IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received March 25, 2021, accepted April 4, 2021, date of publication April 12, 2021, date of current version April 20, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3072375

Priority-Aware Fast MAC Protocol for UAV-Assisted Industrial IoT Systems

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This work was supported in part by the National Research Foundation of Korea (NRF) Grant by the Korean Government through Ministry of Science and ICT (MSIT) under Grant 2019R1F1A1060501.

ABSTRACT Many hazardous industrial incidents can occur due to the inadequate and inefficient monitoring of the offshore plants. Manual inspections of the offshore plants on a regular basis is not only time consuming but also dangerous regarding to human safety. For considering the safety measurement and alleviating the burden of the manual inspection, unmanned aerial vehicles (UAVs) can be effectively utilized to collect data from the remote industrial environment. In an industrial scenario, less delay is required for emergency packets and high throughput is needed for monitoring packets. This paper proposes a priority-aware fast MAC (PF-MAC) protocol for UAV-assisted industrial Internet-of-things (IIoT) systems, ensuring fast and robust data delivery. At first, the IoT devices under the UAV communication range transmit a reservation frame to the UAV to catch transmission opportunities using CSMA/CA. The devices utilize static traffic priority and a novel adaptive backoff mechanism during CSMA/CA. After receiving the reservation frames from the IoT devices, the UAV calculates the dynamic device priority based on their static traffic priority, communication duration, sampling frequency, and remaining energy. Then, time slot is assigned by the UAV to each device for data transmission. To ensure fairness, if a device fails in contention during the CSMA/CA period, the static traffic priority is raised in the next retransmission. There is no prior work in the literature that considers both the traffic priority and the device priority to ensure Quality of Service in IIoT and related systems. According to our performance study, the proposed PF-MAC outperforms the conventional protocols in terms of delay and throughput.

INDEX TERMS Internet of Things, unmanned aerial vehicle, medium access control, traffic priority, device priority, delay, quality of service.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have gained enormous attention from researcher communities and commercial industries [1]. Recently, UAVs are deployed for a numerous applications for example surveillance [2], search and recovery [3], fire and radiation monitoring [4], [5], sports and entertainment [6], and so on. On the other hand, developments in wireless and mobile networking technology have affected every aspect of our everyday lives. The demand for large bandwidth as well as the capability to connect always and everywhere is increasing rapidly.

Conventional networking systems have been expanded to every corner, relying on infrastructure-dependent networks. Due to the lack of mobility, however, they cannot be deployed in remote scenarios. In addition, their implementation cost is very high, which makes them impractical for remote and urgent situations. This situation motivated the implementation of non-traditional communication networks such as Loon project [7] and the drone project of Facebook [8]. Due to their capacity to navigate, easy deployment, ability of hovering, and practical cost, small-size UAVs have gained more attention. UAVs have recently been considered to act as wireless relays to cellular network coverage [9] and satellite communications [10]. In particular, due to Line-of-Sight (LoS) access, less signal blockage, and less shadowing effects, UAVs can facilitate greater communication links between air and land station.

Modern network technologies such as space–air–ground integrated network (SAGIN) have recently created appeal

The associate editor coordinating the review of this manuscript and approving it for publication was Byung-Seo Kim.

to both academia and industry. Many organizations such as Global Information Grid [11], Oneweb [12], and SpaceX [13] began their SAGIN ventures in recent years. SAGIN can be used in many functional areas such as earth observation and mapping, intelligent transport [14], and disaster rescue [15] due to the inherent benefits of broad coverage, high throughput, and good resilience. Satellites, on the other hand, are able to provide consistent coverage to ocean, rural, and mountain areas. UAV-based networks can expand bandwidth for large areas with high service requirements, while Internet of Things (IoT) devices located on ground can provide the connectivity with high data rate. In the next few years, SAGIN will carry many facilities and resources from space to the earth.

Currently, we are experiencing a steady and continuous penetration of IoT concepts into the industrial domain, called industrial IoT (IIoT) or Industry 4.0. Every industry is trying to enjoy the benefits of the industrial revolution by adopting IIoT features. Oil and gas industries are also not an exception in this aspect. However, the processing of offshore oil and gas (O&G) is highly dynamic and precarious. O&G companies find it difficult to obtain a timely and accurate image of their ongoing output due to the remoteness and isolation of offshore rigs. Insufficient monitoring capacity may lead to catastrophic explosions that take a heavy toll on the environment, the lives of employees, and the reputation of companies. Tragic incidents such as the Exxon Valdez [16] and Deepwater Horizon oil spills [17] are examples.

O&G manufacturing requires day-and-night observance of various equipment (pipes, valves, wellheads, and tanks) and parameters (temperature, vibration, friction, flow rates, corrosion, and gas leaks) to maximize efficiency and protection. However, conventional communication methods for linking a large number of different assets on offshore drilling platforms are limited, costly, or cumbersome. Wired technology like supervisory control and data acquisition (SCADA), which is suitable for real-time control management activities, is not equipped for data acquisition from remote locations. In the center of the ocean, cellular connectivity is most possibly absent. In addition, setting up mesh networks is also a difficult effort due to the enormous scale, complexity, and dense structure of oilrigs. The emerging use of UAVs in remote monitoring applications makes it a suitable candidate for O&G industries offshore.

Several UAV-based air–ground IoT systems have already been proposed in the literature, wherein UAV is placed as a mobile base station (BS) [18]. In this manner, UAV-based networks eliminate complex routing schemes and greatly improve data collection capabilities. Analyzing and developing a UAV-based data acquisition system is highly difficult due to the mobility and complex nature of the UAV. Devices can reach UAV when the UAV is near to them because of the mobility of UAVs, and the devices lose their wireless link connection if the UAV flies outside of their coverage. Therefore, limited communication time is one of the challenges while developing a UAV–IoT communication system.

At most times, UAVs are equipped with directional antennas and the formation of coverage in ground is circular. The ground devices can access UAVs at different times. Therefore, fair access to the channel by all ground devices is necessarily important. In addition, a priority-based channel access mechanism may be needed for Quality of Service (QoS) in IoT networks. Furthermore, energy efficiency has become a major challenge for remotely located IoT systems. Such battery-constrained devices can need energy-efficient mechanisms for channel access and transmission control. Therefore, selecting and developing a medium access control (MAC) protocol for data transmissions to handle the challenges is extremely demanding.

Contention-based MAC protocols are popular owing to their comprehensibility, adaptability, and less overhead characteristics. Devices have the ability, without undue overhead, to dynamically enter or quit the network. However, collisions increase when the number of devices is high. However, a time-division multiple-access (TDMA)-based channel access mechanism can solve this problem. The TDMA system is divided into time slots, and each device can only transmit within its own allocated slots. [19]. The key primary disadvantage of TDMA is that if there are a few numbers of IoT devices, the transmission slot can be wasted. Therefore, to construct a scalable and versatile communication system for UAV-IoT communication network, only the contention-based or contention-free mechanism cannot be suitable.

This paper proposes a priority-aware fast MAC (PF-MAC) protocol for UAV-assisted IIoT systems, ensuring fast and robust data delivery. The hybrid PF-MAC protocol integrates the benefits of both contention-based and contention-free protocols for a remote IoT scenario.

This paper's main contributions are as follows:

1) A priority-aware fast MAC (PF-MAC) protocol is proposed for UAV-assisted remotely located IIoT systems with QoS requirements, which is a hybrid MAC protocol incorporated with the CSMA/CA and TDMA mechanisms. The UAV acts to gather data from IoT devices as a wireless relay.
2) We introduce an incremental contention priority (ICP) scheme wherein, if an IoT device fails in contention, its static priority is increased by one in the next retransmission. It ensures the access fairness of devices and prevents the low-priority devices from starvation.
3) We adopt the ABO mechanism wherein the backoff period is calculated according to the collision rate with respect to the maximum retransmission of the channel. It helps to reduce the delay significantly.
4) We design the dynamic priority of the devices based on the static traffic priority, communication duration, sampling rate, and remaining energy. This helps UAV

to allot a timeslot for the devices depending on the significance and emergence of the data frame.
5) Our performance evaluation shows that, the PF-MAC beats the conventional protocols in terms of throughput, and average delay.

The paper is organized in the following way. In Section II, the related works are reviewed. In Section III, the system model of our study is introduced. Subsequently, the proposed PF-MAC protocol is presented in detail in Section IV. In Section V, the proposed PF-MAC is analyzed in terms of major performance metrics. In Section VI, the performance of PF-MAC evaluated via extensive simulation and compared to that of conventional schemes. In Section VII, the conclusion of the paper is drawn.

II. RELATED WORKS

This section presents the related works on UAV-based IoT communication network and the problems of existing studies, which form the motivation of our work.

