A Reliable Channel Reservation based Multi-channel MAC Protocol with A Single Transceiver

(Invited Paper)

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Abstract—The multi-channel MAC protocols have been proposed recently to improve the network capacity by accommodating more concurrent transmissions. In this paper, we propose a distributed multi-channel MAC protocol using reliable multiple channel reservation with only a single transceiver. Specifically, the control handshake information is reserved to be re-broadcasted over the control channel to address the multi-channel hidden terminal problem. Besides, by reserving multiple data transmission opportunities on the selected data channel, the control channel congestion is further relieved. Then we prove that the multi-channel hidden terminal problem can be addressed using reservation on the control channel, and analyze the effectiveness of the proposed protocol in the aspect of the average number of data channels simultaneously utilized. Extensive simulation results show that the proposed protocol is able to achieve nearly 2.5 times the saturation throughput of DCA protocol [15] when *five*-step channel reservation is adopted.

Index Terms—Media access control, Channel reservation, Multi-channel.

I. INTRODUCTION

With the ever-increasing bandwidth demands of services and applications, wireless media becomes more and more congested. In view of the facts that multiple orthogonal bands are already available (e.g., three orthogonal channels in 2.4 GHz and 12 channels in 5 GHz band) [1], high throughput can be achieved by establishing parallel transmissions over multiple frequency channels [2], [3]. Since several wireless standards such as IEEE 802.11n [4] and 802.11ac [5] have been proposed to enhance the network performance under the multi-channel condition. However, due to the inflexibility of channel utilization, and the requirement of simultaneously sensing on all-channels per node, performance of the multi-channel system is thus restricted. In order to maximize the utilization of multiple available spectrum resources, the design of multi-channel medium access control (McMAC) protocol to coordinate multiple channel access becomes a widely studied research topic [6], particularly in the next generation wireless networks [7], where more devices are deployed densely under the limited spectrum resources condition.

In the current researches of McMAC protocols, the most urgent and critical issue is the multi-channel hidden terminal problem [8], [9], which is caused by selecting an unavailable data channel for transmission, and then results in data collisions. In particular, due to the loss of neighbor nodes control handshake messages, collisions of data transmission between one pair of nodes and the other pair of nodes can not be avoided. The open literatures to address this problem roughly involve time synchronization based protocols [8]- [14] and dedicated control channel (DCC) based protocols [15]- [20].

In time synchronization based McMAC protocols, each node is equipped with one transceiver, and clock synchronization is required. An example is the Multi-channel MAC (MMAC) protocol [9], where time is divided into beacon intervals. All nodes in the network negotiate the data channels over a common channel during the Ad-Hoc Traffic Indication Messages (ATIM) window, and then transmit the following data packets over the selected data channels. However, the multi-channel hidden terminal problem is resolved based on time synchronization, which is a difficult task involving considerable overhead and complexity.

In DCC based McMAC protocols, each node is mainly equipped with two separate half-duplex transceivers, the one transceiver is fixed on the dedicated control channel permanently to contend to access data channels, and the other one switches to the selected data channel to transmit data packets. One representative of this approach is Dynamical Channel Assignment (DCA) protocol [15], which avoids the multi-channel hidden terminal problem by incurring significant hardware cost with the availability of multiple transceivers per device. Moreover, when a relative large number of data channels and nodes are present, this dedicated control channel will be highly congested due to the limited bandwidth, especially when the packets are fairly short [11]. Fortunately, the serious congestion on the dedicated control channel is alleviated effectively in [17], by using multi-step channel reservation scheme with multiple transceivers.

In this paper, a distributed multi-channel MAC protocol by using only a single transceiver is proposed, which is named as *m*-RCR, where *m* represents the number of steps

we employ in the channel reservation. In the proposed *m*-RCR protocol, the control handshake information is reserved to be re-broadcasted over the control channel at the appropriate moment, thus the neighbor nodes are able to gather the channel usage information so as to resolve the multi-channel hidden terminal problem. Besides, by reserving multiple data transmission opportunities on the selected data channel with only one successful control handshake, the congestion on the control channel is further relieved. The main contributions of this paper can be summarized as follows:

- We present a novel multi-channel MAC protocol to coordinate multiple channel access using a single transceiver without the requirements for time synchronization.
- The multi-channel hidden terminal problem is addressed by using the reservation on the control channel, which is theoretically proved to be feasible.
- The control channel congestion is relieved by using multi-step reservations on the data channels, and the average number of data channels simultaneously utilized is theoretically analyzed.
- Extensive simulation results demonstrate that the saturation throughput of the proposed protocol is nearly 2.5 times compared with that of the traditional DCA when *five*-step channel reservation is adopted.

