Medium Access Control for Unmanned Aerial Vehicle Based Mission Critical Wireless Sensor Networks in 3D Monitoring Networks

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ABSTRACT In this paper, a novel medium access control (MAC) layer protocol is introduced for unmanned aerial vehicle (UAV)-based mission critical wireless sensor networks (MC-WSN), which is an important application of mission critical sensor and sensor networks (MC-SSN). The UAVs hovering in the three-dimensional monitoring networks are distributed in subsets according to their distance from the center station. UAVs in the same subset are contending for access and transmission, while each subset is allotted a slot based on adaptive time division multiple access (TDMA) scheme. As a multi-channel system, a novel channel allocation algorithm is presented for subset relay transmission period to optimize the performance of networks. The UAV returning period for charging is utilized in the protocol to enhance the transmission throughput and mitigate delay. Detection slot and position prediction algorithm are designed in the UAV returning period to improve the throughput and reduce the delay. The simulation results verify the improvement on throughput and delays of the proposed protocol for UAV-based MC-WSN.

INDEX TERMS Mission-critical wireless sensor networks, UAVs monitoring system, media access control protocol, channel allocation.

I. INTRODUCTION

During past decades, many efforts have been made on the transmission performance improvement of mission critical wireless sensor networks (MC-WSN), which are defined as applications demanding high data throughput in time with reliability and belong to an important application scenario of mission critical sensor and sensor networks (MC-SSN) [1]. The researchers not only focus on improving the performance of general MC-WSN, but also show significant interests on unmanned aerial vehicle (UAV) based MC-WSN [2]. Since UAVs have the advantages of agility, flexibility, low manufacturing cost and a wide application to military and civil fields, such as reconnaissance, remote sensing, traffic monitoring, field search-and-rescue and agricultural information management [3]. As a result, UAV can work as a sensor in the networks of the application fields above. Meanwhile, multi-UAV networking system attracts many attentions, because it has a

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rapider reaction and performs more efficiently than a single UAV [4]. To improve the access and transmission performance of UAV networks, medium access control (MAC) layer of communications has been developed in isolation [5]. However, combining the scanning function of radar system, radar-communications joint access mechanism shows a great research value in UAV networks by utilizing slots sufficiently [6].

In conclusion, MC-WSN systems are defined as systems demanding data delivery bounds in the time and reliability domains. As a result, different network systems have different requirements on throughput and delay. As shown in Figure 1, unlike other networks applied to traffic monitoring, target tracking and climate experiment, UAV based MC-WSN needs a high throughput and a low delay. Therefore, improving throughput and reducing delay are fundamental goals in this paper.

The rest of this paper is structured as follows: The Section II shows the related works. UAVs networks system model of the proposed protocol is described in Section III.
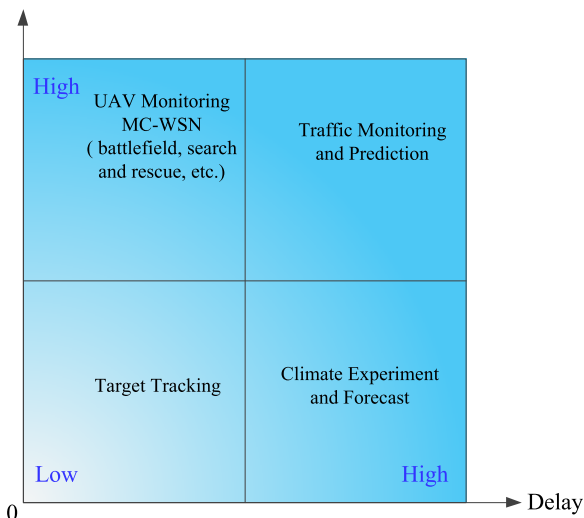
FIGURE 1. Performance requirement on delay and throughput of UAV monitoring MC-WSN and other networks.

TABLE 1. Descriptions of frequently used mathematical notations.

Notations	Descriptions
R	Transmission range of center station
r	Transmission range of UAV sensor node
C_n	The nth wireless channel
U_n	The nth UAV sensor node
$G_{n,m}$	The gain that the mth channel can provide to the nth UAV
$S_{m,n}$	The nth Subset in the mth ring

In Section IV, we introduce the details of the proposed protocol. Then the performance analysis of the proposed protocol is given in Section V. In Section VI, we present the simulation results of our protocol and compare with other relative protocols. Finally, we conclude this paper in Section VII.

For easily reading, the frequently used mathematical notations are presented as Table. 1.

II. RELATED WORKS

Many studies focused on ways to improve the performance of MC-WSN by designing efficient MAC layer protocol [7], especially on throughput improvement and delay mitigation.

A. THROUGHPUT IMPROVEMENT

Combined application requirement of monitoring MC-WSN, one of the most important tasks for the performance improvement of MC-WSN is to increase throughput [8]. Z-MAC [9] is a hybrid MAC layer protocol that combines time division multiple access (TDMA) and carrier sense multiple access (CSMA) to obtain high channel utilization and reduce collision. Although Z-MAC improves the throughput by switching the access scheme depending on contending level, it has a negative influence on bandwidth extension because of utilizing TDMA approach. CAD-MAC [10] is based on

two joint power-channel allocation schemes. It aims at maximizing the data transmission rate and derives the optimal allocation policy by dynamic programming. However, CAD-MAC is too complex for users in WSN and it can be affected by interference and lead to a high delay. In [11], the authors presented a MAC layer protocol aided with physical layer. It uses physical layer components to maximize throughput, and designs an optimization framework by detecting parallel acknowledgement in MAC layer. However, it has a limited practical application because of its selection of suitable physical layer components in a cross-layer scheme.

