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An OFDMA-based joint reservation and cooperation MAC protocol for the next generation WLAN

Yongping Zhang[1] · Bo Li[1] · Mao Yang[1] · Zhongjiang Yan[1] · Xiaoya Zuo[1]

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Abstract The rapidly increasing use of mobile devices and the explosive growth of wireless traffic demands continuously drive the development of wireless networks. IEEE 802.11ax, as the emerging standard for the next generation wireless local area network (WLAN), aims to improve the network throughput in the densely deployed wireless networks. In the dense networks, the increased collisions for the large number of nodes and the inevitable transmission failures for aggregate interference and channel fading severely degrade the network throughput, posing an intractable challenge that urgently requires resolution. Channel reservation scheme that reduces the access collisions, and cooperative relay scheme that enhances the transmission reliability have consequently drawn considerable attention in recent years. Joint channel reservation and cooperation has been proved as a promising way to improve the network throughput in our recent study, but how to design a high-performance medium access control (MAC) protocol combined with reservation and cooperation for the next generation WLAN still remains an open issue. In this paper, we propose an orthogonal frequency-division multiple access (OFDMA) based joint reservation and cooperation MAC (OJRC-MAC) protocol for the next generation WLAN. The OJRC-MAC adopts the channel reservation scheme to reduce the access collisions, and enables the cooperative relay scheme to enhance the transmission reliability simultaneously. A resource unit based Markov model is introduced to analyze the network throughput, and the impacting factors on the throughput can be clarified by the derived closed-from expression. Simulation results validate the analytical results, and show that OJRC-MAC outperforms the basic uplink OFDMA-based random access (UORA), only reservation-enabled MAC (RES-MAC), and only cooperation-enabled MAC (COOP-MAC).

Keywords Channel reservation · Cooperative relay · Medium access control · The next generation WLAN · IEEE 802.11ax

1 Introduction

The increasing number of mobile devices with high capabilities and the emerging bandwidth-hungry Internet services such as video conference, social media, and virtual reality lead to the explosive growth of the mobile traffic, which may soon become beyond the capacity of current wireless networks. The cost-efficient and convenient wireless connection provided by the wireless local area network (WLAN) promotes the proliferation of global Internet Protocol (IP) traffic, and 51% of the mobile data traffic has been offloaded onto WiFi or femtocell in 2016 [1]. Furthermore, it is predicted that the total public WiFi hotspots will grow sevenfold from 2015 to 2020. To meet the traffic demand within these densely deployed WiFi

✉ Mao Yang
yangmao@nwpu.edu.cn

Yongping Zhang
zhyp2010@mail.nwpu.edu.cn

Bo Li
libo.npu@nwpu.edu.cn

Zhongjiang Yan
zhjyan@nwpu.edu.cn

Xiaoya Zuo
zuoxy@nwpu.edu.cn

[1] School of Electronics and Information, Northwestern Polytechnical University, Xi’an, China

networks, the new standard for high efficiency WLAN (HEW), i.e., IEEE 802.11ax, is being developed to achieve at least a four times increase of medium access control (MAC) throughput per station (STA) over the current widely-used IEEE 802.11ac standard [2, 3].

One of the new features of IEEE 802.11ax [4–7] is uplink (UL) multi-user (MU) transmission. To achieve the synchronization among the participating STAs, the trigger frame (TF) has been proposed to initiate the UL MU transmission. The access point (AP) uses the TF to inform the STAs about the transmission parameters and to allocate the transmission resources. The problem therein is that the efficient scheduling is difficult to obtain because the AP knows nothing about the transmission requests from the associated STAs without additional information exchange. Therefore, the trigger frame for random access (TF-R) was introduced to support the MU random access in the UL orthogonal frequency-division multiple access (OFDMA) based random access mechanism. TF-R is a special TF that contains resource units (RUs) for random access. Once the AP sends out the TF-R, the STAs contend for the channel in the frequency domain, i.e., randomly select RUs assigned for random access and simultaneously transmit the UL packets. However, the collision caused by the large number of STAs cannot be avoided, and the increased interference caused by the densely deployed APs may result in a higher frame error rate. Both issues severely degrade network throughput and pose an intractable challenge to be resolved. In recent years, both channel reservation scheme [8–15] and cooperative relay scheme [16–20] have widely been considered to reduce the access collisions and enhance the transmission reliability, respectively.

The channel reservation scheme, reserving the channel resource for the subsequent packet transmission to reduce collisions, can improve the MAC access efficiency. According to the different reserved elements in the channel resource, channel reservation can be categorized into three cases: (1) time slot reservation. Choi and et al. [8] proposed the early backoff announcement (EBA) protocol, in which the collision can be avoided by selecting different backoff values from all the future backoff values, early announced by other nodes. Considering that the reservation information may be missed due to the channel errors or packet collisions, Li and et al. [9, 10] proposed a multiple-step reservation scheme to broadcast the same backoff value for more than once and to improve the reliability of the time slot reservation. With regard to the multi-cell scenarios, He and et al. [11, 12] evaluated the impact of interference on the channel reservation and showed that the time slot reservation still works better than the traditional random backoff method. (2) Spatial reservation. Hasan and Andrews [13] proposed the concept of spatial reservation, which is defined as the reservation zone around each receiver where the interfering transmitting nodes are inhibited, and the authors quantified the optimal trade-off between interference alleviation and spatial reuse to obtain the maximum transmission capacity. Joint spatial reservation and rate adaptation has been considered in our previous work in [14], and an improved network capacity can be achieved by reducing the optimal reservation zone size. (3) Sub-channel reservation. Chakraborty and Misra [15] investigated the optimal number of sub-channels to be reserved for the incoming primary users to control the interference level, caused by the sudden arrival of the primary users and the frequent handoff of the secondary users in cognitive radio networks.

The cooperative relay scheme, in which an appropriate helper is selected to aid the packet transmission from the source to the destination, can combat the error-prone channel condition and enhance the transmission reliability. Two problems arise however: when to cooperate and with whom to cooperate, which need to be addressed for the cooperative MAC protocol [16]. The former problem determines whether to activate the cooperation via source or destination node. The latter problem, also called as the helper selection problem, plays an important role in the categorization of cooperative MAC protocols. (1) Contention-free helper selection. The cooperative MAC (CoopMAC) [17] and the relay-enabled distributed coordination function protocol (rDCF) [18] are two classical cooperative MAC protocols that use contention-free helper selection methods to choose the best helper by collecting the information from potential helpers prior to the packet transmission. (2) Contention-based helper selection. [19] and [20] adopted a two level backoff-based contention solution to reduce collisions among potential helpers in the case that the large number of available helpers are presented in the considered region. Although both contention-free and contention-based cooperation are effective to improve the network throughput, it is worth noting that the cooperative gain typically benefits from enhancing the link reliability of the poor quality link with low signal-to-interference-and-noise ratio (SINR) due to channel fading or co-channel interference. Since the large number of nodes simultaneously contend for the channel in the dense wireless networks, there is little opportunity for a poor quality link to access the channel and successfully establish cooperative transmission.

Employing the cooperative relay to achieve the efficient packet retransmission in WLAN is considered in [21–23]. Lu and et al. [21] proposed the protocol for retransmission opportunistically (PRO), and selected the appropriate helper to retransmit the failed packets in a distributed manner. Cao and et al. [22] considered the packet retransmission to optimize the helper selection algorithm, and Sheu and et al. proposed a retransmission-based cooperative MAC for IEEE 802.11n. Compared with two-hop relay transmission, opportunistic retransmission requires the same number or fewer transmissions to deliver a packet successfully [21]. Therefore, the helper considered in this paper plays the role of retransmitting the failed packets.

