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Adaptive Hybrid MAC Protocols for UAV-Assisted Mobile Sensor Networks

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***Abstract*—This paper proposes novel MAC protocols for an unmanned aerial vehicle (UAV) aided mobile wireless sensor network. UAV and sensors are mobile, and UAV collect data from sensors. In such dynamic aerial network, both the physical contact duration time (CDT) and the data-rate (DR) between mobile nodes and the UAV impact the data collection deeply. We propose hybrid beacon based MAC schemes combing CSMA/CA with physical parameters based scheduling. The UAV broadcasts 'Beacon' evenly to its coverage, and the mobile nodes that receive the 'Beacon' will randomly access to the channel through CSMA/CA. We compare fixed inter-beacon duration combined with a proactive scheduling MAC to an beacon-based IEEE 802.15.4. Through extensive simulations, the proposed MAC protocols have high performance in average delivery ratio and fairness compared to beacon beacon-based IEEE 802.15.4.**

***Index Terms*—Wireless sensor networks, unmanned aerial vehicles, mobility, time synchronization, beacon, medium access control**

I. INTRODUCTION

Recently, the mobile sink has received a tremendous interest and thereby being used in many fields [1]–[4], [8], especially the UAV aided wireless sensor network. A mobile WSN where nodes are moving in an interesting area, and a flying UAV used to collect data from the ground mobile sensor network is investigated in [1]–[4].

UAVs are equipped with various types of smart sensors and antennas to collect data more effectively. As a mobile sink, the UAV is more flexible energy efficient and robust for data transmission compared to other traditional WSNs due to highly free characteristics. Thus, each mobile node needs to coordinate to achieve more real time data and faster response in such application. Hence, efficient data communication in such scenario becomes great challenging in large scale networks. To deal with these issues, many studies have been done, which are detailed in section II. Data gathering in the one-hop case are well addressed in the literature, the need for more efficient schemes persists due to some exponential parameters of the networks. This paper proposes and compares two efficient MAC schemes to address the aforementioned issues. The main contributions of this paper are as following:

- A multi-data-rate scheme and contact duration time between sensors and the UAV are considered. In this work, the relative distance between the nodes and UAV is changed over time, which results in changing the transmission rate and the contact duration time between the nodes and the UAV. The two parameters have a huge impact on the data gathering issues in such context [4].
- Hybrid MAC protocols, Fixed inter beacon Duration and proactive scheduling (named FD-PS MAC) was proposed to coordinate the data communication between sensors. FD-PS MAC includes contention-based period (CBP) and contention-free period (CFP). In CBP, sensors access to the UAV through CSMA/CA. After receiving packets from the sensors, the UAV knows the detailed information of the detected sensors. Thus the reservation of time slots could be done proactively in CFP. FD-PS MAC was further divided into FD-PS MAC I and FD-PS MAC II respectively according to whether the duration of contention based period and contention free period are adaptive or not (which will be detailed in Section III-B). Through extensive simulations, the proposed protocols show a high-performance in the introduced delivery ratio and fairness.

The rest of the paper is organized as follows. The related works are presented in section II. In section III, we introduce the network model and the proposed hybrid MAC protocols. Performance evaluation and simulations are given in section IV. Section V concludes this work.

II. RELATED WORKS

From the research point of view, various studies and schemes have been proposed for WSN employing UAV. They are roughly divided into three categories: *Contention-based*, *Contention-free*, and *Hybrid* protocols.

- **Contention-based Protocols**.

Shigeru et al. [1] proposed an effective data gathering scheme for WSN employing UAV. That is a priority-based contention window adjustment scheme (PCWAS). The scheme adopts a conventional CSMA/CA. So, they introduce a priority-based optimized frame selection (POFS) scheme. In addition to POFS, PCWAS is proposed to define a lower contention window range to a higher transmission priority frame and vice versa. This approach not only minimizes the number of collisions but also allows higher priority of data transmission to sensors that need to transmit first, so that the packet loss in the communication link is dramatically reduced.

