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CogMOR-MAC: A cognitive multi-channel opportunistic reservation MAC for multi-UAVs ad hoc networks

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ABSTRACT

With the rapid increase of the wireless applications, the cognitive radio network as a promising solution has attracted a lot of researches in recent years. One of the critical issues is to solve the rendezvous problem by using one radio. Especially, Unmanned Aerial Vehicles (UAVs), embedded devices or smart devices usually can only equip one radio for various reasons, including energy-saving, cost-saving and size-constraint. In this paper, we present a multi-channel cognitive MAC protocol, namely CogMOR-MAC, which is based on Multi-channel Opportunistic Reservation (MOR) mechanism. The MOR mechanism focuses on solving the rendezvous problem and improving the negotiation efficiency by using only one radio. And the presented MOR mechanism is also used to reduce the impact on frequency hopping and avoid the primary user activities. In the performance evaluation, typical metrics are considered on the performance, such as packet success rate, link latency, link throughput, channel utilization, etc. CogMOR-MAC is also compared with other multi-channel cognitive MAC protocol on performance. The result shows that CogMOR-MAC can adapt to Primary User (PU) activities environment more effectively and provide a reliable communication. Of course, it is not only suitable for the multi-UAVs ad hoc networks, but also can be applied to mobile ad hoc network or wireless sensor network, especially in the severely interfered environment.

1. Introduction

Today, Unmanned Aerial Vehicles, also known as drones, are becoming increasingly popular. And they look set to improve a wide variety of industries and services. UAVs have the potential to deliver profound socio economic benefits. From transforming how businesses deliver their products, to support life-saving services like drug delivery in remote areas and enabling first responders to rapidly assess emergency incidents. In addition, multi-UAVs formations have attracted a lot of attention whether in military applications or in civil applications. Especially, in the face of the serious natural disaster, such as the tsunami, earthquake and mud-rock flow, the mobile base stations usually suffer severe damage. It would result in the areas of communication interrupt and cause many difficulties at the critical moment of post-disaster relief. Fig. 1 illustrates a typical application-utilization scenario of multi-UAVs providing the 4G-LTE/5G networks for mobile users as a temporary base station in natural disaster. When the UAVs fly to the designated airspace, they can provide the 4G-LTE/5G cellular networks for the rescue team or anyone who needs the wireless communication for help. Between the UAVs, a multi-hop relay system is established in order to connecting the 4G-LTE/5G mobile users and the Internet (or base station). For example, the authors of [1] consider the relaying wireless communications (UAVs acting as mobile relays) are able to provide ad hoc self-healing capabilities to cellular networks in overloaded or outage areas. The multi-hop relaying system based on UAVs can not only extend the communication range of the ground network, it can also help to rapidly build and deploy the internet network under the extreme conditions without infrastructure, such as primitive forest, desert or disaster ruins.

Different from the traditional Mobile Ad Hoc Network (MANET) [2] and Vehicular Ad Hoc Network (VANET) [3], the Flying Ad Hoc Network (FANET) [1,4,5] is a new paradigm of wireless communication that provides UAV-to-UAV or UAV-to-infrastructure communication supporting nodes with high mobility. Obviously, FANET has a great significance for multi-UAVs missions. However, current aeronautical communication systems are neither designed to manage such a huge new fleet of UAVs, nor can operate effectively in built-up urban areas and support high bandwidth traffic like streaming video or other internet applications. At the same time, existing mobile ad hoc protocols cannot meet the needs of FANET due to high-speed mobility, frequent topology change and high reliability requirements [6].

For the existing MAC layer protocols in FANET, such as 4G-LTE, IEEE 802.11 and IEEE 802.15.4 (or their improvements and optimizations), these MAC protocols are still widely used in UAV-to-infrastructure and

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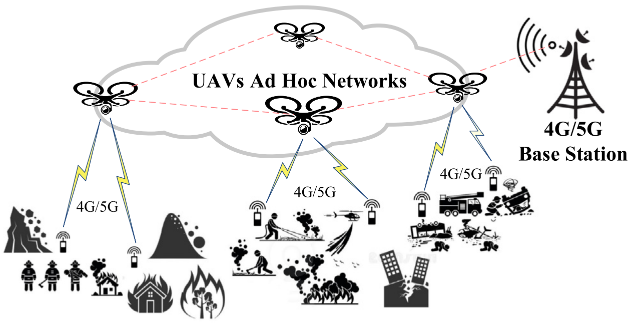


Fig. 1. The 4G-LTE/5G cellular networks service base on multi-UAVs in disaster assistance.

UAV-to-UAV communication with the directional and omnidirectional antennas, although some researchers have found that these solutions are not well adapted to the future development of multi-UAVs communication network [7]. 4G-LTE is unable to provide ad hoc networks communication between UAV-to-UAV without infrastructure. IEEE 802.11 is often used as the MAC protocol for low-load networks. Facing the large-scale fleet of UAVs networking needs, a lot of collisions will occur in IEEE 802.11 [8,9]. Besides, the fluctuates of links caused by topology changes will affect data exchanges [8]. IEEE 802.15.4 has advantages in low power consumption and high connectivity. The authors of [10] have made special optimization and improvement based on IEEE 802.15.4, and provided a scheme to guarantee high packet delivery ratios while maintaining acceptable levels of latency requirements for FANET. However, these IEEE 802.15-based optimization (or improvement) versions are all still low bandwidth and prone to interference. So the use of these IEEE 802.15-based protocols will be seriously restricted in future urban areas multi-UAVs applications.

Thus, FANETs are characterized by rapid changes and activities during network operation. The design of UAVs communication MAC protocol should be highly scalable with low latency requirement. Rapid topology changes resulting from high mobility must be considered in the design of MAC, and it also needs the MAC can provide fairness of UAVs access opportunities and transmission reliability.

The proliferation of performance demanding wireless applications is imposing a rapidly increasing workload to wireless networks. Besides, more and more different wireless networks (such as WiFi, Bluetooth, IEEE802.15.4 networks) coexist in the environment where UAVs operate, and UAVs have to face the problem of spectrum scarcity [11]. The Cognitive Radio Technology (CRT) is expected to improve the spectrum utilization efficiency by opportunistically utilizing unused spectrum, which is known as spectrum holes or white spaces [12]. CRT can bring more available resources, stronger anti-interference capabilities and higher potential bandwidth utilization. All of these advantages have made many researchers begin to pay attention to this hotspot. In the current research, CRT is expected to be able to solve various challenges in the FANET.

Aiming at above problems, this paper proposes a novel cognitive ad hoc MAC protocol for multi-UAVs communication, namely CogMOR-MAC. Different from traditional MAC protocol, the CogMOR-MAC focuses on solving several challenges in the multi-UAVs communication networks. The main characteristics of multi-UAVs network are discussed in detail below.

- *Self organization and autonomous network:* The applications of UAVs are popular day by day, including smart transportation and logistics, disaster assistance and response team, health service logistic support, detection and monitoring, etc. That all these applications of UAVs need the communication network between formations of multi-UAVs is essential to adapt this heterogeneous network and support the ad hoc network architecture without infrastructures.
- *Resource constrained:* In some specific scenarios, the design of UAV devices is essential to take into account the portability, cost, power, lifetime and size. And in general, the device is only equipped with one radio for network communications.
- *Flexible and dynamic adaptive topology changes:* FANETs are widely used in sensitive military and monitoring applications that require guaranteed data delivery. No matter facing urban noise interferes or rapid topology changes, the network should provide quick response and reliable connection. Besides, it is also very important to share the spectrum without interfering the network of PUs. In particular, the PUs may be not predictable (or cooperative). It means the multi-UAVs networks need to have robustness and adaptive ability for the sudden PU activities.

In FANET, the high mobility of UAVs will cause two serious problem: One is the problem of rapid topology change, and the other is the problem that the connection is neither durable nor reliable. This means that the MAC protocol for FANET must have a rapid rendezvous and a strong neighbourhood detection capability. At the same time, for each link with limited life span, the MAC also needs a fair and fast access mechanism. Therefore, we design a Multi-channel Opportunistic Reservation (MOR) mechanism for CogMOR-MAC which is based on opportunistic medium access model with only one radio. Besides, a spectrum-aware transceiver is introduced to provide the capability of wide-band spectrum sensing. It can send and receive data like a traditional transceiver and also can be used as a wide-band spectrum probe. Obviously, it plays an important role in improving the neighbourhood detection capability of the system. MOR mechanism includes two parts: U-MOR and B-MOR. B-MOR is very simple, and it is designed for broadcast. This is mainly for the MAC protocol to provide rapid neighbour discovery. B-MOR gets access opportunities through competition, of course, which will lead to signal collisions. For this reason, a random delay is especially added to it before the competition of access channel starts. The range of random delay will reduce as the number of competitive failures increases, so as to guarantee that each node can access channel fairly. U-MOR is designed for unicast, and it is more complex for higher reliability of data exchange. In FANET, any UAV may experience a failed link, so U-MOR can solve the rendezvous problem without a common control channel and cooperative infrastructures in order to improving robustness. Considering that the life span of the link between two UAVs is usually limited in FANET, U-MOR adopts a batch reservation mechanism for neighbouring nodes in order to improve transmission efficiency. The main purpose of this approach is to reduce the need for controlling message interaction before each transmission.