It is promising to improve the network throughput with the joint channel reservation and cooperative relay by simultaneously reducing the collisions and enhancing transmission reliability. Our previous work [24] obtained a significant throughput gain by jointly employing the optimal size of reservation zone and selecting the best helper within the reservation zone with the concept of reserved cooperative links in a theoretical way. Furthermore, an ALOHA-based joint reservation and cooperation MAC protocol, which adopts reservation-based channel access, while simultaneously enables cooperative transmission, has been proposed [25], and the effectiveness of joint channel reservation and cooperative relay can be validated by the achieved throughput gain in the practical simulation environment. Motivated by the superiority of joint reservation and cooperation obtained in previous research, we propose an OFDMA-based joint reservation and cooperative MAC protocol (OJRC-MAC) to improve the network throughput for the next generation WLAN. The contributions of this paper can be summarized as follows:

– We propose an OFDMA-based joint reservation and cooperative MAC protocol to reduce access collisions and to simultaneously enhance transmission reliability by adopting the joint channel reservation scheme and cooperative relay scheme.
– We analyze the network throughput by introducing an RU-based Markov model, and the derived closed-form expression clarifies the impacting factors on network throughput.
– The simulation results validate the analytical results, and show that OJRC-MAC outperforms the basic uplink OFDMA-based random access (UORA), only reservation-enabled MAC (RES-MAC), and only cooperation-enabled MAC (COOP-MAC).

The remainder of the paper is organized as follows. The preliminary is presented in Sect. 2. In Sect. 3, we introduce the basic idea of OJRC-MAC. A detailed description of the protocol procedure is explained in Sect. 4. In Sect. 5, we introduce an RU-based Markov model and analyze the network throughput. The simulation results and the comparisons with analytical results are shown in Sect. 6. Finally, we conclude this paper in Sect. 7.

2 Preliminary

2.1 OFDMA in IEEE 802.11ax

The new features of IEEE 802.11ax are: efficient channel access, enhanced spatial reuse, improved power efficiency, and robust performance in multipath fading environments and outdoor scenarios. The MU transmission, i.e., multiple simultaneous transmissions to different STAs from the AP in the downlink (DL) and from multiple STAs to the AP in the UL, enabled by OFDMA and (or) multiple-input multiple-output (MIMO), can improve channel utilization efficiency and achieve higher system and user throughput. Dynamic adaptation of the clear channel assessment threshold (CCAT) and transmit power control (TPC) are two effective techniques to improve the spatial reuse by reaching the optimal trade-off between the transmission rate for the individual communication link and the number of concurrent transmissions for entire networks. Through prior determination of a specific time for the individual STA to access the channel, the function of target wake time (TWT) could be used to reduce the power consumption of the inactive STAs by switching to a sleep mode. In addition, some physical layer (PHY) changes, such as larger fast Fourier transformation (FFT) size, narrower subcarrier spacing and longer symbol duration, were introduced to improve the robust performance in the outdoor environment, but the backward compatibility with previous standards has been maintained. In this paper, we mainly concentrate on the efficient MAC protocol design for the next generation WLAN.

It is necessary to highlight that realizing UL MU transmission remains challenging, since the synchronous transmissions of the participating STAs are required. As mentioned before, TF is introduced to initiate the scheduling of the UL MU transmission, and TF-R is introduced to support UL MU random access, i.e., UL OFDMA-based random access. For the OFDMA-based MU transmission, the channel bandwidth is divided into several RUs with a certain number of sub-carriers, and the size of each RU can be 26, 52, 106, 242, 484, 996, and 2×996 sub-carriers. For example, the channel multiplexing with different RU sizes on the 20 MHz bandwidth is illustrated in Fig. 1, and up to 9 STAs can be accommodated for every 20 MHz bandwidth.

The TF-based UL MU transmission is illustrated in Fig. 2. Note that the associated ID (AID) subfield in the TF denotes the address of the scheduled STA. AP sends out the UL TF frame indicating the RU allocation information and transmission duration. Then multiple STAs start transmitting their UL physical layer convergence procedure

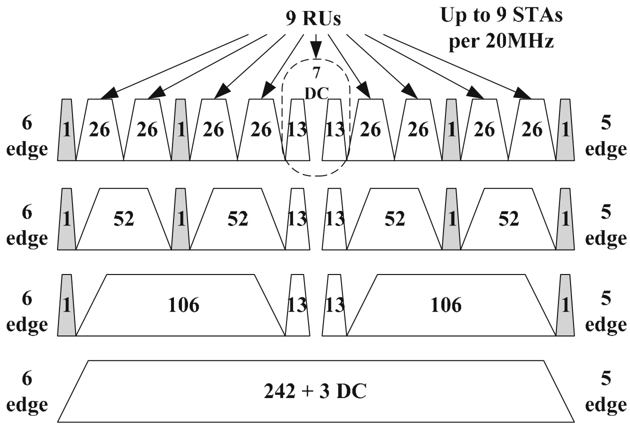

Fig. 1 RU allocation in 20 MHz

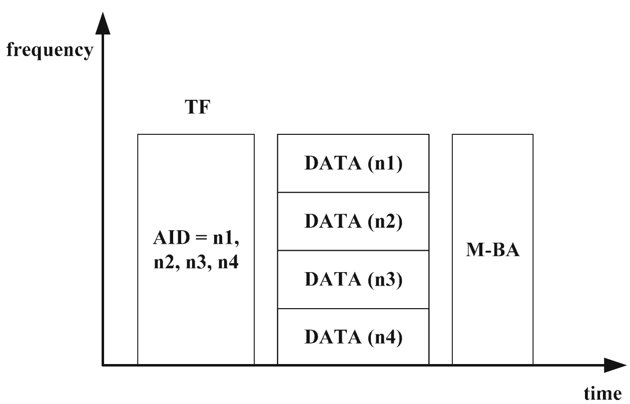

Fig. 2 TF-based UL MU transmission

(PLCP) protocol data units (PPDUs)[1] in the specified RUs at the same time, and end their transmissions simultaneously. The TF-based UL MU transmission is finished with a replied multi-STA block acknowledgement frame (M-BA) to deliver the acknowledgement information from the AP to the participating STAs.

2.2 UORA

To satisfy various traffic and service requirements, the random access protocol is essential for wireless networks. Unlike the traditional random access protocol, the UORA mechanism in the IEEE 802.11ax enables multiple STAs to contend the channel in the frequency domain. The random access procedure is illustrated in Fig. 3.

The AP sends a TF-R frame indicating the assigned RUs for random access to initiate the MU random access. The AID subfield in the TF-R is set to 0 to identify the corresponding RU for random access. Note that the number and start times of multiple cascading TF-Rs can be indicated in the beacon frame for power saving. The STA, which has packets to send, maintains an OFDMA backoff (OBO) counter, and randomly selects an available RU to transmit as soon as the OBO counter expired. The OBO counter is a random number uniformly chosen from the interval $[0, OCW - 1]$, where OCW (OFDMA contention window) denotes an integer with an initial value of OCWmin. If the OBO counter is smaller than the number of RUs assigned to random access in the received TF-R, then the OBO counter decreases to zero. Otherwise, the value of OBO counter is reduced by the number of RUS for random access. When the OBO counter reaches zero, the STA randomly selects an available RU and transmit its UL PPDU. A collision will occur if two or more STAs select the same RU to transmit their PPDUs. M-BA is followed to acknowledge the reception of multiple PPDUs. The more detailed description can refer to [2].

3 Basic idea of OJRC-MAC

We concentrate on one basic service set (BSS), i.e., a wireless network which consists of an AP and N associating STAs with UL traffic, and the interference from the overlapping BSS (OBSS) can be characterized by the frame error rate. In other words, all the STAs are within the transmission range of AP in the considered BSS, but transmission failures may still occur with probability ϵ_{sa} due to the aggregate interference from multiple OBSSs. Each node in the BSS has an omni-directional antenna and operates in the half-duplex mode. The channel bandwidth is divided into c RUs, and the STAs perform random access on the available RUs, indicated by the AP in the TF-R frame. In OJRC-MAC, an RU-based reservation scheme is used to reduce collisions induced by the large number of contending STAs and improve the MAC efficiency, while a MU-based cooperative relay scheme is introduced to retransmit the failed packets in the reserved RU and to enhance transmission reliability.

