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Article

Hybrid MAC Protocol for UAV-Assisted Wireless Sensor Networks

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Abstract: This paper proposes a hybrid medium access control (MAC) protocol for wireless sensor network (WSN) data gathering, employing unmanned aerial vehicles (UAV). The UAV sends a beacon frame periodically to inform sensor nodes regarding its presence. Afterward, each sensor node which receives beacon frame contends to send registration frame to the UAV. The UAV will transmit the second beacon frame to the registered nodes to notify their transmission schedule. The time-slot scheme is used for the transmission schedule. The transmission schedule of each sensor is determined based on their priority. Specifically, the priority of each sensor is determined during the registration process. Furthermore, the architecture of UAV-WSN data gathering system is introduced in this paper. Simulations are performed, showing that the proposed MAC protocol achieves fairness while enhancing network performance.

Keywords: Hybrid, MAC protocol, UAV, wireless sensor networks, system architecture.

1. Introduction

Wireless sensor networks (WSNs) are a well-known emerging technology having a wide range of applications. WSN applications have varying characteristics and network requirements. Generally, each sensor in a WSN collects and processes data, routing it to a sink node or base station via other sensors [1]. WSNs employed in disaster-affected areas have different requirements from those of other applications, because sensors deployed in a location distant from the sink node may lose communications. Thus, mobile sink nodes are needed. Unmanned aerial vehicle (UAV) can be employed as mobile sink nodes for various WSN applications. UAV can move easily and quickly to access real time-sensitive information in disaster-affected areas needing mobility communications for emergency rescue purposes. For industrial applications, UAV can be employed to gather sensor data in agricultural [2] and oil refinery zones [3], where sensors are scattered around large areas far from control stations.

UAV has been used in military applications since their first development. They were initially deployed remotely as individual large autonomous vehicles to accomplish either surveillance or reconnaissance missions. Despite their effectiveness, there are some disadvantages of their deployment (e.g., maintenance costs) [4]. Currently, UAV is less expensive and smaller, making them more attractive to private sectors [5]. Furthermore, WSN applications have enabled the connection of all things mobile. Therefore, the combination of UAV and WSN creates a dramatic new application named UAV-WSN.

UAV-WSN data gathering is different from common WSN data-gathering. In UAV-WSN, the mobile relay node (i.e., fixed-wing UAV) cannot slow down or stop its movement during a task. Thus, sensors have

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small opportunities to communicate with the UAV, because they are always on the move. Additionally, in disaster-affected or agricultural areas, nodes are scattered around large areas form the high-density network. Higher node densities can cause higher collisions among contending nodes, degrading network performance. Nodes also consume more power when deployed in large-scale networks [6]. This occurs because nodes must retransmit data lost during collisions. Additionally, nodes must retransmit data to cover longer distances. Hence, extensive research of this data gathering system is needed to solve its problems

A fundamental limitation of this data gathering system is the medium access control (MAC) protocol. Extant MAC protocols (e.g., mobile ad hoc networks and vehicular ad hoc networks) are unsuitable for UAV-WSN [7]. The carrier-sense multiple access collision avoidance (CSMA/CA) MAC protocol, when implemented in high node density areas, suffers from high delays. The well-known hidden terminal problem also deteriorates network performance, because the distances among nodes are short compared to the distances between the UAV and nodes [8]. The authors in [9] proposed a hybrid MAC protocol for UAV-WSN. The proposed MAC protocol combines the CSMA/CA with physical based scheduling. The authors in [10] proposed a time-division multiple access-based (TDMA) MAC protocol for UAV-WSN data acquisition. The study also investigated a prioritization scheme to offer fair communications. However, these papers only focused on reducing the packet error rate and increasing the packet delivery ratio (PDR).

The data gathering process in UAV-WSNs also relies on time constraints, which can affect the network performance of the system. Time constraints should be considered because the UAV always moves while performing the data gathering process nodes only have a short time to communicate with the UAV, i.e. when the nodes are inside the coverage area of the UAV. The nodes should transmit as much of their data as possible during this period. However, the fairness among contending nodes is affected by this condition. Each node should be able to transmit the same amount of data to the UAV to achieve fairness. Therefore, an appropriate MAC protocol for data gathering in UAV-WSNs is required.

In this paper, a hybrid MAC protocol for data gathering in UAV-WSN is proposed. The proposed MAC protocol uses CSMA/CA during the registration process of sensor nodes and allocates the registered sensor nodes time-slot-based scheduling in the data gathering process. During the registration period, the prioritization scheme is assigned in which each node in the same area will be formed to one group. This prioritization scheme is used to give the highest priority for each node located in the most rear of UAV's coverage area. Then, the most priority group will be given the low $DIFS$ value and vice versa. Furthermore, each node inside of the most priority group will be allocated into the slot in which has the earliest time to access the UAV's channel during the data gathering period. The architecture of UAV-WSN data gathering system is also presented in this paper. The system architecture is build based on three core components which are cloud servers, UAV, and sensor nodes. These three core components has their own task and responsibility to run the system. This system architecture will be elaborated in the Section. 4.

Based on the aforementioned problem and the proposed solution, the contribution of this paper is presented as follows.