The main contributions of this paper are summarized as below:

- A cognitive multi-channel MAC protocol is proposed for multi-UAVs ad hoc networks. The MAC protocol is designed specifically for the high mobility of UAVs.
- The efficient batch reservation approach proposed in CogMOR-MAC can solve saturation problem well in rendezvous.
- The U-MOR and B-MOR mechanism in CogMOR-MAC can effectively improve the throughput of data transfer and reduce signal collisions.
- The performance comparisons validate that the CogMOR-MAC can provide reliable connection between the SUs, and also can adapt well to the sudden PU activities.

We list some key abbreviations and their corresponding explanation in Table 1 for better readability. The rest of this paper is organized as follows. The related work is discussed in Section 2 and the system mode used in CogMOR-MAC is described in Section 3. Then, the CogMOR-MAC design and the analysis of the CogMOR-MAC capability are presented in Section 4. And the performance evaluation and experimental results are shown in Section 5. Finally, conclusions are drawn and future work is discussed in Section 6.

Table 1
Some key abbreviations used in this paper.

Abbreviation	Meaning
UAV(s)	Unmanned Aerial Vehicle(s)
PU(s)	Primary User(s)
SU(s)	Second User(s)
CRT	Cognitive Radio Technology
CRAHN(s)	Cognitive Radio Ad Hoc Network(s)
MANET(s)	Mobile Ad Hoc Network(s)
VANET(s)	Vehicular Ad Hoc Network(s)
FANET(s)	Flying Ad hoc Network(s)
DCC	Dedicated Control Channel
CCC	Common Control Channel
OLSR	Optimized Link State Routing, a routing protocol
DSDV	Destination-Sequenced Distance-Vector, a routing protocol
AODV	Ad hoc On-demand Distance Vector, a routing protocol
SHCS-MAC	Slow Hopping based Cooperative Sensing MAC [13]
SUC	Secondary User Coordinator, a specific device serves the SHCS-MAC protocol [13]
MWC	Modulated Wideband Converter
AIC	Analog-to-Information Converter
QAIC	Quadrature Analog-to-Information Converter [14–16]
PHY	Physical Layer Protocol
MAC	Media Access Control
MPDU	MAC Service Data Unit
TDM	Time Division Multiplexing
CDM	Code Division Multiplexing
OFDM	Orthogonal Frequency-Division Multiplexing
RF	Radio Frequency
OMP	Orthogonal Matching Pursuit [17]
ROMP	Regularized Orthogonal Matching Pursuit [18]
CoSaMP	Compressed Sampling Matching Pursuit [19]
SAMP	Sparsity Adaptive Matching Pursuit [20]
CID	Channel Identifier
PTS	Prepare To Send, a type of MAC control frame
PTR	Prepare To Receive, a type of MAC control frame
ACK	Acknowledgement, a type of MAC control frame
CX	Continue, a type of MAC control frame
MOR	Multi-channel Opportunistic Reservation
U-MOR	Unicast-MOR mechanism
B-MOR	Broadcast-MOR mechanism
UIFS	Unicast Inter-Frame Space
BIFS	Broadcast Inter-Frame Space
BP	Beacon Period
MP	Meeting Period
TP	Transfer Period
TTR	Time-To-Rendezvous
CBR	Constant Bit Rate

2. Related work

The characteristics of multi-UAVs networks not only raised new requirements for the design of MAC protocol, but also had a significant impact on the design of routing protocol and upper layer protocol. In the literature, the MAC protocols specifically designed for multi-UAVs networks are mainly implemented by improving or modifying existing protocols, so as to effectively adapt to specific multi-UAVs application scenarios. The most common approach is based on IEEE 802.11 [9] and IEEE 802.15.4 [21].

But IEEE 802.11 and its variants are not an ideal choice, some researchers introduce the interference cancellation to overcome collision of Aloha [22]. Yaw-Wen Kuo and Jane-Hwa Huang [23] propose a CSMA with automatic synchronization (CSMA/AS) MAC protocol to mitigate the collision problem and large delay variation caused by random access. To overcome channel contention and the multi-channel hidden node problem, Md Akbar Hossain and Nurul I Sarkar [24] present a novel cognitive radio rendezvous protocol based on modified virtual carrier sensing mechanism. Wajiya Zafar and Bilal Muhammad Khan [10] introduce a novel approach based on IEEE 802.15.4 for UAV-to-UAV communication. At the same time, it can be effectively compatible with OLSR, DSDV, AODV and other upper layer routing protocols. In [25], a kind of TDMA MAC protocol is proposed for WSN-UAV systems. It can provide high throughput, fairness and efficiency communication, especially in dense networks. The paper [26] focuses on the long-distance UAV networks, and a hybrid MAC scheme is proposed. It is based on random access mode with a collision-free time slot allocation scheme. Ji Qi, Fei Hu, Xin Li, etc. [27] also introduce a MAC protocol for directional airborne networks, and it not only has throughput-efficient, smooth and low-loss-rate communication but also can achieve powerful anti-jamming performance.

From another perspective, multi-UAVs networks based on cognitive radio technology may be a more promising solution in future. At the same time, it also needs to overcome the existing challenge of wireless cognitive network. The first challenge of cognitive radio network MAC is how to exchange the control information by wireless communication between the SU devices. It is called as rendezvous problem that how to make sure the receiver can receive the messages from transmitter when the transmitter and receiver are in different channel [28]. DCC (or CCC) [29] is a typical way to solve this issue. This solution provides a specific channel for network coordination. However, the limited channel capacity of DCC is also the major bottleneck for network performance, which can cause the saturation problem. Moreover, multi-UAVs network will be disrupted if the PU activities appear on the DCC. Unlike the static allocation DCC, [30,31] provide a periodic channel rotation mechanism to achieve the dynamic DCC reallocation and reconfiguration whenever the control channel becomes unavailable. For the quality of service (QoS) problem in cognitive wireless network, Gulnur Selda Uyanik and Sema Oktug [32] present a fast, distributed, PU temporal activity estimation aided spectrum assignment scheme for a multi-channel DSA system. Sanjib K. Deka and Nityananda Sarma [33] present a hidden Markov model which can effectively learn the PU dynamics on a licenced channel. And the hidden Markov model can predict the availability of a channel with minimum delay. However, there still exists the saturation problem due to the limited channel capacity of DCC.

Therefore, the researches introduce some innovation idea (such as, frequency hopping, rendezvous hopping sequences, etc.) to solve the rendezvous problem. Frequency hopping or channel hopping techniques provide the methods of rendezvous without a DCC. In the channel hopping mechanism, SU nodes hop across channels following the same predetermined frequency hopping pattern which is called hopping list. SU nodes could exchange both control and data information with each other [34]. Obviously, a tight synchronization is needed for all SU nodes in this solution. In [13], there is a special node, called SUC, which is used to keep all SUs in the cluster synchronized by sending beacon periodically. All SU nodes would periodically follow the SUC hop to a new channel. When there is no PU activity, SUs can have a transmission. Otherwise, SUs will keep silence. The authors of [35,36] give a novel channel hopping MAC protocol for cognitive ad hoc networks. It solves the rendezvous problem by repeating the first data frame and looping the detection on all channels. However, the biggest flaw of this solution is high cost, for instance, transmitting multiple replicas or high latency. Aohan Li and Guangjie Han [37] present a fairness-based MAC (FMAC) protocol. The FMAC mainly aims to solve the problem of fairness of channel hopping MAC and provide fair data link allocation among unlicensed Secondary Users. In order to improving the channel utilization or avoiding interference, the paper [38] gives a new idea for optimizing the spectrum sensing. The authors present a prediction model for the state of transmission channels, so as to effectively reduce channel sensing overhead and implement the proactive spectrum sensing handoff. Caixia Song, Guozhen Tan, etc.[39] have focused on the transmission delay problem, and they propose an adaptive multi-priority distributed multi-channel (APDM) MAC protocol based on channel hopping techniques. The APDM MAC protocol can ensure prioritized transmission of safety packets and can effectively reduce the transmission delay of packets.

On the similar idea, rendezvous hopping sequences is a new variant of channel hopping. Tight synchronization is not necessary for this solution. Each SUs will periodically hop to a new channel according to a predetermined hopping list. When the different hopping sequences overlapping occurs, SU users could exchange and disseminate the necessary information with each other. There are numerous studies on the rendezvous protocol designs [40–43]. However, the biggest problem of this technical solution is its inefficiency. In [44], an anti-jamming channel hopping scheme is proposed. This scheme has bounded time to finish the rendezvous. A channel hopping MAC is presented in [45]. It can discover neighbours timely without utilizing any a priori coordination information in FANETs.

For the above problems, CogMOR-MAC is an efficient MAC protocol for multi-UAVs networks. In CogMOR-MAC, MOR mechanism can solve rendezvous problem for multiple transmitter–receiver pairs at one time. At the same time, through MOR mechanism, CogMOR-MAC can not only avoid the saturation problem in DCC or dynamic DCC, but also it can also effectively avoid PU activities or interferences.

3. System mode

3.1. Multi-channel mode

For convenience, the SU is denoted by $\mathbb{U}_i, i = \{1, \dots, N\}$, and the set of SUs is denoted by $\mathbb{SU}$, the set of PUs is denoted by $\mathbb{PU}$. Moreover, there is no interaction (such as message exchange) or other collaboration between PUs and SUs. The SUs monitor the presence of PUs, in order to protect the operation of the primary network and opportunistically access the under-utilized licenced bands whenever possible. Once the PUs are detected on the same band, the SUs should avoid to transmitting packets on the licenced bands. In practice, it is main that the SUs generally focus on detecting the presence of signals or active interferers above a certain signal-level threshold. A wide range of frequencies (e.g. from 1 GHz to 2 GHz) has been partitioned into K disjoint bands.