- **Contention-free Protocols**.

The Prioritized Frame Selection based CDMA MAC protocol (PFSC-MAC), an important MAC protocol for data

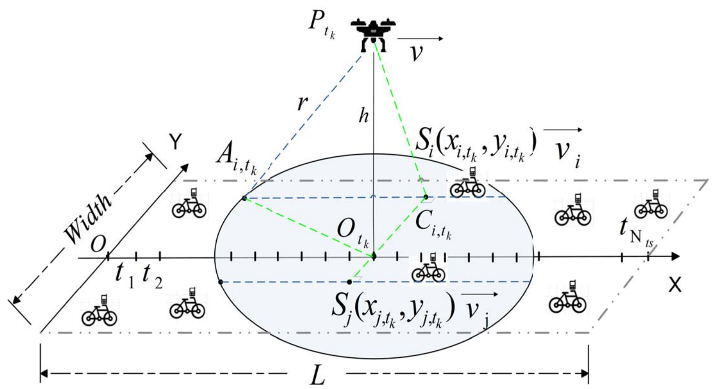


Fig. 1. A UAV-assisted wireless sensor network.

collection in WSN employed with one UAV is proposed in [2]. In this protocol, the sensors are classified into different groups based on priorities and communicate with the UAV by a CDMA-based transmission scheme. This protocol provides a low rate of failed packet due to the mobility of the UAV, which is the most critical metric in these types of applications [6], [7]. However, this scheme pays little attention to the contact duration time between the nodes and the UAV which plays a hugely important role in such dynamic aerial networks.

The authors proposed a contention-free metric, DR/CDT [4], which takes into account the multi-data-rate and the contact duration time schemes between the source node and the destination node with the objective of maximizing data collection. DR/CDT is based on an assumption that the UAV knows the evolution of the network, which is a strong assumption in many applications.

- **Hybrid Protocols**.

Say et al. [5] studied a novel MAC scheme for a super dense aerial sensor network (maximum is 100 UAVs in the simulations in [5]) using UAV. These UAVs are used to sense and collect real-time data from a disaster area, and they consist of one master UAV and many actor UAVs. The proposed scheme, collision coordination based MAC (CC-MAC), combines CSMA/CA and TDMA protocols, which assume that the actor UAVs remain close to another actor UAVs. This would be a strong assumption when there is a big gap between their velocities.

In this work, an UAV and a swarm of mobile nodes (maximum is 2000) are considered. Sensors are deployed on a predefined path and moving along the path, the UAV flying along the path to collect data from the nodes. The speeds of the sensors are no larger than the UAV's. Both multi-data-rate and contact duration time schemes [4] are considered in our work. Hybrid MAC protocols (FD-PS MAC) is proposed based on the two metrics.

III. PROBLEM FORMULATION AND PROPOSED PROTOCOLS

In this section, we will introduce the scenario and the addressed issues.

A. System Model and Problem Statement

In this paper, we consider an UAV aided sensor network which has N mobile sensors. $\mathbb{S} = \{S_i | i \in \mathbb{N}\}$ ($\mathbb{N} = \{1, 2, \cdots, N\}$), is a set of mobile sensors that are deployed along a predefined path (Figure 1). The UAV is flying along this path with a constant velocity v to collect data from the mobile sensors. The sensor S_i has a constant velocity v_i, and $\mathbb{V} = \{v_i | v_i \leq v, i \in \mathbb{N}\}$ is the set of sensors velocities.

According to the figure 1, multiple sensors that deployed nearly (e.g. S_i and S_j in figure 1.) will compete to communicate with the UAV. Thus, how to synchronize the network and reduce the collisions between sensor nodes are challenge in such mobile context.

B. Hybrid MAC Protocols in UAV aided mobile WSN

In this section, we will introduce the proposed hybrid MAC protocols. The authors in [4], [6] have show that the link duration time has huge impact on the network performance. And the data-rate between the nodes and the UAV is changed with the relative distance between them. Thus, data-rate is changed with time. Therefore, we introduce new proposals based on the two schemes. The proposed protocol, FD-PS MAC, is based on a combination of beacon based CSMA/CA and DR/CDT algorithm [4]. In FD-PS MAC, the duration between the two adjacent beacons is fixed.