1. An architecture of UAV-WSN data gathering system is introduced.
2. A prioritization scheme is proposed. The prioritization is achieved based on the node location inside of the UAV's coverage area.
3. A different $DIFS$ value is adopted to improve fairness among contending nodes during the registration period. The nodes belonging to the highest priority area is assigned the smallest $DIFS$ range. Otherwise, nodes belong to the lowest priority area are assigned the highest $DIFS$ range. These nodes have more coverage time inside the UAV's communication range.
4. The groupization of the nodes that located in the same priority area. These nodes are assigned to one group and get the time slot schedule according to their priority.

5. The superframe of MAC protocol is divided into four periods such that the network performance of the system can be maintained.

The rest of this paper is organized as follows. Section II describes the UAV networks and the related works. Section III explains the UAV-WSN network model. Section IV introduces the UAV-WSN system architecture. Section V presents the proposed MAC protocol. Section V shows our results and analysis. Finally, Section VI presents our conclusions.

2. Overview of UAV Network

UAV network is one of emerging research area in ad-hoc network topics. The increasing popularity of UAV due to its advantage make numerous people use it to assist their work. At the same time, the IoT is implemented in almost every aspect nowadays. This situation emerges researchers to propose a new technology called flying ad-hoc networks (FANET) to makes UAV, and IoT can cooperate [11]. However, there are many aspects should be investigated to make FANET can be appropriately operated.

FANET employ UAV as a flying node that has high mobility on it. This aspect makes FANET has different network model with the other ad-hoc technology such as mobile ad-hoc networks (MANET) and vehicular ad-hoc networks (VANET) [12]. The network model of FANET can be distinguished based on the communication method. In FANET, a number of UAVs can be connected with a decentralized manner. This communication method called a UAV-UAV wireless communications method. The other one is UAV-to-ground communications method in which the ground control station manages UAV. In this paper, the UAV-to-Ground communication is used with one UAV is used to gather the data from the scattered ground nodes. The UAV is controlled from the ground control station in which connected to the cloud server. The ground control generated the flight path data and stored it in the cloud server. Afterward, The cloud server forwards the flight path data through the cellular communication link to the UAV. Therefore, the communication range issue between the ground control station and UAV can be avoided.

2.1. Related Works

There have extensive researches been done on employing UAV for the data gathering. The IEEE 802.11 CSMA/CA suffers from the long contention delay between nodes and UAV. This delay problem might become more serious when the network density is high. The IEEE 802.11p MAC protocol that proposed for vehicular ad hoc network (VANET) faces the same problem with the IEEE 802.11 CSMA/CA. The IEEE 802.11p might have long contention delay when it used to handle the communication between UAV and nodes [13]. Even though UAV-WSN network and VANET have some similarities concerning communication scheme, the number of nodes in UAV-WSN is more high leads the network becomes dense that can cause long contention delay. In VANET, all of the nodes have the same link quality to the receiving unit. The receiving unit in VANET able to covers the road completely. In comparison, the nodes in UAV-WSN are scattered in the large area. All of the nodes have different link quality and duration to communicate with the UAV based on their location. Moreover, both of the IEEE 802.11 CSMA/CA and IEEE 802.11p MAC protocol do not have prioritization mechanism. Therefore, the fairness and network performance can be degraded when these MAC protocols are implemented in UAV-WSN.

The authors in [14] study the energy consumption for UAV-based data gathering with WSN clustering. The paper proposed a WSN clustering method that can minimize the number of cluster heads (CHs). Also, the UAV should flies according to the CH as a way-point to minimize the UAV's energy consumption. The authors in [15] proposed a solution to achieve an efficient energy consumption for UAV during its task to collect the data. The proposed solution combined the sensor nodes wake up scheduling with the UAV's trajectory. Moreover, the authors in [16] presents a more complex solution. The proposed solution is based

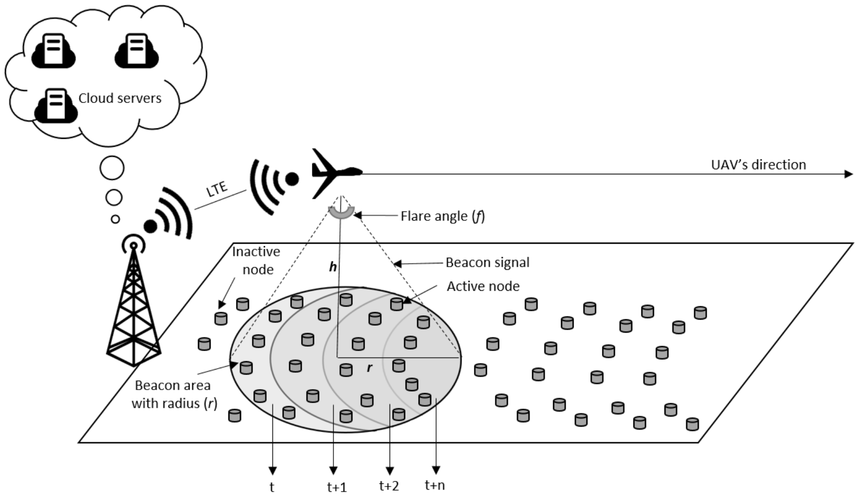

Figure 1. UAV-WSN network models

on the multi-objective bio-inspired algorithm for data acquisition employing UAV in WSN. The sensing, energy, time, and risk utilities are the category that used for the bio-inspired algorithm to get an optimal UAV path planning.

