

# Design and Analysis of Multi-Channel MAC Protocol with Channel Grouping in Wireless Ad-Hoc Networks

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**SUMMARY** This paper presents a Multi-channel MAC protocol with channel grouping for multi-channel ad-hoc networks. The proposed protocol has both concepts of the multiple rendezvous and the single control channel protocols, which were proposed as a MAC protocol for multi-channel ad-hoc network without centralized stations. In the proposed protocol, all the channels are divided into some groups and each group has a control channel. Network nodes circulate among the groups and channel negotiations are carried out on a control channel of the group. By applying the channel grouping, it is possible to enhance network throughput without reducing the channel-usage probability. Because there is an optimum group number for obtaining the highest throughput, this paper gives analytical expressions of maximum network throughput for the proposed protocol as a function of system parameters. The effectiveness of the proposed protocol is shown from simulation results. In addition, the validity of the analytical expressions is confirmed from quantitative agreements between analytical predictions and simulation results.

**key words:** multi-channel, channel grouping, control channel, multiple rendezvous, throughput analysis

## 1. Introduction

Multi-channel technology is one of the strategies for throughput enhancement [1]–[13]. In the WLANs, the access point can send channel information and indicate usage channel to network nodes. In the ad-hoc networks, however, a transmitter needs to determine a channel for a DATA-frame transmission with a receiver [4]–[13]. Therefore, it is necessary to design a MAC protocol with usage-channel decisions. The previous multi-channel MAC protocols are roughly classified into two approaches. One is multiple rendezvous protocol and the other is single control channel one.

In the multiple rendezvous protocols [2]–[7], an RTS/CTS handshake is carried out posterior to a DATA-frame transmission and the DATA frame is transmitted in the same channel as RTS/CTS handshake. For achieving communications, a transmitter and a receiver should be on the same channel. Therefore, a transmitter needs to circulate

among multiple channels following pre-defined or random sequences [5], [6]. Because network nodes are distributed to multiple channels in average, the channel congestions can be mitigated. As a result, channel usage probability increases, which enhances network throughput. It takes, however, a long time for a transmitter to meet a receiver as channel number increases, which is a disadvantage of rendezvous-type protocols. It is seen that there is a trade-off relationship between the throughput enhancement and overhead reductions.

In the single control channel protocol [8]–[12], one control channel is prepared and all network nodes carry out RTS/CTS handshakes on the control channel [8], [9]. A channel for DATA-frame transmission is negotiated in the RTS/CTS handshake [11], [12]. Because all nodes know the control channel, it takes short time to meet a receiver compared with the multiple rendezvous protocol, which is one of the advantage in the single-channel protocol. The channel-usage probability for DATA-frame transmission, however, decreases as the node number and/or transmission opportunities increase in the network. This is because RTS/CTS handshake failures often occur in these situations. In this case, even if there are sufficient channel number, most of the channels are not used. It is considered that the channel-usage probabilities increase when the multiple control channels are prepared, which is our idea in this paper.

This paper proposes a MAC protocol for multi-channel ad-hoc networks, which has both concepts of the multiple rendezvous and the single control channel protocols. In the proposed protocol, which is called Multi-channel MAC protocol with Channel Grouping (McMAC-CG), all channels are divided into some groups and each group has one control channel. Network nodes circulate among the groups like multiple rendezvous protocols and channel negotiations are carried out on the control channel of the group like single control channel protocols. DATA-frame transmission is carried out at DATA-frame-transmission channel in the same group. Because of the channel grouping, the node number at each control channel decreases. Therefore, the control-frame collisions can be reduced compared with single control channel protocols. On the other hand, the rendezvous channel decreases compared with multiple rendezvous protocols, which reduces the time for transmitter to meet a receiver. Obviously, there is an optimum group number for obtaining the highest throughput, which depends on the node and channel numbers. This paper gives analytical expressions

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of the maximum network throughput for McMAC-CG as a function of system parameters. Additionally, the optimum group number and the contention window size for obtaining the highest network throughput can be predicted by using analytical expressions, which is one of the applications of the analytical expressions. The effectiveness of the proposed protocol is shown from simulation results. In addition, the validity of the analytical expressions is confirmed from quantitative agreements between analytical predictions and simulation results.