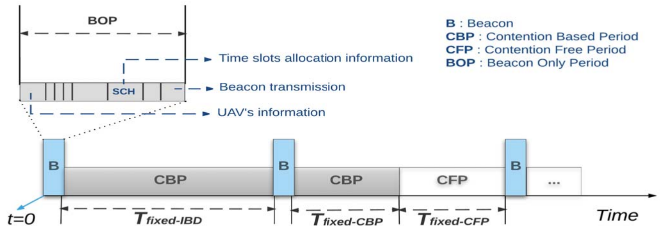
The UAV broadcasts a 'Beacon' message which contains the details of scheduling information (SCH). The covered sensors that received the 'Beacon' message compete to communicate with the UAV in the following contention based period. Nodes only send 'first packet' to the UAV when they have opportunities to communicate. The 'first packet' contains the properties of the node such as the node ID, position, velocity, the remaining packets and so on. After receiving the 'first packet', the UAV gets the details of the node, then, processes the data and gets 'SCH' information for contention free period. The details of the proposed protocols as follows:

Figure 2 presents the FD-PS MAC. Similarly, two models of FD-PS MAC are introduced: FD-PS MAC I (Figure 2(a)) and FD-PS MAC II (Figure 2(b)).

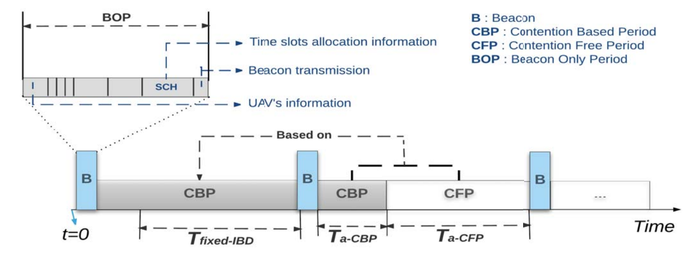
1) Proposed FD-PS MAC I: In FD-PS MAC I, both contention based period and proactive scheduling period are fixed. The UAV gets the details of the nodes and broadcasts a beacon which contains 'SCH' for contention free period within the next inter-beacon duration.

However, the time slots reservation for the detected nodes is not guaranteed because of the fixed contention free period. Thus, FD-PS MAC II, which has adaptive contention based period and contention free period, is proposed.

2) Proposed FD-PS MAC II: The inter-beacon duration is fixed at T_0 ($T_0 \leq T_{Ubd}$). During the first inter-beacon duration, there is no contention free period. Thus, the contention based period in the first inter-beacon duration is T_0. From the second inter-beacon duration, the network gets information that have been detected in the one ahead. Thus, we can estimate the duration for the next inter-beacon. In the following, we will



(a) fixed CBP and fixed CFP



(b) adaptive CBP and CFP

Fig. 2. Hybrid protocols based on fixed inter-beacon duration.

introduce how to adapt the contention based period and contention free period from the second inter-beacon duration.

The contention based period and contention free period in the k^{th} ($k \geq 2$) inter-beacon duration are denoted by T^k_{CBP} and T^k_{CFP} respectively. The number of nodes that the UAV detected in the k^{th} inter-beacon duration is denoted by N_k. The set of the sensors that successfully sent 'first packet' in k^{th} contention based period is denoted by $\mathbb{S}_k = \{S_{r_1}, \cdots, S_{r_{N_k}}\}$. The set of remaining packets for sensors in $\mathbb{S}_k$ is denoted by $\mathbb{Q}_{sk} = \{Q_{sr_1}, \cdots, Q_{sr_{N_k}}\}$. The data-rate between these nodes and the UAV is denoted by $\mathbb{DR}_k = \{DR_{r_1}, \cdots, DR_{r_k}\}$. Then, the contention free period in the k^{th} inter-beacon duration is theoretically calculated by

$$T^{k+1}_{CFP} = \sum_{i=1}^{N_k} \left\lceil \frac{Pk\_Size \cdot Q_{sr_i}}{DR_{r_i} \cdot \alpha} \right\rceil \cdot \alpha. \tag{1}$$

where α is the duration of one time slot.