Regarding the MAC protocol, the authors in [17] proposed a MAC protocol for UAV collision avoidance system. However, their proposed MAC protocol is not suitable to implement for data gathering system. The authors in [18] proposed a cooperative sensing data collecting framework for UAV-WSN. The proposed scheme is based on the IEEE 802.11 CSMA/CA MAC protocol. The neighboring nodes can receive and store the overhearing data into their received buffer. The neighboring node can retransmit the overhearing data when it needed such as in the case of an original node does not able to transmit their data to UAV because of its position already outside the UAV communication range. In [9], the adaptive MAC protocol is proposed. The proposed MAC protocol combines the IEEE 802.11 CSMA/CA with physical parameters scheduling. The UAV sends beacon periodically and for each node that receives the beacon signal randomly access channel by using IEEE 802.11 CSMA/CA. The authors in [19] proposed a MAC protocol based on IEEE 802.11 CSMA/CA for data gathering in UAV-WSN. The proposed MAC protocol prioritize the transmission based on the location of the node. Nonetheless, the length of *CW* is the same among the contending nodes that leads the network performance deteriorated.

3. Network Model

The UAV-WSN system can be easily deployed for numerous data-gathering applications in both small and large areas. A node that is powered up but inactive still consumes energy. UAV-WSN systems can improve nodes' power consumption efficiency by dynamically deactivating unused nodes [20]. Furthermore, network performance may improve, owing to better line-of-sight (LoS) between the UAV and nodes [21]. Exponent path loss is small compared to sensor-to-sensor communications. Therefore, the UAV-WSN causes data gathering process to be more efficient than that in common WSN system. However, the data gathering process in UAV-WSN is quite different from the common WSN data gathering. UAV-WSN faces several challenges, such as short-term fairness and throughput. The common problem in IEEE 802.11 CSMA/CA MAC protocol (e.g., the hidden terminal problem) can also affect UAV-WSN systems, owing to different network density. In the UAV-WSN system, while the UAV moves according to its flight path, it collects data from the nodes spread across the ground. Hence, data gathering is limited by time and space.

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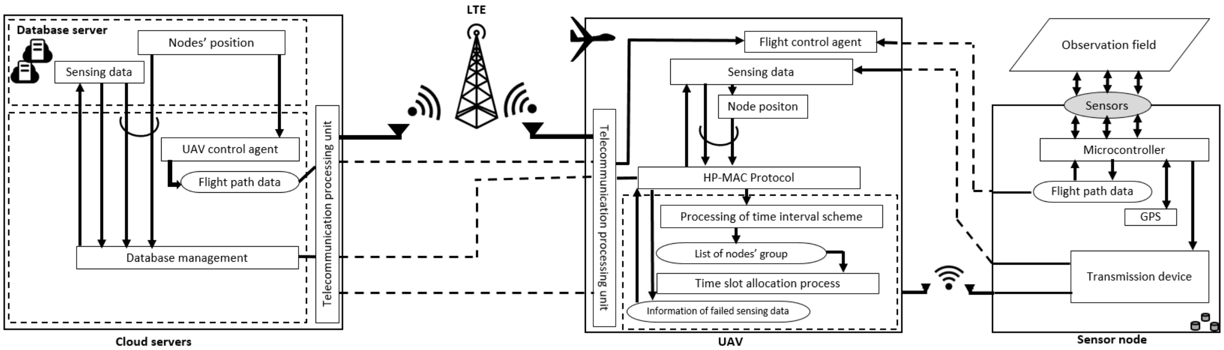

Figure 2. UAV-WSN system architecture

In this paper, nodes are active when in the vicinity of the UAV's communications range. Otherwise, nodes will be in sleep mode to save the energy. The UAV transmits a beacon frame periodically to announce its presence to the nodes. Sensors neither know the UAV flight schedule nor its position until they receive a beacon frame from the UAV. UAV and nodes use the Global Positioning System (GPS) to track and inform their network locations. GPS information is essential in this proposed prioritization scheme. The GPS information is used to acknowledge UAV trajectory for the nodes and to distinguish priority levels. Each node compares its position with the UAV trajectory to determine prioritization. Also, the ground nodes are assumed to act as CHs that have the task of gathering data and transmitting it to the UAV. The CH has already gathered the data from its cluster before the arrival of the UAV. Each CH might gather a particular type of data with a different priority from the nodes inside of its cluster. The CHs have a similar type of data to transmit to the UAV. Additionally, the CH always has a packet of data to communicate to the UAV such that the network is always in saturation mode. In the rest of the paper, CH refers to nodes that have a responsibility to communicate and transmit data to the UAV.

As depicted in Figure. 1, the UAV flies at a constant speed and height, denoted by v and h respectively. Specifically, a fixed-wing model of UAV is used in this work such that the UAV cannot stop or slow down the speed during the mission. The reason to choose a fixed-wing model is due to the capability of the model. Compared to the quadcopter model, the fixed-wing model is suitable to deploy in the large area because of the high durability and longer duration of flight time. The UAV uses a directional antenna with a specific flare angle that denoted by f. In this paper, we specified $f = 60^\circ$ such that the distance between UAV and the farthest node inside of communication range is equal to the diameter of UAV communication range. The communication range of UAV is achieved from $r = h\,tan(\frac{f}{2})$ with r as a radius from the circle of UAV communication range. Furthermore, the UAV flies according to its predetermined flight path. During the flight, the UAV gathers data from the nodes scattered along the ground.