The remainder of the paper is organized as follows. First, the system model is described in Section II. Then in Section III, the operational details of the proposed *m*-RCR protocol is presented, which is followed by the theoretical analysis given in Section IV. In Section V, performance evaluation is presented to demonstrate the effectiveness of our proposed protocol. Finally, some conclusions are drawn in Section VI.

II. SYSTEM MODEL

We consider a distributed network, which consists of N contending nodes. Each node is equipped with a single half-duplex transceiver, each transceiver is able to switch among the control channel and all the data channels. We assume that there are $K + 1$ orthogonal frequency channels with equal bandwidth. One of the channels is configured as the control channel (CH), and the other K channels are configured as data channels, denoted as $DH_i, i = 1, ..., K$. Moreover, it is assumed that the size of all the data packets in the networks is identical, and all the channel conditions are ideal. Therefore, no channel transmission errors exists.

For the sake of our protocol design, we modify the control packets by adding some new fields based on the traditional IEEE 802.11 Distributed Coordination Function (DCF).

The request-to-send (RTS) packet has four new fields: a) the available channel list (ACL), which contains the current available data channels of its own; b) the number of reservation steps (m); c) the time cycle of the reservation on the control channel (T_C); and d) the time cycle of the reservation over data channels (T_D). The RTS packet is represented as $RTS(ACL, m, T_C, T_D)$.

The clear-to-send (CTS) packet also has four new fields: a) the number of reservation steps (m); b) the time cycle of the reservation on the control channel (T_C); c) the time cycle of the reservation over data channels (T_D); and d) the index of selected data channel (DH_S). The CTS packet is represented as $CTS(DH_S, m, T_C, T_D)$, which is transmitted over the control channel to inhibit its neighborhood from using the same data channel.

The reservation (RES) packet is constructed and transmitted over the control channel to confirm the channel reservation, which is also used to inhibit its neighborhood from using the same data channel. The structure of RES packet is similar to the CTS, it can be represented as $RES(DH_S, m, T_C, T_D)$. Furthermore, compared with DCA protocol, there are three new additional items in our proposed *m*-RCR protocol, including m, T_C and T_D.

Without loss of generality, suppose that each control channel handshake is preceded by a random back-off procedure, which is expressed as t_{BK}. $t_C \triangleq t_{RTS} + t_{CTS} + t_{RES} + 2t_{SIFS}$ represents the duration of a successful handshake on the control channel, and $t_D \triangleq t_{Data} + t_{SIFS} + t_{ACK}$ is the duration of a data transmission. Moreover, each node pair turns back to the control channel to carry on virtual carrier sensing after finishing each reserved data transmission. The duration of carrier sensing on the control channel is represented as $\mathbb{R}$.

III. THE PROPOSED *m*-RCR PROTOCOL

The basic idea of our proposed *m*-RCR protocol consists of two aspects. First, the RES packet is reserved to be re-broadcasted over the control channel at the appropriate time, to address the multi-channel hidden terminal problem. Next, multiple data transmission opportunities are reserved in advance on the selected data channel with only one success control handshake, the control channel congestion is then relieved.

The proposed protocol contains four stages, which are illustrated in Fig. 1.

- **Control handshake**. The source node and destination node exchange the control packets (including the RTS/CTS/RES packets) over the dedicated control channel, to negotiate the frequency channel for the following data transmissions.
- **Reservation on the control channel**. The RES packet is reserved to be re-broadcasted by both the source node and the destination node over the control channel, respectively. Therefore, the control handshake information is guaranteed to be received by the neighbor nodes, then the multi-channel hidden terminal problem is addressed.
- **Multi-step reservations on the data channels**. Multiple data transmission opportunities are reserved in advance with only one success control handshake on the selected data channel, thus the control channel congestion is effectively relieved.
- **Collision avoidance**. A new handshake process over the control channel will not start until waiting a period of time, to avoid the collisions with the neighbor nodes.

As a reference, the pseudo codes of the source node and destination node are given in *Algo*.1 and *Algo*.2, respectively.