B. DELAY MITIGATION

To reduce delay, X-MAC/BEB is proposed in [12]. It extends X-MAC [13] with a binary exponential back-off (BEB) algorithm. With the extension, X-MAC/BEB enhances the throughput effectively, but the performance of X-MAC/BEB in multi-hop wireless networks is debatable. Specifically, in UAV based MC-WSN, each UAV is regarded as a flying sensor node, so the whole system is seen as a WSN too. Therefore, appropriate MAC protocols are needed to improve the performance of UAV based MC-WSN [14]. A MAC scheme based on full-duplex radios and multi-packets reception capability is proposed by Cai et al. in [15] for UAV networks mainly focus on delay reducing. However, the combinatorial optimization and discrete stochastic algorithm complicate the protocol. In [16], a data acquisition framework for UAV sensors networking is presented to enhance the transmission performance by contention reduction scheme. Unfortunately, it can be easily affected by UAV distributions. Radar-communications convergence is designed in [17] to improve the throughput of UAV communication, but not applied to large scale UAV networks. Wei et al. described a UAV networks transmission scheme and improved the real-time capacity [18]. However, the transmission slot designed in the protocol has a negative influence on the networking scalability.

Nowadays, in the MAC protocol design of UAV based MC-WSN, researchers not only aim at delay and throughput, but also focus on improving the performance of high mobility UAV networks [19]. However, the MAC protocols for three-dimensional (3D) UAV based MC-WSN are seldom researched and designed in specialty. This kind of network is widely used in agricultural management, remote sensing, and boundary detection etc., in which multiple UAVs are distributed around a center station. Usually, UAVs act as sensors and can be equipped with radar.

In this article, we propose a protocol in MAC layer for 3D monitor UAV networks to enhance the capacity and delay. The proposed protocol utilizes a novel distribution of subsets to match up an adaptive TDMA scheme among subsets. In each subset, a novel contending access scheme is utilized to reduce delay. In addition, a channel allocation algorithm is presented to provide a higher gain in multi-channel scheme of intersubset transmission. Furthermore, in the return path of UAV charging, it can collect data from other UAVs around
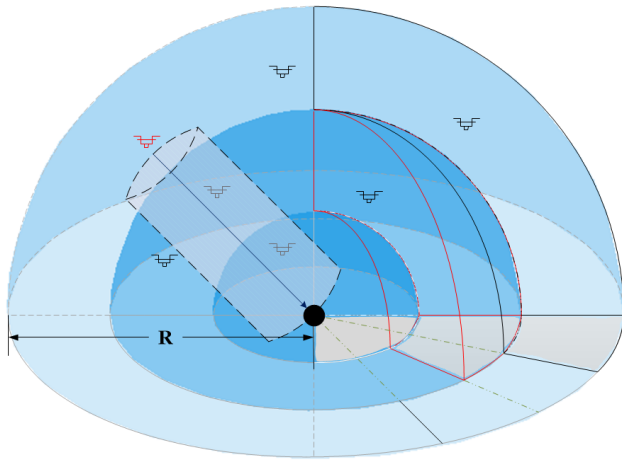
FIGURE 2. UAVs hovering around a center station and subsets distribution.
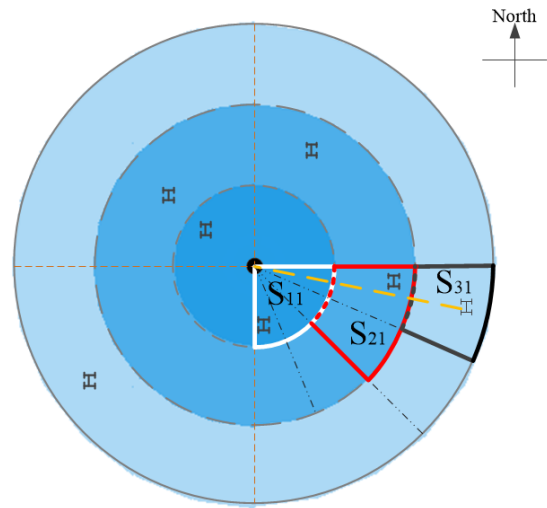

FIGURE 3. The vertical projection perspective of UAVs subsets distribution.

the path and take to center station directly. In the design of return path access scheme, radar scanning is utilized to assist time slots allocation. Subjecting to battery capacity, UAVs return for charging frequently, so it would be better if taking full use of UAVs returning to transmit data. Compared with existing MAC protocol, the proposed protocol can improve the throughput while reduce delay effectively.