The theoretical value calculated in equation (1) makes sure that each node that detected in the k^{th} contention based period was allocated enough time slot in $k+1^{th}$ contention free period.

If $T^{k+1}_{CFP} < T_0$, then the contention based period in $k+1^{th}$ inter-beacon duration is defined as, $T^{k+1}_{CBP} = T_0 - T^{k+1}_{CFP}$. If $T^{k+1}_{CFP} \geq T_0$, then $T^{k+1}_{CBP} = 0$. This definition provide a guaranteed time slots reservation for nodes that detected in k^{th} contention based period. Hence, $T^{k+2}_{CFP} = 0$, and $T^{k+2}_{CBP} = T_0$. This phenomenon is normal in high density network. The longer the contention based period, the unfairer of the network.

IV. PERFORMANCE EVALUATION

A. System Performance

1) Packets Delivery Ratio: The packets delivery ratio (PDR) of the system as the ratio of the number of packets

Algorithm 1 FD-PS MAC II

Input: L, T, T_0, v, $width$, T_{Ubd}
Output: *PDR, Fairness*
T_{now} = 0, $k = 1$;
while $T_{now} < T$ **do**
Step 1. Synchronization;
UAV sends 'Beacon' messages;
Network update, get $\mathbb{S}_k$;
Step 2. Data Communication;
i. *CBP :*
Sensors in $\mathbb{S}_k$ send 'first packet' to the UAV through CSMA/CA protocol. Nodes that successfully send 'first packet' to the UAV in CBP period was denoted by $\mathbb{S}_{kB}$.
ii. *CFP :*
Calculate T^{k+1}_{CBP} and T^{k+1}_{CFP};
Sensors in $\mathbb{S}_{kB}$ reserve time slots for CFP period according to DR/CDT algorithm and send packets to the UAV in the reserved time slots;
Update T_{now};
$k = k + 1$.
end while
Calculate and **return** PDR, Fairness;
End of algorithm.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Range	100 m	Nodes speeds	[0,10]ms^{-1}
UAV speed	10 ms^{-1}	Network size	2000
Fly height	15 m	Pk_Size	127 $Bytes$
Move path	10 m × 6000 m	Deployed path	10 m × 1000 m

received by the UAV over the sum of packets of all mobile sensors that successfully sent one packet to the UAV. The sensor set that successfully sent one packet to the UAV is denoted by $\mathbb{F}$. $Pk\_Se(i)$ is the number of packets that S_i ($S_i \in \mathbb{F}$) successfully sent to the UAV. $Pk\_Sum(i)$ is the sum of packets that S_i has. Then, the packets delivery ratio of the system is given by

$$PDR = \frac{\sum\limits_{S_i \in \mathbb{F}} Pk\_Se(i)}{\sum\limits_{S_i \in \mathbb{F}} Pk\_Sum(i)} . \tag{2}$$

2) Fairness: Here, we adopt the standard deviation to measure the fairness of the network. Thus, the smaller the standard deviation value, the fairer the network. The network is fair when the standard deviation is zero.

The main objective of the proposed protocols is maximizing PDR and minimizing standard deviation.

B. Simulation Setup

In this section, we run the simulation with several parameters, including network size, the inter beacon duration and the deployed topology. Simulations are conducted in MATLAB. The simulation results are obtained from multiple runs and finally results are the mean value of 30 simulation runs (with a 95% confidence level and 5% confidence intervals).

The system model is evaluated by means of a UAV and a swarm of mobile nodes moving along a $Path$ (10 m × 6000 m). The swarm consists of 2000 mobile nodes that are randomly deployed within an area of 10 $m \times 1000$ m (named $Path_d$).