Several studies have considered UAV-based IoT networks. Different types of gateway selection algorithms and cloud-based stability-control mechanisms for flying ad-hoc networks (FANETs) is presented in [20], where FANET and its protocol architectures are also discussed. To provide seamless network coverage in dense urban areas, an energy-efficient UAV deployment strategy is presented in [21], which optimizes both UAV deployment and UAV recharging strategy using particle swarm optimization (PSO). The efficient path planning of UAVs for data gathering from IoT devices is a widely popular research area. A previous study [22] investigated the timely delivery of information using UAVs as relays by optimizing UAV flight trajectory. Using a bio-inspired algorithm, UAV path planning is developed in [23]. A joint optimization technique for UAV trajectory and resource allocation is considered in [24]. UAV is an essential element for creating a future smart city. In [25], a smart city architecture is proposed where UAVs form a 5G hierarchical IoT network in the sky, linking to a number of BSs on the ground. An architecture is presented in [26] considering UAV-aided IoT for air quality sensing in smart cities. These studies mainly focused on network architecture and UAV trajectory optimization. Only few of them have worked on the UAV–IoT data communication protocol. However, it is very important for efficient data gathering from IoT devices.

The integration of UAVs with terrestrial and satellite networks has shown a new research path to the industries and researchers. In [27], a comprehensive survey on space–air–ground-integrated (SAGIN) network is presented that covers design of network, resource allocation, and optimization. In [28], a SAGIN-based scheduling approach for task offloading is presented where IoT devices can offload their tasks to closer UAVs. Based on the task's importance and weight, the UAV decides whether to transfer the task to a nearby BS or satellite. In [29], a methodology for resource allocation by optimizing the hovering altitude of UAV and controlling the power of ground users in SAGIN environment is discussed.

Recently, machine learning-based techniques are becoming famous for its adaptability with the dynamic environment. A Q-learning-based resource allocation algorithm is presented in [30] by handling the channel collision problem in dense wireless local area networks. In order to reduce energy consumption, a Q-learning-based MAC protocol is proposed in [31] which is called greenMAC. Energy consumption decreases by managing the channel collisions properly, which also enhances system reliability.

Some studies have recently focused on the MAC protocol regarding the communication process between the UAV and ground IoT devices. A comprehensive survey of MAC protocols for UAV-based IoT is presented in [32]. A UAV-based IoT data collection system for aggressive and inaccessible areas was proposed by Lin *et al.* [33]. The key aim of their analysis was to improve the entire system's energy efficiency. For data collection, slotted ALOHA-based approach is followed. However, considerable energy is wasted due to collided slots, empty slots, and overhearing. CSMA/CA-based MAC protocol for a UAV-based IoT network was explored by the authors of [34]. For each device in each cluster, the size of the contention window is modified according to the communication period between the IoT and the UAVs. The CW size must be periodically measured and modified, adding to the system's consumption of energy and time.

In [35], a TDMA-based workflow model is introduced where UAVs work both as a data collector and wireless power transferor to the ground IoT devices. However, due to the usage of the TDMA for modeling the multi-workflow, high synchronization overhead is predicted. Our PF-MAC can handle these problems by utilizing both contention-based and contention-free mechanisms. Only successful devices in contention use the timeslots for data transmission during a contention-free process. Hence, no energy is wasted due to empty slots. We used a predefined CW size for each IoT device according to its static priority. Therefore, there is no need of frequent calculation of the CW size. Moreover, the integration of contention-based and contention-free mechanisms helps to reduce the large synchronization overhead, which is a major problem in TDMA mechanism if we use it for the entire process. Our proposed study will be presented exhaustively in Section IV.

III. SYSTEM MODEL

We consider an industrial offshore environment such as oil/gas rig monitoring, situated far away from the main industry that is difficult and dangerous for human access on a daily basis. It is quite impossible to obtain cellular connectivity in the middle of the ocean. The remote location and isolation of offshore rigs make it difficult to obtain a proper estimation of the ongoing output for O&G companies. O&G businesses rely on manual data reading and visual inspection to track large parts of their processes, equipment and facilities owing to the lack of a cost-effective and scalable communication

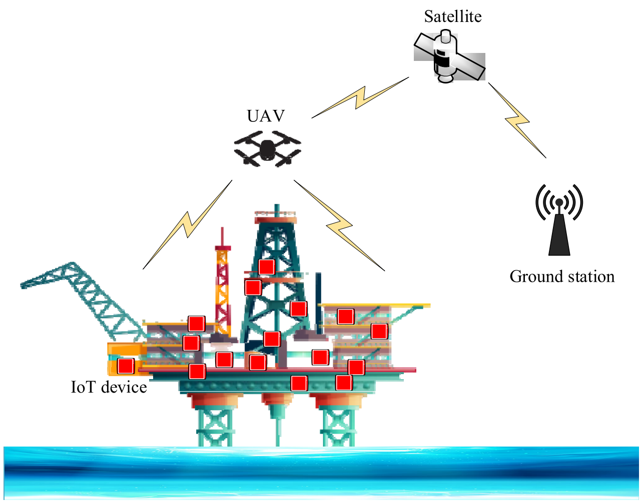

FIGURE 1. An application scenario of data gathering in a UAV-assisted industrial IoT system.

solution. This is highly inefficient, error-prone, and dangerous to field workers.

In this paper, a SAGIN-based scenario is considered wherein a UAV manages data gathering from IoT devices and relay data to the distant ground station with the help of satellites. However, UAVs are not considered to manage the internal process of the industry; UAVs are only used to inspect, monitor, and gather data from numerous pipes, valves, wellheads, and tanks, which are dangerous and hazardous for human access.

Fig. 1 shows an application scenario of data gathering in a UAV-assisted industrial IoT system. A low-earth-orbit (LEO) satellite, a multi-rotor UAV, and N number of IoT devices are considered. Let $\varphi = \{m_1, m_2, \ldots.m_N\}$ denote the set of the IoT devices. The limited-capability IoT devices are spread over the given area and the monitored data are collected continuously. To support as many IoT devices as possible, the UAV is dispatched to the specified area on a regular basis. All IoT devices are fixed in their position, and we consider no mobility of IoT devices. The flight path and time of a UAV are preplanned before starting its mission by using a central controller system. It is assumed that UAV will fly at a fixed height H ($H > 0$). The UAV's location u_l at given time t is $\left(x_{uav,t}, y_{uav,t}, z_{uav,t}\right)$. The IoT devices location m_n is given by (x_i, y_i, z_i). The distance $d(u_l, m_n)$ between UAV and IoT devices is computed as follows:

$$d(u_l, m_n) = \sqrt{(x_i - x_{uav,t})^2 + (y_i - y_{uav,t})^2 + (z_i - z_{uav,t})^2}. \quad i = 1, 2, \ldots.N, \quad t = 1, 2, \ldots N \tag{1}$$

We assume that, for every IoT device, data packet arrival process is considered as a Poisson arrival process and packet arrival rate is defined as λ. As we consider a controlled scenario, we assume that packet arrival rate for all IoT devices are the same. In each device, a packet is buffered as long as it gets the opportunity for transmission and completes the transmission. Before the transmission of data, if a new packet arrives, the new packet will replace the former packet. It ensures that there is always only one packet in the buffer of each device.

We have assumed an offshore industrial plant situated in the middle of the ocean. There is no significant obstacles in the area of interest except the industrial plant itself. Signal propagation for air-to-ground over the sea area is the same as the open space with different surface reflectivity and roughness. Propagation over sea can also be hampered by the height of waves, which causes anomalous index of refraction variation with heights and results in propagation loss less than that of free space [36]. By considering these facts, we have measured the propagation loss PL with two-ray path loss model as in [37]. It can be calculated with the following equation in Decibels:

$$PL_{two-ray} = -10\log_{10}\left\{(\frac{\lambda}{4\pi d})^2\left[2\sin\left(\frac{2\pi h_T h_R}{\lambda d}\right)\right]^2\right\}, \tag{2}$$

where λ is the wavelength in meters, d represents the propagation distance in meters, and h_T and h_R are the height of transmitter and receiver, respectively. However, the path loss totally depends on the area of interest. Our framework can be adjusted into a different path loss model under different environmental conditions as well.

TABLE 1 shows the notations used in the paper.

A. UAV, IoT DEVICES, AND ANTENNA TYPE

Owing to its flexibility and easy mobility, rotary-wing UAVs are well suited for inspection applications. For an extended duration, rotary-wing UAVs may conduct precision maneuvering and hold a visual on a single target. The greatest value of rotary-wing UAVs is their ability to vertically take off and land. In our scenario, both UAV and IoT devices are equipped with directional antenna (phased array) [38], [39], [40], a software-defined radio, and a global positioning system (GPS). Software-defined radio allows the IoT devices and the UAV to work on different channels. By concentrating on not only transmitting energy in one direction but also on decreasing interference and fading, directional antennas promote communication efficiency. The use of directional antennas has other benefits such as lower latency, higher spatial reuse, and high quality of links that provide higher throughput. We have assumed that UAV is capable of full-duplex communication. Therefore, it can collect the data from IoT devices in downlink and transfer the data to the control station via satellite in uplink simultaneously. The UAV and IoT devices exchange their location information via control packets. Hence, the UAV and the IoT devices can direct their beams towards each other during the communication process, which can reduce the direction alignment problem significantly. The phased array based directional antennas can electronically steered to point in different directions without moving the antennas physically.

TABLE 1. Notations used in this paper.