III. SYSTEM MODEL

As shown in Fig.2, there are n UAVs hovering in a hemispherical 3D area surrounding a center station. The transmission range of UAV is r. The center station is allocated in the ground whose responsibilities are transmitting control command to UAVs, collecting monitor information from UAVs and providing energy to UAVs. The radius of the area is equal to the maximum transmission range of the center station and denoted as R. Each UAV can be regarded as a sensor node in the networks while the center station acts as a sink node. When any UAV need to be charged, it flies directly to the center station. During the charging, UAV can also deliver information to center station by wire transmission. After charging, UAV returns to its initial position and continues monitoring. Normally, the center station can transmit information to UAVs directly as it has enough energy to provide high power. However, subjecting to energy limitation and battery capacity, UAVs do not have enough power to transmit data to center station directly. Hence, it is necessary to research multi-hops MAC scheme between UAVs and center station, in other words, it is a collected data transmission.

For describing the model and MAC protocol more clearly, the reasons for choosing the proposed model are presented as follows. First of all, to maximize the monitoring area, the control station (center station) of UAV monitoring based MC-WSN is usually deployed on the ground in the center of monitoring area. Hence, the maximum range is considered in the model, which is a hemispheroid with a radius at R.

Then, all UAVs contend for access at the same time lead to a heavy collision. On the other hand, UAV node accessing one by one based on TDMA scheme will waste time slots resource. Hence, it is necessary to propose a new distribution for UAVs. In addition, to best of our knowledge, there is only few literature making contributions on UAVs hovering based 3D monitoring for MC-WSN especially when considering throughput maximization and delay mitigation. So it is necessary to build a novel model for this kind of networks.

In this paper, we divide the whole hemispherical 3D area into subset areas as shown in Fig.2 and Fig.3, Fig.3 is the vertical projection perspective of Fig.2. In subset division, firstly the area is divided into hemisphere rings as shown in Fig.2, which is the circular ring in Fig.3. From inside to outside, the rings are represented from 1 to n, where n is an integer. Secondly, for the mth ring, it is divided into 2^{m+1} equivalent blocks; the UAVs in each block compose a subset of UAV networks. Normally, the UAV transmits its collecting data to center station subset by subset from outside to inside, so the width of the ring should be set to make sure the two UAVs in two adjacent subsets of two rings can communicate with each other, e. g. the two UAVs in red and black subset. Particularly, when a UAV returns to center station for charging, it collects the data from other UAVs which are in its transmission range along the return path, and then delivers the collected data to center station by wire line when it is charging. Additionally, each UAV is equipped with radar to detect other UAVs in returning path to arrange transmission slots properly. In this way, the networks throughput is improved and the transmission congestion is relieved.

In addition, because the area of each subset is fixed after the setting, the boundary coordinates of the subset can be stored in the UAVs. Also the coordinate value of center station is assumed as (0, 0, 0). As a result, the UAVs know their own
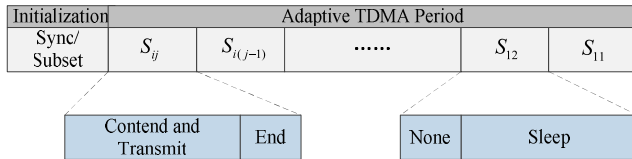
FIGURE 4. Transmission slot design of all hover period based on adaptive TDMA scheme.

subsets as long as they know their own position coordinates. In the proposed model, the UAVs can obtain their position usually by the Global Navigation Satellite System (GNSS). If the GNSS loses its efficacy, relative positioning between center station and UAVs is necessary. The position of UAVs can be obtained based on received signal strength indication (RSSI). Furthermore, if the station is not located at the center of the monitoring area, the proposed protocol still can be used with the maximum transmission as the radius can cover the whole area.

IV. NETWORKS PROTOCOL DETAILS

A. ALL HOVER PERIOD

Normally, the adaptive TDMA happens when all UAVs hover around the center station, so it is defined as all hover period in this paper. The first state of this period is the initialization, including the synchronization of all UAVs in each subset of the networks. To reduce the transmission collision, an adaptive TDMA scheme is utilized in transmission after the initialization, in which the UAVs can switch modes between work and sleep adaptively in each TDMA slot. The transmission sequence of subsets in TDMA period is from outside to inside, since the inside one can act as a relay of the transmission between outside node and center station. In this way, the nodes in outside subsets switch to sleep as soon as they complete the transmission to save energy.

As shown in Fig.4, at the beginning of a transmission cycle is the initialization, including the synchronization of all subsets and center station. Then the adaptive TDMA period starts after the initialization. In the networks, it is assumed that S_{mn} represents the nth subset in the mth rings of the subsets segmentation, where i and j are the maximum values of m and n, respectively. The transmission slot allocation is from the outer ring to the inner ring. For each ring, the order is from large to small according to the value of j. As demonstrated in Fig.2, the first number of each ring is start from east to south, like S_{31}, S_{21} and S_{11}. In the transmission slot of each subset, nodes are contending for access and transmission. There is avoidance in the section of [0, CW] after collision, where CW is short for contending window. For the first collision of one node, the value of CW is the minimum CW. It increases with the times of collisions until to the maximum CW, then returns to the minimum CW. At the end of each subset slot, there is an 'End' beacon to inform next subset and the current subset switches to sleep mode. The details of contending process is shown as Fig.5.