Specifically, for the source node in *Algo*.1, the control handshake mainly consists of *line 2 ∼ line 6*, reservation on the control channel mainly consists of *line 7 ∼ line 11*, multi-step reservations on the data channels mainly consist of *line 12 ∼ line 33*, and finally the collision avoidance mainly consists of *line 34 ∼ line 40*. Moreover, for the destination node in *Algo*.2, the control handshake mainly consists of *line 1 ∼ line 5*, reservation on the control channel mainly consists of *line 6 ∼ line 8*, and finally multi-step reservations on the data channels mainly consist of *line 9 ∼ line 24*.
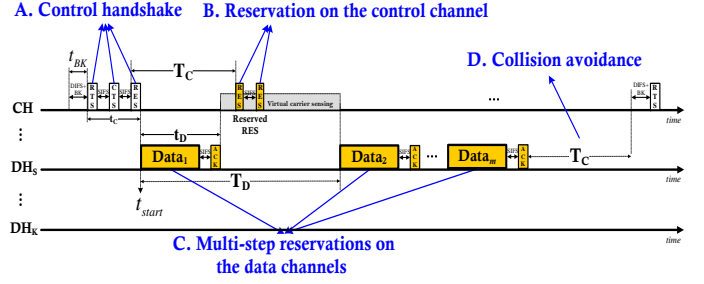

Fig. 1. The operation of *m*-RCR protocol. The process contains four stages: Control handshake (including RTS/CTS/RES packets exchange), Reservation on the control channel (the RES packet is reserved to re-broadcast on the control channel by both of the source node and destination node, respectively), Multi-step reservations on the data channels (multiple data transmissions are reserved with only one successful control handshake), and Collision avoidance (a new control channel handshake will not be initiated until after a period of time).

Algorithm 1 Source Node

1: Sensing on the CH
2: **if** $ACL_S \neq \emptyset \wedge$ (condition ***a*** or ***b*** in the Control Handshake) **then**
3:     Start to backoff by following the rule of IEEE 802.11 DCF
4:     Transmit an $RTS(ACL_S, m, T_C, T_D)$ packet over the CH
5:     **if** receiving a $CTS(DH_S, m, T_C, T_D)$ packet **then**
6:         Reply a $RES(DH_S, m, T_C, T_D)$ packet over the CH
7:         $timer_C \leftarrow T_C$
8:         Start decrementing $timer_C$
9:         **if** $timer_C$ timeout **then**
10:             Transmit the reserved $RES(DH_S, m, T_C, T_D)$ packet over the CH
11:         **end if**
12:         Switch the transceiver to the DH_S and start to transmit a reserved data packet
13:         **for** m = reservation step; $m \neq 0$; $m - -$ **do**
14:             **if** $m \neq 0$ **then**
15:                 $timer_D \leftarrow T_D$
16:                 Start decrementing $timer_D$
17:             **end if**
18:             **if** receives an ACK packet **then**
19:                 Switch the transceiver back to the CH and sensing
20:                 **if** $timer_D$ timeout **then**
21:                     Go back to Line 12
22:                 **end if**
23:             **else**
24:                 $CW \leftarrow CW_{min}$
25:                 Increase the number of retrials
26:                 **if** the number of retrials = the maximum of trials **then**
27:                     $CW \leftarrow CW_{min}$
28:                     Drop the packet and reset the number of retrials
29:                 **else**
30:                     Go back to Line 2
31:                 **end if**
32:             **end if**
33:         **end for**
34:         **if** $m = 0$ **then**
35:             $timer_{Wait} \leftarrow T_C$
36:             Start decrementing $timer_{Wait}$
37:             **if** $timer_{Wait}$ timeout **then**
38:                 Go back to Line 2
39:             **end if**
40:         **end if**
41:     **end if**
42: **else**
43:     Continue sensing on the CH
44: **end if**

A. Control handshake

Suppose that a source node 'S' wants to transmit data packets to its destination node 'D'. At least one of the fol-

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Algorithm 2 Destination Node

1: **if** an RTS packet is received correctly over the control channel **then**
2:     Select a data channel $DH_S \in (ACL_S \bigcap ACL_D)$
3:     Reply a $CTS(DH_S, m, T_C, T_D)$ packet on the control channel after $SIFS$
4:     Receive the RES packet
5: **end if**
6: **if** Receive the reserved RES packet **then**
7:     Transmit the reserved RES packet over the control channel after $SIFS$
8: **end if**
9: **for** m = reservation step; $m \neq 0$; $m - -$ **do**
10:     Switch the transceiver to the selected data channel DH_S and to receive the data packet
11:     **if** The data packet receives correctly **then**
12:         **if** $m \neq 0$ **then**
13:             $timer_D^* \leftarrow T_D^*$ $(T_D^* \leftarrow T_D - t_D)$
14:             Start decrementing $timer_D^*$
15:         **end if**
16:         Transmit an ACK packet to the source node over DH_S
17:         Switch the transceiver back to the CH
18:     **end if**
19:     **if** $timer_D^*$ timeout **then**
20:         Go back to Line 9
21:     **else**
22:         Continue sensing on the CH
23:     **end if**
24: **end for**