Notation	Description
H	UAV altitude
u_v	UAV velocity/speed
u_l	UAV location
m_n	IoT device location
C_d	Data channel
C_c	Control channel
L_r	Reservation frame
L_d	Data frame
CW	Contention window
P_s	Static traffic priority
P_d	Dynamic device priority
t_e	Emergency traffic
t_m	Monitoring traffic
P_t	Total device priority
σ	Static traffic priority factor
b_n	Notification beacon message
b_a	Announcement beacon message
BO	Backoff
ICP	Incremental contention priority
ABO	Adaptive backoff
RP	Reservation period
NP	Notification period
AP	Announcement period
DCP	Data collection period
t_{slot}	Time slot
c_p	Communication duration priority factor
v_c	Communication priority value
s_p	Sampling factor
RmE	Remaining energy factor
CW_{lmax}	Large CW size maximum
CW_{lmin}	Large CW size minimum
CW_{smax}	Small CW size maximum
CW_{smin}	Small CW size minimum

B. MULTICHANNEL STRUCTURE

As shown in Fig. 2, the use of two channels is conducted: a control channel C_c and a data channel C_d. The control channel C_c is dedicated for exchanging control information such as broadcasting beacons, exchange of control packets and acknowledgment between the UAV and the IoT devices. On the contrary, remaining communication is performed using data channel C_d. The UAV flies over the target area and starts to transmit beacon, b_n via control channel C_c. The IoT devices receive the beacon in control channel C_c and then send control packets (reservation frame, L_r) to the UAV. Upon reception of the control packets, the UAV calculates the dynamic device priority and transmits another beacon b_a to the IoT devices, including the data transmission scheduling and synchronization information. The UAV switches to the data channel C_d immediately after sending the beacon b_a. The beacon b_a carries the data channel information. After receiving beacon b_a, the IoT devices switch to the data channel C_d immediately and wait for their designated transmission slot, t_{slot}. After transferring the data frame L_d to the UAV, the IoT devices switch back to control channel C_c and wait for the next beacon period. The CC2420 and the more sophisticated CC2500, with a channel switching time of only 300 μs and 90 μs, respectively, are typical transceivers for short-range wireless communication [41]. However, the channel-switching mechanism is not focused in this paper.

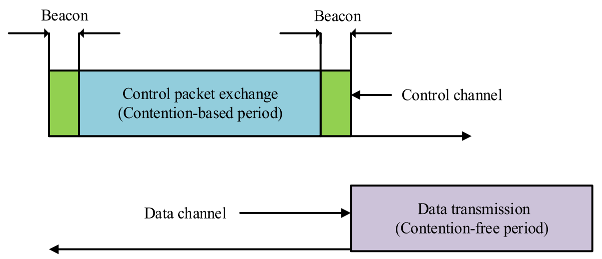

FIGURE 2. Channel switching.

C. PRIORITY OF IoT DEVICES

In this subsection, we describe the priority outline of IoT devices based on static traffic priority and dynamic device priority in detail.

1) STATIC TRAFFIC PRIORITY P_s

IoT devices are heterogeneous in nature. The nodes' static priority depends on the criticality of the traffic generated by the node. It is assumed that every IoT device can produce two types of traffic: emergency traffic t_e and monitoring traffic t_m. Based on its static traffic priority P_s, the traffics are prioritized. We can denote the static traffic priority factor with σ.

a: EMERGENCY TRAFFIC t_e

This refers to critical and urgent traffic. These packets need to be sent to the UAV as soon as possible. However, it is assumed that the generation of emergency traffic t_e does not occur frequently and is only generated when the system does not perform in a normal manner and something goes wrong internally. This type of situation is life threatening and hazardous to humankind. A few circumstances when emergency traffic can be generated are fire alarm, oil/gas leakage, and high air-pollution level. For emergency traffic t_e the value of σ is 1.

b: MONITORING TRAFFIC t_m

Monitoring traffics t_m are generated regularly for monitoring purposes and do not have any deadline bound. Considering the characteristics of the monitoring traffic, the static traffic priority factor for monitoring traffic t_m is $\sigma = 0$; this is because it does not have any urgency of transmission.

2) DYNAMIC DEVICE PRIORITY P_d

Only static traffic priority, P_s of the device cannot fully and accurately determine the priority of the IoT devices where QoS requirements are much necessary. Due to UAV mobility and remoteness of the system environment, other few criteria play a great role in deciding the total priority P_t of an IoT device. Therefore, we design the dynamic device priority P_d based on static traffic priority P_s and some other factors such as communication duration, sampling rate, and remaining energy. The details discussion of dynamic device priority P_d is given below.

a: COMMUNICATION DURATION PRIORITY FACTOR c_p

It is very important for UAV to collect all the data from IoT devices during its single flight period. When the UAV is within the contact range of IoT devices, the IoT devices get the opportunity to connect with the UAV. Therefore, each IoT device has limited communication time due to the mobility of UAV. If the UAV is within the communication range of IoT devices, the IoT devices are also within the scope of communications of the UAV. If the communication range of UAV is R_u, the velocity of the UAV is u_v. The communication duration, T_i between the UAV and the IoT devices can be measured [34] as:

$$T_i = \frac{2R_u \cos\theta}{u_v}, \quad i = 1, 2, \ldots .N, \tag{3}$$

where $\theta_i \in (0, \pi/2)$ denotes the device positions based on created angle between UAV and IoT device and can be computed as $\theta_i = \arcsin(y_i/R_u)$.

The higher the communication duration is, the lower its priority is, and vice versa. However, to make the calculation easier, we assign communication priority value, $v_c = 1, 2, \ldots K$ to the values of T_i in descending order. If the communication time is the lowest, it will get the highest communication priority value. On the contrary, if the communication time is the highest, then it will get the lowest communication priority value.

b: SAMPLING FACTOR s_p

The weight of the traffic is measured by the sampling factor, s_p, of the IoT devices. The level of the sampling frequency variates from the regular sampling frequency indicates the importance of the IoT device-generated data frames. If the value of s_p is high, the priority of the device is also high. For example, the temperature variates from regular values extend when the internal process is not in the normal condition. The sampling factor, s_p, can be defined as

$$s_p = \left| \frac{(s_u - s)^2 - (s - s_l)^2}{(|s_u| + |s_l|)^2} \right|, \tag{4}$$

where s, s_u, and s_l denote the sampling frequency of the device, standard sampling frequency upper, and lower bounds respectively.

c: REMAINING ENERGY FACTOR RmE_i

We assume that each IoT device is battery-powered and contains a certain amount of energy depleted over time. We also assume that after reaching a certain threshold energy level, the device is considered unable to communicate with the UAV. The device will therefore not complete the transmission of data. The remaining energy can be calculated as follows:

$$RmE_i = E_{present,i} - E_{transmission,i}, \tag{5}$$

where $E_{present,i}$ and $E_{transmission,i}$ the present level of energy and energy consumed during data transmission by device i respectively, are represented.

3) TOTAL DEVICE PRIORITY P_t

In this section, the calculation of total device priority based on the above-discussed criteria will be discussed. The static traffic priority factor σ and sampling rate factor s_p are two relatively simple assessment criteria of the priority correlated with the device itself. These two factors are related to the IoT device itself rather than the communication process. The static traffic priority factor, σ, communication duration factor, c_p and sampling rate factor, s_p and their total aggregated amount are utilized as follows to measure the basic level of priority of the IoT devices:

$$P_{base,i} = floor(c_{p,i} + \sigma_i + s_{p,i}), \quad i = 1, 2, \ldots .N, \tag{6}$$

Remaining energy factor, RmE_i, is the most important factor in the entire priority system. It is because, if the IoT device does not have a minimum remaining energy, it cannot execute other tasks. Moreover, if RmE_i of the IoT device is less than the threshold level, the communication between UAV and the IoT device will not take place. Therefore, we consider that if RmE_i is less than the threshold level, the total device priority becomes zero. By considering RmE_i, we can obtain the total dynamic priority of device, $P_{t,i}$, as follows:

$$P_{t,i} = \begin{cases} P_{base,i} & if\,(RmE_i > RmE_{th,i}) \\ 0 & otherwise, \end{cases} \quad i = 1, 2, \ldots .N. \tag{7}$$

IV. PRIORITY-AWARE FAST MAC

This section shows the frame structure of PF-MAC and the detailed communication process between the IoT devices and the UAV are discussed. In our scenario, there exists three communication processes: communication between the IoT devices and the UAV, communication between the UAV and the satellite, and communication between the satellite and the ground terminal. We herein focus only on communication between the IoT devices and the UAV. The entire process of communication is divided into four parts: notification period (NP), reservation period (RP), announcement period (AP) and data collection period (DCP).

A. FRAME STRUCTURE OF PF-MAC

Fig. 3 shows the frame structure of the proposed PF-MAC. The notification beacon message b_n includes the packet type, UAV ID, GPS position of the UAV at a particular time, and

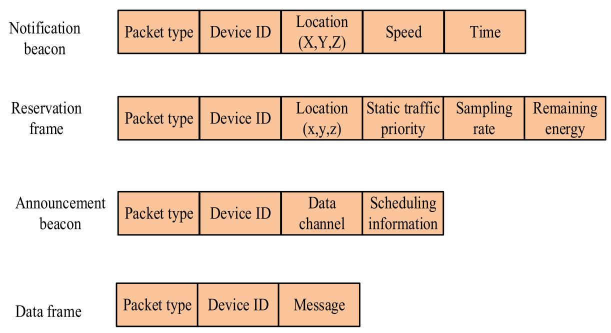

FIGURE 3. Frame structure of PF-MAC.