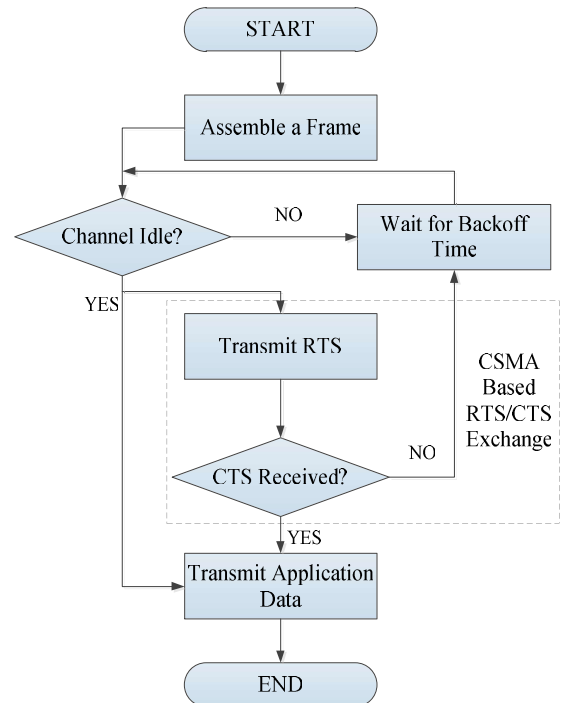If there is no node in the subset has a transmission mission, all nodes keep in sleep mode. Furthermore, the proposed

FIGURE 5. The details of contending process in the all hover period.

protocol is adaptive, even if there is no UAV in a subset, the subset will not be allocated transmit slot in the adaptive TDMA period.

B. RELAY TRANSMISSION

The transmission range of UAV nodes is much smaller than center station's transmission range, thus the relay transmission happens when the UAV cannot deliver data to center station directly. Normally, the UAVs in inside subset $S_{(i-1)\lceil j/2 \rceil}$ act as relay nodes of the UAVs in outside subset S_{ij}, where the symbol '$\lceil \rceil$' means round up to an integer. For example in the Fig.2, the S_{11} can act as the relay subset of the transmission between S_{21} and center station.

As shown in Fig.6, the first step of relay transmission is pair matching of senders and relay receivers. The UAVs in S_{ij} selects idle UAVs in $S_{(i-1)\lceil j/2 \rceil}$ as relay nodes. To avoid collision for multi-channel transmission, a channel allocation algorithm is introduced to maximize transmission gain. First of all, it is assumed that the total bandwidth for transmitting is W. In addition, there are as many as M equal bandwidth channels used to transmit, so the bandwidth for each channel is W/M. Also, it is assumed there are U_t UAVs having transmission tasks. For detailed presentation, we have following definitions.

Definition 1, $G_{u,m}$ is the gain that the mth channel can provide to the uth UAV. Of course, the precondition is that different channels provide different transmission gain values to a specific UAV. Meanwhile, different UAVs have different transmission gain values in a fixed channel. In addition, the channel gains are presented in relative values that just used to describe the channel allocation algorithm.
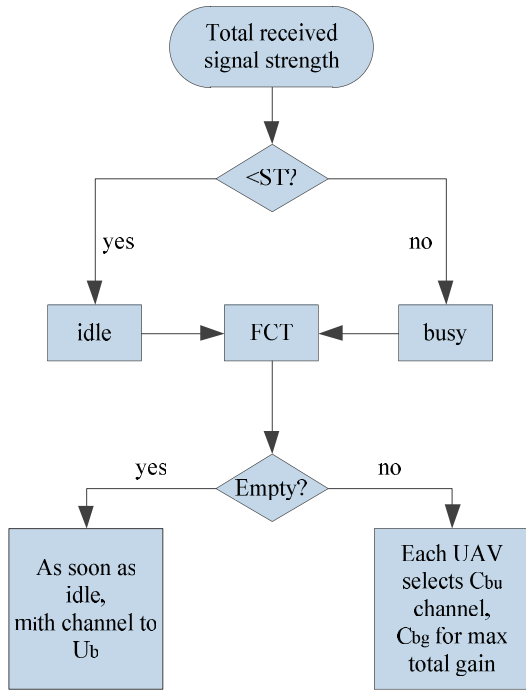
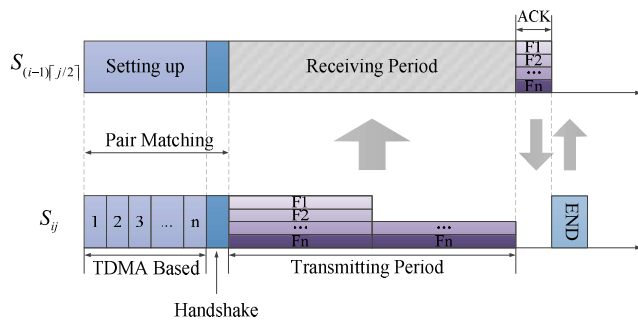**FIGURE 6.** The details of channel allocation steps.

FIGURE 7. The slots design of transmission period in relay transmission between subsets.

Definition 2, for all UAVs that can transmit in the mth channel, U_{bm} is the UAV which can get the best gain. It is also described as the best UAV for the mth channel.

Definition 3, for all channels than can provide gain to the uth UAV, C_{bu} can provide the best gain to the UAV. Similarly, it is described as the best channel for the uth UAV.