In this network model, nodes are active at least once when they receive a beacon frame from the UAV. All of the nodes inside of the communication range of UAV can hear each other. Therefore, the hidden terminal problem able to be avoided. As observed from Figure. 1, the nodes located farthest from the communication range area of the UAV have only a short time to communicate. To increase the fairness, the nodes inside of UAV's communication range are divided based on their location. The nodes are divided into several areas inside of UAV communication range depend on the position of the nodes when the UAV is approaching. Later, this area information is used to form a group of each node, and the UAV will give priority to each group depends on where it located inside of UAV communication range. The group that located in the most rear area of the UAV communication range have the highest priority access the UAV channel and vice versa. Hence, the fairness of each node able to maintain.

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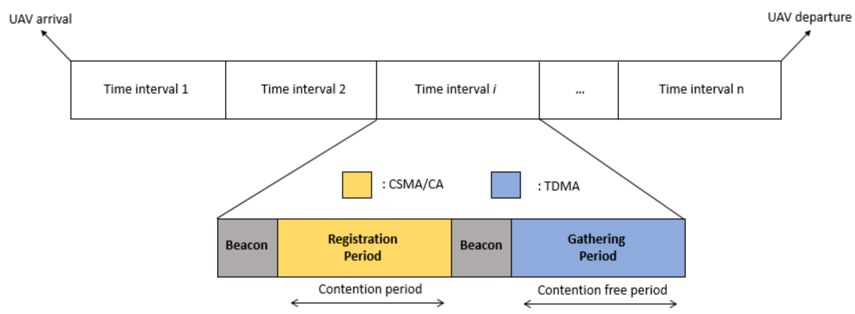

Figure 3. Time diagram and superframe

Table 1. Frame formats

Name	Size	Description	Name	Size	Description
Beacon frame format			**Registration frame format**		
Preamble	2 bytes	Syncronization	Preamble	2 bytes	Syncronization
Header	10 bytes	Control	Header	10 bytes	Control
Location	3x4 bytes	X, Y, Z	Location	3x4 bytes	X, Y, Z
Speed	1 bytes	m/s	ID	2 bytes	
Time	4 bytes	s			

4. UAV-WSN System Architecture

In this section, the system architecture of UAV-WSN for data gathering is elaborated. As illustrated in Figure. 2, three core components build the proposed system architecture. These three core components are cloud server, UAV, and sensor nodes. Each of core component has own task and responsibility. In the cloud server, the UAV control agent and database management service are provided. The determined flight path data is provided by the UAV control agent in the cloud server. Moreover, all of the gathered data including the position of each node are stored in the database server. Later, these data can be used to determine the flight path of UAV through the UAV control agent for the next following data gathering mission. The LTE or other cellular links are used to provide the reliable communication between the cloud server and the UAV. In this work, we assume that the connection between the cloud server and UAV is ideally established.

The second component in the proposed UAV-WSN system architecture is UAV. UAV has a responsibility to gather the data. As mentioned, UAV received flight path information from the cloud server through the cellular link. These flight path data then processed by flight control agent to navigate the UAV. The UAV is equipped with the networking device such that make it able to communicate with the sensor nodes on the ground. During the flight, UAV gathers the data from the nodes with the help of the proposed MAC protocol to increase the network performance of the system. The mechanism of the proposed MAC protocol such as time interval scheme and the time slot allocation process will be explained in the Section. 5.

As for the sensor node, it has a responsibility to collect the actual sensing information. Specifically, this sensor might be used to measures the environmental data. The sensor nodes included a microcontroller and connected to the several sensors. The GPS is also attached to the microcontroller to provide the exact location of the nodes. All of the sensing data will be transmitted to the UAV once the node is inside of the UAV communication range.

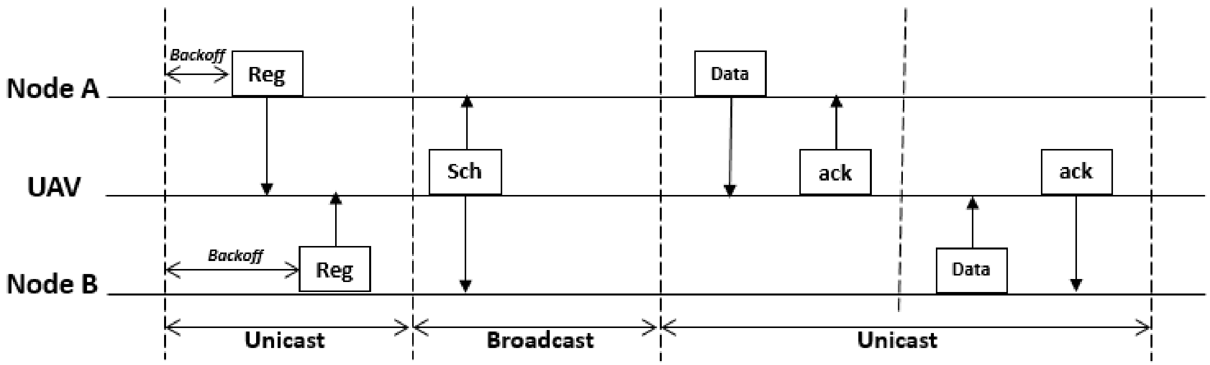

Figure 4. Communication mechanism of each node

5. Hybrid MAC protocol

In this section, we present the mechanism and the frame format of the proposed hybrid MAC protocol (HP-MAC). Figure. 3 depicts the time diagram and superframe of HP-MAC. In the HP-MAC, the channel is divided into fixed-length durations according to the UAV presence. As introduced, UAV has a limited time to communicate to the nodes as well as for the nodes to transmit their data to the UAV. Hence, we divided the superframe of HP-MAC to several periods in each time interval. The HP-MAC superframe consists of two critical periods which are registration period and gathering period. CSMA/CA is used during the registration period while during the gathering period the time slot schedule is assigned to each registered node. Moreover, the HP-MAC superframe includes two beacons to synchronize the communication of UAV and sensor nodes.

