area given that the UAV is moving forward.

A. Spatial Reuse-based Partnership Model

In this proposal, before sensor nodes transmit the ambient data to the UAV, they are required to pair into a group of two. As depicted in Figure 2, sensor nodes that are already classified into clusters initiate a pairing session in order to create a partnership with their peer nodes. Each partnership must consist of two sensor nodes belonging to different frames, for instance, node N-1 and N-2 as given in the figure. For this, we introduce an algorithm I to allow sensor nodes to initiate a pairing session and formulate a partner with their neighbors. The detailed description of algorithm I is described as follows.

Our proposed algorithm begins with certain initialization and parameters such as $node(i)$, $neighbor(i)$, $node(i).fid$, and $distance(i, ...)$; the descriptions of which are given in the top part of the algorithm. Each node that is identified with a unique index i belongs to a separate cluster or frame

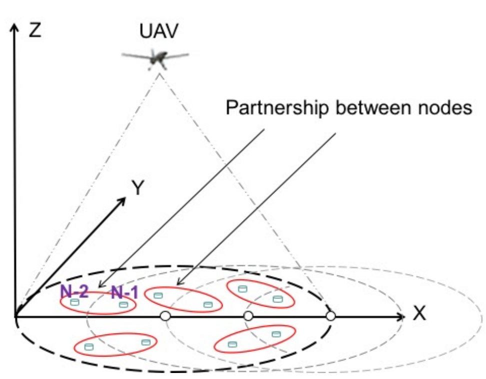

Fig. 2. Illustration of a partnership model between nodes in the network

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node(i) : the node that sends request for pairing;
node(j) : the node that receives request for pairing;
neigbhor(i) : list of neighboring nodes of node(i);
node(...).fid : the frame id of each node(...);
distance(i, ...) : distance between node(i) and neighbor(i);
while node(i) in the coverage area do
    read neighbors(i);
    node(i) sends request to neighbors(i);
    while node(j) in neighbors(i) do
        check request from node(i);
        if node(i).fid == node(j).fid then
            ignore node(j);
            proceed to node(j+1);
        else
            find distance(j, ...);
            if nearest node of node(j) is node(i) then
                check distance(i, ...);
                if nearest node of node(i) is node(j) then
                    node(j) sends response to node(i);
                    pair node(i) & node(j);
                else
                    ignore node(j);
                end
            else
                ignore node(j);
            end
        end
    end
end
```

Algorithm 1: An algorithm for formulating a partnership or pairing session between nodes in the UAV's coverage area

represented by frame id fid. In this algorithm, two significant drivers for initiating a pair session between sensor nodes are the frame id, fid, that each node belongs to and the relative distance between the sensor node and its peer. In other words, nodes can be paired together if they belong to different frames and have the closest distance. As a result of this algorithm, we have a list of pair of sensor nodes as shown in Figure 2.

B. Partnership-based MAC Protocol

After the pairing session, the node needs to compete for a transmission channel in order to transmit the ambient data to the UAV. In this work, IEEE 802.11 CSMA/CA MAC protocol [15] is adopted to handle data transmission efforts. Leveraging this protocol and its original concept, we introduce a partnership model between the transmitting nodes. For this, we aim to enable a coexistence of multiple data transmission as well as to reduce a time latency in the process. We name our proposed protocol as a partnership-based MAC and its detailed description is given in the following manner.