To describe the definitions clearly, Table. 1 is shown as examples. There is a system that includes three channels (C1, C2 and C3) and six UAVs (U1 to U6); the values of channel gain are shown in Table. 1. According to the Definitions 2 and 3, C_{b1} is the channel 1 with $G_{1,1} = 0.9$, U_{b1} is the UAV 3 with $G_{1,3} = 1$. Similarly, other values can also be obtained.

The details of channel allocation steps are shown in Fig.7 with the descriptions as follows,

1) UAVs monitor the total received signal strength (TRSS) if no transmission happens. The channel is marked as idle if its TRSS of it is below the sensing threshold (ST), or it is a busy channel. Then, all of the idle channels are recorded in the free channel table (FCT) of UAVs.

TABLE 2. Values of channel gain in examples.

	C1	C2	C3
U1	0.9	0.8	0.6
U2	0.8	0.4	0.3
U3	1.0	0.9	0.2
U4	0.8	0.3	0.2
U5	0.1	0.1	0.5
U6	0.2	0.6	0.3

2) Each UAV checks its FCT at the start of transmission.

a. If its FCT is empty, that is, there is no idle channel. Once a channel becomes idle, which is assumed as channel m_i, then m_i will be allocated to U_{bm_i} for transmission.

b. Each UAV selects its own C_{bu} from all available channels if its FCT is not empty. For example in Table. 2, the 2nd channel is idle and the 5th and 6th UAVs have transmission tasks, the 6th will first accesses the channel to transmit since $G_{5,2} < G_{6,2}$ and the gain is maximized.

c. In the circumstances that there are more than one idle channel and more than one UAV having transmission tasks, the best channel group C_{bg}, which can provide the highest total channel gain, is needed for transmission.

For instance, if all UAVs in the Table.1 want to use the three idle channels to deliver data, the total gain can be computed as

$$G_{total} = G_{a,1} + G_{b,2} + G_{c,3}, \quad (1)$$

where $a \leq 6, b \leq 6, c \leq 6$ and $a \neq b \neq c$. As a result, the selection is U3 in C1, U1 in C2, and U5 in C3 with the G_{total} achieve 2.3.

To mitigate collision in pair matching period, the UAVs in transmitter subset sense and select channels for transmission based on TDMA scheme to maximize the gain according to the steps in Figure 6. Meanwhile, the UAVs in receiving subset are allotted to each channel one to one correspondingly. If there are redundant UAVs or channels, they are left unused. Then, in the handshake slot, each transmitter UAV transmits in allocated channel and handshakes with receiver UAVs in the channels to prepare data transmission.

After the pair matching, the UAVs in S_{ij} start the transmission period, while the nodes in $S_{(i-1)\lceil j/2 \rceil}$ begin to receive data. In the transmitting period of S_{ij}, different UAVs are allocated in different channels with different frequency to transmit data.

The channel allocation is completed in pair matching, each receiving node in $S_{(i-1)\lceil j/2 \rceil}$ switches to the same channel as the sending node before receiving period begins. As the transmitting period shown in Fig.7, UAVs deliver data in the corresponding channels which are matched in last period. The UAVs that complete the transmission switch to sleep until the last one finishes transmission. After the transmitting/receiving period, the receiver UAVs in $S_{(i-1)\lceil j/2 \rceil}$ send ACK beacon in their own channels which are allocated in
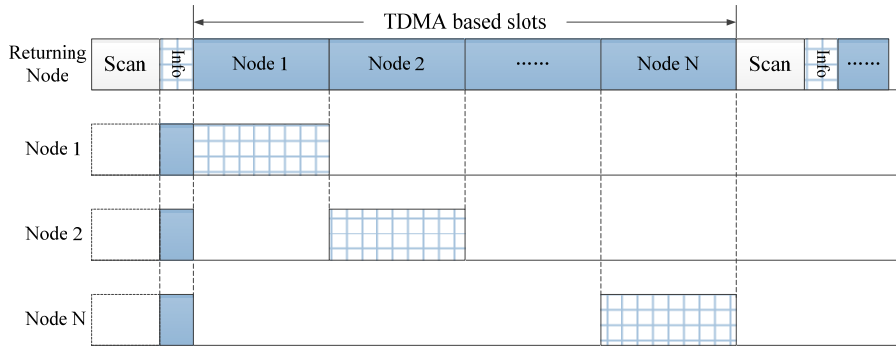
FIGURE 8. The slots design of UAVs returning period. The UAVs are seen as sensor nodes in the systems.

pair matching phase, followed by END beacon to finish relay transmission.

C. UAV RETURNING PERIOD

The process that UAVs return to center station for charging is defined as UAV returning period in this paper. As is well-known, the UAV returning period can be utilized to collect data in return path and deliver the collected data to center station by cable communications while charging, which not only reduces the total transmission time, but also enhances the reliability. This subsection focuses on presenting a slot design for UAV returning period to improve the transmission performance. For a UAV node, to maximize the utilization of UAV's, the UAV returning period has the highest priority. In other words, when a UAV node stays in its hover period but not in transmission, it will switch to UAV returning transmission period if there is a UAV passing by.