3.1 RU-based reservation scheme

The RU-based reservation scheme is shown in Fig. 4. A contending STA, such as 'n1', can access the channel on the randomly selected RU once its OBO counter reaches zero. Along with the UL PPDU, the reservation request is also piggybacked in the MAC header of PPDU. After the AP successfully receives the PPDU, the replied M-BA[2]

[1] PPDU is created by appending the PLCP preamble and header to the DATA frame from the MAC layer. Hence, the terms of PPDU and DATA are used interchangeably in the following description of MAC procedure.

[2] The existence (or non-existence) of acknowledgement (ACK) information for single STA in M-BA is denoted by ACK (or blank). The terms of M-BA and multiple ACKs are used interchangeably in the following description of MAC procedure.

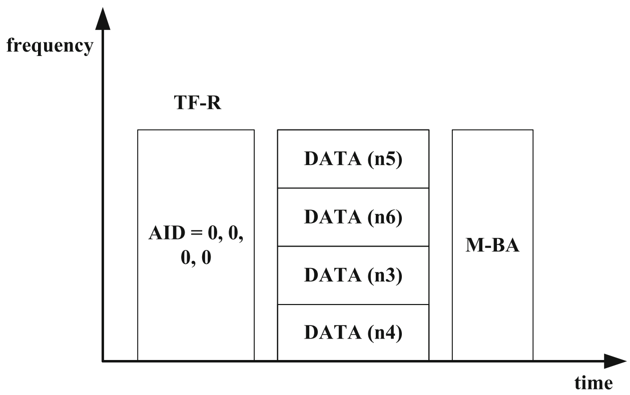

Fig. 3 UORA

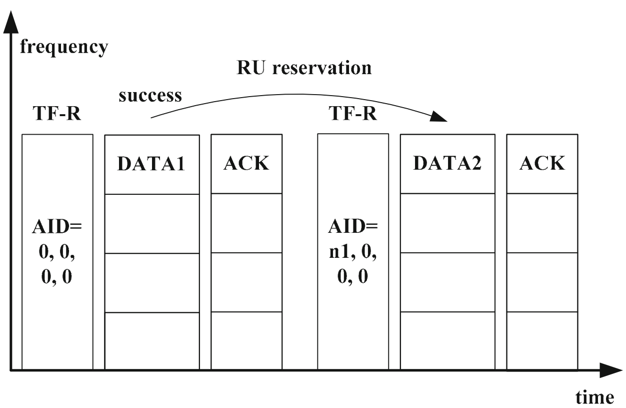

Fig. 4 RU-based reservation scheme

will confirm the channel reservation and one or more RUs in the subsequent TF-Rs can be reserved for its channel access. The number of reserved RUs is called the reservation step and is denoted as m. When a new TF-R frame, containing the reserved RU is sent out, STA n1 can directly transmit its UL PPDU on the specified RU without contention. To facilitate the protocol implementation and performance analysis, AP is assumed to be always willing to accept the reservation request, and the general extension to certain acceptance criteria is straightforward.

The implementation of the RU-based reservation is similar with the scheduling-based access mechanism, however, the role played in the channel access for the STA is different. Instead of the reactive accepting the scheduling information, the STA can deliver its proactive request for channel resources in the RU-based reservation scheme. Hence, a more flexible channel access manner according to the different traffic and service requirements can be readily achieved.

3.2 MU-based cooperation scheme

The MU-based cooperation scheme is shown in Fig. 5. Once an error occurs for the reserved transmission, i.e., AP cannot successfully decode the packet on the reserved RU, a corresponding helper STA will be employed to retransmit the failed packet. If retransmission fails, including the empty retransmission of the helper and the unsuccessful reception of AP, AP will schedule the reserved STA to send the new packet on the subsequent reserved RUs. The dedicated helper STA which can access and overhear the channel with full bandwidth is considered to aid the transmission from the source STAs to the AP. Note that it is a feasible extension to select a normal STA as the helper with necessary signalling exchange. As expected, only the normal STA, which successfully receives the source data, has the opportunity to become an active helper STA.

Considering the feature of MU transmission in the OFDMA-based channel access, one dedicated helper STA can overhear and cache multiple reserved PPDUs to serve a group of source STAs. Therefore, only a small number of helper STAs is required to enable the cooperation scheme in the BSS, and the induced extra cost still remains acceptable. Moreover, the initial appropriate deployment of helpers is readily accomplished and the communication overhead of cooperative transmission can be minimized. An example for the deployment of two helpers is shown in Fig. 6. The circular coverage area of BSS is equally divided into two sector regions, and the source STAs in each sector are served by one helper STA.

4 Protocol description

4.1 Protocol overview

The protocol procedure is shown in Fig. 7. The number of TF-Rs and the start time of each TF-R are indicated in the beacon frame for power saving. Note that only the STAs that successfully receive the beacon frame can perform the UL MU random access mechanism. Hence, we define the reservation cycle as the interval of two consecutive beacon frames, which contains a certain number of TF-Rs denoted by M. In general, one reservation request cannot reserve multiple RUs across different reservation cycles. After the beacon frame, the TF-R frame is sent out by AP in the predetermined time to initiate UL MU random access. The STA that has a packet to send adopts the OFDMA-based backoff process specified in the UORA in Sect. 2.2 to contend the channel. Once its OBO counter reaches zero, the STA randomly selects one available RU to transmit the UL PPDU piggybacked with the reservation request. After the successful reception of PPDU, the replying M-BA will confirm the reservation and indicate the reserved RUs in one or more subsequent TF-Rs. One STA can only reserve one RU in a TF-R, and the number of reserved RUs in a reservation cycle is called the reservation step, which is denoted by m.

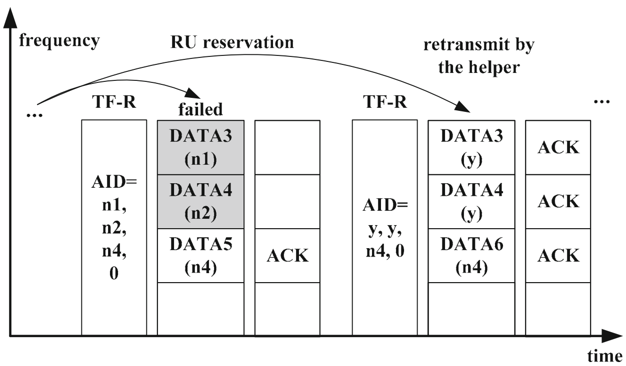

Fig. 5 MU-based cooperation scheme

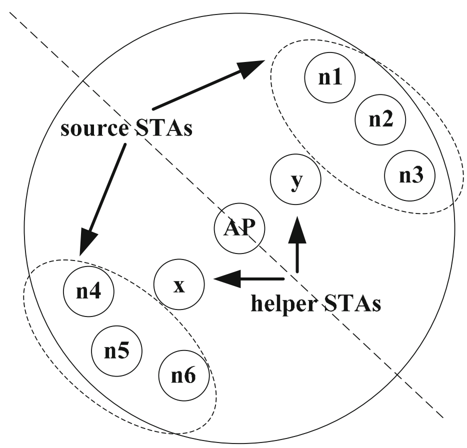

Fig. 6 Deployment of two helper STAs

Once receiving the TF-R frame that contains the reserved RU, the corresponding STA directly transmits its UL PPDU without contention. This reservation-based access is continuously performed until the maximum reservation step has been reached. During the consecutive reserved transmissions, the channel fading or the aggregate interference from multiple OBSSs may lead to transmission failures. Since the dedicated helper STA is always overhearing the reserved transmissions and caching the UL PPDUs, the AP will immediately activate the cooperative transmission in the following TF-R and let the helper STA retransmit the failed packet. Upon successful reception, the AP directly replies the acknowledgement information to the source STA in the M-BA. Benefiting from the MU transmission in the OFDMA-based channel access, one helper STA can simultaneously overhear and extract multiple PPDUs, and the MU-based cooperation can be realized by retransmitting the failed PPDUs for more than one source STAs.