UAV speed. The reservation frame L_r comprises of the type of the packet, IoT device ID, GPS location of the IoT device, static traffic priority indicator, sampling rate of the generated data, and remaining energy of the device. The announcement beacon message b_a, generated by the UAV after receiving the reservation frame, includes the packet type, device ID, data channel information, and scheduling information. Finally, upon receiving the announcement beacon message, the IoT devices transmit the data frame L_d that includes information on the packet type, IoT device ID, and the message itself.

B. NOTIFICATION PERIOD (NP)

After arriving to the designated location, the UAV broadcasts a notification beacon message b_n to notify its presence to all K number of devices in the field of UAV coverage. After receiving notification beacon b_n message, the devices that have data to send will wake up. To conserve energy, the devices with no data will go to sleep mode. The notification beacon message b_n includes UAV speed u_v and location u_l.

C. RESERVATION PERIOD (RP)

This period is contention-based period and follows CSMA/CA mechanism.

1) IOT DEVICES IN RP

After receiving notification beacon message b_n, the active devices will contend with each other for reservation opportunity using the basic access mechanism of CSMA/CA. Two contention windows CW are selected based on the static traffic priority P_s of the IoT devices. The IoT devices whose $\sigma = 1$ will use small CW size, allowing them to access the channel within a shorter time. Therefore, they can transfer their reservation frame, L_r with lower delay. The devices with $\sigma = 0$ are not delay-sensitive. Hence, they utilize larger CW so that they obtain channel access after the higher-priority devices. The devices within the UAV coverage area, which has data to send, will send reservation frame L_r to the UAV. The devices with no data to send will switch to sleep mode. The contention becomes successful when only one device sends the data at a time. A collision happens if more than one device sends reservation frame, L_r within the same time interval. After collision, if the UAV is still under the communication range of the IoT devices, following an ABO (described in Subsection IV-C.3) mechanism, reservation frame L_r is retransmitted to the UAV for a limited number of times. If the transmission is successful, the IoT device will receive an acknowledgment ACK message from UAV and hence stops retransmitting L_r and waits for the AP duration. If the device does not receive any ACK from the UAV and retransmission time is exceeded, then the frame is dropped. Algorithm 1 shows the reservation period communication from IoT side.

Algorithm 1 Reservation Period – IoT Side

Input: Notification beacon message, b_n, reservation frame, L_r
Output: Successful transmission of reservation frame, L_r

```
1: for each IoT device i ∈ N
2:     if b_n is received in C_c
3:         try to transmit L_r in m-th transmission
           where m ≤ 7
4:         check the static traffic priority factor, σ
5:         if (σ == 0)
6:             utilize large CW range
7:         else
8:             utilize small CW range
9:         end if
10:        if (L_r fails in contention in m-th transmission)
           where m ≤ 7
11:            calculate BO using (8) and perform BO
12:            in (m+1)-th transmission, increment σ
               by 1
13:            if (successful)
14:                σ returns to original value
15:            else
16:                go to step 11
17:            end if
18:        else
19:            receive ACK
20:        end if
21:    end if
22: end for
```

2) UAV IN RP

After receiving the reservation frame from the IoT devices, UAV performs a prioritization process, discussed in Subsection III-C.2. Algorithm 2 demonstrates the reservation period mechanism from UAV side.

3) ADAPTIVE BACKOFF (ABO) MECHANISM

In the conventional IEEE standard 802.11 CSMA/CA mechanism, if a packet transmission fails, to determine the BO duration, the CW size gets doubled and a random backoff value is chosen. It only considers packet transmission failure. Other parameters such as current channel status and collision rate are ignored. Our ABO considers the collision rate with respect to the maximum number of retransmission of the

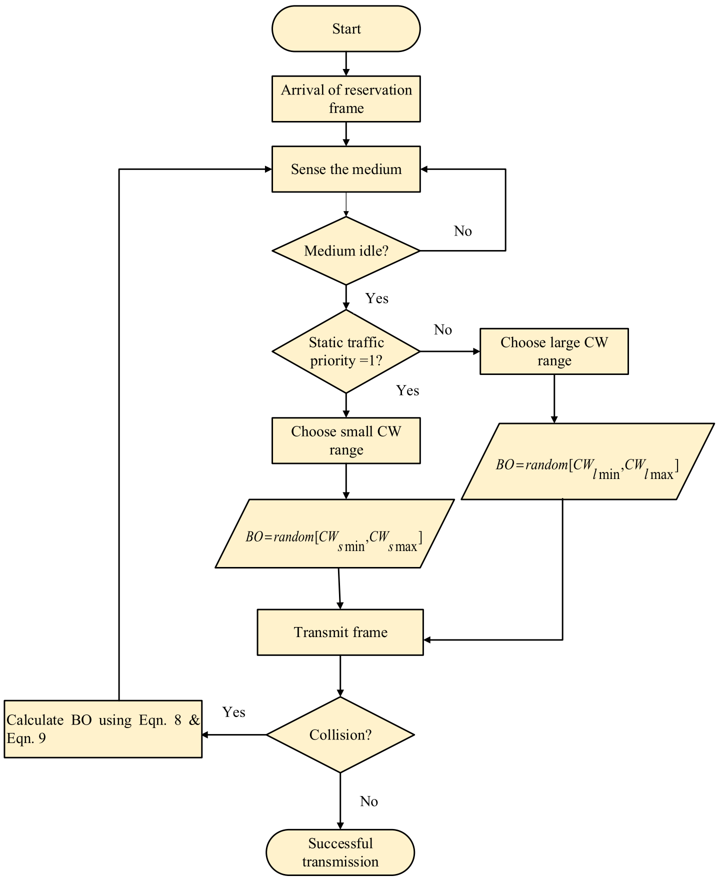

FIGURE 4. Flowchart of the ABO mechanism.

Algorithm 2 Reservation Period – UAV Side

```
Input: Reservation frame L_r
Output: TDMA scheduling information
D_list ← {}
C_list ← {}
K = number of IoT devices, v_c = K + 1
for each IoT device i ∈ K
    calculate c_p using (3)
    insert (C_list [i])
end for
sort_ascending (C_list)
for each IoT device i ∈ K
    C_list [i] = v_c − 1
    calculate s_p using (4)
    calculate RmE using (5)
    if (RmE_i > RmE_th,i)
        calculate P_t using (6)
        insert (D_list[i])
    else
        P_t = 0
    end if
end for
sort_descending (D_list)
assign t_slot to D_list
```

packet in the channel. In comparison to the traditional backoff mechanism where the CW size always gets increased in the same way without considering the current condition of the channel, our ABO adjusts the BO length according to the medium collision rate.

Fig. 4 shows the flowchart of the ABO mechanism. The primary backoff period BO_0 is set to CW_{min}. The next BO is determined with the following equation after a packet is dropped due to collisions in the channel:

$$BO_j = \Omega_j \times (2^{CW_{\max}} - 1) \times \alpha, \tag{8}$$

where Ω_j presents the collision rate in the channel in the j-th attempt. CW_{max} is the maximum value of CW, α is a random number, the value of which lies in [0, 1].

The collision rate Ω_j can be calculated with the number of transmission failures and the maximum retransmission limit after each transmission of reservation frame. Hence, collision rate Ω_j in respect to the maximum retransmissions can be calculated using the following equation:

$$\Omega_j = \frac{\Im_{\max} - \psi_j}{\Im_{\max}}, \tag{9}$$

where ψ_j presents the number of collisions in the channel in the j-th attempt and $\Im_{\max}$ represents the maximum number of retransmissions ($\Im_{\max} = 7$).

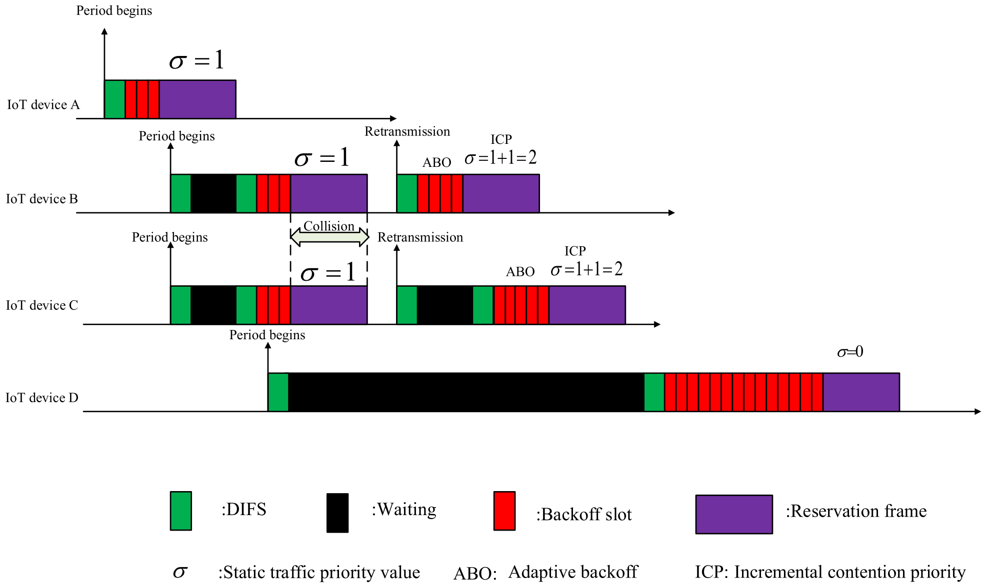

FIGURE 5. ABO mechanism and ICP model.