Figure 3 shows a data transmission architecture for a partnership-based MAC protocol. As mentioned earlier, sensor nodes are paired into groups. An example of one particular group consisting of node N-1 and N-2 is presented in Figure

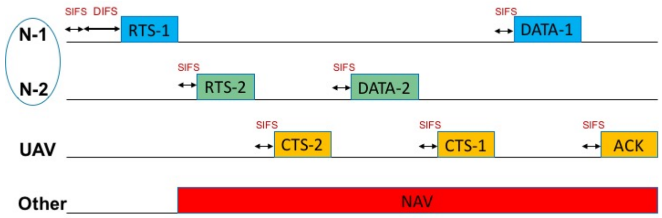

Fig. 3. Data transmission architecture for a partnership-based MAC model

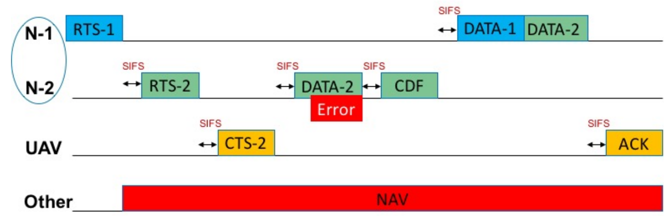

Fig. 4. Data transmission protocol for a cooperative data forwarding model

2. In our proposed partnership-based MAC, when the first node for instance N-1 wants to transmit data to the UAV, it will send a request-to-send message (RTS-1) to the UAV and also to the rest of the sensor nodes inside the UAV's coverage area. Since the node N-2 and N-1 are paired together, the node N-2 will also send its request-to-send message (RTS-2). The rest of the sensor nodes receiving the first RTS will back-off and move to network allocation vector (NAV). After receiving both RTS-1 and RTS-2 from both nodes in the same pair, the UAV will check for the frame id that each node belongs to. Accordingly, because the node N-2 belongs to a frame with lower frame id, the UAV will reply with a clear-to-send message (CTS-2) to allow the node N-2 to transmit data first. The node N-2 transmits it own data packet to the UAV soon after receiving CTS-2. After successfully received data from the node N-2, the UAV will reply with CTS-1 to allow the node N-1 to transmit data. The node N-1 then transmits its own data packet to the UAV and the UAV will finally reply with ACK message to notify the rest of the nodes inside its coverage area that the channel is now idle and available for everyone again.

C. Cooperative Data Forwarding Model

Due to the mobility of the UAV, the nodes might lose their direct communication links to the UAV while transmitting their data packets. This situation occurs mostly to the node located inside the rear edge-side of the UAV's coverage area; in our case, it can affect nodes belonging to the frame with the smallest frame id. As a result, the node that already occupied the channel and is involving in transmission process cannot maintain its stable packet delivery, thereby leading to a lower packet delivery ratio and decrease in packet performance. To alleviate the aforementioned packet loss, we introduce a cooperative data forwarding model in addition to the partnership-based MAC protocol. The description is given in the following.

According to Figure 5, the node N-1 and N-2 are paired together as a group. Assuming that while the node N-2 is transmitting its own data packet, it suddenly loses a direct connection to the UAV (out of range) due to the fact that the UAV is moving in the forward direction. In that case, normally, the remaining data packets of the node N-2 will be discarded and considered as loss. Therefore, to compensate such packet loss, the node N-2 that already stays close to its partner, node N-1, needs to forward its remaining data packets to the node N-1. We name this approach as a cooperative data forwarding process and a description of its protocol is given in Figure 4.

In Figure 4, while node N-2 is transmitting its own data packets, it detects an error that can be primarily caused by a loss in direct link to the UAV. In that case, the node N-2 will send a cooperative-data-forwarding message (CDF) containing the remaining the data packet of node N-2 to its partner, node N-1. After receiving CDF from the node N-2, node N-1 realizes that certain packet of node N-2 cannot be transmitted successfully to the UAV. Therefore, instead of waiting for a response from the UAV, CTS-1 as given in Figure 3, node N-1 will transmit its own data packet, plus the remaining data packet it received from node N-2, to the UAV. In doing so, we can avoid a packet loss at node N-2. Upon successfully receiving data packet from node N-1, the UAV will reply with ACK to notify the rest of the nodes inside its coverage area about the available state of the channel.