Specifically, the beacon frame contains essential information related to the UAV such as UAV current location and UAV speed. Table. 1 shows the frame formats of the proposed MAC protocol. Each node that receives beacon frame sends the registration frame to the UAV. The registration frame of each node contains their GPS location information.

6. Overview of HP-MAC Mechanism

As aforementioned, the UAV broadcast the first beacon, and the nodes will be active. The active nodes contend to send a registration frame during the registration period. As illustrated in Figure. 4, node A and node B contend to send the registration frame to the UAV. Hence, both of the nodes start backoff mechanism. Since node A has access to the UAV channel, it will transmit its registration frame by unicast. During this moment, node B should wait until node A end its communication to the UAV.

The UAV receives a registration frame from the nodes and use it as information to determine the schedule. The UAV knows which nodes and how many nodes that requested to send their data. Moreover, the UAV knows the size of packet data that each node wants to transmit. Unlike in the registration period, the UAV will broadcast the schedule information to the all of registered nodes. The transmission schedule is determined based on the node locations during the time interval of UAV. The information of node locations is contained inside of the registration frame.

After the registration period and the transmission schedule is already determined, all of the registered nodes transmit the packet data according to their time slot. Each registered node accesses the UAV channel in unicast. The UAV will transmit the ack packet whenever it successfully receives the packet data from the nodes. The scheduling rule will be elaborated in the following subsection.

6.1. Time Interval Scheme

The UAV sends the first beacon periodically to inform its presence to all of the nodes inside of UAV's coverage area. This beacon contains UAV's information includes location and speed of the UAV. Each node that receives beacon frame sends the registration frame to the UAV. However, the coverage area of UAV should be estimated in time interval since UAV always move during the operation. The idea of estimating the coverage area of UAV was initially proposed in the study of [22]. In this paper, we used the time-interval scheme to form a group of sensor nodes. Therefore, each node located in the same area will be formed into one group. Later, the most rear group from UAV's coverage area get a prioritize to access a channel in the time-slot scheduling.

As illustrated in Figure. 5, the UAV periodically transmits beacon frame while it is moving to the forward direction. Hence, the coverage area of UAV always changes along with the UAV's direction. Specifically, the UAV has coverage A at time t with radius $r_{uav}(t)$. Afterward, UAV moves forward, and the UAV coverage area will be covered area B at time $t+1$ with $r_{uav}(t+1)$ as coverage radius. After passing coverage B, UAV covered new area which is area C at time $t+2$ with coverage radius $r_{uav}(t+2)$.

The group of nodes can be determined after knowing the coverage area of UAV based on its movement in the time interval. The most priority nodes group is given to all of the nodes inside of the first coverage area of UAV indexed as $i = 1$. This indexing scheme designates the priority level from the first area that indexed by $i = 1$ until the lowest priority area that indexed with $i = n$ where n is the number of areas. Specifically, the first group is obtained based on (1):

$$Groups(1), \begin{Bmatrix} (nodes & \subset & r_{uav}(t)) \\ \cap(nodes & \not\subset & r_{uav}(t+1)) \end{Bmatrix}, \tag{1}$$

where all of the nodes inside of the coverage area at time t are included. The following groups can be estimated based on the equation (2) as follows:

$$Groups(i), \begin{Bmatrix} (nodes & \subset & r_{uav}(t)) \\ (nodes & \subset & r_{uav}(t+(i-1))) \\ (nodes & \not\subset & r_{uav}(t+1)) \end{Bmatrix}, \tag{2}$$

where these groups are the group in the coverage area in which indexed by $i \in [2, (n-1)]$. The lowest priority group is given to the nodes located in the most front of UAV coverage area. this group can be obtained in the equation (3) where the area is indexed by $i = n$.

$$Groups(n), \begin{Bmatrix} (nodes & \subset & r_{uav}(t)) \\ \cap(nodes & \subset & r_{uav}(t+n)) \end{Bmatrix} \tag{3}$$

6.2. Registration Period

As mentioned, the random access scheme is used during the registration period. In this paper, we used different $DIFS$ values in the HP-MAC to ensure higher priority nodes have a chance to transmit earlier than the lower priority nodes. The lower priority nodes have a higher $DIFS$ value than higher priority nodes. The $DIFS$ value is obtained from the sum of the $DIFS$ value of previous level priority and the CW of previous level priority. This sum of $DIFS$ value is defined as follows:

$$DIFS_{sf} = DIFS_{sf+1} + CW_{sf+1} \tag{4}$$

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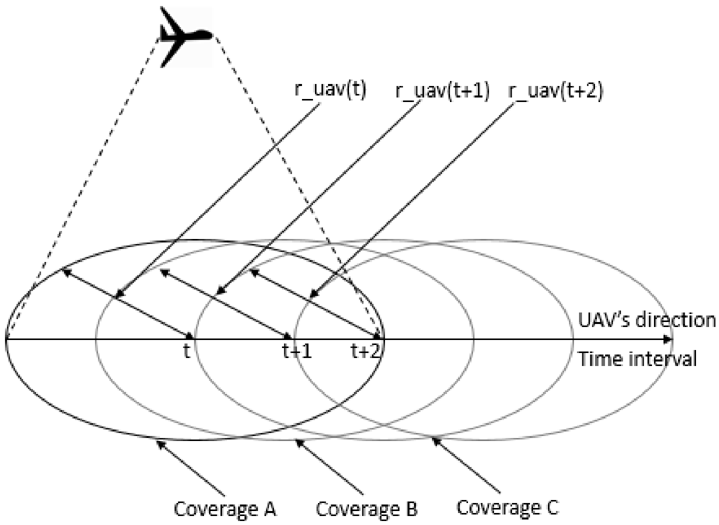