In each band, signal bandwidth of any SU or PU does not exceed the bandwidth of the band. At the same time, a band is considered as active if it contains signal energy above a certain threshold. Otherwise, the band is considered as inactive. In this paper, any inactive band can be regarded as an available channel for SUs. For notation simplicity, the channels are denoted by $C_i, i = \{1, \dots, K\}$, and the set of all channels is denoted by $\mathbb{C}$. In each channel, the sub-channel division and the carrier modulation/demodulation algorithm used in PHY are unlimited, such as TDM, CDM, OFDM, etc. However, the details in the PHY are beyond the scope of this article.

3.2. Spectrum-aware transceiver

In the CR system, the spectrum sensing is in charge of measuring the power spectral density of the signal, detecting the presence of signals in the observed band and analysing the underutilized bands where they are located. In this paper, a spectrum-aware transceiver structure is presented, and it seems to be most likely achieved in future. The spectrum-aware transceiver is illustrated in Fig. 2.

In the multi-UAVs network, each SU is equipped with one spectrum-aware transceiver which provides the ability of dynamic spectrum accessing and wide-band spectrum sensing. The SUs are able to set up their network quickly as an ad hoc network without any infrastructure. Comparing with traditional transceiver, the spectrum-aware transceiver has three work modes: transmitting, receiving and sensing. Once sensing mode is active, the spectrum sensing path will get to work. It will detect where the active bands and inactive (underutilized) bands are located across a wide range of frequencies. Once receiving mode is active, the receiver path can not only receive the data signal in a given channel, it also can be used as a narrow band detector for detecting the interfere of current channel.

As shown in Fig. 2, the different components from traditional transceivers will briefly be introduced in detail below.

- Antenna switch: The antenna switch combines the individual spectrum sensing path, receiver path and transmitter path. Only one of these working modes can be activated by antenna switch each time.
- Spectrum sensing RF front-end: It is a multi-branch analog-to-information converter (AIC) which is specifically designed to blind sub-Nyquist sampling of sparse multi-channel signals. The AIC based on the compressed sensing theory allows to sample at a rate defined by the information bandwidth rather the instantaneous bandwidth and compress the analog signal at the same time. In recently, a wide-band interferer detector chip has been successfully produced [14,15], and the detection duration is in microseconds. In the spectrum-aware transceiver, QAIC [14,16] is used as the spectrum sensing RF front-end.
- Signal reconstruction process & Interference analysis: This part is in charge of the digital signal processing associated with spectrum sensing. It contains two major blocks: signal reconstruction process block and interference analysis block. More specifically, after sampling by the spectrum sensing RF front-end, the measurements obtained will be input into the signal reconstruction process block. The OMP [46] is employed by the block to recovery the sparse multi-band signal. Of course, the sparse signal recovery algorithm is not limited to just OMP. Other recovery algorithm is a viable alternative, such as ROMP [18], CoSaMP [19], SAMP [20], etc. Once the original signals is reconstructed, they go to the interference analysis block for further processing. Energy detection [47] is used as the interference detection algorithm in interference analysis block. Since the energy detection is a representative blind detection, no prior knowledge on the noise or PU signals is needed.

4. CogMOR-MAC Design

The following subsections are organized as follows: first of all, we will be briefly describe the working process of the CogMOR-MAC. Then, we will give a detailed description of the Multi-channel Opportunistic Reservation (MOR) mechanism. At last, same key issue in CogMOR-MAC will be discussed by theoretical analysis.

4.1. Overview of the CogMOR-MAC

In CogMOR-MAC, each SU is only equipped with one spectrum-aware transceiver. When the transceiver is idle without transmission or reception, the transceiver will work on sensing mode as the default work mode. In default work mode, transceiver will continuously sense all available channels to detect the presence of PU activities or a few large interferers.

It is supposed that each unused channel can be used by SUs as an potentially transmission channel. The set of all unused channel without PU activities or interferes is called as a channel pool denoted by Ω. Meanwhile, each channel will be assigned a Channel Identifier (CID) as a unique identification. Then, a channel (or a band) can be easily identified exactly through a CID.

Before we launch into a detailed discussion of MOR mechanism, we will take a moment to review the MAC frame of the CogMOR-MAC. There are six types of control frames, including beacon B1 frame, beacon B2 frame, Prepare To Send (PTS) frame, Prepare To Receive (PTR) frame, ACK frame and CX frame. As shown in Fig. 3, the data frame of CogMOR-MAC is the MPDU frame. The following is a brief introduction to control frames.

- Beacon B1: It contains two subtypes, one is for unicast transmission, and the other is for broadcast transmission. Both specific types of control signals can be identified by a transceiver working in sensing mode. The transmitter uses it to initiate the process of MOR. If any SU sends the beacon B1 frame, all of its neighbours working in sensing mode can receive this frame and start the process of MOR.
- Beacon B2: It also includes two subtypes for unicast and broadcast, and it is very similar to beacon B1. The difference is that beacon B2 is used to reply the beacon B1 by receiver.

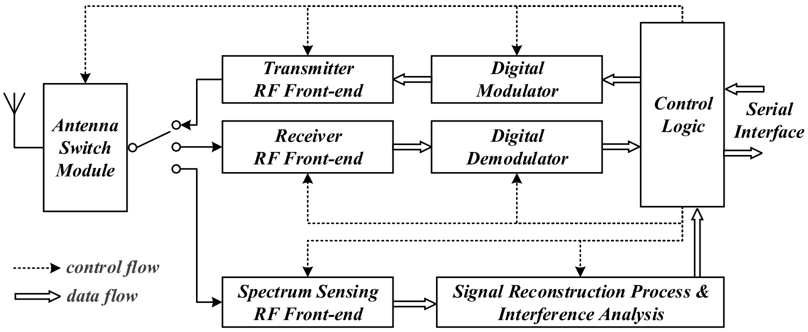


Fig. 2. Example of a spectrum-aware transceiver structure.

2 bytes
Frame control

2bits	2bits	4bits	1bit	1bit	1bit	1bit	4bits
Protocol Version	Type	SubType	More Fragments	Retry	Flag	Order	Reserved Bits

2 bytes	2 bytes	6 bytes	4 bytes
Frame control	MAC address	MAC address	CRC

(1) The format of Beacon B1 frame, Beacon B2 frame, ACK frame and CX frame

2 bytes	2 bytes	2 bytes	6 bytes	6 bytes	4 bytes
Frame control	Duration	Channel	MAC address	MAC address	CRC

(2) The format of PTS frame and PTR frame

2 bytes	2 bytes	6 bytes	6 bytes	2 bytes	0~2312 bytes	4 bytes
Frame control	Duration	MAC address	MAC address	SC	Frame body	CRC

(3) The format of MPDU frame

Fig. 3. The format of control frames in CogMOR-MAC.

- PTS: It contains a CID, a transmitter MAC address and a receiver MAC address.
- PTR: It contains a CID, a transmitter MAC address and a receiver MAC address. It is used to reply to transmitter from receiver.
- ACK: It is used as an acknowledgement frame.
- CX: It notifies the neighbouring SUs that they need to keep listening at the current channel for a reception.

In highly dynamic environment, the spectrum availability varies in time, space and frequency. Obviously, it is hard to establish a high-reliability DCC for control information exchange and dissemination. In order to solve the rendezvous problem, the MOR mechanism is introduced to the CogMOR-MAC.

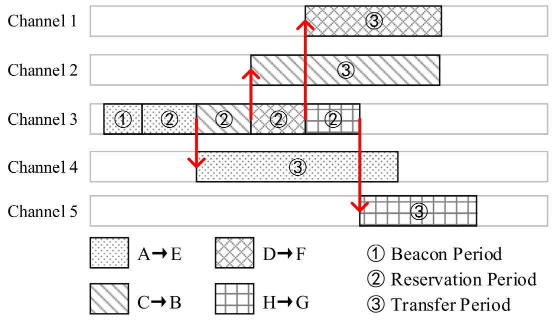
The MOR mechanism can be further subdivided into two types of MOR: (1) U-MOR. It is specifically used for unicast transmission. (2) B-MOR. It is specially designed for broadcast (or multicast) transmission.

U-MOR consists of three main phases, they are a beacon period, a reservation period and a transfer period. This U-MOR mechanism can greatly improve the rendezvousing efficiency. For example, as shown in Fig. 4(a), there are several transmitter–receiver pairs, and they are $A \rightarrow E, C \rightarrow B, D \rightarrow F, H \rightarrow F$. In Fig. 4(a), node A initiates the U-MOR process. During the beacon period, node A sends a beacon B1 in channel 3 to notify the neighbouring nodes to start the U-MOR process, and node E reply a beacon B2 to A node in channel 3. Then, in the reservation period, node A will send PTS frame to notify the neighbouring nodes that the channel 4 is reserved for the data transmission. And node E will reply a PTR frame to node A, PTR frame has the same function as PTS frame. At last, both node A and node E will hop to the channel 4 for data transmission, and the duration of data transmission is called a transfer period. Any other node which wants to have a transmission with node A or node E will also hop to the channel 4.