## 2. Multi-Channel MAC Protocols for Ad-Hoc Networks

Figure 1 shows an example topology of the multi-channel ad-hoc network. It is considered in the following explanations that all nodes in Fig. 1 are in the carrier sensing range.

### 2.1 Multiple Rendezvous Protocol

Figure 2 shows an example operations of the multiple rendezvous protocol. In multiple rendezvous protocols, each network node circulates among multiple channels following pre-defined or random sequence [5]–[7]. In Fig. 2, Node B is on *ch0* when Node A transmits an RTS frame on *ch0*. In this case, Node A can communicate with Node B at *ch0*. On the other hand, when Node C transmits an RTS frame at *ch2*, Node D is on a different channel. In this case, Node C cannot communicate with Node D. Node C hops to another channel after Node C recognizes the RTS/CTS handshake failure. Node C cannot communicate with Node D until Nodes C and D are on the same channel simultaneously. In the multiple rendezvous protocol, nodes are distributed at entire channels in average. Therefore, frame-collision probability decreases as channel number increases. On the other hand, it is a problem that the meeting probability of a transmitter and a receiver decreases. It is seen that there is a trade-off relationship between the throughput enhancement and overhead reductions against increase in the channel number.

### 2.2 Single Control Channel Protocol

The single control channel protocols prepare a special channel, which is used only for RTS/CTS handshakes with DATA channel negotiation [8]–[12]. Figure 3 shows an example operations of the single control channel protocol. In Fig. 3, *ch0* is a control channel. Namely, all the RTS/CTS handshakes are performed on *ch0*. Because all network nodes know which is the control channel, it is easy to meet a receiver compared with the multiple rendezvous protocols. In Fig. 3, the RTS/CTS handshake between Nodes A and B is in success. Additionally, they negotiate that DATA-frame communication is carried out on *ch1*. Therefore, both Nodes A and B switch the channel to *ch1*. After channel switching, Nodes A transmit a DATA frame to Node B. Similarly, Nodes C and D switch a channel from *ch0* to *ch3* for DATA-frame transmission in Fig. 3. When an RTS/CTS handshakes are often failed, for example, high node density and high rate of

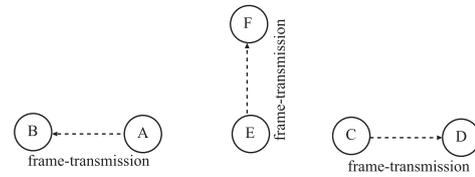


Fig. 1 An example topology.

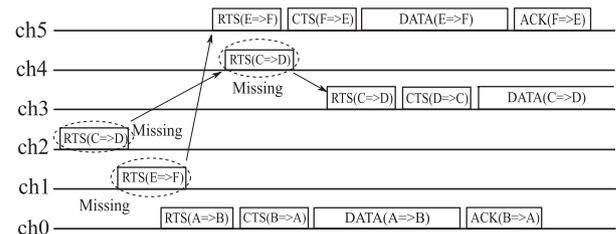


Fig. 2 An example operations of the multiple rendezvous protocol.

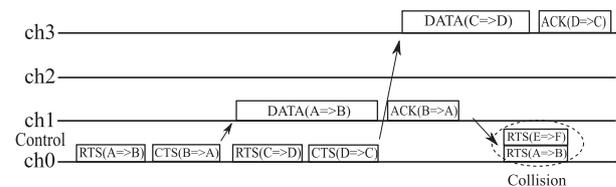


Fig. 3 An example operations of the single control channel protocol.

frame occurrences, the transmission opportunities increase in the network. As a result, the channel-usage probability decreases even if there are sufficient multiple channels at high node density and/or high rate of frame occurrence probability. It is an intuitive idea that the channel-usage probability can increase by preparing multiple control channels.