IV. Numerical Results

The data gathering effort presented in this work consists of sensor nodes and the UAV. Sensor nodes have packets to send to the UAV, while the aircraft type UAV is moving in the forward direction. Having said that, to accurately estimate the packet performance of a system, we need to take into account both a packet failure in a data transmission, $DATA_{loss}$, and a packet loss in a connection link, $LINK_{loss}$, between sensors and the UAV. Precisely, the data loss, $DATA_{loss}$, refers to the loss occurs when sensor nodes send data packets to the UAV and the packets are discarded due to packet collisions or expiration, and the link loss, $LINK_{loss}$, refers to a failure that occurs when sensor nodes lose direct connections to the UAV during data transmission. The link loss happens as a result of

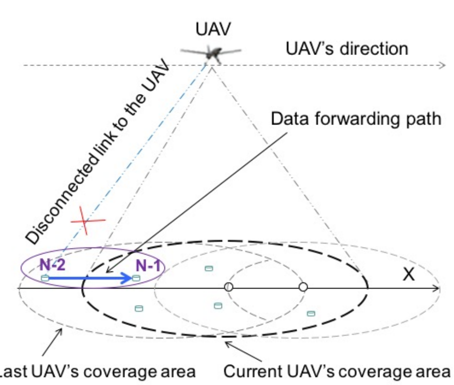

Fig. 5. Illustration of a cooperative data forwarding model in the network

the UAV's mobility. In other words, data packets transmitted from nodes to the UAV will be considered as successful only if they are not experiencing a loss in both data transmission and communication link. Accordingly, we use the data loss and link loss parameters to calculate the successfully received packet, SRP, and its expression is given as:

$$SRP = (1 - DATA_{loss}) * (1 - LINK_{loss}) \qquad (1)$$

Mobility simulations are conducted using Matlab Simulator to measure the performance of packet reception. Utilizing the proposed partnership and on-demand data forwarding model, we simulate the flight performed by the UAV. In our simulations, the UAV is used to collect the ambient data from cooperative sensor nodes on the ground. Based on the proposed network model and our design choice, performance metrics such as throughput and time delay are estimated at each time interval during the flight operation. For this, we can calculate the average throughput and time delay that each sensor node will have employing our proposed framework. To simplify the data collection procedure, we assume that the UAV flies based on a specific predefined route as described in [14]. Different network conditions and scenarios are also taken into consideration when running the simulations. The flight operation conducted by the UAV is repeated many times in order to get the average results. Performance comparisons are given to validate the significance of our work in terms of throughput and average time delay. Simulation parameters and the corresponding values presented in Table I are taken into consideration. To present the efficiency of our proposal: partnership and data forwarding model in terms of data gathering efforts in UAV-based sensor network, we compare the results utilizing our proposed framework, represented as the Proposed MAC Protocol, to those of the conventional WSN-UAV system using the IEEE 802.11 MAC CSMA/CA protocol.

Figure 6 presents comparison results of a packet delivery ratio as a function of the number of sensor nodes: our proposed MAC protocol and the WSN-UAV utilizing the IEEE 802.11 MAC protocol. Results show that the percentage of packet delivery ratio keeps linearly decreasing as the number of sensor nodes in the network increases. It can also be found that regardless of the number of sensor nodes, the higher packet delivery ratio is maintained utilizing our proposed framework, which is a combination of cooperative partnership and data forwarding model. This can be explained as follows. Firstly, the partnership model allows sensor nodes to transmit data packets faster when in a group and as a result more data packets can be successfully received at the UAV. In other words, we can maximize the packet reception during data transmission. Secondly, the cooperative data forwarding model allows sensor nodes that lost a direct link to the UAV while transmitting data due to the UAV's mobility to forward their remaining data to their peers. For this, we can alleviate a packet failure occurring when nodes do not locate inside the UAV's coverage area. Indeed, combining these two methods together, we can achieve the higher packet delivery ratio.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Network area $[m^2]$	300 × 300	Packet, l	256 Bytes
Number of nodes	500 - 1000	MAC	34 Bytes
UAV's altitude $[m]$	100	PHY	16 Bytes
UAV's speed $[m/s]$	10	ACK	14 + PHY
UAV's beam angle $[deg]$	60	RTS	20 + PHY
UAV's time interval $[s]$	1	CTS	14 + PHY
Data bit rate, $[Mb/s]$	1	SIFS	10 $[\mu s]$
CW_{MIN}	32	DIFS	50 $[\mu s]$
CW_{MAX}	1024	Slot Time	10 $[\mu s]$

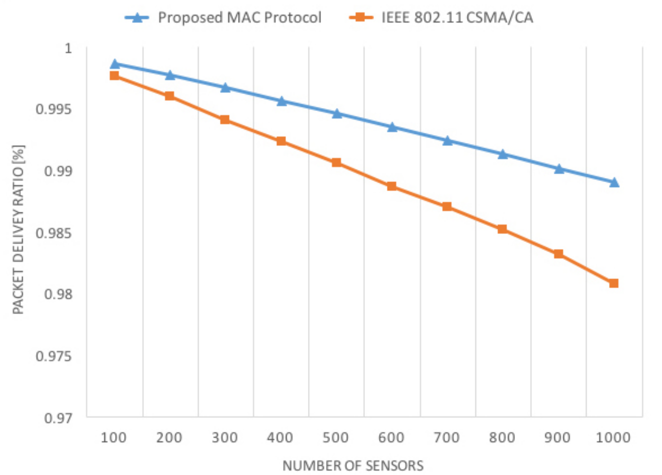

Fig. 6. A comparison of a packet delivery ratio as a function of the number of sensor nodes utilizing different data access protocols

In Figure 7, we show results of an average throughput as a function of the number of sensor nodes utilizing different access schemes. Different number of sensor nodes are taken into account to present the flexibility of the scheme. According to the figure, results utilizing the proposed MAC protocol as introduced in this paper outperforms those of the IEEE 802.11 MAC protocol. In other words, no matter how density of nodes in the network is, our framework can increase the system throughput by more than 20%. The significantly increase in system throughput as presented in the results is due to the robustness of the proposed scheme that allows nodes to be paired into groups and transmit data faster than the conventional IEEE 802.11 CSMA/CA protocol. However, because of an increase in the density of the network, the results of the network throughput utilizing both schemes keep descending. This respects to the core feature of IEEE 802.11.