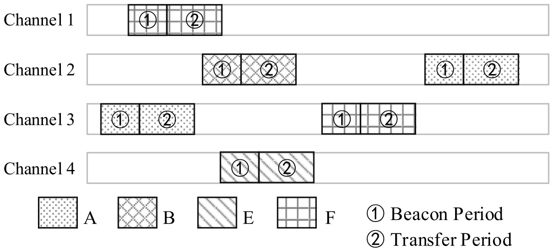
When node A and node E finish the channel reservation process through PTS and PTR, other nodes will continue to start a new reservation period and to start a new channel reservation process for data transmission. As shown in Fig. 4(a), node C and node B access the channel 3 and send PTS/PTR by competition. After the process of channel reservation, they will hop to channel 2 for data transmission. In the same way, the rest of transmitter–receiver pairs can direct finish the channel reservation process without additional time-to-rendezvous.

However, the batch channel reservation method is able to save additional time-to-rendezvous, but it is not suitable for broadcast. Because the neighbour range of each node is different. If the broadcast message is delivered by U-MOR, the propagation scope of the broadcast message will be severely limited. Therefore, the CogMOR-MAC introduces B-MOR mechanism to deliver the broadcast message.

B-MOR is illustrated with a simple example as shown in Fig. 4(b). Node A wants to send a broadcast frame. At first, it will send beacon B1 which is different from beacon B1 in unicast to its neighbours. Any node received the beacon B1 in sensing mode must reply a beacon B2 to the transmitter. Obviously, if any beacon B2 or signal collision is detected by node A, node A can direct go into transfer period. In the transfer period, node A will broadcast the frame to the neighbours. After that,



(a) U-MOR



(b) B-MOR

Fig. 4. Two examples of MOR mechanism.

Table 2
Notations used in CogMOR-MAC.

Variable	Meaning & value
R	The frame sending rate
L_{b1}	The size of beacon B1 frame
L_{b2}	The size of beacon B2 frame
L_{pts}	The size of PTS frame
L_{ptr}	The size of PTR frame
L_{ack}	The size of ACK frame
L_{cx}	The size of CX frame
L_{data}	The size of MPDU frame
T_{Sx1}	The period of $Sx1$ slot, T_{sx1} = 500 μs
T_{Sx2}	The period of $Sx2$ slot, T_{sx2} = 200 μs
T_{Sx3}	The period of $Sx3$ slot, T_{sx3} = 200 μs

the B-MOR is over. Otherwise, if a channel is idle after the node A sends the beacon B1, that means no neighbours around is ready to receive the broadcast frame. Then, node A needs to wait for a next retransmission.

4.2. Multi-channel opportunistic reservation mechanism

In this section, the U-MOR will be discussed in detail at first. And the B-MOR will be described in detail later. In addition, the notations used for describing in CogMOR-MAC are shown in Table 2.

In addition, CogMOR-MAC employs a slotted access mechanism as presented in Figs. 5 and 6. And the state machine of MOR is shown in Fig. 7. In CogMOR-MAC, there are several types of time slots, and different slots will have different durations. The durations of $Sx1$ slot, $Sx2$ slot and $Sx3$ slot are fixed time slots, and the others are flexible time slots. If the duration of time slot is fixed, only the timer of duration goes off, and this time slot is over. The flexible time slot includes $Bx1$ slot, $Bx2$ slot, Tb slot, Tu slot, Ru slot, Tx slot, Rx slot and Cx slot, and each time slot has a timeout period. If a corresponding frame is received or sent during the timeout period, the flexible time slot will end early. Meanwhile, the next time slot will immediately start timing. Otherwise the flexible time slot will not end until the timeout period is expired.

The U-MOR mechanism consists of three phases: (1) The Unicast Beacon Phase; (2) The Opportunistic Reservation Phase; (3) The Unicast Data Transfer Phase. See Fig. 5 for the details. Unicast Beacon Phase and Opportunistic Reservation Phase are generally used to solve the rendezvous problem without a dedicated CCC. Data Transfer Phase is specially used for aggregate transmission between the transmitter and the receiver.

4.2.1. Unicast Beacon Phase

The duration of Unicast Beacon Phase is called Beacon Period (BP). A BP includes two different time slots: a $Bx1$ slot and a $Bx2$ slot.

The two slots of the BP are respectively designed for the transmission of beacon B1 frame and beacon B2 frame. Each time a unicast packet needs to be delivered and the SU is in the default mode, then the SU will find a reservation channel δ_{RC} at first. The reservation channel is an idle channel selected from channel pool Ω. Obviously, to make sure that the SU can have enough time to finish the spectrum sensing work for finding a reservation channel δ_{RC}, the SU should stay in the sensing mode for a Unicast Interframe Space (UIFS) duration at least.

For convenience, the transmitter is denoted by $\mathbb{U}_s$, and the receiver is denoted by $\mathbb{U}_r$. When $\mathbb{U}_s$ initiates a U-MOR process and succeeds in selecting a reservation channel δ_{RC}, $\mathbb{U}_s$ will switch the transceiver to transmitting mode, and send beacon B1 frame at the $Bx1$ slot. The beacon B1 frame contains the MAC addresses of the transmitter and receiver.

Obviously, if this UIFS is a constant value, it will be very easy to cause the signal collision. For this reason, it is specially added a random delay before the competition starts. The range of random delay will reduce as the number of competitive failures increases, so as to guarantee that each node can access channel fairly. Then, let the duration of UIFS be denoted by T_{uifs}, and it can be calculated by the following formula,

$$T_{uifs} = T_{sifs} + T_{cw} = T_{sifs} + \lambda T_{slot} \tag{1}$$

where λ is a random integer, $\lambda \in [0, 2^{\tau} - 1]$, $\tau \in [4, 8]$, T_{slot} is the basic time unit in CogMOR-MAC. T_{sifs} is a minimum time interval for which receiver wait before sending a MAC frame. λT_{slot} is the random delay. Then, the range of random delay can be controlled by τ. In CogMOR-MAC, when the transmission is over, τ will reset to a maximum value. As time goes on, τ becomes smaller and smaller until it reaches its minimum value.

When a beacon B1 frame is sent out, the $Bx1$ slot is over. If $\mathbb{U}_r$ receives a beacon B1 frame and $\mathbb{U}_r$ is also in the sensing mode, $\mathbb{U}_r$ will start the U-MOR process and reply a beacon B2 frame at $Bx2$ slot. If $\mathbb{U}_s$ receives the beacon B2 frame, $Bx2$ slot will end and start the opportunistic reservation phase.

Of course, if $\mathbb{U}_r$ does not catch the beacon B1 frame, $\mathbb{U}_s$ will wait for response until the timeout of $Bx2$ slot. Then, $\mathbb{U}_s$ will turn into the sensing mode and wait for a next retransmission.

If the other SUs (excluding $\mathbb{U}_s$ and $\mathbb{U}_r$) receive the beacon B1 frame, they will also switch the transceiver from sensing mode to receiving mode. Then, they will continue to keep listening in the channel δ_{RC} whether there will be a beacon B2 frame following up to response to the $\mathbb{U}_s$. If any SU receives a beacon B2 frame, the SU will start U-MOR process following $\mathbb{U}_s$ and $\mathbb{U}_r$. And these SUs will directly hop to opportunistic reservation phase.

4.2.2. Opportunistic reservation phase

The duration of Opportunistic Reservation Phase is called Reservation Period. And the Reservation Period contains Φ_{MP} consecutive Meeting Period (MP). The first MP is a particular case which only includes a $Sx1$ slot, a Tu slot and a Ru slot. The subsequent $(\Phi_{MP} - 1)$ MP consists of a $Sx2$ slot, a Tu slot and a Ru slot.

$Sx1$ slot is a fixed time slot, each SU will switch the transceiver to sensing mode at $Sx1$ slot, then each SU can analyse the utilization of all channels. Each SU will update the channel pool Ω after the spectrum sensing. If $\delta_{RC} \notin \Omega$, it indicates that the current reservation channel is

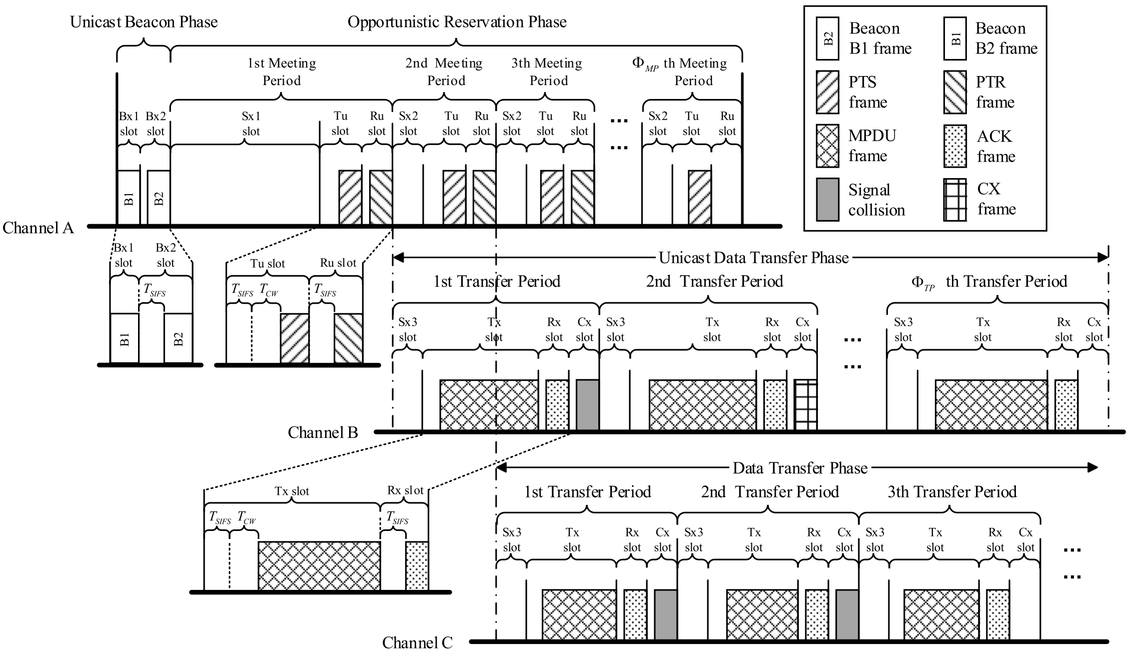


Fig. 5. The structure of U-MOR.