The parameter α in (8) is effectively used to avoid collisions between the same static priority devices with similar σ value. For example: if device A and device B have the same static priority and both have encountered the similar number of collisions, then they will have similar backoff value and will collide again. To resolve this problem, we consider a random value α and multiply it by the collision rate. Hence, the calculated backoff value will never be the same with each other. Each IoT device locally calculates the number of collisions after transmission failure. The next backoff stage can adjust its length according to the collision rate. In case of high collision rate, the backoff window size can be minimized in order to transmit the packet as soon as possible. On the other hand, if the collision rate is low, then the backoff length will be larger and the packet will get time to get transmitted in the next transmission.

For example, as shown in Fig. 5, four IoT devices A, B, C, and D compete to transmit reservation frames. Devices A, B, and C have emergency traffic t_e and hence have a similar σ value of 1. However, device D has monitoring traffic t_m and the value of σ is 0. Devices A, B, and C utilize a small CW range and hence have the opportunity to transmit reservation frame L_r rather than device D. Fig. 5 shows that after the collision occurred between devices B and C, *BO* does not get doubled. Instead, ABO calculates *BO* efficiently and reduces extra delay in channel access.

4) INCREASING PRIORITY OF IOT DEVICES USING ICP MODEL TO MAINTAIN FAIRNESS

The PF-MAC's key function is to ensure QoS for different traffic types and transmission of emergency traffic t_e over normal monitoring traffic t_m with minimum delay Ø. However, the protocol should also be fair enough for data gathering. The devices can fail during the RP in contention. When a device fails frequently during contention, the transmission efficiency of the device would degrade dramatically. Moreover, due to the static traffic priority P_s of the devices, the low-priority devices will suffer from starvation. Moreover, when two or more high priority devices try to transmit at the same time, they will face collision. Our ICP model helps to ensure fairness among the same priority devices and protect the low-priority devices from starvation. In ICP, if reservation frame of a specific device fails during transmission, the priority of that frame is increased by one to get channel access in the next transmission. After increasing the priority, when the device transmits the data successfully, the phase of increasing priority will be halted and the device priority will return to the preliminary level. Fig. 5 shows that when a collision occurs between B and C, following ICP, each device increments its σ value by 1 during retransmission. This mechanism helps fair access among the IoT devices with different priorities. However, due to the use of different *CW* sizes for the different priority of traffic, most of the time, only emergency traffic t_e will compete and no normal monitoring traffic will compete with them. It also guarantees that to access the channel, competition between different types of traffic will not occur. Therefore, emergency traffic t_e will always be transmitted before monitoring traffic t_m.

D. ANNOUNCEMENT PERIOD (AP)

In this period, UAV broadcasts the announcement beacon message to all devices under the communication range of UAV. The announcement beacon message includes the transmission scheduling information of the data packets. Synchronization information for TDMA is also included in the beacon message. Upon receiving announcement beacon, the IoT devices that succeeded in RP switch to data channel and prepare to send data packets according to their designated time slot.

E. DATA COLLECTION PERIOD (DCP)

Algorithm 3 displays the data packet transmission during data collection period. In this period, the devices that became successful in the RP start sequentially transmitting their data using the TDMA mechanism. The timeslots of TDMA are divided into M number of equal timeslots, which is indexed by $n = 1, \ldots.., M$ with each of length ∂_t. In general, the duration of ∂_t tends to be small. Therefore, we can assume that the position change of the UAV in ∂_t is insignificant. Timeslots for each IoT device are selected by the UAV according to the dynamic device priority so that the device with the highest dynamic device priority gets the timeslot allocated faster than the other devices. UAV works as a mobile sink and it synchronizes with the IoT devices using the announcement beacon message.

Algorithm 3 Data Collection Period

```
Input: TDMA scheduling information via announcement
beacon message, b_a
Output:Successful data transmission
for each IoT device i ∈ K
    if b_a is received
        switch to C_d
        synchronizes with the UAV
        IoT devices wait for their time slot
        IoT devices transmit data in their designated t_slot
    else
        go to sleep mode
    end if
end for
```

According to the application scenario, the IoT devices should periodically collect and transmit data. It is very much important to synchronize the IoT devices clocks with the UAV's clock. It is because the clocks can shift due to the drift in crystal oscillators and data transmission delay. After receiving the announcement beacon message, all the IoT devices are synchronized by taking the UAV's clock as a global time. Therefore, all the IoT devices will have the same clock as the UAV's clock and thus all IoT devices are synchronized. As we do not use any other control frames for synchronization, it reduces control overhead in comparison to the conventional TDMA mechanism. After proper synchronization, the devices transmit their data packets according to the scheduled time slot using the data channel.

F. WHOLE COMMUNICATION SCENARIO

Fig. 6 illustrates the whole communication scenario of our proposed PF-MAC protocol. For simplicity, we have considered three IoT devices and a UAV. When UAV reaches to the monitoring area, it starts broadcasting notification beacon via control channel. As shown in Fig. 6, after receiving notification beacon, the active devices A, B, and C contend with each other for reservation opportunity using the basic access mechanism of CSMA/CA. In the figure, we assume that IoT devices A and B have high static priority with $\sigma = 1$ and IoT device C has low static priority with $\sigma = 0$. Two contention windows are selected based on the static traffic priority P_s of the IoT devices.

The IoT devices A and B use small CW size, allowing them to access the channel within a shorter time. Therefore, they can transfer their reservation frame with lower delay. IoT device C is not delay-sensitive. Hence, it utilizes larger CW so that it can obtain channel access after the high-priority devices. As shown in Fig. 7, the IoT devices A and B have the same value of σ. Both IoT devices A and B use the small CW window and try to transmit the reservation frame. However, unfortunately, they face a collision due to the transmission at the same time. Therefore, following ICP model (in Section IV.C-4), the σ value of both devices is increased by 1 and becomes 2. Both of the devices calculate the backoff period using the ABO method (in Section IV.C-3) and then again try to retransmit the reservation frame. This time IoT device A gets the chance to transmit earlier than IoT device B and sends the reservation frame successfully.

On the other hand, after DIFS time, device B can sense that the channel is busy and hence it waits for some time. After waiting for some time, when the channel becomes free, IoT device B transmits its reservation frame successfully. Then, the priority value σ returns to the initial value. In the meantime, IoT device C uses large CW value and after DIFS and backoff time, it sends the reservation frame successfully. The devices with no data to send will switch to sleep mode. The UAV replies with an ACK packet to the every IoT device, which has successful transmission. As we consider a controlled scenario and UAV is going to collect data on a regular basis from the IoT devices, the UAV will aware of all the IoT devices after the first round of data collection.

We do not consider any mobility of the IoT devices and hence their position will not change. The IoT devices will send their location information only in the first round of the data collection. If a new device joins the network, it will send the location information to UAV only during its first data transmission. Therefore, UAV is well aware of all IoT devices and ends the RP period after collecting all reservation frame. After getting all the reservation frame, the UAV extracts all the information from the reservation frame such as location information, residual energy, sampling rate, and static priority value. Then, UAV calculates the dynamic device priority of the devices, which is mentioned in detail in Section III.C-2. Subsequently, UAV assigns TDMA time slot to the IoT devices based on the calculated dynamic priority. The UAV notifies the IoT devices about the timeslots with the announcement beacon message in AP duration. Upon receiving the announcement beacon message, the IoT devices immediately switch to the data channel and start to transmit data in the designated timeslot.

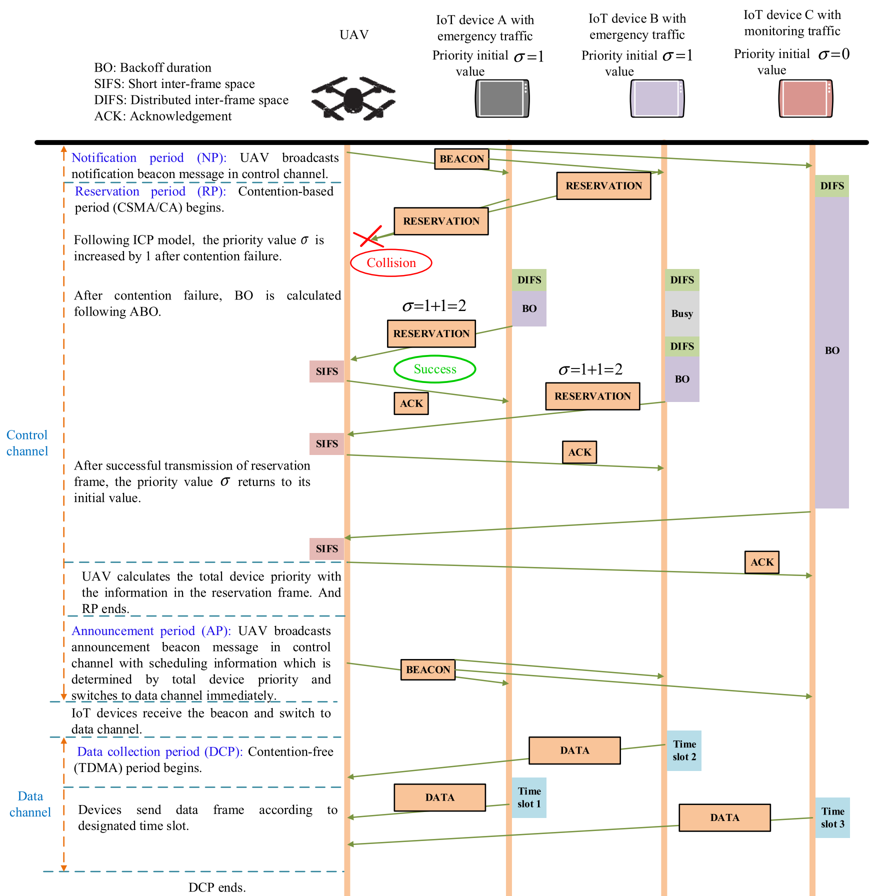

FIGURE 6. Communication process of PF-MAC.