Figure 5. Prioritization of sensor nodes in respect to UAV time interval and sensor nodes location

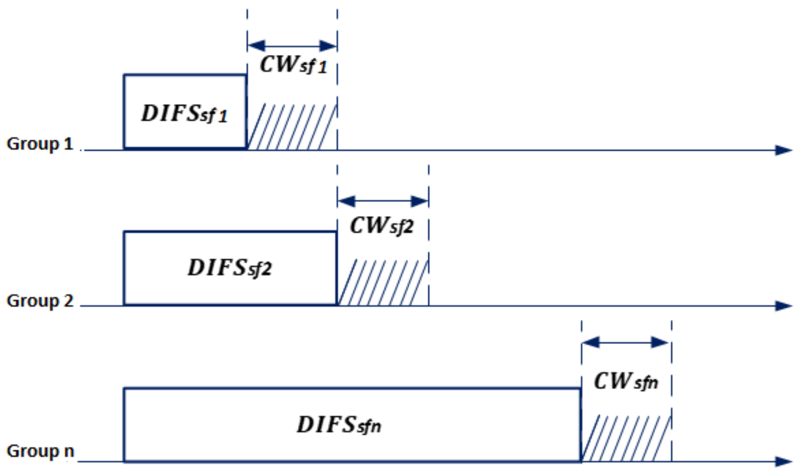

Figure 6. Different DIFS values of each side level frame

As illustrated in Figure. 6, nodes inside of Group 1 have a lower $DIFS$ value than Group 2. The $DIFS$ values of nodes within Group 2 are acquired from the sum of lower-priority $DIFS$ and CW values in Group 1. Hence, all nodes within Group 1 have a chance to transmit their data earlier than nodes in the Group of lower priority. This is because nodes inside of Group 1 only have a short time to verify the availability status of the UAV channel.

6.3. Gathering Period

In the gathering period, the UAV sends the second beacon which contain schedule information of each node. Hence, all of the nodes inside of prioritizing group will get their schedule information from UAV. As depicted in Figure. 7, each node located in Group 1 assigned in the first slot of transmission time within the superframe. The time slot is assigned to m level which is respectively $g_1, g_2, ..., g_m$ where $g_1 \geq g_2 \geq ... \geq g_m$. The frame time is set as T slots where T values is obtained from the sum of $t_1, t_2, ..., t_m$. By doing this, each node has their schedule to transmit the data. Each node is assigned based on their group such that for nodes in the prioritize group has a chance to transmit earlier than the other group.

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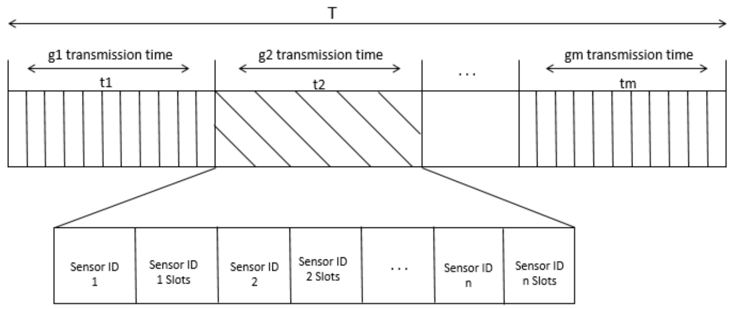

Figure 7. Time slot-based scheduling

Moreover, the sensor ID along with the allocated slot for each respected sensor ID is provided on each time slot schedule field.

The Algorithm. 1 shows the operation of MAC protocol in UAV and can be described as follows.

1. The UAV flies according to a flight path and transmits periodic beacon frame to inform nodes of its presence. Simultaneously, nodes are activated when they received the beacon signal.
2. The registered node is added in UAV once the UAV received registration frame from the nodes.
3. The UAV can receive data frame from the registered node that still inside of coverage area.

The process of MAC protocol on each node inside of UAV communication range is showed in the Algorithm 2.

1. The nodes will active after receiving beacon frame from the UAV.
2. Each node will be grouped based on the Eqs. (1), (2), and (3).
3. Based on the previous step, the UAV assigns a different $DIFS$ range for each node. Thus, fairness can be guaranteed for all nodes inside of the communication range of the UAV. Nodes located farthest from the UAV have the same chance to transmit their registration frame as those located closest to the UAV.
4. The registered sensors send the data according to their schedule.
5. The nodes will removed from registered list after successful transmission.

Algorithm 1 The MAC algorithm of UAV

$Registeredsensor \leftarrow 0$
while mission = On **do**
    Send beacon frame
    $Registeredsensor \leftarrow Registeredsensor + 1$
    $Exptime \leftarrow Exptime(Registeredsensor)$
    Send expiration frame
    Received data frame
end while

6.4. Energy Consumption

One of MAC protocol main concern is to bring energy efficiency. Moreover, most of the nodes deployed in WSN are energy constrained. In HP-MAC, the energy consumptions of the node can be maintained. The node is only active during inside of the UAV's coverage area. Otherwise, the nodes are on sleep state to conserve its energy.