The transmission process slot design of UAV returning period is presented in Fig.8. For easier understanding, the red UAV in Fig.1 is illustrated. In its way back to center station, all UAVs that are covered in its transmission range (shadow area in Fig.1) are scanned by the radar equipped with red UAV. The whole transmission period is divided into many cycles, and each of them starts with one-circle scanning. Then the returning UAV broadcasts transmission sequence information due to other UAVs' positions. To make full use of time slots and enhance reliability, hovering UAVs that in the scanning area transmit data to returning UAV from the farthest to nearest according to the distance of hovering UAVs and center station. All hovering UAVs acquire equal sub-slots to transmit; each UAV wakes up in its own sub-slot until the last one finish transmission in this circle. The hovering UAVs switch to relay transmission period as soon as their sub-slots finish. In the next circle, the returning UAV has moved to another position and starts the second scanning. The transmission process is repeated until the UAV returns to center station and delivers collecting data by cable communications.

In addition, to predict the position of returning UAV more precisely, a position prediction algorithm will be used in the networks. At first, the position coordinates of a returning UAV θ are defined as $\{x_\theta, y_\theta, z_\theta\}$, where θ is the ID of UAV. Meanwhile, $\{v_{x\theta}, v_{y\theta}, v_{z\theta}\}$ is the velocity vector of the UAV θ.

Then, the prediction position is defined as $\{x_{\theta p}, y_{\theta p}, z_{\theta p}\}$, which is represented as

$$\begin{cases} x_{\theta p} = x_\theta + v_{x\theta}\Delta t \\ y_{\theta p} = y_\theta + v_{y\theta}\Delta t \\ z_{\theta p} = z_\theta + v_{z\theta}\Delta t \end{cases} \tag{2}$$

where Δt means the flying time interval of UAV. Finally, depending on the prediction position, the access and transmission become more efficient.

V. ANALYSIS OF THE PROTOCOL

In this section, the performance of the proposed protocol applied to UAV networks is analyzed in terms of throughput, collision probability and delay, respectively.

First of all, it is assumed that the data arrival follows Poisson distribution which can be represented as $P(X = k) = \frac{\lambda^k}{k!}e^{-\lambda}, k = 0, 1, 2\ldots$. That is, in the presented UAV networks, for a fixed UAV sensor node in the subset S_{ij} time slot τ, the probability of transmission is defined as P_{ij}^τ and follows Poisson distribution. As a result, for a total subset S_{ij}, the probability that at least one transmission happens can be represented as

$$P_{ijt} = 1 - (1 - P_{ij}^\tau)^{N_C}, \tag{3}$$

where N_C is the number of contending sensor nodes. It means that there are nodes' contending for access and transmission, only one node wins while others need to wait for a backoff. This probability also indicates that the transmitters are not always more than receivers when outer UAVs transmit to inner UAVs. If N_{col} is the number of collision sensor nodes, then the successful transmission probability is obtained as

$$P_{ijs} = \frac{\binom{N_C}{1} P_{ij}^\tau (1 - P_{ij}^\tau)^{N_C - N_{col}}}{P_{ijt}}. \tag{4}$$

This probability is based on the situation that there is at least one transmission happens. As a consequence, the collision probability can be represented by

$$P_{ijc} = \frac{\binom{N_C}{N_{col}} P_{ij}^\tau (1 - P_{ij}^\tau)^{N_C - N_{col}}}{P_{ijt}}. \tag{5}$$

In this way, based on the equation (4) and (5), the total collision probability can be obtained by

$$
\begin{aligned}
P_{col} &= 1 - P_S \\
&= 1 - [(1 - P_{ijc})(1 - P_{(i-1)\lceil j/2 \rceil c})(1 - P_{(i-2)\lceil j/2^2 \rceil c}) \\
&\quad \cdots (1 - P_{1\lceil j/2^{i-1} \rceil c})],
\end{aligned} \tag{6}
$$

where the P_S is the successful transmission probability.

Then, the networks throughput is defined as the rate of successful transmission payload bits expectation with the time used for transmission period. That is

$$
\begin{aligned}
T_H &= \frac{\mathrm{E}[successful\ transmission\ payload\ bits]}{\mathrm{E}[transmission\ period\ time]} \\
&= \frac{P_S L_{total}}{\mathrm{E}[T_{tr}]},
\end{aligned} \tag{7}
$$

where L_{total} means the total transmission payload, including directly transmission and retransmission payload. Meanwhile, T_{tr} represents the transmission period time, which is defined as

$$
T_{tr} = \mathrm{E}[T_{idle}] + P_S T_S + P_{col} T_{col}, \tag{8}
$$

in which $\mathrm{E}[T_{idle}]$ means the idle slots between two consecutive successful transmission and it is defined as

$$
\mathrm{E}[T_{idle}] = \sum_{k=1}^{\infty} (1 - P_{ij}^{\tau})^k = \frac{1}{P_{ij}^{\tau}} - 1. \tag{9}
$$

Finally, as another important performance, the transmission delay in the networks is described as the time period from the transmission start to the first successful transmission finish, it can be indicated as

$$
D = \frac{\sum_{t=1}^{\tau_R} [(t-1)(T_{col} + T_{idle}) + (T_S + T_{idle})](1 - P_S)^{t-1} P_S}{1 - (1 - P_S)^{\tau_R}}, \tag{10}
$$

where τ_R is the retransmission times and can be defined as any positive integer.