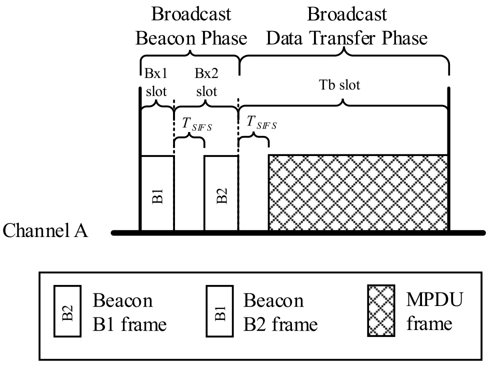


Fig. 6. The structure of B-MOR.

occupied by PU activities, every SU must turn into sensing mode and wait for a next retransmission in order to avoiding a disruption to the PU activities. If $\delta_{RC} \in \Omega$, each SU will continue to start the next time slot.

The Tu slot and Ru slot are the following time slots, and they are designed for sending PTS frame and PTR frame respectively as shown in Fig. 5. The PTS/PTR frame contains a CID, and the CID indicates a Data Channel (DC) which is used for data transfer. $\delta_{DC}^{s\to r}$ is used to denote the DC. Obviously, SU should select a channel as DC from Ω before transmitting the PTS frame.

For the first MP, $\mathbb{U}_s$ has a priority on any other SUs to access the channel δ_{RC} after the $Sx1$ slot. $\mathbb{U}_s$ can just wait for a interval T_{sifs} before transmitting a PTS frame to $\mathbb{U}_r$. After the transmission, Tu slot is over and Ru slot starts. If $\mathbb{U}_r$ receives the PTS frame, $\mathbb{U}_r$ will reply a PTR frame to $\mathbb{U}_s$ at Ru slot.

If a signal collision is detected at Tu slot, other SUs will keep silence during the period of Ru slot. Then transmitter will find that the transmission is failure, and the transmitter will wait for a next Tu slot for retransmission.

When $\mathbb{U}_s$ receives the PTR frame, Ru slot is over. And both $\mathbb{U}_s$ and $\mathbb{U}_r$ will hop to $\delta_{DC}^{s\to r}$, and go into the data transfer phase. Any SUs receiving the PTS/PTR frame can also hop with $\mathbb{U}_s$ and $\mathbb{U}_r$ to the channel $\delta_{DC}^{s\to r}$, if they want to have a transmission with $\mathbb{U}_s$ or $\mathbb{U}_r$.

For the subsequent ($\Phi_{MP} - 1$) MP, $Sx2$ slot is also a fixed slot, but it is different from the $Sx1$ slot. Each SU will turn into receiving mode and keep detecting whether there is PU activities or interference in δ_{RC} during the period of $Sx2$ slot. SUs will update the channel pool Ω according to the results of detection. If $\delta_{RC} \notin \Omega$, it indicates that channel δ_{RC} is no longer suitable for exchanging control information, and SUs should stop the U-MOR process and turn into sensing mode waiting for a next retransmission. If $\delta_{RC} \in \Omega$, SUs will continue to start a new Tu slot.

In the subsequent ($\Phi_{MP} - 1$) MP, each SU can access the channel δ_{RC} at Tu slot by contention. All SUs must wait a interval ($T_{sifs} + T_{cw}$) before transmitting a PTS frame in channel δ_{RC}. When a SU transmits a frame before others, other SUs should give up this opportunity to make the reservation. The rest SUs which fail in contention need to wait for a next Tu slot for retransmission.

Just like the first MP, if there is a signal collision at the Tu slot, the channel reservation is failure. And the SU must wait for a new Tu slot in next MP. Obviously, there is no reception or transmission during the whole period of Tu slot and Ru slot. Every SU will turn the transceiver into sensing mode.

4.2.3. *Unicast data transfer phase*

Unicast Data Transfer Phase is also composed of Φ_{TP} consecutive Transfer Period (TP). Each TP includes a $Sx3$ slot, a Tx slot, a Rx slot and a Cx slot.

$Sx3$ slot is designed for interference detection in channel $\delta_{DC}^{i\to j}$, and all SUs in the channel $\delta_{DC}^{i\to j}$ should keep silence during the period of $Sx3$ slot, where $\delta_{DC}^{i\to j} \in \Omega$, $\mathbb{U}_i \in \mathbb{SU}$, $\mathbb{U}_j \in \mathbb{SU}$

After updating the channel pool Ω, only if the channel $\delta_{DC}^{i\to j} \in \Omega$, the next Tx slot will start. Otherwise, the data transfer will fail, and SUs will turn their transceiver to sensing mode.

The $\mathbb{U}_i$ has a priority on any other SUs in channel $\delta_{DC}^{i\to j}$ to access the $\delta_{DC}^{i\to j}$ at first Tx slot. $\mathbb{U}_i$ just needs to wait a interval T_{sifs} before sending MPDU frame to $\mathbb{U}_j$ at the Tx slot. For the rest ($\Phi_{TP} - 1$) TP, every SU can access channel $\delta_{DC}^{i\to j}$ by contention. Each SU needs to wait a interval ($T_{sifs} + T_{cw}$) before access the channel $\delta_{DC}^{i\to j}$. If a SU successfully obtains channel access rights, other SUs need to wait for a next Tx slot.

Rx slot is designed for transmitting response. If the receiver SU receives a MPDU frame from transmitter SU, it will reply a ACK frame

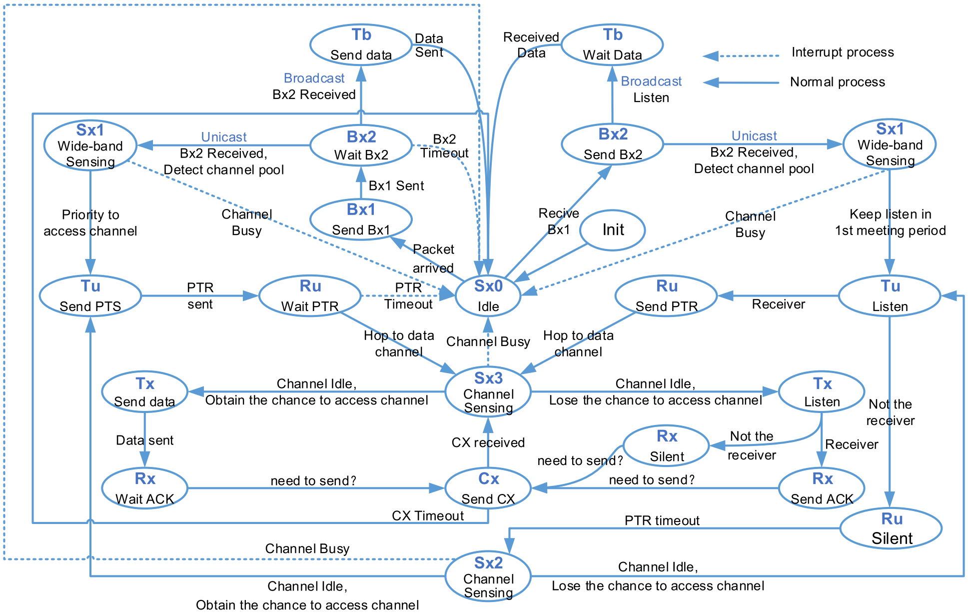


Fig. 7. The state machine of MOR in CogMOR-MAC.

to the transmitter node at Rx slot. Of course, before receiver SU replies a ACK frame, the receiver needs to wait a interval T_{sifs}.

Cx slot is used for sending CX frame. After the Tx slot and the Rx slot, if any SU still wants to have a transmission with $\mathbb{U}_i$ or $\mathbb{U}_j$, they will send a CX frame at Cx slot. Of course, if the channel is silent without any signal collision or CX frame during the period of T_{cx}^{max}, SUs will exit unicast data transfer phase and back to sensing work mode. Otherwise, the unicast data transfer phase will continue and a new TP period will start timing. Of course, the maximum number of TP is Φ_{TP} in each unicast data transfer phase. After the last TP, all SUs should exit the U-MOR and work in the sensing mode. The main aim of this measure is to ensure the fairness of channel access for every SU.

4.2.4. B-MOR

The support for multicast and broadcast is critical capability for a multi-UAVs ad hoc networks, without the support for multicast and broadcast higher layer protocols cannot operate properly. For example, the address resolution cannot be carried out without broadcast. But, for multi-channel MAC, SUs often belong to different channel, it is very difficult to deliver the message to every neighbour at the same time. Then, CogMOR-MAC employs B-MOR to address this problem.

The B-MOR mechanism consists of two phases: (1) Broadcast Beacon Phase; (2) Broadcast Data Transfer Phase. See Fig. 6 for the details. Broadcast Beacon Phase contains two time slots, they are $Bx1$ slot and $Bx2$ slot.