Algorithm 2 The MAC algorithm of UAV

$Registeredsensor \leftarrow false$
$Receivedbeacon \leftarrow 0$
$Groupsassignment \leftarrow 0$
if $receivedbeacon > 0$ **then**
    node = active
    $Registered \leftarrow true$
else if $Exptime > 0$ **then**
    $Senddataframe \leftarrow basedontimeslotschedule$
    $Registered \leftarrow false$
else
    $Groupsassignment \leftarrow calctheposition$
    Send registration frame
end if

Table 2. Simulation Parameters

Parameters	Value
Area of nodes distribution	2000 x 2000
Sensors	Static
UAV's mobility	Constant velocity mobility model
UAV's speed [m/s]	50
UAV's flare angle [degree]	60
UAV's altitude [m]	1000
Maximum DIFS	SIFS+17*slot
SIFS	10
Packet generation	Constant Bit Rate
Minimum Contention Window	16
MAC queue size (Packets)	10
Packet length (Bytes)	512

6.5. Overhead Packets in HP-MAC

In WSN, the overhead of packets is not neglectable because the packet data size is relatively small [23]. In UAV-WSN system, the nodes communicate and transmit their data to the UAV (many-to-one). Hence, the RTS/CTS handshake is not suitable to implement in the UAV-WSN system. This is because the RTS and CTS packets are required to exchange for each transmission. The HP-MAC can reduce the number of packets. The UAV broadcasts the first and second beacon only one time to all of the nodes inside of communication range. On the other hand, each node transmits their data packet to the UAV based on their time slot. Therefore, the number of packet transmission is reduced.

7. Performance Evaluation

7.1. Simulation Setup

To evaluate the performance of the proposed MAC protocol, we used Matlab 2017b. The simulation parameters are listed in Table 2. The number of nodes is the key parameter for determining the performance of the proposed protocol. Moreover, Figure. 8 indicates the simulation model of the proposed systems in which UAV is circled with red color and nodes are scattered over the area of the network.

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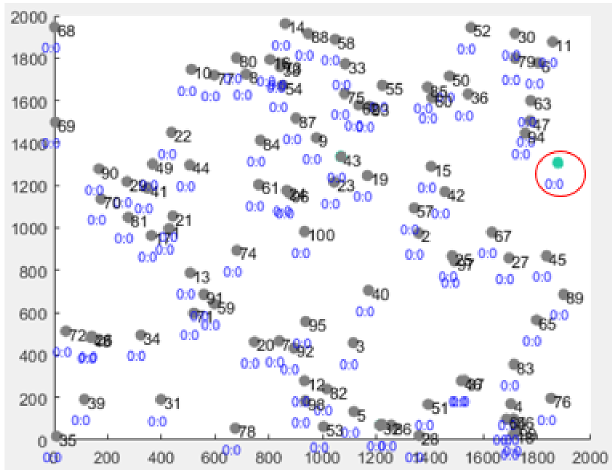