Figure 8, furthermore, compares results of an average time delay between the two different access schemes: the proposed MAC protocol and IEEE 802.11 MAC protocol. Results show that a lower time delay is obtained utilizing the proposed

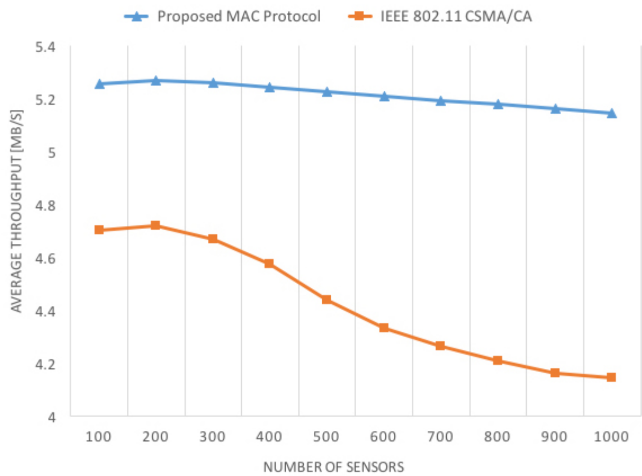

Fig. 7. Average throughput as a function of the number of sensor nodes

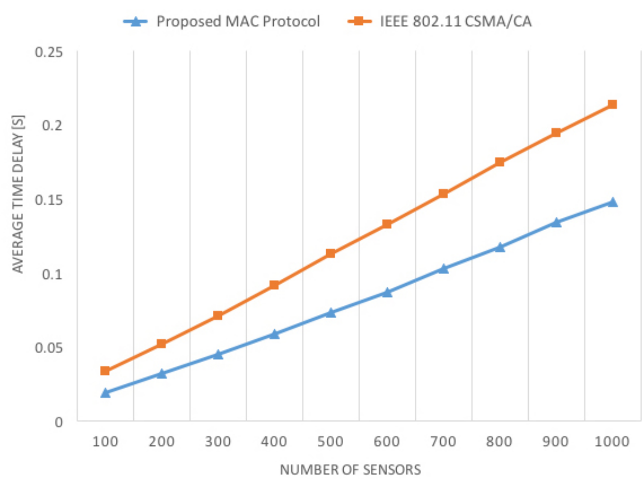

Fig. 8. Average time delay as a function of the number of sensor nodes

MAC protocol, regardless of the number of sensor nodes in the network. It can also be found that the time delay keeps linearly increasing as the network is packed with more sensor nodes. Another particular thing to notice in the figure is that as the network gets denser, the gap of time delay between the two schemes is getting larger too. As matter of fact, when not so many nodes exist in the UAV's coverage area, our proposed framework does not generate so much difference in terms of time delay. However, with more sensor nodes in the network, more groups or pairs are formulated, and as a result faster data packets can be transmitted to the UAV. This results in a shorter time delay for each sensor nodes to successfully transmit the ambient data because an unnecessary delay like back-off timer, SIFS, or DIFS are reduced when packet collisions occur.

V. Conclusion

A UAV-based data acquisition architecture is presented in this paper with the goal of enhancing the data collection efforts. Taking into account the mobility of the UAV and positions of sensor nodes in the network, we have introduced a cooperative partnership and data forwarding model along with the frame selection technique. The proposed framework not only organizes sensor nodes into different frames or clusters, but also allows sensor nodes in the network to individually pair with their peers in order to transmit data simultaneously while alleviating the packet loss in the rear edge-side of the UAV's coverage area. We have verified our proposed framework through an extensive number of simulation studies. Numerical results presented in the last section of this paper have confirmed that a huge performance improvement is achieved utilizing our proposed data collection technique.

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