Before a SU wants to broadcast a packet, it should keep in sensing mode for a Broadcast Interframe Space (BIFS) duration. $\mathbb{U}_b$ denotes the transmitter, the duration of BIFS is denoted by T_{bifs}, and it can be calculated by the following formula,

$$T_{bifs} = T_{sifs} + T_{cw} = T_{sifs} + \varepsilon T_{slot} \tag{2}$$

where ε is a random integer, $\varepsilon \in [0, 2^{\sigma} - 1]$, $\sigma \in [4, 8]$. εT_{slot} is also a random delay which has the same effect as the λT_{slot} in Eq. (1).

Then, after T_{bifs} period, $\mathbb{U}_b$ will select a channel as δ_{RC}. Then, if $\mathbb{U}_b$ is still in sensing mode, $\mathbb{U}_b$ will send a beacon B1 frame in channel δ_{RC}.

Of course, $\mathbb{U}_b$ can easily determine whether to continue to send broadcast packet at Tb slot by the state of the channel δ_{RC}. If the channel δ_{RC} is detected as idle during the $Bx2$ slot, it illustrates that there is no other SU ready to receive the packet. Then $\mathbb{U}_b$ will back to sensing mode for at least T_{bifs} period and wait for another retransmission. If the channel δ_{RC} is detected as busy during the $B2$ slot, $\mathbb{U}_b$ will end the $B2$ slot, and start broadcast data transfer phase.

For broadcast, there is no need to acknowledge, so the broadcast data transfer phase is very simple. After waiting for a T_{sifs} period, $\mathbb{U}_b$ will send the MPDU frame in channel δ_{RC}. When the transmission is finished, the broadcast is over and the transceiver will back to sensing mode.

4.3. Theoretical analysis

In this section, it is introduced two performance metrics for evaluating the CogMOR-MAC by theoretical analysis. What should be noted here is that the evaluation analysis is focused on the performance of unicast. The two performance metrics are described as follows.

- Average time-to-rendezvous: Before $\mathbb{U}_i$ sends a MPDU frame to its neighbour $\mathbb{U}_j$, $\mathbb{U}_i$ needs an amount of time T to find $\mathbb{U}_j$ and prepare for exchanging control message with $\mathbb{U}_j$ the time T is usually called to time-to-rendezvous (TTR). The average value of N transmitter–receiver pairs' TTR is the average time-to-rendezvous.
- Maximum throughput: Throughput is the rate of successful message delivery over a communication link. Then, in unit time, the maximum successful delivery of all link is the maximum network throughput.

4.3.1. Average time-to-rendezvous

Without loss of generality, it is assumed that at the beginning all SUs are in the default (sensing) mode, which is denoted by $Sx0$ in Fig. 7. In most cases perfect radio conditions without interference or PU activities are assumed so as to simplify the analysis. Considering what has been discussed in the sections above, it is easily obtained the duration of various states in the state machine as follows,

$$\begin{cases} T_{Bx1} = L_{b1}/R + T_{uifs} \\ T_{Bx2} = L_{b2}/R + T_{sifs} \\ T_{Tu} = L_{pts}/R + T_{uifs} \\ T_{Ru} = L_{ptr}/R + T_{sifs} \\ T_{Tx} = L_{data}/R + T_{uifs} \\ T_{Rx} = L_{ack}/R + T_{sifs} \\ T_{Cx} = L_{cx}/R + T_{sifs} \\ T_{Tb} = L_{data}/R + T_{bifs} \end{cases} \tag{3}$$

where the description of variables is shown in Table 2.

It is considered there are N transmitter–receiver pairs SUs in the network, where all of these SUs are neighbours to each other. Otherwise, if they are not neighbours, their TTR will not be affected. Obviously, TTR only needs to consider the case of U-MOR. As shown in Figs. 5 and 7, the TTR of 1st transmitter–receiver pairs is given by,

$$T_1^{ttr} = T_{Bx1} + T_{Bx1} + T_{Sx1} \tag{4}$$

Of course, for the ith transmitter–receiver pairs, if $i \leqslant \Phi_{MP}$, the ith TTR is as follows,

$$\begin{aligned} T_i^{ttr} =& T_{Bx1} + T_{Bx1} + T_{Sx1} \\ &+ (i-1)(T_{Sx2} + T_{Tu} + T_{Ru}) \end{aligned} \tag{5}$$

Because only Φ_{MP} transmitter–receiver pairs can be rendezvoused after once U-MOR. If $i > \Phi_{MP}$, it takes several times U-MOR to complete the rendezvous of all transmitter–receiver pairs. In Fig. 5, it can be derived the expression of ith the TTR as follows.

If $i > \Phi_{MP}, (i \bmod \Phi_{MP}) = 0$, than

$$\begin{aligned} T_i^{ttr} = & \left\lfloor \frac{i}{\Phi_{MP}} \right\rfloor [T_{Bx1} + T_{Bx2} + T_{Sx1} + (\Phi_{MP} - 1) \\ & \times (T_{Sx2} + T_{Tu} + T_{Ru})], \end{aligned} \tag{6}$$

If $i > \Phi_{MP}, (i \bmod \Phi_{MP}) \neq 0$, than

$$\begin{aligned} T_i^{ttr} = & \left\lfloor \frac{i}{\Phi_{MP}} \right\rfloor [T_{Bx1} + T_{Bx2} + T_{Sx1} + (\Phi_{MP} - 1) \\ & \times \ (T_{Sx2} + T_{Tu} + T_{Ru})\big] + T_{Bx1} + T_{Bx2} + T_{Sx1} \\ & + \big[(i \bmod \Phi_{MP}) - 1\big] \times (T_{Sx2} + T_{Tu} + T_{Ru}), \end{aligned} \tag{7}$$

The expression of average TTR is given by,

$$\bar{T}^{ttr} = \frac{1}{N} \sum_{i=1}^{i=N} T_i^{ttr} \tag{8}$$

For the sake of analysis, it is defined that $\alpha_1 = T_{Bx1} + T_{Bx2} + T_{Sx1}$, and $\alpha_2 = T_{Sx2} + T_{Tu} + T_{Ru}$. Besides, α_1 and α_2 can be approximated as a constant according to Eq. (3). Through combining the Eqs. (5)–(8), it can be obtained the average TTR (denoted by $\bar{T}^{ttr}$) as below.

If $N \leqslant \Phi_{MP}$, then the $\bar{T}^{ttr}$ is given by,

$$\bar{T}^{ttr} = \alpha_1 + \frac{(N-1)}{2}\alpha_2 \tag{9}$$

If $N > \Phi_{MP}$, $(i \bmod \Phi_{MP}) = 0$, then the $\bar{T}^{ttr}$ is given by,

$$\bar{T}^{ttr} = \left\lfloor \frac{N}{\Phi_{MP}} \right\rfloor \left[\frac{\Phi_{MP}}{N}\alpha_1 + \frac{\Phi_{MP}(\Phi_{MP}-1)}{2N}\alpha_2 \right] \tag{10}$$

If $N > \Phi_{MP}$, $(i \bmod \Phi_{MP}) = j \neq 0$, the $\bar{T}^{ttr}$ is given by,

$$\begin{aligned} \bar{T}^{ttr} = & \left\lfloor \frac{N}{\Phi_{MP}} \right\rfloor \left[\frac{\Phi_{MP}}{N}\alpha_1 + \frac{\Phi_{MP}(\Phi_{MP}-1)}{2N}\alpha_2 \right] \\ & + \left[\frac{j}{N}\alpha_1 + \frac{j(j-1)}{2N}\alpha_2 \right] \end{aligned} \tag{11}$$

Then, it can be found by observing, Eqs. (9)–(11) can be further converted to the following expressions,

$$\bar{T}^{ttr} = \alpha_1 + \frac{(N-1)}{2}\alpha_2, N \leqslant \Phi_{MP} \tag{12}$$

$$\begin{aligned} & \bar{T}^{ttr} = \theta\alpha_1 + \frac{\theta(\Phi_{MP}-1)}{2}\alpha_2, \\ & N > \Phi_{MP}, (N \bmod \Phi_{MP}) = 0 \end{aligned} \tag{13}$$

$$\begin{aligned} \bar{T}^{ttr} =& \theta\alpha_1 + \frac{\theta(\Phi_{MP}-1)}{2}\alpha_2 \\ & + \left[\frac{j}{N}\alpha_1 + \frac{j(j-1)}{2N}\alpha_2 \right], \\ & N > \Phi_{MP}, (N \bmod \Phi_{MP}) \neq 0 \end{aligned} \tag{14}$$

where $\left\lfloor \frac{N}{\Phi_{MP}} \right\rfloor \Phi_{MP} = \theta N$, $\theta \leqslant 1$ and $(i \bmod \Phi_{MP}) = j < \Phi_{MP}$.

Before jumping to any conclusions, we need to consider a traditional MAC protocol which is based on DCC or dynamic DCC. The rendezvous of each transmitter–receiver pair needs to be processed serially on DCC or dynamic DCC. Let the β_1 denote the waiting time spent on the waiting access DCC or dynamic DCC, β_2 denote the transmission time spent on exchanging information between the transmitter and receiver on DCC or dynamic DCC. In additional, Y_i^{ttr} denotes the ith TTR of traditional MAC, the $\bar{Y}^{ttr}$ is the average TTR of traditional MAC. The conclusions can easily be derived as follows,

$$Y_i^{ttr} = \beta_1 + (i-1)(\beta_1 + \beta_2) \tag{15}$$

$$\bar{Y}^{ttr} = \beta_1 + \frac{N-1}{2}(\beta_1 + \beta_2) \tag{16}$$

Obviously, comparing Eqs. (12)–(14) and (16), it may be found that the $\bar{Y}^{ttr}$ will increase with the constant increase of N, because Eq. (16) is a function of linear growth, where β_1 and β_2 can be approximated as a constant, N is a variable.