## 3. Protocol Description

### 3.1 Outline

Figure 4 shows example operations of the McMAC-CG. In the McMAC-CG, all channels are divided into some groups and each group has a control channel. Network nodes circulate among groups like the multiple rendezvous protocols. When a transmitter is in the same group as a receiver, the transmitter can transmit a DATA-frame to the receiver posterior to RTS/CTS handshake with channel negotiation, which follows the single-channel protocol. Because of the channel grouping, the node number at each control channel decreases. Therefore, the RTS/CTS-frame collisions can be reduced compared with the single control channel protocol. On the other hand, the channel number for rendezvous is the same as the group number. Therefore, the McMAC-CG reduces the time to meet a receiver.

Each node has a channel usage list of the existing group, which includes available DATA channel. The channel usage list consists of a bit called *avail\_bit*, which indicates channel availability, and a timer called *avail\_timer*. *avail\_timer* indicates the remaining time in which a channel is not available.

Every when a channel becomes unavailable (*avail\_bit* = 0), its timer is set to expire after a DATA-frame transmission duration. When the timer expires, the corresponding channel becomes available (*avail\_bit* = 1). When a node joins a new group, all *avail\_bit* are set to one. Nodes know available DATA channels by overhearing RTS/CTS handshakes.

### 3.2 Operations of Network Nodes

Figure 5 shows a flowchart of the McMAC-CG. Now the node operation starts from idle mode, which is shown in

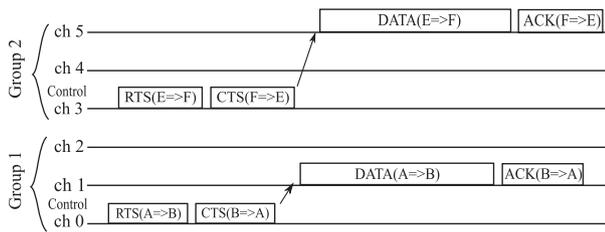


Fig. 4 Example operations of the McMAC-CG.

top-right of Fig. 5. A network node sets a Hopping Timer (HT) value. The node decreases HT simultaneously when the backoff timer value (BT). When the HT becomes zero, the node hops a group randomly. Posterior to the group hopping, the node sets a new HT.

#### 3.2.1 RTS-Frame Transmission

The left-hand side of Fig. 5 shows the flow for DATA-frame transmissions. When a node generates a DATA frame, which call DATA-transmission node, the node sets a *BT*. *BT* is randomly chosen in the range [0, *CW*], where *CW* is the contention window (*CW*) value. The DATA-transmission node decreases *BT* when the control channel is idle. When the *BT* becomes zero, the DATA-transmission node selects DATA channel from the channel list, which is included in the RTS frame as a candidate of the DATA-frame transmission channel. The DATA-transmission node transmits an RTS frame on the control channel of the own group to a DATA-reception node. After transmitting the RTS frame, the node sets *CTS-wait* timer to *CTS-frame* duration.