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lowing two conditions should first be satisfied: ***a***) the number of yet-to-be-sent data packets is no less than a threshold, which means that there are enough data packets waiting in the queue, ***b***) the maximum queuing delay of data packets is larger than a tolerable value, which indicates that the packets waiting in the queue should be transmitted as soon as possible. If one of the two conditions is satisfied, node 'S' searches for all the candidate data channels and records in its available channel list ACL_S, and then transmits an $RTS(ACL_S, m, T_C, T_D)$ packet to node 'D' after a successful competition over the control channel if $ACL_S \neq \emptyset$.
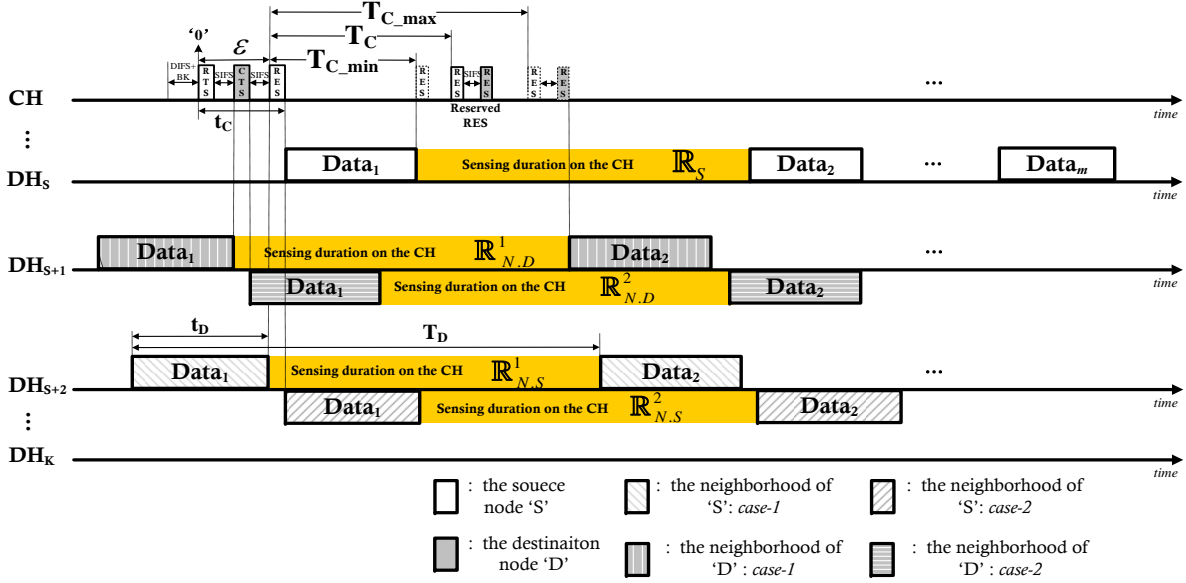
Fig. 2. The analysis of T_C. Suppose the neighborhood of the destination node and the neighborhood of the source node transmit data packets over the data channel DH_{S+1} and DH_{S+2}, respectively. The missed control handshake information can be received by all of the neighbor nodes only if the transmission time of the two reserved RES packets within the intersection of $\mathbb{R}_{N.S}$, $\mathbb{R}_{N.D}$ and $\mathbb{R}_S$. The detailed proof is presented in Section IV.

On receiving the RTS packet, node 'D' selects one of the common available data channels $DH_S \in (ACL_S \bigcap ACL_D)$, and then replies with a $CTS(DH_S, m, T_C, T_D)$ packet. After receiving the CTS packet successfully, node 'S' transmits a $RES(DH_S, m, T_C, T_D)$ packet to confirm the channel reservation.

B. Reservation on the control channel

After finishing the control handshake successfully, the RES packet is reserved to be re-broadcasted by node 'S' over CH according to the time period of T_C, where $T_C \in [t_{RES} + t_D, \ T_D - t_D - t_{CTS} - 2t_{RES} - 2t_{SIFS}]$ and $T_D \geq 2t_D + 3t_{RES} + 2t_{SIFS} + t_{CTS}$. The theoretical proof is given in section IV. Receiving the RES, node 'D' re-broadcasts the RES packet over the control channel after $SIFS$, to inhibit its neighborhood from using the same data channel.

