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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 combining 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.

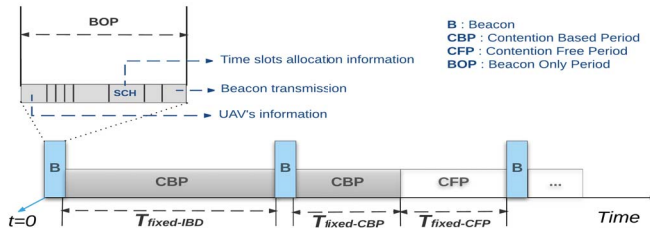
### • Contention-based Protocols.

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.

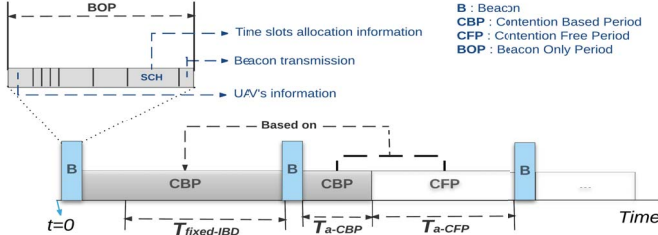
### • Contention-free Protocols.

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





(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  $T_{CBP}^k$  and  $T_{CFP}^k$  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  $\mathbb{S}_k = \{S_{r_1}, \dots, S_{r_{N_k}}\}$ . The set of remaining packets for sensors in  $\mathbb{S}_k$  is denoted by  $\mathbb{Q}_{sk} = \{Q_{sr_1}, \dots, Q_{sr_{N_k}}\}$ . The data-rate between these nodes and the UAV is denoted by  $\mathbb{DR}_k = \{DR_{r_1}, \dots, DR_{r_k}\}$ . Then, the contention free period in the  $k^{th}$  inter-beacon duration is theoretically calculated by

$$T_{CFP}^{k+1} = \sum_{i=1}^{N_k} \left[ \frac{Pk\_Size \cdot Q_{sr_i}}{DR_{r_i} \cdot \alpha} \right] \cdot \alpha. \quad (1)$$

where  $\alpha$  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  $T_{CFP}^{k+1} < T_0$ , then the contention based period in  $k+1^{th}$  inter-beacon duration is defined as,  $T_{CBP}^{k+1} = T_0 - T_{CFP}^{k+1}$ . If  $T_{CFP}^{k+1} \geq T_0$ , then  $T_{CBP}^{k+1} = 0$ . This definition provide a guaranteed time slots reservation for nodes that detected in  $k^{th}$  contention based period. Hence,  $T_{CFP}^{k+2} = 0$ , and  $T_{CBP}^{k+2} = T_0$ . 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  $T_{CBP}^{k+1}$  and  $T_{CFP}^{k+1}$ ;

  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 $\times$ 6000 m	Deployed path	10 m $\times$ 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

$$PDR = \frac{\sum_{S_i \in \mathbb{F}} Pk\_Se(i)}{\sum_{S_i \in \mathbb{F}} Pk\_Sum(i)}. \quad (2)$$

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  $\times$  6000 m). The swarm consists of 2000 mobile nodes that are

randomly deployed within an area of  $10\text{ m} \times 1000\text{ m}$  (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 ( $4.8\text{ Kb/s}$ ). Hence,  $\alpha = Pk\_Size/DR_{lowest}$ , that is  $0.2117\text{ s}$ . The 4-pairwise communication parameters setting are defined as in literature [4].

### C. Results and Analysis

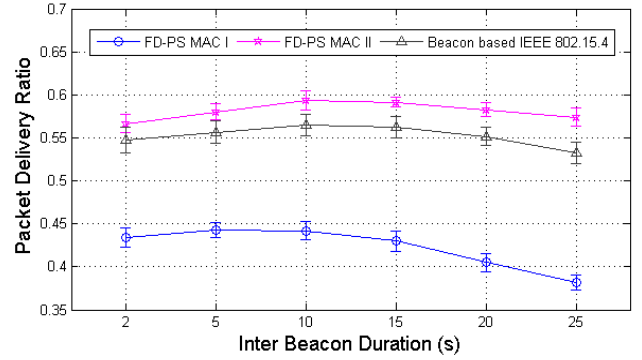
Here, we will compare the proposed hybrid MAC protocols with existing hybrid MAC protocols. In order to study it more detail, we will modify the inter-beacon duration. This section will present the impact of the inter-beacon duration on the system performance. And the inter-beacon duration changes from 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  $10\text{ s}$ , 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  $10\text{ s}$ . On the contrary, the fairness shows different change. All metrics achieve the optimal performance around  $10\text{ s}$ . 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 unfaier 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 unfaier for the nodes.

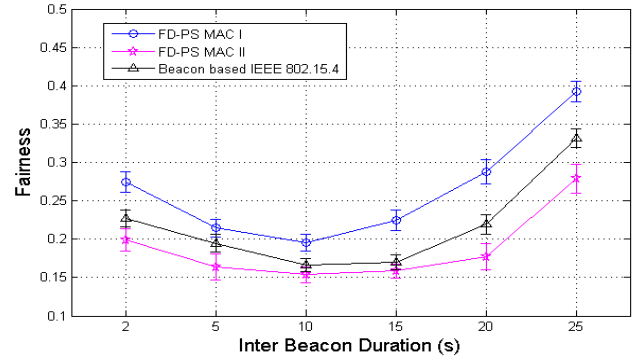
According to the results, FD-PS MAC II perform very well with a larger number of mobile nodes.

## 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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