VI. SIMULATION RESULTS

In this section, NS-3.26 simulator is utilized to evaluate the performance of the proposed protocol and compare with other relative protocols. UAV sensors are randomly distributed in a hemisphere with a radius at 3km. The simulation parameters are presented in Table. 3. The simulations focus on throughput and delay, which are important evaluation of performance in UAV based MC-WSN.

To show the superiority of the proposed protocol in UAV based MC-WSN on throughput and delay, we not only compare the protocol to CSMA/CA protocol, but also to other related approaches in [12] named X-MAC/BEB, and [18] which utilizes 27-TDMA scheme. For easy description, they are represented as X-MAC/BEB and 27-TDMA in the simulations, respectively.

The X-MAC/BEB runs a binary exponential backoff (BEB) algorithm on top of an X-MAC protocol to reduce

TABLE 3. Simulation parameters.

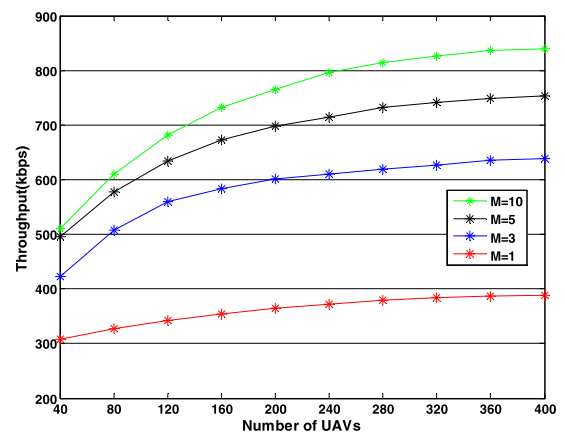| Parameter	Value	Parameter	Value
Hemisphere radius of UAVs	3km	RTS	160bits
Number of UAVs	20-200	CTS	112bits
Returning speed	100/120/150km/h	ACK	112bits
Transmission range of UAVs	500m	SIFS	28μs
Bandwidth	1.5MHz(at 2.4-2.48GHz)	DIFS	128μs
CW min	15	Data packet	2014bits
CW max	1023	Battery	1.44× 10^6 J
Receiving Power	90mW	Transmitting Power	60mW
Sleep Power	2mW		

FIGURE 9. The simulation results of throughput versus the number of UAV in different number of channels.

collision and enhance throughput, especially in densely populated wireless sensor networks. Meanwhile, X-MAC is a lightweight asynchronous duty cycle MAC protocol that proposed for delay mitigation and throughput improvement. In 27-TDMA, 27 cubes form a cluster and cover the monitoring area. This design really does improve the performance of UAV networks, but due to the cube design, the boundary of total subsets cannot fit the whole transmission area of center station well. As a result, the 27-TDMA scheme either leads to resource waste or gives rise to UAV missing. What is more, when taking relay transmission into consideration, the cube design makes relay algorithm complicated.

In the multi-channel MC-WSN system, the results of throughput versus the number of UAV in different channel number are shown in Fig.9. It is obvious that more channels leads to a more network throughput by using the channel allocation algorithm presented in this paper. However, more channels also lead to a more complex channel allocation and a higher requirement of UAV hardware. Furthermore, when the number of UAV nodes is more than 240, the networks are close to throughput saturation. That is why the throughput increases slowly when there are more than 240 nodes
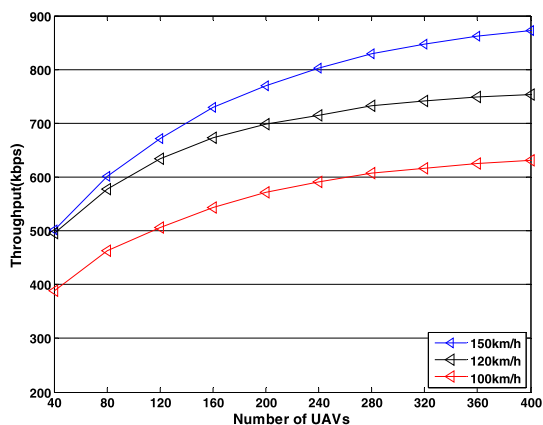
FIGURE 10. Throughput comparison of different UAV returning speed values.

FIGURE 11. The simulation results of throughput using different protocols.

FIGURE 12. The simulation results of average successful transmission probability of per UAV.

in the networks. Comparing to a single channel networks, five channels design has an almost 100% improvement on throughput, which is more significant than three channels that can provide a nearly 67% improvement and little less than ten channels system that can provide a 112% improvement. As a result, taking UAV hardware cost and algorithm complexity into consideration, five channels design is utilized in the following simulations. Furthermore, for fair comparison, other compared protocols still use the proposed channels allocation algorithm at the beginning of the protocol to allocate channels. That is, the processing of the compared protocols starts to transmit in the channel determined by the proposed channels allocation algorithm.

A throughput comparison of different UAV returning speed values is shown in Fig. 10 with five channels system. Higher speed results in a lower throughput when the number of UAVs is fixed. The reason is that high speed motion can affect subsets distribution, and then leads to transmission collision. When the speed is increased from 100km/h to 120km/h, the reduction of throughput is not obvious. But if we keep increasing the speed to 150km/s, the throughput severely degrades nearly 28% compared to 120km/h. In addition, the throughput increases slowly when the UAV nodes are more than 280, which leads to a decrease of average throughput of per node. Therefore, considering the returning efficiency, the speed at 120km/h is selected in simulations of this section.