C. Multi-step reservations on the data channels

Meanwhile, *m* data transmission opportunities are reserved in advance with only one successful control handshake, i.e., the reserved time instants are $t_{start} + i \times T_D$, $i = 0, 1, ..., m-1$, as shown in Fig. 1. m is the reservation steps, and t_{start} represents the time instant to transmit the first reserved data packet.

D. Collision avoidance

Finally, when the last reserved data packet is transmitted, node 'S' will not start to initiate a new handshake process over the control channel until its waiting a time period of T_C, so as to prevent from colliding with the reserved RES packet of its neighbors.

IV. THEORETICAL ANALYSIS

In this section, we prove that the multi-channel hidden terminal problem can be addressed by using reservation on the control channel in Theorem 1, where the range of T_C is derived. Then the average number of data channels simultaneously utilized is analysed in Theorem 2, which reflects the "capacity" for the multi-channel system from the theoretical point of view.

Theorem 1. Suppose that all the channel conditions are ideal, thus no channel transmission errors exists. If $T_C \in [t_{RES} + t_D, \ T_D - t_D - t_{CTS} - 2t_{RES} - 2t_{SIFS}]$, where $T_D \geq 2t_D + 3t_{RES} + 2t_{SIFS} + t_{CTS}$, then the control channel handshake information can be correctly received by all of the neighbors.

Proof: All of the neighbor nodes can be classified into two categories: the neighborhood of the destination node (e.g., node 'D'), and the neighborhood of the source node (e.g., node 'S'). The missing of control handshake information is caused by the simultaneous data transmission over the other channels. Suppose the neighborhood of the destination node and the neighborhood of the source node are simultaneously transmitting data packets over the data channel DH_{S+1} and DH_{S+2}, respectively. To guarantee the control channel handshake information be received by all of the neighbors, we should make sure that the neighborhood of node 'D' and the neighborhood of node 'S' receive the reserved information over the control channel independently. Therefore, we analyze two extreme cases, i.e., the data transmission of the neighborhood just finishes at the beginning of the handshake (e.g., the CTS/RES packets), or the data transmission just starts at the end of the handshake, as illustrated in Fig. 2.

Denote $\mathbb{R}^1_{N.S}$, $\mathbb{R}^2_{N.S}$, $\mathbb{R}^1_{N.D}$ and $\mathbb{R}^2_{N.D}$ as the sensing durations of the neighborhood of the source node and the neighborhood of the destination node in two extreme cases, respectively. Consider the moment of transmitting RTS packet as the starting time, then we have

$$
\begin{aligned}
\mathbb{R}^1_{N.D} &= [t_{RTS} + t_{SIFS}, t_{RTS} + t_{SIFS} + \Delta] \\
\mathbb{R}^2_{N.D} &= [t_{RTS} + t_{SIFS} + t_{CTS} + t_D, t_{RTS} + t_{SIFS} + \\
&\quad t_{CTS} + t_D + \Delta] \\
\mathbb{R}^1_{N.S} &= [t_{RTS} + 2t_{SIFS} + t_{CTS}, t_{RTS} + 2t_{SIFS} + t_{CTS} \\
&\quad + \Delta] \\
\mathbb{R}^2_{N.S} &= [t_C + t_D, t_C + t_D + \Delta],
\end{aligned}
\tag{1}
$$

where $\Delta = T_D - t_D$. Then the overlapped sensing durations can be obtained as

$$
\begin{aligned}
\mathbb{R}_{N.D} &= \mathbb{R}^1_{N.D} \cap \mathbb{R}^2_{N.D} \\
&= [t_{RTS} + t_{SIFS} + t_{CTS} + t_D, t_{RTS} + t_{SIFS} + \Delta] \\
\mathbb{R}_{N.S} &= \mathbb{R}^1_{N.S} \cap \mathbb{R}^2_{N.S} \\
&= [t_C + t_D, t_{RTS} + 2t_{SIFS} + t_{CTS} + \Delta].
\end{aligned}
\tag{2}
$$

Moreover, denote $\mathbb{R}_S$ as the sensing duration over the control channel of the source node, where $\mathbb{R}_S = [t_C + t_D, t_C + t_D + \Delta]$. Then the missed control handshake information can be received by all of the neighbor nodes only if the transmission time of the two reserved RES packets is within the intersection of $\mathbb{R}_{N.S}$, $\mathbb{R}_{N.D}$ and $\mathbb{R}_S$. According to Fig. 2, we have

$$
\mathbb{R}_S \cap \mathbb{R}_{N.S} \cap \mathbb{R}_{N.D} = [t_C + t_D, t_{RTS} + t_{SIFS} + \Delta]. \tag{3}
$$