Figure 8. Simulation model of the proposed systems

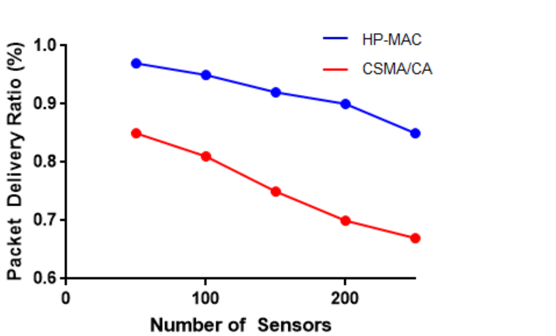

Figure 9. Packet delivery ratio with different number of nodes

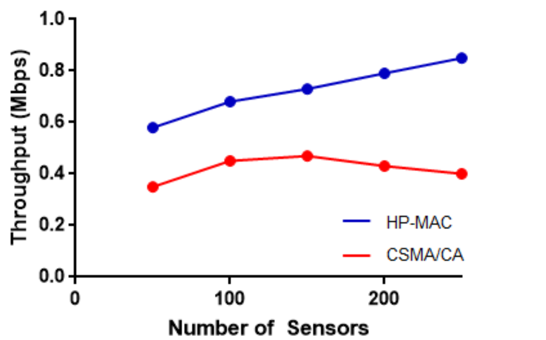

Figure 10. Throughput with different number of nodes

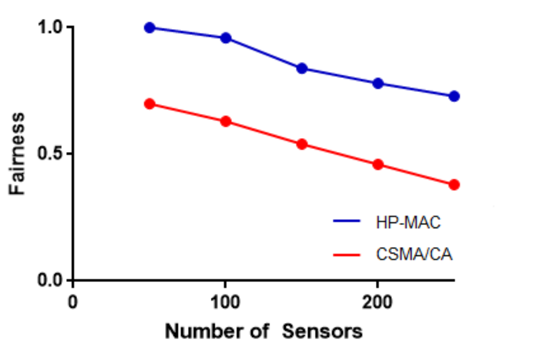

Figure 11. Fairness with different number of nodes

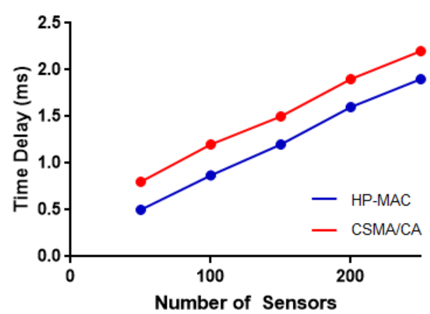

Figure 12. Time delay with different number of nodes

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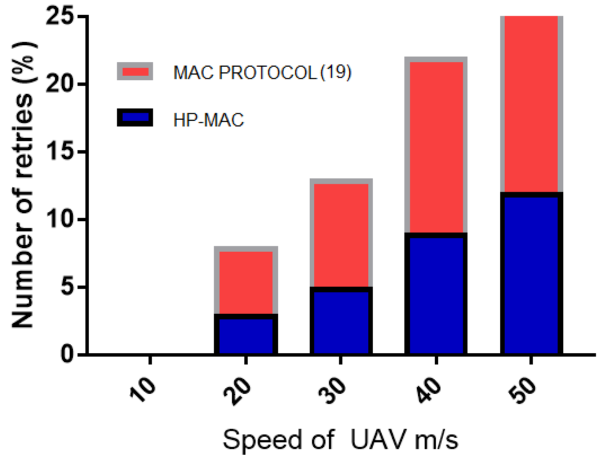

Figure 13. Number of retries against the speed of UAV

7.2. Simulation Results

Figure. 9 depicts the simulation result of the HP-MAC protocol regarding PDR, compared by different numbers of nodes. The number of nodes used for this simulation range from 50 to 250 nodes. According to the figure, the PDR of the HP-MAC protocol is higher than that of the IEEE 802.11 CSMA/CA MAC protocol, owing to the use of different $DIFS$ values and the time-slot-allocation scheme. Each node belonging to the highest priority group has a smaller $DIFS$ range. Hence, those nodes only need a short time to identify the condition of the UAV channel, and the failures are reduced. However, as the number of nodes increase, the PDR reduces, because a high number of contending nodes are attempting to access the UAV channel.

Figure. 10 shows the simulated throughput of the HP-MAC protocol with various numbers of nodes. The throughput of the HP-MAC protocol increases with the number of nodes. Alternatively, the throughput of the IEEE 802.11 CSMA/CA MAC protocol was lower than that of the HP-MAC protocol, because the HP-MAC uses the prioritization mechanism to reduce packet collisions, even when the network becomes denser.

Figure. 11 presents the fairness of the HP-MAC protocol for various numbers of nodes. The fairness of both MAC protocols reduces when the number of nodes increases, owing to the number of contending nodes trying to transmit. However, the fairness of HP-MAC protocol can be maintained, because all nodes can transmit their data even for the most rear nodes inside of UAV's communication range. The HP-MAC protocol surpasses the IEEE 802.11 CSMA/CA MAC protocol in terms of fairness, owing to the different $DIFS$ values for each group and time-slot allocation scheme.

The average time delay is also considered as a metric for evaluating the performance of the proposed MAC protocol. Figure. 12 illustrates the average time delay of the HP-MAC protocol compared to that of the IEEE 802.11 CSMA/CA MAC protocol. The results show that the period required for each node to transmit data until successful receipt by the UAV increases with the number of nodes. However, the average time delay can be reduced because of the time interval scheme, which divides the UAV's coverage area based on the number of nodes contending to access the UAV channel.

The HP-MAC protocol also compared with the MAC protocol that proposed by [19] in terms of the number of retries. To analyzed it, we used a different speed of UAV and each node transmitted five packets of data. As depicted in Figure. 13, the number of retries of both MAC protocol is 0% when the speed of UAV is 10m/s. It is observable that by increasing the speed of UAV, the number of retries also increased. This is happened due to the limited time of each node to communicate with the UAV. Therefore, the nodes

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experienced with the noise and collisions among contended nodes. However, the HP-MAC protocol has less number of retries as compared with the proposed MAC protocol in [19].

8. Conclusion

This paper presented a novel MAC protocol designed for UAV-WSN data gathering named HP-MAC protocol. The HP-MAC protocol is a hybrid MAC protocol that based on the IEEE 802.11 CSMA/CA MAC protocol and TDMA protocol. The superframe of HP-MAC protocol is divided to four periods which are first beacon period to inform the presence of UAV, registration period that used for unregistered node to send their REG frame to the UAV, second beacon period for UAV to broadcast the schedule information for all registered nodes, and gathering period in which each registered node transmits the data according to their time slot schedule.

Different $DIFS$ value is used during the registration period to maintain the fairness of each node to access the UAV channel. The $DIFS$ value is assigned to each node according to their priority based on their location inside of UAV's communication range. Furthermore, each node that located in the same priority level is grouped into one group. The architecture of UAV-WSN for data gathering system is also introduced in this paper. The communication between UAV and cloud server through cellular links bring the reliable communication. This architecture can tackle the limited communication range of ground control station to transmit the flight path data to the UAV. The proposed MAC protocol was tested and evaluated, showing that it achieves fairness for data gathering in UAV-WSN systems. The network performance, in terms of throughput, PDR, and average time delay is better than that of the existing MAC protocol. As for the future work, the multi-UAV scenario is considered such that the interference between the UAVs can be investigated. The optimal flight path design as well as clustering mechanism also considered as future work.

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