The simulation results of throughput using different protocols are given in Fig.11. It is defined that the returning speed of UAV is 120km/h. Because of the subsets distribution design and channel allocation scheme, UAVs can take full use of slots to transmission, while the collision is reduced. As a result, the proposed protocol provides a much higher throughput than CSMA/CA. Also, it significantly improves the networks throughput when the number of UAVs is more than 120 in the system comparing to X-MAC/BEB and 27-TDMA scheme. This is because a larger number of UAV sensors yield a higher collision in X-MAC/BEB and 27-TDMA, but it has a less influence in the proposed protocol due to its subsets transmission slots design.
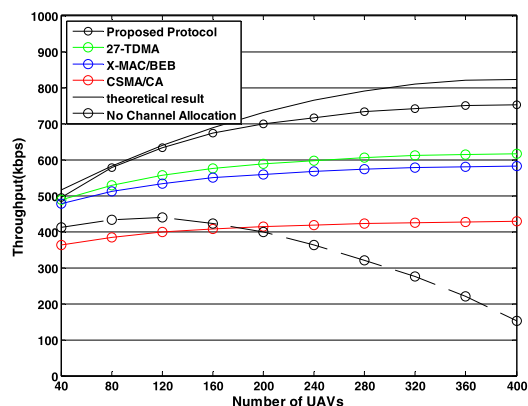
In addition, compared to the theoretical result of the proposed protocol, the simulation throughput has a lower saturated throughput. The throughput of a networks consisting of 80-120 UAV nodes is closest to theoretical results, which can be regarded as a tradeoff between the number of UAVs and network throughput. Then, we present the throughput simulation result of the proposed protocol with random channel allocation instead of the proposed algorithm in this paper to show the advantage. It is obvious that the throughput deteriorates sharply without proposed channel allocation due to the collisions caused by random access.

In Fig.12, the average successful transmission probability of per UAV is evaluated based on X-MAC/BEB, 27-TDMA and the proposed protocol, respectively. As the area of all UAV MC-WSN is fixed in the radius at 3km, more UAVs lead to more transmission congestions and collisions, so the average successful transmission probability surely reduces. However, because of the allocation-contending hybrid slots design, the transmission failure rate of the proposed protocol is restrained effectively by as much as 14%.

Finally, the simulation results of transmission delay versus the number of UAVs by using different protocols are given in Fig.13, attached with the theoretical result of the proposed protocol. Efficient hybrid transmission slots design results in the minimum delay among the four protocols.
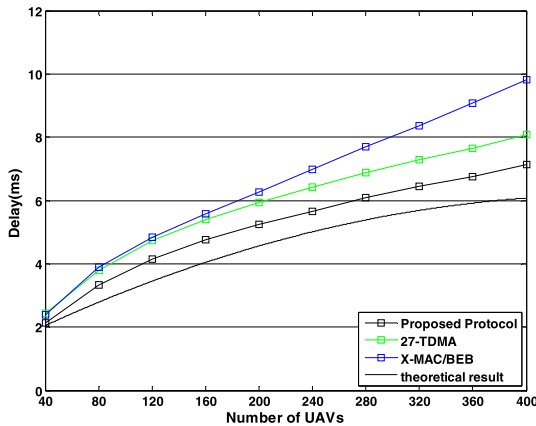

FIGURE 13. The simulation results of transmission delay versus the number of UAVs by using different protocols.

Comparing to CSMA/CA, X-MAC/BEB and 27-TDMA, the proposed protocol can reduce the delay by 43%, 31% and 13%, respectively. In addition, the larger the number of UAVs is, the more significant the reduction is. On the other hand, the delay gap between theoretical result and simulation result of the proposed protocol becomes larger with the increase of the number of UAV nodes. In a word, the proposed reduce the delay of UAV monitoring networks compared to other protocols.

VII. CONCLUSION

In this paper, a novel MAC layer protocol for UAV based MC-WSN is introduced to improve the transmission performance of 3D UAV hovering networks, which are widely used but seldom researched. Firstly, a spatial subsets distribution scheme of the UAV networks is proposed. Distant UAVs can transmit data to station center by nearby UAVs as relays. Next, a MAC layer access and transmission slots design of the protocol is described in details depending on the subsets distribution. To reduce collision and take full use of slots, the contenting scheme is used in subset internal transmission, while the adaptive TDMA scheme is used in intersubset transmission. We select TDMA scheme as the foundation of subsets' access scheme in the proposed protocol because of a tradeoff with contending access scheme on transmission performance. Specifically, in relay transmission period of UAVs, we present a channel allocation algorithm to maximize the total transmission gain. Meanwhile, in returning period of UAVs, radar detection slot, combining position prediction scheme is utilized to improve the transmission slot design. Finally, simulation results of the proposed protocol are given to show the improvement that brings to UAV based MC-WSN on throughput and delay compared to some existing works.

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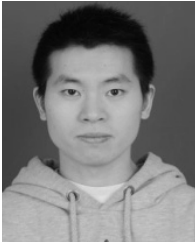
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