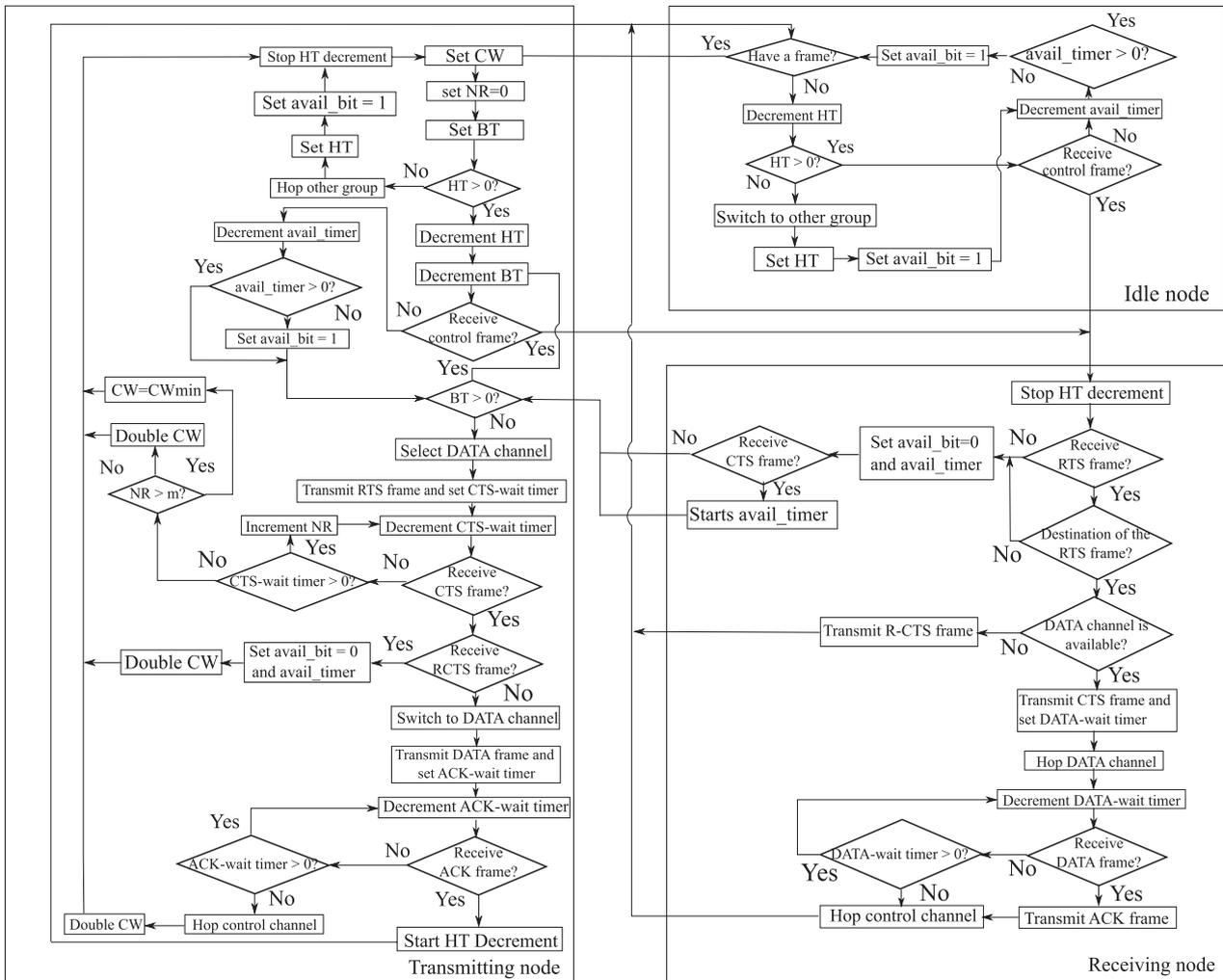


Fig. 5 Flowchart of the McMAC-CG.

### 3.2.2 CTS/R-CTS Frame Reply

The bottom-right side of Fig. 5 shows DATA-frame CTS/R-CTS frame reply procedure. When the DATA-reception node, which is a destination node of the RTS frame, receives an RTS frame, the node checks whether the preference DATA channel is available or not from own channel list. If the preference DATA channel is available, the DATA-reception node transmits a CTS frame to the RTS-frame transmission node. If the DATA channel is occupied, the DATA-reception node transmits a Rejecting CTS (R-CTS) frame for informing that the preference DATA channel is used in the DATA-reception node list. When the DATA-reception node transmits a CTS frame, the node sets DATA-wait timer. On the other hand, the DATA-reception node goes back to the idle state when the DATA-reception node transmits an R-CTS frame.