RU index	AID of reserved STA	remaining reservation step	success flag of last reserved transmission	AID of helper STA

Fig. 8 Structure of RCT

4.2 Implementation of reservation and cooperation

In the OFDMA-based channel access, the reserved transmission and cooperative transmission are implemented in the similar way with the scheduling-based transmission. A reserved cooperative table (RCT) is maintained at the AP side, and its structure is shown in Fig. 8. Five items are included in the RCT: RU index, AID of reserved STA, remaining reservation step, success flag of the last reserved transmission, and AID of helper STA. Initially, the RCT is empty, and all the RUs can be used for random access in the TF-R frame. The source STA issues the reservation request with the reservation step and the corresponding AID of helper STA. Once the AP successfully receives the UL PPDU and the embedded reservation request, it will record the reservation information of reserved STA AID, remaining reservation step, and helper STA AID into the RCT for the occupied RU. By scheduling the reserved STAs in the sequent TF-Rs within the reservation step, the reserved transmissions can be readily accomplished. Similarly, the cooperative transmissions are realized by scheduling the corresponding helper STA in the RCT to retransmit the failed packets when reserved transmission errors occur. The detailed operational procedures from the

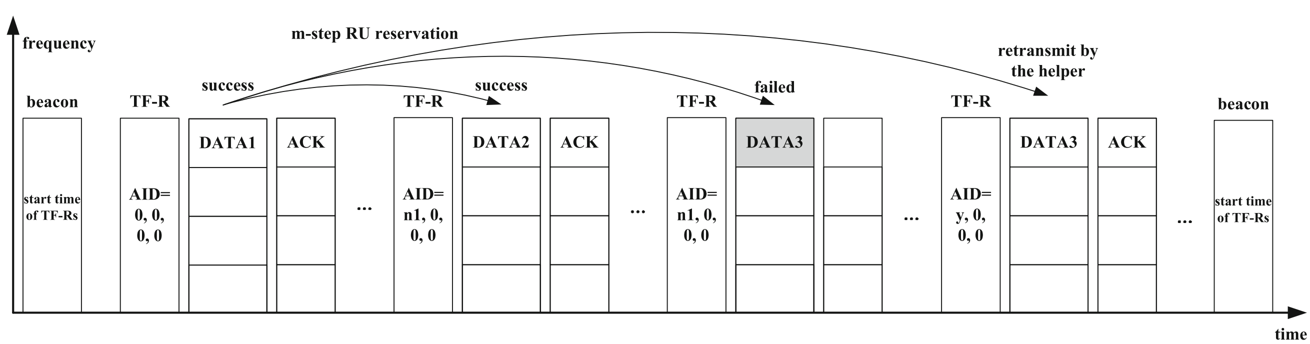

Fig. 7 Protocol procedures

perspective of the AP, source STA, and helper STA are summarized in Fig. 9.

It is worth noting that, the TF-based scheduling transmission with full knowledge of buffer states for all associated STAs may achieve more efficiency than our proposed TF-R based joint reservation and cooperation MAC protocol. However, only the current transmission requirements of the STAs can be reflected in the buffer state information. For the future transmission requirements according to the characteristics of different traffic types, e.g. periodic traffic, the extra communication overhead and delay are induced by the collection of buffer state information. Therefore, it is more flexible for the RU-based reservation scheme that offers the STAs an alternative way to access the channel based on the traffic or service pattern.

Since the cooperative transmission is activated after the error occurs for the reserved transmission, the positive effect of the cooperative relay scheme is only taken for the transmission from the source STA located in the edge of the BSS to the AP, which suffers the low SINR for the long link distance. Benefiting from the feature of MU transmission in the OFDMA-based channel access, one helper STA can be deployed for the cooperative retransmissions of multiple sources STAs. Therefore, the device cost of extra dedicated helper STAs can be minimized by the MU-based cooperation scheme for the BSS-edge source STAs.

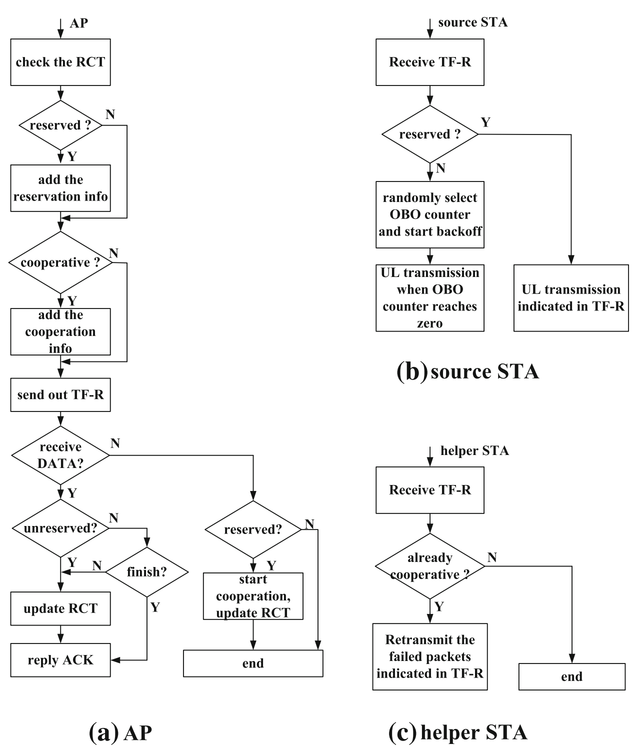

Fig. 9 Operational procedures of AP, source and helper STA

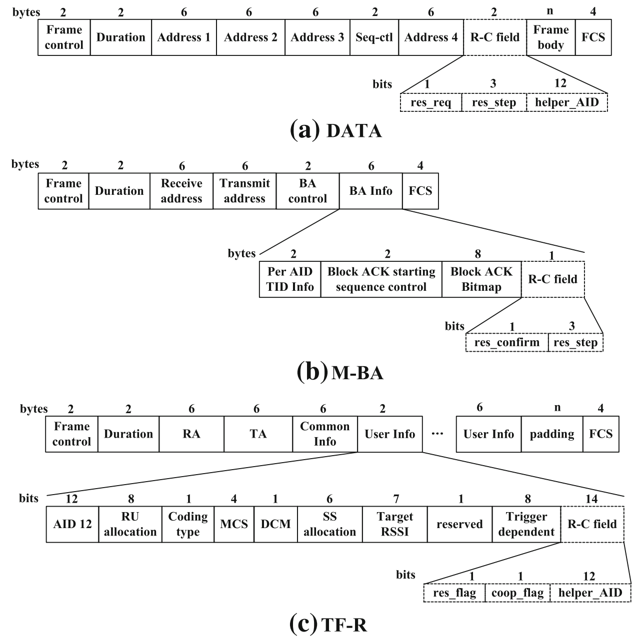

Fig. 10 Frame formats of DATA, M-BA, and TF-R

4.3 Frame structure extension

The frame structure defined by IEEE 802.11ax is extended to support the OJRC-MAC protocol. As shown in Fig. 10, the extending reservation-cooperation field (R-C field) is added into the end of the MAC frame header. The reservation request flag, the reservation step, and its corresponding AID of helper STA are added into the DATA frame in Fig. 10(a). The reservation confirm flag and reservation step are added into the BA information field of M-BA in Fig. 10(b). Note that it is trivial to contain the reserved RU information, which is exactly the same as the RU used to transmit the DATA. The reservation enabled flag, cooperation enabled flag, and the AID of the helper STA are added into the user information field of the TF frame in the Fig. 10(c).