Comparing with the $\bar{Y}^{ttr}$, when $N < \Phi_{MP}$, the $\bar{T}^{ttr}$ has the same growth pattern as traditional MAC. But when $N > \Phi_{MP}$, $\bar{T}^{ttr}$ has a fixed upper bound value. That means the U-MOR mechanism can provide effective access mechanism for large-scale networks to solve the rendezvous problem.

4.3.2. *Maximum throughput*

In this section, we will evaluate the maximum throughput of the U-MOR mechanism at full capacity. It is defined that there are N transmitter–receiver pairs SUs in the network, where all of these SUs are neighbours to each other. Each transmitter needs to deliver M frame to the receiver. According to Fig. 5, it can easily be found that if all the meeting periods and transfer periods in U-MOR are fully used by different transmitter–receiver pairs, the system can reach to the maximum throughput.

In order to achieving the peak throughput, these following conditions should be met,

$$\begin{cases} K \geqslant \Phi_{MP} + 1, \\ M \leqslant \Phi_{TP}, \\ N \leqslant \Phi_{MP} \end{cases} \tag{17}$$

where $C_k \in \mathbb{C}$, $i = \{1, \dots, K\}$.

As shown in Figs. 5 and 7, the maximum cumulative delivery quantity of one U-MOR is $Q_{max} = \Phi_{MP}\Phi_{TP}L_{data}$.

The next step is to calculate the duration of the whole process. Obviously, the whole process is over when the last transmitter–receiver pair finishes their transmission. The following expression can be obtained,

$$\begin{aligned} T_{max} =& T_{Bx1} + T_{Bx2} + T_{Sx1} - T_{Sx2} \\ & + \Phi_{MP}(T_{Tu} + T_{Ru} + T_{Sx2}) \\ & + \Phi_{TP}(T_{Sx3} + T_{Tx} + T_{Rx} + T_{Cx}) \end{aligned} \tag{18}$$

Then, it is easy to obtained the maximum throughput as follows,

$$\begin{cases} \xi_1 = T_{Bx1} + T_{Bx2} + T_{Sx1} - T_{Sx2} \\ \xi_2 = T_{Tu} + T_{Ru} + T_{Sx2} \\ \xi_3 = T_{Sx3} + T_{Tx} + T_{Rx} + T_{Cx} \\ P_{max} = \dfrac{\Phi_{MP}\Phi_{TP}L_{data}}{\xi_1 + \Phi_{MP}\xi_2 + \Phi_{TP}\xi_3} \end{cases} \tag{19}$$

Eq. (19) can be further converted to the following expressions,

$$P_{max} = \frac{L_{data}}{\dfrac{\xi_1}{\Phi_{MP}\Phi_{TP}} + \dfrac{\xi_2}{\Phi_{TP}} + \dfrac{\xi_3}{\Phi_{MP}}} \tag{20}$$

From Eq. (20), it can be seen that the greater the value of Φ_{MP} and Φ_{TP} is, the greater the upper limit of the total throughput. However it will take more time to wait for the receiver to exit the U-MOR, when a transmitter cannot find this receiver. Therefore, blindly increasing the value of Φ_{MP} and Φ_{TP} will lead to the decrease in the fairness of random access channels.

To better understand the parallel advantages of MOR, we consider a typical multi-channel MAC protocol with CCC [48] as an example. For convenience of description, X-MAC is used to denote this kind of MAC protocols with CCC [48]. X-MAC has a common control channel for exchanging control message, and X-MAC will use other channels for data transmission. It means that no matter how fast the data is transmitted on data channels, the system bottlenecks will be primarily determined by the single control channel. But for CogMOR-MAC, only nodes in the neighbourhood are affected by the bottleneck effect, not the entire network. There usually need several parallel U-MOR processes to cover the whole network.

Besides, batch reservation is another advantage of MOR. To make it easier to understand the differences, it is also considered there are N transmitter–receiver pairs SUs in the network. D_{data} denotes the cumulative delivery quantity of each transmitter–receiver pair. $T_{detection}$ denotes the time required to finish the spectrum sensing. T_{data} denotes the time cost for data transmission. $T_{control}$ denotes the time required to exchange control information for a pair of transmitter–receiver. T_{wait} denotes the idle waiting time after a transmission. All the random access models (including IEEE 802.11 DCF) will have this overhead (T_{wait}), and it is inevitable. But for CogMOR-MAC, every Φ_{MP} exchanging of control message will add an extra T_{wait}. When the values of these variables (D_{data}, $T_{detection}$, T_{data}, $T_{control}$ and T_{wait}) in CogMOR-MAC and X-MAC are the same, it can be roughly deduced the following result.

$$\begin{cases} P_1 = \dfrac{N D_{data}}{\lfloor \frac{N}{\Phi_{MP}} \rfloor (T_{detection} + T_{control} + T_{wait}) - T_{wait} + T_{data}} \\ P_2 = \dfrac{N D_{data}}{N(T_{detection} + T_{control} + T_{wait}) - T_{wait} + T_{data}} \\ P_1 > P_2 \end{cases} \tag{21}$$

where P_1 is the maximum throughput of CogMOR-MAC, P_2 is the maximum throughput of X-MAC. Obviously, there is a certain maximum throughput advantage over multi-channel MAC protocols which rely on a common control channel.

5. Performance evaluation

In this section, we present the validation and performance evaluation of CogMOR-MAC protocol on NS-2.35 simulator which is extended from the Chunxiao Chigan's cognitive radio cognitive network testbed [49]. For more reasonable performance comparison, SHCS-MAC [13] is selected as a comparison. Because SHCS-MAC has the same radio cost (i.e. with only one single radio) and it is also a multi-channel MAC protocol. The difference is that in SHCS-MAC the node accesses the unused channel by periodic polling, but not opportunistic reservation. In this section, firstly the baseline comparisons is presented in term of cumulative delivery quantity, delivery rate, average packet delay with SHCS-MAC. Later, it will be illustrated the impact of PU activities through the real-time throughput curve of the two MAC protocols. Besides, If ones are interested in the implementation particulars, the correlative CogMOR-MAC source code can be found in [50].

5.1. Simulation settings

In the experiments, 5 SU nodes are deployed in a 1000 m × 1000 m area, and the location is shown in Fig. 8. For each SU node, there are 10 licenced channels (numbered from 0 to 9) as the available channel pool. The communication range is 225 m for SU nodes, while the maximum effective range of PU signal is 550 m. Limited by the lack of wireless signal modulator–demodulator modules in the simulator's PHY layer, the capabilities for spectrum sensing cannot be implement in the experiments. So, it is assumed that if the equipped radios (using for transceiver or spectrum sensing) can get enough detection duration and reception signal power, the radios can successfully detect the PU activities or interference signals. In addition, some essential parameters are represented in Table 3.

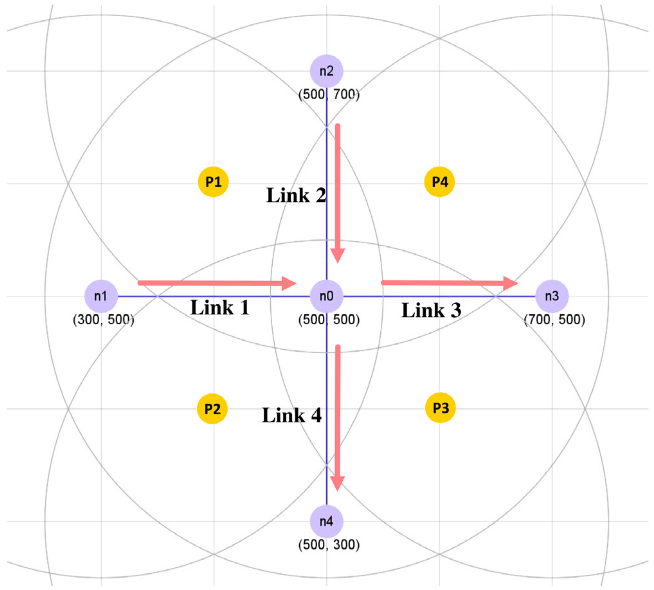


Fig. 8. Example of a MOR mechanism for parallel transmissions.

Table 3
Parameter values for evaluation.

Parameter	Value
Packet sending rate	6 Mbps
Packet size of UDP playload	1000 B
$flow1$	CBR traffic flows from n1 to n0 by UDP
$flow2$	CBR traffic flows from n2 to n0 by UDP
$flow3$	CBR traffic flows from n0 to n3 by UDP
$flow4$	CBR traffic flows from n0 to n4 by UDP
T_{sifs}	Response wait interval, $T_{sifs} = 10$ µs
T_{bifs}	Broadcast wait interval, $T_{bifs} \in [11, 73]$ µs
T_{uifs}	Unicast wait interval, $T_{uifs} \in [11, 73]$ µs
T_{eifs}	Collision blocking time, $T_{eifs} = 100$ µs
T_{nifs}	Interference blocking time, $T_{nifs} = 1$ s
T_{slot}	The basic time unit, $T_{slot} = 1$ µs

We set up 4 Constant Bit Rate (CBR) traffic flows during the whole experiment, and they are $flow1$, $flow2$, $flow3$ and $flow4$, respectively. Furthermore, we place 4 PU nodes in the same area with SU nodes, as shown in Fig. 8. At first, the PU nodes will not be active. And the PU nodes will begin their activities after 100s of the experiment. Then the PU nodes will select 4 channels as their active channels.