Thus the range of T_C is derived as

$$
\begin{aligned}
&[T_C^{\min}, T_C^{\max}] \\
&= [t_C + t_D - \varepsilon, t_{RTS} + t_{SIFS} + \Delta - \varepsilon - 2t_{RES} - t_{SIFS}] \\
&= [t_{RES} + t_D, T_D - t_D - t_{CTS} - 2t_{RES} - 2t_{SIFS}].
\end{aligned}
\tag{4}
$$

Where $\varepsilon = t_{RTS} + t_{CTS} + 2t_{SIFS}$. Besides, considering the inequality relations of $T_C^{\max} \geq T_C^{\min}$ should be satisfied, we can further obtain that $T_D \geq 2t_D + 3t_{RES} + 2t_{SIFS} + t_{CTS}$. Then the control channel handshake information can be received by all of the neighbors and the inappropriate data negotiation is accordingly avoided. Therefore, the multi-channel hidden terminal problem is finally addressed. ∎

Theorem 2. Let $\mathcal{N}_{DCA}$ and $\mathcal{N}_{RCR}$ be the average number of data channels simultaneously utilized in DCA and our proposed m-RCR protocol, respectively, then we have

$$
\mathcal{N}_{RCR} \overset{\sim}{\leq} m \cdot \mathcal{N}_{DCA}. \tag{5}
$$

Where the symbol "$\overset{\sim}{\leq}$" means that it is an approximated upper bound.

Proof: Denote $\overline{t_{BK}^{DCA}}$ and $\overline{t_{BK}^{RCR}}$ as the average duration of the random back-off procedure in DCA and m-RCR protocols. Then if a bottleneck problem happens in DCA, the average number of data channels can be simultaneously utilized [11] can be obtained as

$$
\mathcal{N}_{DCA} \triangleq \frac{t_D}{\overline{t_{BK}^{DCA}} + t_C^{DCA}}, \tag{6}
$$

where t_C^{DCA} and t_D represent the duration of a successful control handshake in DCA and the duration of a data transmission. In addition, because m data transmission opportunities are reserved in m-RCR with only one successful control handshake, then we can obtain

$$
\mathcal{N}_{RCR} \triangleq \frac{m \cdot t_D}{\overline{t_{BK}^{RCR}} + t_C^{RCR}}, \tag{7}
$$

where t_C^{RCR} represents the duration of a successful control handshake in m-RCR protocol. Due to the little complements of the control packets based on DCA, then we have $t_C^{RCR} \approx t_C^{DCA}$. By using the reservation on the control channel in m-RCR, the RES packet is re-broadcasted over the control channel, then the average duration of random back-off procedure is enlarged, i.e., $\overline{t_{BK}^{RCR}} \geq \overline{t_{BK}^{DCA}}$, where the equality normally holds under the few contentions condition. Therefore, we can finally obtain

$$
\mathcal{N}_{RCR} = \frac{m \cdot t_D}{\overline{t_{BK}^{RCR}} + t_C^{RCR}} \overset{\sim}{\leq} m \cdot \frac{t_D}{\overline{t_{BK}^{DCA}} + t_C^{DCA}} = m \cdot \mathcal{N}_{DCA}. \tag{8}
$$

This completes the proof. ∎

It can be seen that compared with DCA protocol, the number of data channels simultaneously utilized in m-RCR is improved by close to m times, which effectively relieves the control channel congestion.

V. PERFORMANCE EVALUATION

In our simulations, we consider a single-hop wireless network, in which all nodes are within the reach of each other's transmission range. All channels are assumed to be ideal, in the sense that no channel transmission errors exists. There are 50 contending nodes (50 flows) in the network, and each flow is with the constant bit rate (CBR) traffic, where the packet size is 1024 bytes. Some other simulation parameters are given in Table I.

TABLE I. Simulation Parameters.

Parameters	Values
Transmission rate for data channels	11 Mbps
Transmission rate for the control channel	2 Mbps
$CW_{\min}$	15
$CW_{\max}$	1023
SIFS	10 μs
DIFS	50 μs
Slot time	20 μs
The MAC queue length	50
T_C	1 ms
T_D	7 ms

Compared with IEEE 802.11 DCF and DCA protocols, the performance of m-RCR is evaluated by extensive simulations using ns-2 simulator [21] (ns-2.33), in terms of the aggregate throughput and the average packet delay.