Meanwhile, in order to reduce the impact of network topology on the simulation results, 50 simulations are done. The finally results in the figures are given by the mean value of 30 simulations except the best 10 simulations and the worst 10 simulations. The simulation parameters applied in the following are presented in Table I.

The time slot used in the following is considered as the time that the sensor need to successfully send one packet at the lowest data rate (4.8 Kb/s). Hence, $\alpha = Pk\_Size/DR_{lowest}$, that is 0.2117 s. The 4-pairwise communication parameters setting are defined as in literature [4].

C. Results and Analysis

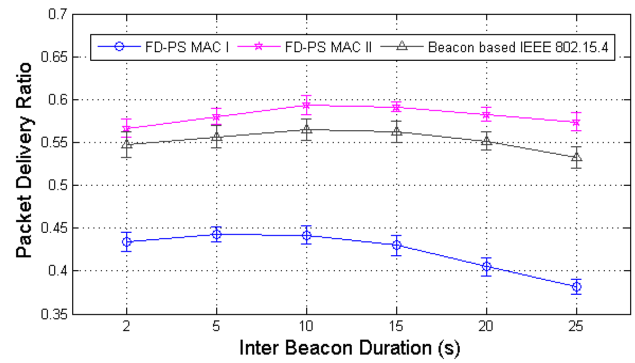
Here, we will compare the proposed hybrid MAC protocols with existing hybrid MAC protocols. In order to study it more detail, we will modify the inter-beacon duration. This section will present the impact of the inter-beacon duration on the system performance. And the inter-beacon duration changes from 2 seconds to 25 seconds.

Figure 3 shows a comparison of an average delivery ratio and fairness between proposed MAC and the beacon based IEEE 802.15.4. From figure 3(a) We can notice that when inter-beacon duration is smaller than 10 s, the packet delivery ratio of the three hybrid metrics is increasing as the inter-beacon duration increasing and it shows opposite phenomenon when inter-beacon duration is larger than 10 s. On the contrary, the fairness shows different change. All metrics achieve the optimal performance around 10 s. In fact, the shorter the IBD is, the fewer number of sensors that detected in last contention based period have opportunities to reserve time slots, the lower delivery ratio and the unfairer of the network. Similarly, the longer the inter-beacon duration is, the longer waiting time for the detected sensors to send packets in the next contention free period, the lower delivery ratio of the system. In fact, many of them are out of the range of the UAV before the next contention free period coming, they only send packets during contention based period, thus, it is unfairer for the nodes.

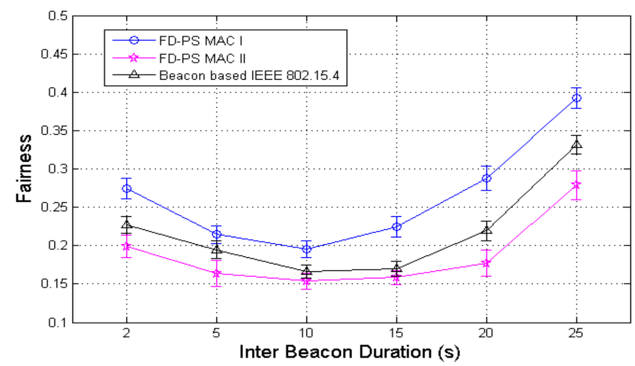
According to the results, FD-PS MAC II perform very well with a larger number of mobile nodes.

V. Conclusion

This paper has introduced efficient MAC protocols (FD-PS MAC I and FD-PS MAC II), for data collection in UAV-assisted mobile networks. Both of them adopt a combination of beacon based CSMA/CA and DR/CDT. Both contention based period and contention free period are fixed in FD-PS MAC I and adaptive in FD-PS MAC II. The simulation results confirmed that the FD-PS MAC II outperform the FD-PS MAC I and beacon based IEEE 802.15.4 in larger scale mobile WSN with a flying Sink.



(a) PDR



(b) Fairness

Fig. 3. The impact of inter-beacon duration.

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