5 Performance analysis

5.1 Parameters and assumptions

A single BSS consisting of one AP and N associating STAs with saturated UL traffic is considered in the analysis. The influence of the aggregate interference from multiple OBSSs and the channel fading are characterized by the probability of frame error rate. The frame error rate from the source STA to AP is denoted by ϵ_{sa}, and frame error rate from the source STA to the helper and that from the helper to AP are denoted by ϵ_{sh} and ϵ_{ha} respectively. The channel bandwidth is divided into c RUs, and an RU-based reservation scheme is enabled to access the channel for each STA besides the basic OFDMA-based random access mechanism. The reservation step is denoted by m, and the number of TF-Rs in the reservation cycle is M. Considering the fairness among multiple STAs, the reservation-based access can be employed once for each STA per reservation cycle. The cooperation is activated to retransmission in the following TF-R if the error occurs for the reserved transmission in the current TF-R frame. The initial value of OCW is denoted by W, and generally exceeds the number of available RUs in the reservation cycle, i.e., $W \geq c \cdot M$.

5.2 RU-based Markov model

For the STA which successfully establishes the m-step reservation, there must be a corresponding RU reserved for m step. Let R_k be the reservation state for a given RU with k remaining reserved transmissions. For consistency, the RU in the contending state can be denoted by the special case of $k = 0$, and then $0 \leq k \leq m$ holds obviously. If the reserved transmission on the RU fails, the RU enters the cooperation state denoted by C_k. Note that the state of any RU is independent from other RUs. Thus, it is possible to model the setup of joint reservation and cooperation with an RU-based Markov chain depicted in Fig. 11. In the Markov model, the one-step transition probabilities can be expressed by

$$P\{R_m|R_0\} = (1 - \epsilon_{sa}) \cdot p_t \ , \tag{1}$$

$$P\{R_0|R_0\} = 1 - (1 - \epsilon_{sa}) \cdot p_t \ , \tag{2}$$

$$P\{R_{k-1}|R_k\} = 1 - \epsilon_{sa} \quad k \in [1, \ m], \tag{3}$$

$$P\{C_k|R_k\} = \epsilon_{sa} \quad k \in [1, \ m] \ , \tag{4}$$

$$P\{R_{k-1}|C_k\} = 1 \quad k \in [1, \ m] \ , \tag{5}$$

where p_t denotes the contention-based success probability that only one STA transmits its DATA on the RU after the OFDMA-based random access. The first equation in Eq. (1) shows that the m-step reservation can be successfully established when neither collisions nor transmission errors occur for the RU. The second equation in Eq. (2) means that the RU remains available in the following TF-R for random access either for collisions or transmission errors in the current TF-R. In Eqs. (3) and (4), if the reserved transmission would be successful, the reservation step decreases by one and the reservation state for the RU changes accordingly. Otherwise, the state of the RU will be switched to the corresponding cooperation state. Finally, the fifth equation Eq. (5) illustrates that regardless of whether the cooperative retransmission fails, the state of RU returns to the reservation state with the decrement of the reservation step.

Let p_k be the stationary probability of being in the reservation state R_k, and let q_k be the stationary probability of being in the cooperation state C_k for the RU, then we have

$$p_m = p_0 \cdot (1 - \epsilon_{sa}) p_t \ , \tag{6}$$

$$q_k = p_k \cdot \epsilon_{sa} \quad k \in [1, \ m] \ , \tag{7}$$

$$p_{k-1} = p_k \cdot (1 - \epsilon_{sa}) + q_k \quad k \in [1, \ m] \ . \tag{8}$$

Note that the RU should be in the one state of the contending state, reservation state, and cooperation state, the normalization condition of the Markov chain can be expressed by

$$1 = p_0 + \sum_{k=1}^{m} p_k + \sum_{k=1}^{m} q_k. \tag{9}$$

According to the equations from Eqs. (6) to (9), the stationary probabilities of the contending state, reservation state, and cooperation state can be readily derived by

$$p_0 = \frac{1}{m(1 - \epsilon_{sa}^2) p_t + 1} \ , \tag{10}$$

$$p_k = \frac{(1 - \epsilon_{sa}) p_t}{m(1 - \epsilon_{sa}^2) p_t + 1} \quad k \in [1, \ m] \ , \tag{11}$$

$$q_k = \frac{(1 - \epsilon_{sa}) \epsilon_{sa} p_t}{m(1 - \epsilon_{sa}^2) p_t + 1} \quad k \in [1, \ m] \ . \tag{12}$$

When the channel reservation scheme is not enabled, i.e., $m = 0$, the RU is always being in the contending state,

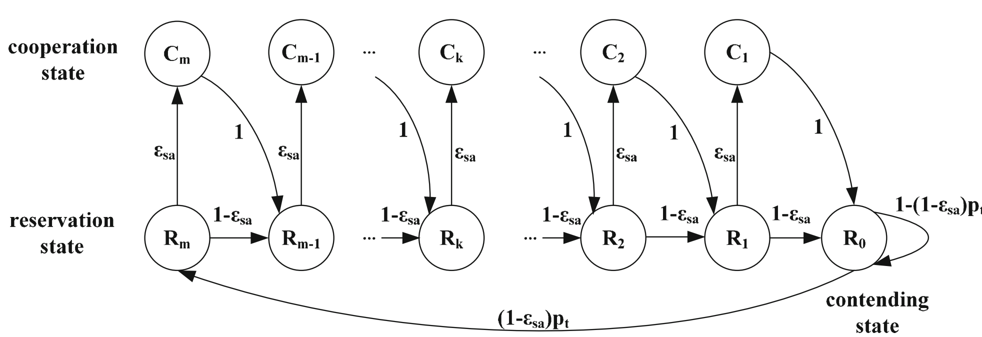

Fig. 11 RU-based Markov model

i.e., $p_0 = 1$. With the growth of the reservation step $m > 0$, the stationary probability of the contending state decreases. Although the stationary probabilities of individual reservation state p_k and individual cooperation state q_k decrease as well, the corresponding overall probabilities, either being in the reservation state or cooperation state, are improved for the increased number of reservation states and cooperation states. In addition, the frame error rate ϵ_{sa} plays an important role in the stationary probabilities. The perfect channel conditions with $\epsilon_{sa} = 0$ leads to a probability of zero for the cooperation state, suggesting that no cooperation is needed to retransmit the failed packets. With the growth of frame error rate, the stationary probability of contending state increases since it is difficult to establish the channel reservation successfully in the poor channel conditions.

The contention-based success probability for the RU p_t is determined by the number of contending STAs N and the size of OCW W. A fixed value of OCW is assumed, and the opportunity to access the channel and establish the reservation for each STA is allowed once per reservation cycle. Since the maximum available number of RUs in one reservation cycle is calculated by $c \cdot M$, the value of OCW should not be smaller than that to provide the access opportunity for each RU, i.e., $W \geq cM$. Therefore, the contention-based success probability for one RU can be expressed by

$$p_t = \binom{N}{1} \frac{1}{W} \left(1 - \frac{1}{W}\right)^{N-1} = \frac{N(W-1)^{N-1}}{W^N}. \tag{13}$$

Substituting Eq. (13) into the equations from Eqs. (10) to (12), yields the relationship between the stationary probabilities and the impacting factors including STA number N, RU number c, TF-R number M, reservation step m, and frame error rate ϵ_{sa} can be derived readily.

5.3 Throughput analysis

Since the joint reservation and cooperation scheme is proposed to improve the throughput of UL OFDMA-based random access, the overheads of contending the channel for transmitting TF-R frame and the behaviors of nodes between two consecutive TF-Rs are not considered in the throughput analysis. According to the analysis of the stationary probabilities in the RU-based Markov chain, we can obtain the packet success probability for each RU, p_s, expressed by

$$\begin{aligned} p_s =& (1-\epsilon_{sa})p_0 p_t + (1-\epsilon_{sa})\sum_{k=1}^{m} p_k \\ &+ (1-\epsilon_{sh})(1-\epsilon_{ha})\sum_{k=1}^{m} q_k . \end{aligned} \tag{14}$$

That is to say, the event of successful packet transmitted on one RU occurs in three cases, i.e., only one STA contends the RU successfully and transmits a packet without error in the contending state, the reserved transmission is successful in the reservation state and the cooperative transmission is successful in the cooperation state.