Fig. 3 shows that the aggregate throughput achieved by IEEE 802.11 DCF, DCA and our proposed m-RCR protocols,
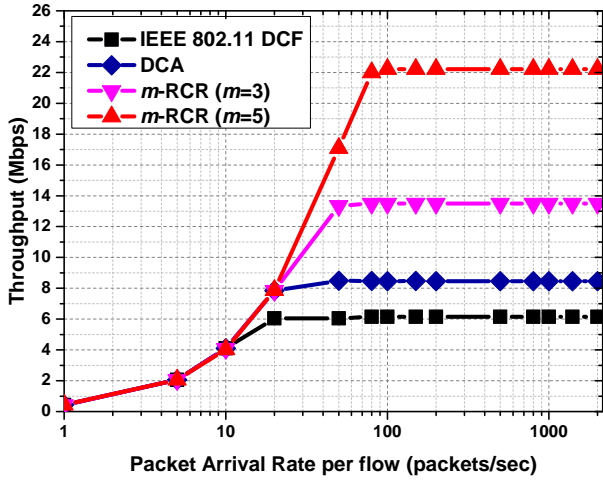
Fig. 3. Aggregate throughput versus packet arrival rate per flow.

Fig. 4. Throughput versus number of data channels.

Fig. 5. Average packet delay versus number of data channels.

respectively. In Fig. 3, we consider that there are one control channel and ten data channels. It can be seen that the system throughput is increased as the traffic rate increases, and *m*-RCR obtains higher throughput than DCA. This is mainly because more data channels can be utilized to bear the ever-increasing data traffic, which can be verified by checking Fig. 4. Therefore, the control channel congestion is alleviated, and the system throughput is improved, especially when reservation step is appropriately large. We can also see that the saturation throughput of *m*-RCR is almost 2.5 times of that of DCA when *five*-step reservations on the data channels is adopted.

Fig. 4 shows the system throughput versus the number of data channels under the saturation traffic condition. It can be seen that due to the capability of utilizing multiple channels, the network throughput of DCA and *m*-RCR are both improved when the number of data channels increases. Furthermore, the control channel has been already saturated in DCA when just two data channels are used, thus the system
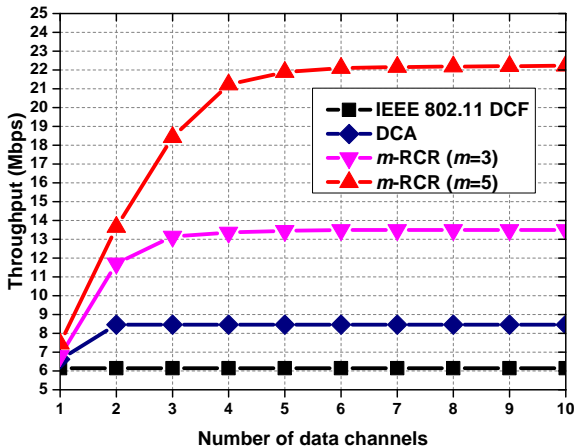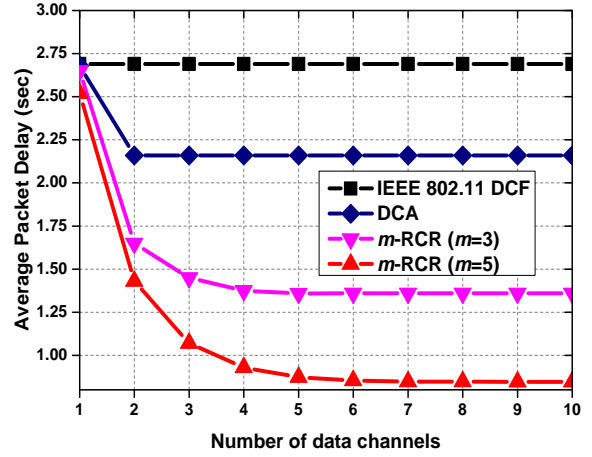
throughput is restricted. Conversely, almost eight data channels can be utilized in *m*-RCR protocol by using *five*-step channel reservation, which coincides with the Theorem 2.

Finally, the average packet delay for different number of data channels is illustrated in Fig. 5. When the number of data channels increases, the average packet delay decreases for both DCA and *m*-RCR protocols, and *m*-RCR obtains much lower delay when the reservation step is appropriately large. This is mainly because that multiple data transmission periods are reserved in advance in *m*-RCR, then the following data packets are guaranteed to be transmitted on time without collisions.