G. COMPUTATIONAL COMPLEXITY

The computational complexity of the proposed PF-MAC is based on the presented three algorithms. The complexity of the algorithm for reservation period at the IoT side mainly depends on the number of transmissions and the number of IoT devices. If the number transmissions is m and the number of IoT devices is n, then the complexity of Algorithm 1 is $O(mn)$. The most expensive process of Algorithm 2 is the sorting mechanism. By implementing, merge sort, even in the worst-case scenario, the time complexity of Algorithm 2 can be reduced to $O(n\log n)$. Similar to Algorithm 1, the complexity of Algorithm 3 can be calculated in $O(mn)$ time. Finally, the overall computational complexity of the proposed PF-MAC can be calculated as: $O(mn) + O(n\log n) + O(mn) = O(mn)$ because $m > \log n$.

V. ANALYSIS OF PF-MAC

A. PROBABILITY OF SUCCESSFUL TRANSMISSION

We assume that there are $k \in N$ number of IoT devices under the coverage area of UAV and each device belongs to one of $Q + 1$ static priority classes. More clearly, $= \sum_{q=0}^{Q} k_q \in N$, where k_q represents the number of IoT devices in a q static priority class. The priority of each device class does not remain constant during the whole RP period. The static priority increases after each transmission failure or collision. We also assume that the packet generation follows a Poisson arrival rate λ for each device. In the buffer of each device, there always remains only one packet. If a new packet arrives before transmission, the new one replaces the previous packet. Furthermore, we assume that if the reservation frame collides, then the packet is dropped and device retransmits the reservation frame with increased priority by 1.

Let us assume that γ represents the duration of the unit backoff period and $N(\gamma)$ is the number of packets that arrive during the γ time interval. Let P_0 is the probability that at least one new packet is produced during the γ interval. Then, we can calculate the P_0 with the following equation:

$$P_0 = P(N(\gamma) \geq 1). \tag{10}$$

During RP, if at least one IoT device with static traffic priority class q transmits the reservation frame, the channel will be busy. Then, we can measure busy channel P_b as follows:

$$P_b = 1 - (1 - \tau_q)^k, \tag{11}$$

where τ_q represents the probability that an IoT device in a static priority q class transmits during a unit backoff period. The collision occurs if at least one of remaining $k - 1$ IoT device transmits a packet at the same time. The collision probability P_c can be expressed as

$$P_c = 1 - (1 - \tau_q)^{k-1}. \quad (12)$$

On the other hand, P_s represents the successful transmission probability that the reservation packet is transmitted successfully, which will only be take place if no IoT device transmits in the same time. Therefore, successful transmission probability P_s can be expressed as follows:

$$P_{s,RP} = \frac{k\tau_q(1 - \tau_q)^{k-1}}{P_b}. \quad (13)$$

Let the total number of generated reservation packets be M. Then, the total number of successfully received reservation packets can be calculated as follows:

$$\xi_{RP} = M \times P_{s,RP}. \quad (14)$$

During DCP, we consider that all IoT devices are synchronized with UAV and no synchronization error occurs during TDMA. There is no collision during TDMA period and IoT devices transmit data during their designated time slot. Transmission failure of packet loss can only occur due to the transmission delay of the packets. UAV allocates timeslot to all of the IoT devices based on their dynamic device priority. If the total number of data packet is G and the total number of timeslots are T, then the number of successfully received data packets can be given as

$$\xi_{DCP} = G \times P_{s,DCP}, \quad (15)$$

where $P_{s,DCP}$ represents the probability of successful transmission during DCP. $P_{s,DCP}$ can be calculated as following equation:

$$P_{s,DCP} = \binom{k}{1} p_i \left(1 - p_i\right)^{k-1}, \quad (16)$$

where p_i represents successful data packets transmission in time slot t_i.

Therefore, combining (13) and (16), we can calculate the total successful transmission probability during RP and DCP as follows:

$$\begin{aligned} P_s &= P_{s,RP} + P_{s,DCP} \\ &= \frac{k\tau_q(1 - \tau_q)^{k-1}}{P_b} + \binom{k}{1} p_i(1 - p_i)^{k-1}. \end{aligned} \quad (17)$$

B. DELAY

The delay observed by each IoT devices can be computed by dividing the process into two steps: reservation period (RP) and data collection period (DCP).

1) DELAY IN RP

RP is contention-based and follows the CSMA/CA mechanism. Hence, extra delay can be observed due to collisions. So, delay in the RP phase can be calculated as follows:

$$\delta_{RP} = \delta_{gen} + \delta_{BO} + \delta_{DIFS} + \delta_r + \delta_{collision} + \delta_{ACK} + \delta_{SIFS}, \quad (18)$$

where δ_{gen}, is the time to generate L_r, δ_{BO} is total BO duration, δ_{DIFS} represents the DIFS time, δ_r is L_r transmission time, $\delta_{collision}$ is the time spent due to the collision, δ_{ACK} is the time spent for receiving ACK, and δ_{SIFS} is the SIFS time. The reservation frame transmission time δ_r can be calculated by

$$\delta_r = \frac{L_r}{\hbar}, \quad (19)$$

where L_r is the length of reservation frame and $\hbar$ is the data transmission rate.

2) DELAY IN DCP

DCP follows the TDMA mechanism. Therefore, there is no delay occurring due to collisions. δ_{DCP} represents the delay in DCP.

$$\delta_{DCP} = \delta_{switch} + \delta_{sense} + \delta_{wait} + \delta_{medium} + \delta_{prop}, \quad (20)$$

where δ_{switch} is the channel-switching time, δ_{sense} is the data sensing time for IoT devices, δ_{wait} is the waiting time in queue before it is transmitted, δ_{medium} is the time placing a packet into medium, and δ_{prop} represents the propagation time. Here, δ_{medium} and δ_{prop} can be represented as

$$\delta_{medium} = \frac{L_d}{t_d} \quad (21)$$

and

$$\delta_{prop} = \frac{\chi}{s_t}, \quad (22)$$

respectively, where L_d represents the length of the data packet, t_d is the data transmission time, χ is the distance between IoT device and UAV, and s_t is the propagation period.

The waiting time in queue t_{wait} can be calculated as

$$t_{wait} = \sum_{i=1}^{PL} S_i + w, \quad (23)$$

where S_i is the service period of each IoT device, w is the waiting time until it is scheduled, and PL denotes the number of priority levels for different IoT devices based on the dynamic device priority.

Combining (18) and (20), we can get the total delay as follows:

$$\delta_{Total} = \sum_{i=1}^{N} \delta_{RP} + \sum_{i=1}^{N} \delta_{DCP} \quad (24)$$

C. THROUGHPUT

Let T be the system total throughput. T represents the data transmitted over a transmission time. The throughput for RP and DCP duration can be separately calculated as

$$T_{RP} = \frac{P_{s,RP} \times L_r \times 8 \times \hbar}{\delta_{RP}} \quad (25)$$

and

$$T_{DCP} = \frac{P_{s,DCP} \times L_d \times 8 \times \hbar}{\delta_{DCP}}, \quad (26)$$

respectively. Combining (25) and (26), we can calculate the total throughput of the system:

$$T = T_{RP} + T_{DCP} = \frac{P_{s,RP} \times L_r \times 8 \times \hbar}{\delta_{RP}} + \frac{P_{s,DCP} \times L_d \times 8 \times \hbar}{\delta_{DCP}}. \quad (27)$$

D. NORMALIZED CONTROL OVERHEAD

Normalized control overhead is the ratio of control packet transmission for packets being delivered from the source node to the destination node. If the number of transmitted control packets is N_c and the number of successfully transmitted data packets is N_d, then the normalized control overhead (NCO) can be calculated with the following equation:

$$NCO = \frac{\sum N_c}{\sum N_d}. \quad (28)$$

E. ENERGY CONSUMPTION

In this section, the explanation is given for energy-consumption of PF-MAC. We consider that UAV power is rechargeable, obtains power from the control center, and harvests energy from the sun during the daytime. The IoT devices are battery-powered and non-replaceable. Thus, we mainly concentrate on the energy consumption of IoT devices. We calculate the energy consumption of each IoT device based on all phases of communication.

In NP period, all IoT devices inside the UAV coverage area obtain the notification beacon message from the UAV. Then, we can calculate the total energy consumption during NP period for k number of IoT devices with the following equation:

$$E_{NP} = k \times E_{Rx}, \quad (29)$$

where E_{RX} represents the receiving energy consumption for IoT devices.