The throughput can be defined as the ratio of packet size of successfully transmitted packets in the transmission for one TF-R to the duration of transmission from TF-R to M-BA, i.e.,

$$S = \frac{\sum_{k=1}^{c} p_s L}{T_{PPDU} + T_{overhead}} , \tag{15}$$

where L denotes the uniform packet length of PPDU, and the overhead can be calculated by $T_{overhead} = T_{TF-R} + T_{M-BA} + 2 * SIFS$. The duration of TF-R, PPDU, and M-BA are denoted by T_{TF-R}, T_{PPDU}, and T_{M-BA}, and the short inter frame space is denoted by $SIFS$.

Let R be the fixed and uniform transmission rate on the full channel bandwidth for each STA, then the corresponding transmission rate on each RU is R / c. Hence, Eq. (15) becomes

$$S = p_s \cdot R \cdot \frac{T_{PPDU}}{T_{PPDU} + T_{overhead}} . \tag{16}$$

Without loss of generality, the normalized throughput independent with the length of PPDU and the transmission rate on the full bandwidth can be expressed by

$$\hat{S} = p_s . \tag{17}$$

Substituting the equations from Eqs. (10) to (14) into Eq. (17), we can readily obtain the normalized throughput of OJRC-MAC by

$$\hat{S}^{OJRC} = \frac{m + 1 - m\epsilon_{sa}(\epsilon_{sh} + \epsilon_{ha} - \epsilon_{sh}\epsilon_{ha})}{m(1+\epsilon_{sa}) + \frac{W}{N(1-\epsilon_{sa})}\left(\frac{W}{W-1}\right)^{N-1}} . \tag{18}$$

In particularly, the normalized throughput of the basic UORA without reservation and cooperation for $m = 0$ can be obtain by

$$\hat{S}^{UORA} = (1-\epsilon_{sa}) \cdot p_t . \tag{19}$$

Moreover, the normalized throughputs of the RES-MAC and COOP-MAC can be derived in the similar way by

$$\hat{S}^{RES} = \frac{m(1-\epsilon_{sa}) + 1}{m + p_t/(1-\epsilon_{sa})} , \tag{20}$$

and

$$\hat{S}^{COOP} = \frac{1 - \epsilon_{sa}[1 - (1-\epsilon_{sh})(1-\epsilon_{ha})(1-p_t)]}{1 + \epsilon_{sa}(1-\epsilon_{sh})p_t} \cdot p_t , \tag{21}$$

respectively. Due to the space limitation, the expression of p_t in Eqs. (19), (20), and (21) is not substituted by the Eq. (13).

It is worth noting that the idea of multiple-step reservation in [10] is employed in the RES-MAC, but the RU based reservation without dissemination of reservation information makes the RES-MAC different from the multiple-step distributed in-band channel-reservation (*m*-DIBCR) in [10]. In the COOP-MAC, the contention-free helper selection method is drawn from [17], but the helper is adopted to retransmit the failed packets by overhearing the replied acknowledgement information from AP, which is similar with the opportunistic retransmission [21].

6 Results and discussions

6.1 Simulation environment and settings

The throughput performance of OJRC-MAC protocol is evaluated by extensive simulations using the network simulator 2 (ns-2) with version 2.35. Besides the proposed OJRC-MAC, UORA, COOP-MAC, and RES-MAC are also implemented in the simulations.

We consider the UL MU transmission scenario in one BSS, i.e., multiple source STAs employs the OFDMA-based channel access to transmit their UL traffic to the same AP located in the center of BSS. The influence of interference from the multiple OBSSs and channel fading is characterized by the average frame error rate ϵ. If two or more STAs contend the same RU simultaneously, collision occurs and transmission fails. Otherwise, the transmission can be successful with a probability of $1-\epsilon$. A few number of dedicated helper STAs are deployed in advance to retransmit the failed packets.

Unless otherwise noted, 60 source STAs and 4 helper STAs are distributed on the BSS coverage area with a $60\,\text{m} \times 60\,\text{m}$ plane. The frame error rate from the source STA to AP is set by $\epsilon_{sa} = 0.3$, and the frame error rate from the source STA to the helper and that from the helper to AP are set by $\epsilon_{sh} = 0.05$ and $\epsilon_{ha} = 0.05$ respectively. Without loss of generality, a full channel bandwidth of 20 MHz with maximum transmission rate of 54 Mbps is divided into 4 RUs, and the number of TF-Rs in the reservation cycle is set by $M = 20$. The fixed OCW is exactly the same as the number of available RUs in one reservation cycle, i.e., $W = 80$. The saturated traffic is assumed in the simulation and the packet length is 1400 bytes. Both for the OJRC-MAC and RES-MAC, the throughputs of 1-step and 2-step reservation are investigated. The simulation duration is 30 s, and the main parameters are summarized in Table 1.

6.2 Model validation

To validate the RU-based Markov model, we compare the analytical results with the simulation results under different simulation parameters. Figures 12 and 13 show the throughput performance with different TF-R numbers in one reservation cycle for UORA, COOP-MAC, RES-MAC, and OJRC-MAC under the condition of 9 RUs and 4 RUs, respectively. Both for the 1-step and 2-step reservation, the accuracy of the analytical model increases with the growth of the number of TF-Rs in one reservation cycle. It is the main reason that the derived throughput expression of reservation and cooperation in the analysis depends on the stationary probability of the reservation state, cooperation state and contention state, while in the simulation the insufficient number of TF-Rs may cause that part of the RUs cannot enter the steady state. Therefore, the simulated throughputs are lower than the analytical results for the small number of TF-Rs. It can be observed that the analytical results in the dotted line coincide well with the simulation results in symbols for more than 20 TF-Rs.

Both Figs. 12 and 13 show that the throughput first increases and then decreases with the increasing number of TF-Rs in one reservation cycle. The optimal number to maximize the throughput is 6 (14) in Fig. 12 (Fig. 13), in which the total number of available RUs in the reservation cycle approximates to the number of source STAs. The main reason is that only one opportunity to establish the channel reservation is allowed for each STA, and the extra TF-Rs (or RUs in these TF-Rs) may be wasted if the opportunities of all the STAs are used up. Therefore, with the growth of the TF-R number, the throughput increases for the increased number of STAs accessing the channel under the condition of small TF-R number, and it decreases

Table 1 Simulation parameters

Symbol	Description	Value
N	Source STA number	60
M	TF-R number in reservation cycle	2–30
c	RU number in full bandwidth	4
W	OFDMA contention window	80
ϵ_{sa}	Frame error rate from STA to AP	0.3
ϵ_{sh}	Frame error rate from STA to helper	0.05
ϵ_{ha}	Frame error rate from helper to AP	0.05
m	Reservation step	1, 2
L	Packet size	1400 bytes
T_{SIFS}	Short inter frame space	16 μs
B	Channel bandwidth	20 MHz
R	Transmission rate	54 Mbps
T_{sim}	Simulation duration	30 s

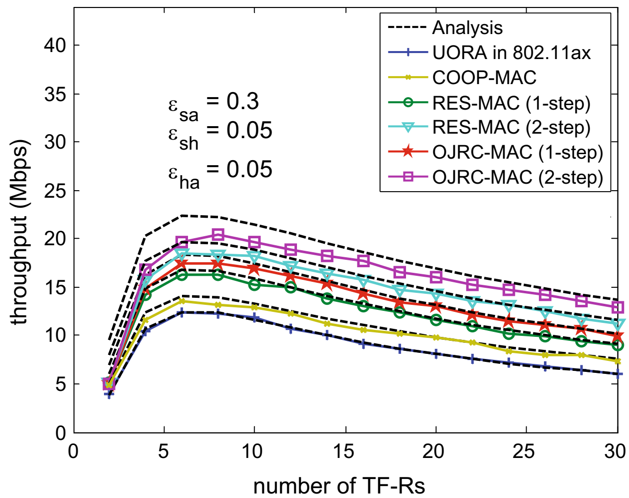

Fig. 12 Throughput with different TF-R numbers (9 RUs)