5.2. The baseline comparisons between CogMOR-MAC and SHCS-MAC

The baseline comparisons are aimed at studying the performance trends of the two MAC protocols. From Fig. 9, it can be found that the cumulative delivery quantity of CogMOR is better than that of SHCS-MAC. However, the fairness of channel access is a key index to control traffic flows for the network. Obviously, CogMOR-MAC has an advantage over SHCS-MAC in fairness of channel access, because each link can have opportunities to deliver at least 1×10^7 Bytes data for CogMOR-MAC. By contrast, there is no guarantee of fairness in SHCS-MAC, and most of opportunities to access the channel are assigned to $flow1$ and $flow2$.

As shown in Fig. 9, the average packet delay of CogMOR-MAC is relatively higher than that of SHCS-MAC, it is because CogMOR-MAC must go through the MOR mechanism to start a transmission. In order to further study the delay characteristic in CogMOR-MAC, the packet delay distributions are shown in Fig. 10. Although these packet delay costs

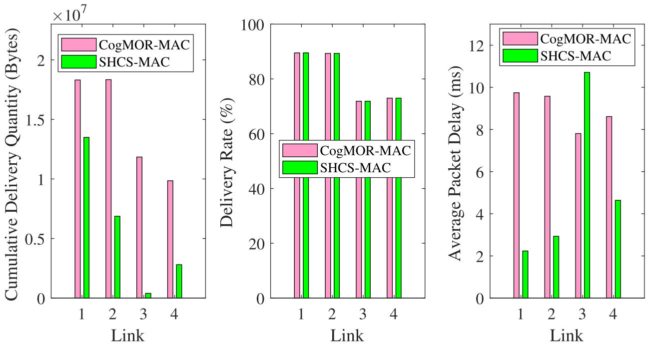


Fig. 9. The baseline comparisons in term of cumulative delivery quantity, delivery rate, average packet delay.

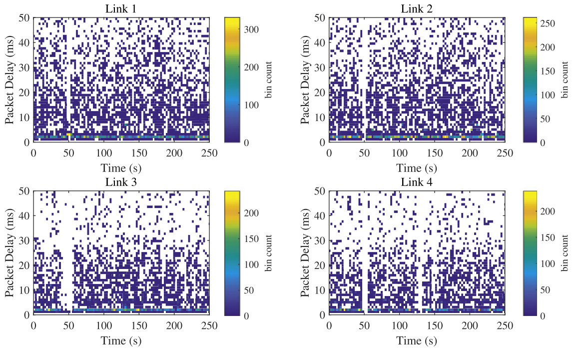


Fig. 10. The packet delay distributions for CogMOR-MAC.

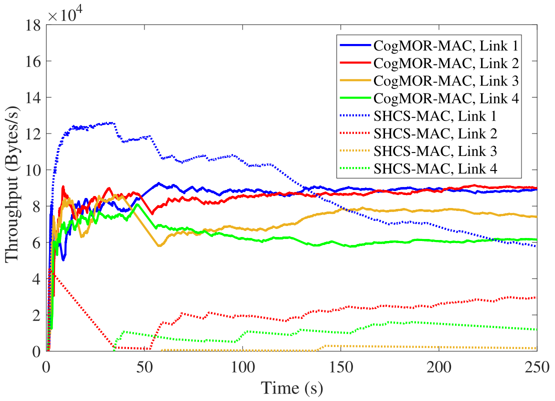


Fig. 11. The throughput curve of the CogMOR-MAC and SHCS-MAC.

are unavoidable, they can be controlled within an acceptable range. In Fig. 10, most of the markers are below 10 ms.

Of course, SHCS-MAC has no absolute advantage in average packet delay. In Fig. 9. it can be noticed that the CBR traffic flow on Link 3 is mostly blocked by the other traffic flow. Although the delivery rate is very high on Link 3, the traffic flow has few opportunities to access the channel on Link 3. So, the average packet delay on Link 3 is much higher than the Peak value of CogMOR-MAC.

5.3. *The impact of PU activities comparisons between CogMOR-MAC and SHCS-MAC*

Then, by the throughput curve of the two MAC protocols, as shown in Fig. 11, it shows the impact of PU activities comparisons between CogMOR-MAC and SHCS-MAC. In Fig. 11, although the throughput rate of each link is different, the throughput of CogMOR-MAC is almost completely unaffected by the PU activities when the PU starts to activate at 100 s in the experiment. For each link, the CogMOR-MAC provides a relatively stable transmission efficiency. Then, we recorded the maximum throughput rate of all links and calculated the average value. At last, CogMOR-MAC's average value of maximum throughput rate on each link is 87.75 KB/s, and SHCS-MAC's average value of maximum throughput rate on each link is 50.75 KB/s. So that the throughput of CogMOR-MAC is 72.9% higher than that of SHCS-MAC.

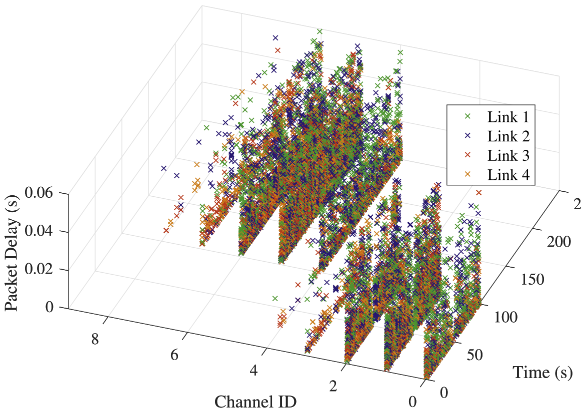


Fig. 12. The channel utilization of CogMOR-MAC.

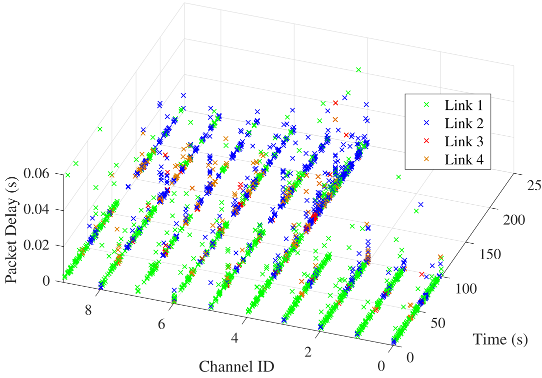


Fig. 13. The channel utilization of SHCS-MAC.

It is worth noting that SHCS-MAC can provide a very high throughput rate on link 1 before it is severely affected by PU activities at 100s. Of course, it will further be studied later what causes this phenomenon. Then, we focus on link 2, link 3 and link 4, we find that they do not seem to have any negative effects from PU activities. Instead, as throughput rate on link 1 goes down, the throughput rate of link 2, link 3 and link 4 starts going up slightly. Obviously, it can further verify the defect of SHCS-MAC in the fairness of random access channels. When the high throughput transport link is affected by the PU activities, other nodes have more opportunities to access the channel for transmission.

5.4. *The channel utilization comparisons between CogMOR-MAC and SHCS-MAC*

In order to further study the relationship between PU activities and MAC protocol transmission, we make statistics on the channel utilization of CogMOR-MAC's experiment and SHCS-MAC's experiment respectively. The results are as shown in Figs. 12 and 13. The most notable feature of the results is that Both CogMOR-MAC and SHCS-MAC are capable of parallel data transmission using multiple channels. All available channels are used by SHCS-MAC, but its efficiency is not high. Compared with SHCS-MAC, only 5 channels are used simultaneously in CogMOR-MAC, but the efficiency is relatively higher than SHCS-MAC.

Today, spectrum resources are increasingly scarce. In a way, SHCS-MAC is a waste of spectrum resources, because it is hard for other cognitive radio system to coexist with it.

In Fig. 13, we finally find the answer to the question in the previous subsection. When the PU activities is appear at 100 s, it cannot be confirmed that neither of CogMOR-MAC and SHCS-MAC can use the channel 0, channel 1, channel 2 and channel 3. This will naturally result the throughput rate of SHCS-MAC goes down. By contrast, CogMOR-MAC does not have this problem. CogMOR-MAC can quickly migrate to other channels for transmission. More importantly, it is through the MOR mechanism to improve efficiency rather than using more spectrum band resources.

6. Conclusion

In this paper, we propose a CogMOR-MAC protocol which designed for CRAHNs. CogMOR-MAC could offer a reliable data communication services between SUs with only one radio. In CogMOR-MAC, the MOR mechanism is used to accomplish resource reservation according to the transmission requirements before carrying out the data transmission. The MOR mechanism is able to reduce signal collisions and waiting time. At last, this paper demonstrates the performance evaluation comparing with SHCS-MAC. And the results show that CogMOR-MAC could have significant throughput improvement comparing with the SHCS-MAC, at the same time CogMOR-MAC can also achieve greater adaptability of responding PU activities or noise interference. So, the CogMOR-MAC is be well-suited for multi-UAVs ad hoc networks, and it can also be used for vehicular ad hoc networks, wireless sensor networks, etc.

In future work, an effective and practical spectrum sensing method is expected to be complemented, thus completing the whole CogMOR-MAC protocol design and implementation. And the performance results in a more realistic CR environment will be investigated. Besides, a better version MOR mechanism would deserve further research, and some additional measures should be adopted in order to recover from the failure of rendezvous quickly.

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