VI. CONCLUSION

In this paper, we propose a distributed multi-channel MAC protocol, i.e., *m*-RCR, which exploits multi-channel reservation to coordinate channel access by using only a single transceiver. The multi-channel hidden terminal problem is addressed based on reservation on the control channel, and the control channel congestion is relieved by reserving multiple data transmission opportunities in advance. Extensive simulations demonstrate that the saturation throughput of *m*-RCR is close to 2.5 times of that of DCA when *five*-step channel reservation is adopted.

REFERENCES

[1] Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, IEEE standard 802.11, Aug. 1999.
[2] Cetinkaya, C., "Multi-Channel Cooperative MAC Protocol for Wireless LANs," Ad Hoc Networks, pp. 1-21, 2015.

[3] Almotairi, K.H. and Shen, X.S., "A Distributed Multi-Channel MAC Protocol for Ad Hoc Wireless Networks," IEEE Trans. Mobile Comput., vol. 14, no. 1, pp. 1-13, Jan. 2015.

[4] IEEE 802.11n-2009, IEEE Standard for Local and Metropolitan Area Networks ł Telecommunications and Information Exchange between Systems ł Local and Metropolitan Area Networks ł Specific Requirements ł Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput, 2009.

[5] IEEE 802.11ac/D3.0, Draft Standard for Information Technology ł Telecommunications and Information Exchange Between Systems C Local and Metropolitan Area Networks ł Specific Requirements ł Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 4: Enhancements for Very High Throughput for Operation in Bands Below 6 GHz.

[6] J. Mo, H.-S. W. So, and J. Walrand, "Comparison of multichannel MAC protocols," IEEE Trans. Mobile Comput., vol. 7, no. 1, pp. 50-65, Jan. 2008.

[7] Deng, Der-Jiunn, Kwang-Cheng Chen, and Rung-Shiang Cheng, "IEEE 802.11 ax: Next generation wireless local area networks," Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine), 2014 10th International Conference on. IEEE, pp. 77-82, 2014.

[8] Yan Zhang, Loukas Lazos, Kai Chen, Bocan Hu, and Swetha Shivaramaiah, "FD-MMAC: Combating Multi-Channel Hidden and Exposed Terminals Using a Single Transceiver," in Proc. of IEEE INFOCOM, pp. 2742-2750, 2014.

[9] J. So, N. Vaidya, "Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver," in Proc. of MobiHoc, pp. 222-233, 2004.

[10] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks," in Proc. of ACM MobiCom, pp. 216-230, 2004.

[11] Tie Luo, Motani, M., "Cooperative Asynchronous Multichannel MAC: Design, Analysis, and Implementation," IEEE Trans. Mobile Comput., vol. 8, pp. 338-352, Jan. 2009.

[12] Dang, Duc Ngoc Minh, Choong Seon Hong, and Sungwon Lee, "A hybrid multi-channel MAC protocol for wireless ad hoc networks." Wireless Networks, pp. 1-18, 2014.

[13] J. Zhang, G. Zhou, C. Huang, S.H. Son, and J.A. Stankovic, "TMMAC: An energy efficient multi-channel mac protocol for ad hoc networks," in Proc. of ICC, pp. 3554-3561, 2007.

[14] S. L. Wu and J. Y. Yang, "A novel channel assignment scheme for improving channel reuse efficiency in multi-channel ad hoc wireless networks," Computer Communications, pp. 3416-3424, 2007.

[15] S. L. Wu, C. Y. Lin, Y. C. Tseng and J. P. Sheu, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," in Proc. of I-SPAN, pp. 232-237, 2000.

[16] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu, "A multi-channel MAC protocol with power control for multi-hop mobile ad hoc networks," Comput. J., vol. 45, no. 1, pp. 101-110, 2002.

[17] B. Yang, B. Li, Q. Qu, Z. Yan, "A New multi-channel MAC protocol based on multi-step channel reservatio," in Proc. of IEEE ICSPCC, pp. 603-607, 2014.

[18] N. Jain, S.R. Das, and A. Nasipuri, "A multichannel CSMA MAC protocol with receiver-based channel selection for multihop wireless networks," In Proc. of the ICCCN Conference, pp. 432-439, 2001.

[19] Almotairi, K. H., Shen, X., "MMAC-HR: Multi-channel medium access control with hopping reservation for multi-hop wireless," in Proc. of IEEE GLOBECOM, pp. 1-5, 2010.

[20] T. Shu, S. Cui, and M. Krunz, "Medium access control for multi-channel parallel transmission in cognitive radio networks," In Proc. of the GLOBECOM, pp. 1-5, 2006.

[21] The Network Simulator ns-2, http://www.isi.edu/nsnam/ns.