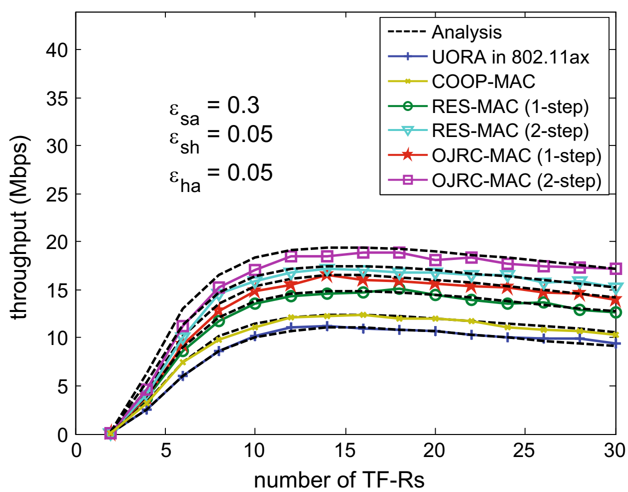

Fig. 13 Throughput with different TF-R numbers (4 RUs)

for the reduced utilization efficiency of the RUs under the condition of a large TF-R number.

Moreover, the maximum throughput with 9 RUs in Fig. 12 outperforms that with 4 RUs in Fig. 13. Since the overheads of TF-R duration, M-BA duration and inter frame space duration are exactly identical, the scenario with 9 RUs costs more time to transmit the PPDU for the lower transmission rate on the individual RU than that in the scenario with 4 RUs divided by the same bandwidth. Hence, the corresponding MAC efficiency can be improved by increasing the number of RUs allowing more STAs to transmit their PPDUs simultaneously.

Figure 14 shows the throughput performance of UORA, COOP-MAC, RES-MAC, and OJRC-MAC with different numbers of STAs under the condition of 4 RUs and 20 TF-Rs in one reservation cycle. With the increasing number of the nodes, the throughput first increases and then decreases for all four protocols. Optimal throughput performance can be achieved by the OJRC-MAC, compared with that of UORA, COOP-MAC, and RES-MAC. The node number plays an important role in the resulting node collision, and 1-step and 2-step reservation in the RES-MAC can improve the throughput significantly by reducing the collision probability efficiently. In addition, the cooperative relay scheme also takes effects for the achievable throughput gain of OJRC-MAC over the RES-MAC.

Figure 15 shows the influence of frame error rate from the source STA to AP on the throughput of UORA, COOP-MAC, RES-MAC, and OJRC-MAC under the condition of 4 RUs and 20 TF-Rs in one reservation cycle. Undoubtedly, the throughput decreases with the increase of the frame error rate ϵ_{sa} for all four protocols. It is interesting to highlight that, the throughput of 1-step (or 2-step) reservation in the RES-MAC drops faster than that of UORA. The underlying reason is that the successful channel reservation brings about additional reserved channel access, while the poor channel condition cause them to fail in packet transmission. However, by adopting the cooperative relay scheme, OJRC-MAC not only has more opportunities for channel access and packet transmission, but can also utilize these extra opportunities effectively. Therefore, the joint reservation and cooperation in OJRC-MAC obtains the optimal throughput among all four protocols.

6.3 Performance evaluation

For the practical wireless networks, the STAs are randomly distributed on the coverage area of AP, and the frame error rates of different communication links are varied by the channel fading, stochastic interference and random location. In this section, the practical physical layer (PHY),

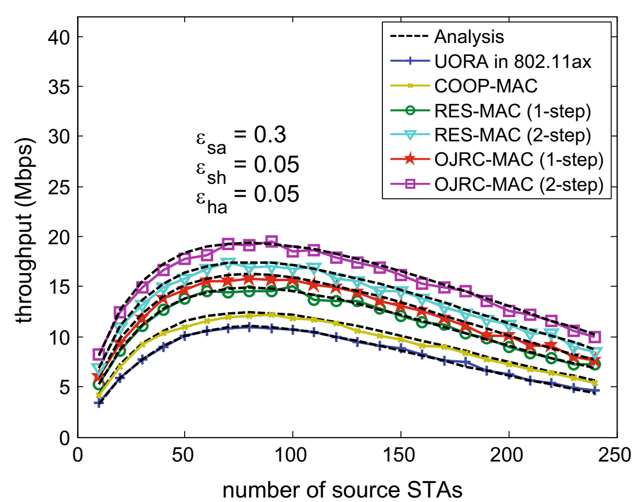

Fig. 14 Throughput with different node numbers (4 RUs)

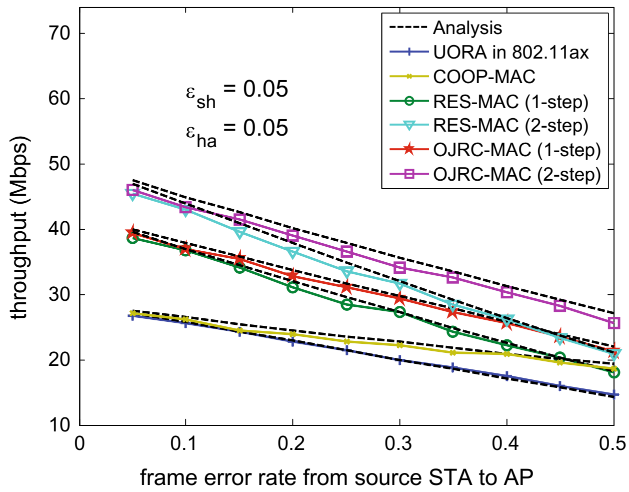

Fig. 15 Throughput with different frame error rates from the source STA to AP (4 RUs)

described in the integrated link-system level simulation platform for IEEE 802.11ax [26], is used to evaluate the throughput performance of OJRC-MAC in the practical scenario. The received power is calculated according to the TGax channel model [27] and the frame error rate is calculated with the received power and channel matrix [28].

As mentioned before, the BSS consisting of one AP and 60 STA with saturated UL traffic is considered. The simulation topology is shown in Fig. 16, the AP is located in the center of BSS, and 60 STAs are randomly distributed in the annular zone, which is a region bounded by two concentric circles with radius r and $r + \Delta r$. The path loss, fading and shadowing between the STA and AP are considered in the channel model [27]. For the stochastic interference, only one interfering STA, which is randomly located outside the carrier sensing range of source STA but inside the carrier sensing range of AP, is considered to affect the reception of AP.

In the simulation, the transmit power for all nodes, including AP, source STAs, helper STAs, and interfering STAs, is fixed as 20 dBm, and the carrier sensing threshold is set by −82 dBm. 4 helper STAs are uniformly distributed on the circle with a radius of 30 m around the AP. Other settings are similar with that listed in Table 1, i.e., 20 MHz bandwidth is divided into 4 RUs, and the fixed modulation and coding scheme (MCS) of MCS6, which adopts the 64 quadrature amplitude modulation (64-QAM) and 3/4 coding rate, is used to transmit the packets. The simulation is conducted to investigate the throughput of UORA, COOP-MAC, RES-MAC, and OJRC-MAC with 1-step and 2-step reservation.

Figure 17 shows the relationship between the throughput and the distributed area of the STAs under the condition of 4 RUs and 20 TF-Rs in one reservation cycle. When the source STAs are located closely to the AP, such as $r \leq 45$ m ($\Delta r = 2$ m), the throughput of UORA can be improved by the RES-MAC and OJRC-MAC with 1-step and 2-step reservation. The throughput gain is benefiting from the channel reservation scheme, which significantly reduces the collisions. Since the transmission reliability can be provided by the sufficiently strong received signal strength, the transmission errors rarely occur, and the throughput of the COOP-MAC remains the same as that of UORA.