During the RP period, m contending devices sends a reservation frame to the UAV. The total energy consumption can be calculated by

$$E_{RP} = \sum_{i=1}^{m} (E_{idle,i} + E_{collission,i} + E_{Tx,i} \times L_r), \quad (30)$$

where E_{idle} is the energy consumed during the idle time preceding the channel's busy period (collision or success), $E_{collission}$ is the energy consumed during the collision, E_{TX} is the energy consumed for successful transmission of a packet and L_r is the length of reservation packet.

During the AP period, the UAV broadcasts announcement beacon message to all successful devices to provide the scheduling information for the DCP. Therefore, E_{AP} is the total energy used for the reception of the announcement beacon message from the UAV during AP is calculated by

$$E_{AP} = m \times E_{Rx}. \quad (31)$$

During the DCP period, if the transmission scheduling information is received from UAV with announcement beacon message, the device will transmit its data packet to the UAV at its designated *ith* time slot, t_i.

$$E_{trans} = \sum_{i=1}^{m} E_{Tx,i} \times t_i, \quad (32)$$

Failed devices in contention go to idle mode during DCP. Thus, it consumes the following energy:

$$E_{in} = (k - m) \times t_i, \quad (33)$$

Therefore, during DCP, the overall energy intake is

$$E_{DCP} = E_{trans} + E_{in}, \quad (34)$$

Therefore, during the whole process, the overall energy consumption of all devices is

$$E_{total} = E_{NP} + E_{RP} + E_{AP} + E_{DCP}, \quad (35)$$

The energy of transmitter, E_{Tx}, can be calculated by two different equations according to communication distance. After the signal is produced by the transmitter, the amplifier will empower it using different power according to the transmission distance. If the distance between IoT device and UAV is less than the threshold value d_0, it uses the free space model; otherwise, multi-path fading model is adopted to calculate the energy consumption. If the distance is d between IoT device and UAV, the transmission energy for l-bit data is calculated as:

$$E_{Tx}(l,d) = \begin{cases} l.E_{elec} + l.\varepsilon f_s.d^2, & if\ d < d_0 \\ l.E_{elec} + l.\varepsilon_{mp}.d^4, & if\ d \geq d_0, \end{cases} \quad (36)$$

where E_{elec} denotes the power the transmitter use, εf_s denotes the amplifier power for free-space model, and ε_{mp} denotes the amplifier power for multi-path fading model. We can calculate the threshold value d_0 using the following formula:

$$d_0 = \sqrt{\frac{\varepsilon f_s}{\varepsilon_{mp}}}. \quad (37)$$

Then, the energy receiver consumes to receive l-bit data can be measured by

$$E_{Rx}(l) = l.E_{elec}. \quad (38)$$

VI. PERFORMANCE EVALUATION

In this section, the performance of the proposed PF-MAC is evaluated through computer simulation and compared with the modified CSMA/CA [34] and the conventional TDMA with UAV mechanism. The modified CSMA/CA [34] is the most recent MAC protocol proposed for UAV-based IoT systems. On the contrary, conventional TDMA with UAV has been used in most data transfer processes of UAV-based IoT systems where throughput maximization is the main concern. The five performance metrics of average transmission delay, network throughput, normalized control overhead, average energy consumption and network lifetime are evaluated.

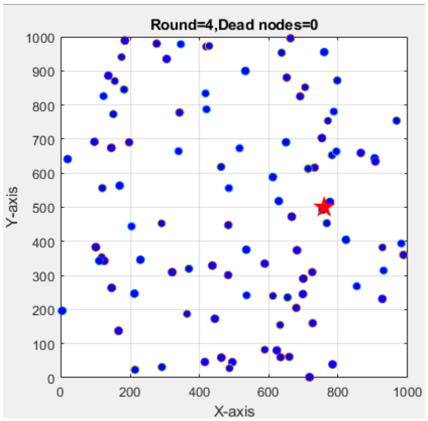

FIGURE 7. Simulation area of 1000*m* × 1000*m*.

MODIFIED CSMA/CA [34]: In this protocol, the IoT devices are divided into different clusters. In each cluster, CW size is dynamically adjusted for each device according to the communication duration with the UAV. The devices with low communication duration get the channel access earlier than the devices with long communication duration. If the collision occurs, binary exponential backoff mechanism is adopted to calculate the backoff value. The fixed wing UAV is used which follows a straight trajectory.

CONVENTIONAL TDMA WITH UAV: We use the conventional decentralized TDMA mechanism with UAV. The IoT devices broadcast short beacon packets periodically after a specified time interval to be synchronized with each other, which reduces collisions during data transmission to UAV. The UAV follows S-path mobility model for data collection.

A. SIMULATION ENVIRONMENT

Fig. 7 demonstrates the simulation area of 1000 m × 1000 m where IoT devices are randomly distributed. The simulation is performed varying the number of IoT devices with repeated number of rounds. The UAV altitude is approximately 100 m and flies with a speed of 20 m/s. We have assumed that UAV follows a predefined trajectory. UAV adopts an S-shape mobility model, which makes the UAV to be in the communication area of IoT devices for sufficient amount of time. We assume that each IoT device can generate two types of traffic: emergency traffic and monitoring traffic. Of the total IoT devices, 20% generate emergency traffic; 80% of the total traffic cover the normal monitoring traffic. We assume the real-time data collection scenario from IoT devices. Hence, no data aggregation is performed in any device. During the RP, the CSMA/CA mechanism is followed. Based on the traffic types, the CW size is dynamically selected. The emergency traffic utilizes the small CW size to obtain access with lower delay; the minimum value is 15 and the maximum value is 30. As the normal monitoring data are delay-tolerant, a large CW size is required, ranging from 31 to 1023. For both

TABLE 2. Simulation parameters.

Parameter	Value
Network simulator	MATLAB
Network area	1000 m × 1000 m
UAV transmission range	100 m
UAV altitude	100 m
Number of UAVs	1
Number of IoT devices	10–100
Transmission range	100 m
UAV speed	20 m/s
Reservation frame duration	22.2 μs
Notification message duration	10 μs
Announcement message duration	10 μs
Data payload size	150 *bytes*
CW range	15–30,31–1023
DIFS,SIFS	128 μs,28 μs
Transmission energy	50 μJ
Receiving energy	40 μJ
Idle energy	20 μJ
Data rate	250 *kbps*
Propagation model	Two-ray path loss

monitoring and emergency traffic, 150 bytes of payload size is selected.

Each simulation is run until the energy level of all IoT devices decreases below the threshold level. All other related parameters regarding to UAV flight, data communication, and simulation conditions are summarized in TABLE 2. The IoT devices are fixed in their position and the UAV is moving. We assume that both IoT devices and UAV are equipped with directional antennas (phased array). By exchanging necessary location information with each other, the beams of both transmitter and receiver can point to each other during communication. These type of antennas have been used in some UAV applications such as [38].

B. SIMULATION RESULT AND DISCUSSION

1) TRANSMISSION DELAY

Fig. 8 presents the transmission delay of the emergency data, which is averaged for repeated runs. It is apparent from the figure that the average transmission delay for emergency data is proportionally high for conventional TDMA and modified CSMA/CA in comparison to our proposed MAC. As the modified CSMA/CA and TDMA with UAV mechanisms do not maintain the QoS requirements during data transmission, the prioritization of emergency data is not performed in these two protocols. Furthermore, the channel access delay is the key contributor to the transmission delay. If the channel becomes excessively busy, to complete the channel access, the devices have to back off for more times, creating longer channel access delays.

In PF-MAC, to reduce channel access delay, different CW sizes are considered based on the IoT-device static traffic

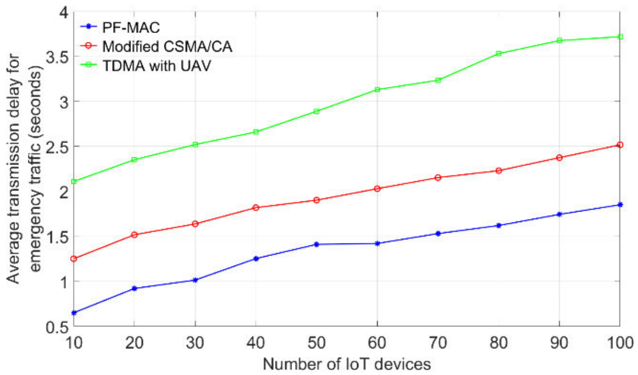

FIGURE 8. Transmission delay for emergency traffic.

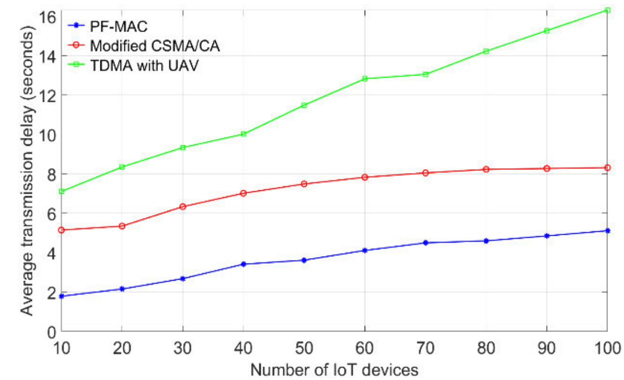

FIGURE 9. Average transmission delay.

priority. The devices that have high static traffic priority utilize lower CW size to obtain channel access earlier than the devices, which has lower static traffic priority. Moreover, ABO helps select proper backoff time based on the collision probability of the channel, thereby reducing the delay in transmission of emergency data to a considerable extent. Moreover, the proper prioritization process by UAV helps to transmit the emergency data transmit faster by getting the earlier timeslot.