If the distance between the STA and AP increases, the transmission reliability is reduced by the channel fading and stochastic interference, and the throughputs of all four MAC protocols decrease dramatically. It can be observed that, the COOP-MAC outperforms UORA, and the OJRC-MAC outperforms RES-MAC either for 1-step or 2-step reservation. Therefore, the throughput of UORA can be

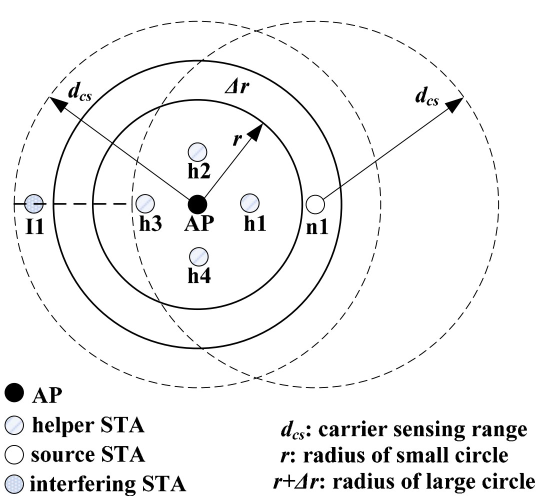

Fig. 16 Simulation topology

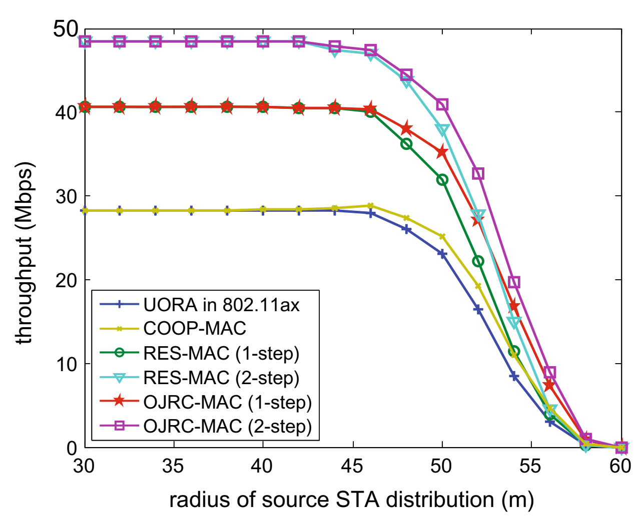

Fig. 17 Throughput with distributed area of STAs (4 RUs)

improved by the cooperative relay scheme, which efficiently enhances the transmission reliability.

With the further increasing of the distance between the STA and AP, such as $r \geq 54$ m, the throughput of RES-MAC drops faster than that of OJRC-MAC either for 1-step or 2-step reservation in Fig. 17. Furthermore, the throughput of RES-MAC with 2-step reservation is lower than that of OJRC-MAC with 1-step reservation for $r \geq 56$ m. The main reason is that, although the RES-MAC could reduce the collisions among the contending STAs by the channel reservation scheme, the transmission failures cannot be avoided due to the channel fading or interference. In the OJRC-MAC, the joint reservation and cooperation can reduce collisions and enhance transmission reliability simultaneously, and then can achieve the optimal throughput.

It is worth noting that the throughputs of all four MAC protocol drop to zero for $r \geq 60$ m in Fig. 17. This is because the fixed MCS6 is adopted for each STA to transmit its packets, and the long distance makes the successful reception of AP impossible. It is interesting to investigate an appropriate link adaptation scheme to optimize the performance of OJRC-MAC, but that is another important issue and is out the scope of this paper.

7 Conclusions and future work

In this paper, we propose OJRC: an OFDMA-based joint reservation and cooperation MAC protocol for the next generation WLAN. The OJRC-MAC adopts the channel reservation scheme to reduce the transmission collision and to enable the cooperative relay scheme, thus enhancing the transmission reliability. An RU-based Markov model is introduced to analyze its network throughput, and the impacting factors on the throughput can be clarified by the derived closed-from expressions. Simulation results validate the analytical results, and show that the joint reservation and cooperation can effectively improve the network throughput.

In our future work, the signaling exchange to select the normal STA as the helper will be considered, and the influence of induced overhead on the throughput performance will be evaluated in the generalized OJRC-MAC protocol. In addition, the deployment of the dedicated helper STAs is also worth studying in the practical OBSS scenarios.

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Yongping Zhang received bachelor degree in communication engineering in 2010 from Northwestern Polytechnical University (NPU). He is currently a doctor candidate of information and communication system in NPU. His research interests include MAC design and performance evaluation in wireless networks, and interference management for the next generation WLAN.

Bo Li received the B.E., M.S., and Ph.D. degree in telecommunication engineering from Xidian University in 1994, 1997, and 2002, respectively. From 1997 to 1998, he was a visiting scholar in the Department of Engineering, Shizuoka University. From 2002 to 2004, he was a postdoctor in the University of Trento. From July 2007 to Dec. 2007, he was a visiting Professor in the Institut National des Sciences Appliquées (INSA), LYON. He is currently a Professor in the School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China. His research interests are in the area of wireless networking and communications, including the next generation cellular network (5G) and WLAN (e.g. IEEE 802.11ax and 11ay), the MAC and higher layer technologies, non-orthogonal multiple access for 5G. He has published over 80 research papers and has over 40 granted and pending International and Chinese patents. He is a member of the IEEE.

Mao Yang received the B.S., and M.S. degrees both from Xidian University, China, and received his Ph.D. degree from Tsinghua University, China, in 2014. He is currently an Associate Professor (exceptional promotion) at School of electronic information, Northwestern Polytechnical University, China. His research interests include future mobile and wireless networking (5G and the next generation WLAN), non-orthogonal multiple access technologies, software defined wireless networks, and wireless network virtualization and slicing. He has published more than 50 technical papers, including an ESI Most Cited Paper. At present, his papers have been cited by other authors nearly 400 times. He has authorized/applied more than 30 international and national invention patents. He also proposes 7 IEEE and IETF standard proposals. He is serving as reviewers for IEEE Communications Magazine, IEEE Wireless Communications, IEEE Transactions on Vehicular Techonology, IEEE Access, IEEE Communications Letters, Journal of Network and Computer Applications, Journal of Communication and Networks, and etc. He is serving as the organization member of ChinaCom 2017. He is serving as IEEE member, IEEE cloud computing society member, IEEE software defined network (SDN) society member, IEEE vehicular technology society member, Chinese Electronic Society member, and the director of Alumni Association of Tsinghua University.

Zhongjiang Yan received the B.E. and Ph.D. degree in telecommunication engineering from Xidian University in July 2006 and 2011, respectively. From Sept. 2010 to Dec. 2011, he was a visiting Ph.D. student in the Department of Electrical and Computer Engineering, University of Alberta. In Dec. 2011, he joined School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China, where he is currently an Associate Professor. His research interests are in the area of wireless networking and communication, including protocols design and their FPGA implement of the media access control layer, radio resource management, and traffic scheduling strategy of the wireless networks, e.g., 5G, WLAN and etc.. He is a member of the IEEE. He has published over 40 research papers and has over 20 granted and pending International and Chinese patents.

Xiaoya Zuo received the B.S., M.S., and Ph.D. degrees in communication engineering from Northwestern Polytechnical University, Xi'an, China, in 2005, 2008 and 2011 respectively. He is currently a lecturer in the School of Electronics and Information, Northwestern Polytechnical University. From September 2008 to September 2009, he was a visiting scholar in the Department of Electrical and Computer Engineering, University of Victoria, Victoria, British Columbia. His research interests include broadband wireless communications, ultra-wideband communications, single carrier communication systems with frequency domain equalization and multiple-input multiple-output ultrawideband communication systems.