In Fig. 9, the average transmission delay of the PF-MAC is presented. In the proposed PF-MAC, a fixed committed channel is allotted for the control packets and a dedicated channel for data packets. Control channel experiences less interference and interruptions due to the static use of a single channel. Moreover, the utilization of ABO based on the collision rate of the channel and priority-based channel access mechanism helps it to achieve less delay during transmission. As the number of IoT devices rises, the average transmission delay also gets high. This is because of the fact that as the number of IoT devices increases, more collisions occur during RP, causing more delay. However, PF-MAC provides better performance than the other two protocols in terms of delay.

2) THROUGHPUT

Fig. 10 displays the network throughput of the proposed protocol. The PF-MAC provides better performance compared

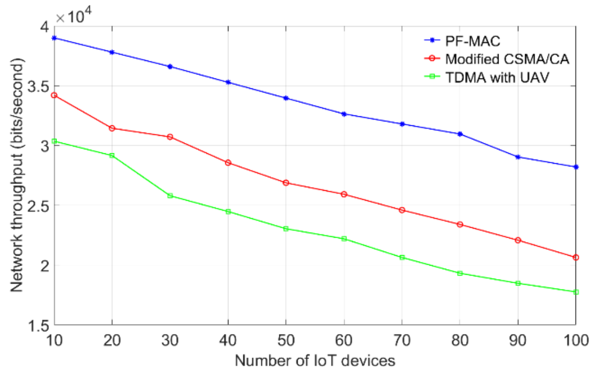

FIGURE 10. Average throughput.

to the modified CSMA/CA and conventional TDMA mechanisms. It is because during the CSMA/CA period, it only exchanges very small reservation packets, thus reducing the number of collisions. Moreover, our proposed PF-MAC protocol uses a multichannel directional antenna, reducing interference and fading by directing the signal in only one direction. The ICP model helps in delivery of packets after experiencing collisions, which results in better throughput. The communication time between IoT devices and the UAV is hampered by UAV's mobility.

The proper prioritization process helps the IoT devices to transfer the data to the UAV during the TDMA period within a short communication time. On the contrary, modified CSMA/CA uses only CSMA/CA mechanism, so collisions increase due to the transmission of large data packets. The TDMA with UAV suffers from low throughput owing to the absence of the prioritization process. The TDMA with UAV mechanism does not allocate a timeslot to the IoT devices according to the traffic urgency and need. Therefore, most of the time, packet loss occurs due to the link disconnection with the UAV. Therefore, PF-MAC gives better performance than the other two protocols in terms of throughput and achieves an overall 32% increase in average throughput.

3) NORMALIZED CONTROL OVERHEAD

As depicted in Fig. 11, when the number of IoT devices is not more than 20, the normalized control overhead of our proposed PF-MAC is higher than TDMA and similar to modified CSMA/CA. However, when the number of IoT devices increases, PF-MAC outperforms the TDMA but still has higher control overhead than modified CSMA/CA. Our proposed PF-MAC protocol utilizes a uses a reservation frame, ACK and beacons as control packet. On the contrary, CSMA/CA uses the RTS/CTS/ACK mechanism for establishing a connection between the UAV and the IoT devices. In the case of the TDMA with UAV mechanism, it suffers from high synchronization overhead resulting in higher control overheads. It is because, the IoT devices need to communicate with each other with synchronization packets in order to avoid collisions in the same time slot. However,

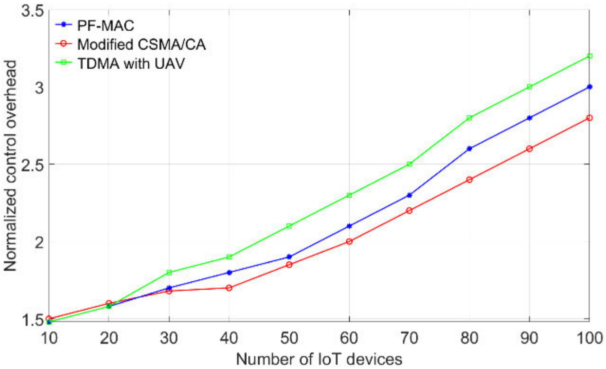

FIGURE 11. Normalized control overhead.

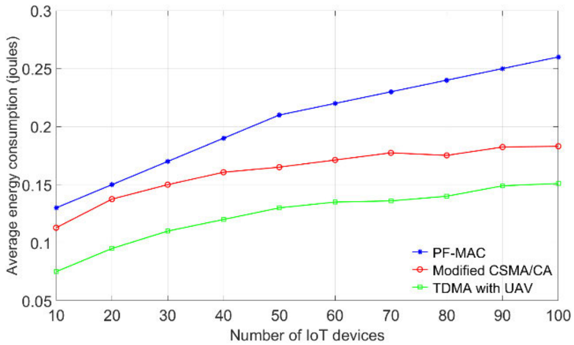

FIGURE 12. Average energy consumption per IoT device.

though the PF-MAC has higher control overhead than modified CSMA/CA, it can ensure higher throughput with less packet loss and delay.

4) ENERGY CONSUMPTION

Fig. 12 shows energy consumption comparison among the PF-MAC, modified CSMA/CA, and conventional TDMA mechanisms. The comparison shows that our proposed PF-MAC has higher energy consumption than modified CSMA/CA and TDMA. It is because our proposed PF-MAC more focused on guaranteed data delivery to achieve high throughput rather than energy efficiency. The transmission of a reservation frame before transmitting the data frame ensures the guaranteed packet delivery. However, our proposed PF-MAC only permits the devices to transmit a small size reservation frame during the RP and utilizes ABO techniques. Thus, the energy consumption due to collisions is reduced significantly. Moreover, the IoT device that fails in the reservation period goes into the sleep mode to preserve energy. On the contrary, modified CSMA/CA and TDMA with UAV requires only one transmission for transmitting data. Moreover, TDMA has the lowest energy consumption among the three protocols because no energy is wasted due to collisions. However, the proposed protocol's modest energy consumption contributes to higher throughput.

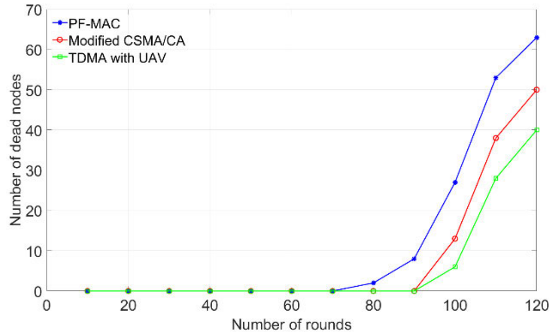

FIGURE 13. Network lifetime.

5) NETWORK LIFETIME

The network lifetime of the proposed PF-MAC is calculated in terms of the number of dead nodes after running the simulation for 120 rounds. Fig. 13 demonstrates the network lifetime of the PF-MAC. It is clearly observed from the figure that, after 70 rounds, the IoT devices start to die. However, until round 90, only less than 10% IoT devices run out of energy, which is quite low. On the other hand, both the modified CSMA/CA and the conventional TDMA with UAV have better network lifetime than PF-MAC. It is because our proposed PF-MAC emphasizes on more on guaranteed data delivery to increase throughput rather than the energy aspect. However, the number of dead nodes until round 90 is almost similar in all of the three protocols. Also, it should be noticed that, even though the energy consumption of the IoT devices is higher than that of the other two protocols, the network lifetime is not much unsatisfactory compared to other two existing protocols.

VII. CONCLUSION

In this paper, we have proposed a hybrid MAC protocol named PF-MAC for UAV-based IIoT networks to achieve the QoS requirements of the target system. In our protocol, the operation of the whole communication process is divided into four parts: NP, RP, AP, and DCP. Heterogeneous devices with two types of static traffic priority contend the channel during the RP. During the DCP, time slots for data transmission will only be allocated to the successful devices in contention. To maintain fairness among the devices, the static traffic priority of the device failing in contention at the former transmission will be increased by 1 at the next retransmission. In the RP, the ABO mechanism is implemented based on the collision rate of the channel. Moreover, during the DCP, a transmission opportunity is provided based on the dynamic device priority. We evaluated the average transmission delay, throughput, normalized control overhead, energy consumption and network lifetime to show the performance of our proposed PF-MAC protocol in comparison to the existing protocols. The performance study makes it apparent that the IoT devices can transfer emergency traffic to the UAV with less delay and the transmission of normal monitoring traffics achieves higher throughput.

In our future study, we are going to exploit an artificial-intelligence-enabled MAC protocol with an optimized UAV trajectory, which can help to reduce the energy consumption of the whole system. We also plan to incorporate multi-UAV scenarios and emphasize on the increasing the lifetime of UAV-assisted IoT systems.

ACKNOWLEDGMENT

The authors thank the editor and the anonymous referees for their comments that have helped improve the quality of this paper.

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