### 3.2.3 RTS/CTS Handshake Failure

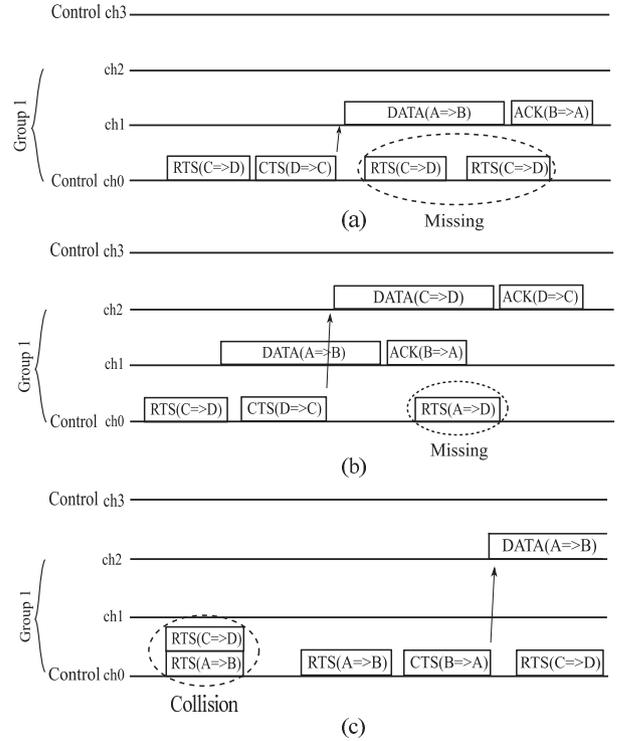
In McMAC-CG, there are three cases that an RTS/CTS handshake is not succeeded. Figure 6 shows RTS-frame transmission failure scenarios in the McMAC-CG. When a DATA-frame receiver is not in the same group as a DATA-frame transmitter, the RTS frame cannot be reached to the receiver as shown in Fig. 6(a). It is also failure case that a DATA-frame receiver communicates with another node in the same group as shown in Fig. 6(b). Figure 6(c) shows the third case, where an RTS frame collided with other RTS frames due to concurrent transmission. In these cases, DATA-frame transmitter can receive no CTS/R-CTS frame during CTS-wait timer. DATA-transmission node returns to the initial state with doubling its CW value.

### 3.2.4 DATA-Frame Transmission

When the DATA-transmission node receives the CTS frame from the DATA-reception node within CTS-wait timer, the transmitter also switches to the DATA channel. After the channel switching, the DATA-transmission node starts to transmit a DATA frame. Posterior to the DATA frame transmission, the node sets ACK-wait timer. When the DATA-reception node receives a DATA frame successfully, the reception node transmits an ACK frame to the DATA-transmission node. After the reception node transmits the ACK frame, the node returns to the control channel. When the DATA-transmission node receives an ACK frame within ACK-wait timer, the node also returns to the control channel and moves to idle mode. When DATA-transmission node receive no ACK frame during ACK-wait timer, the node returns to the initial state with doubling its CW.

### 3.2.5 Channel Information Updates

Nodes can make their own channel usage lists through overhearing RTS/CTS handshake. Nodes, which are not both the DATA-transmission and DATA-reception nodes in the same



**Fig. 6** Frame transmission failure examples of the McMAC-CG. (a) In case that a receiver is not the same group. (b) In case that a receiver transmit another.

control channel, can overhear the control frames. When a node overhears an RTS frame, the node updates its channel usage list by setting its  $avail\_list(x) = 0$  and sets  $avail\_timer(x)$  for DATA-frame transmission, where  $x$  is the usage channel label including in the RTS frame. When a node overhears a CTS frame, it starts  $avail\_timer(x)$ . When a node overhears an R-CTS frame, the node set  $avail\_list(x) = 1$  for correcting the RTS-frame information.

## 4. Throughput Analysis of McMAC-CG

This section presents analytical expressions of maximum throughput of ad-hoc networks with McMAC-CG. RTS-Frame transmission probability, RTS/CTS handshake failure probability, contending node number in one group, and existing time on DATA channel are expressed for the network throughput derivation.

The analysis in this paper is based on the following assumptions.

1. Each node always has equal to or more than one transmission frame. Namely, the network is in saturation state.
2. A node is in the carrier sensing range of all other nodes in the network.
3. Channel condition is ideal. Namely, transmission failures occur only by frame collisions.
4. After a successful RTS/CTS handshake, DATA-frame is

received successfully. Namely, no DATA-frame transmission failures occur.

5. R-CTS-frame-reply occurrences can be ignored in the saturation state.
6. Inter channel interference can be ignored.
7. Time for switching channels is zero.
8. There are the identical number of channels in each group.
9. All network nodes make homogeneous operation. Namely, all nodes transmit identical length DATA frames with identical frame-occurrence probability.

The assumptions 3, 4, and 6 are the idealizations about physical-layer (PHY) characteristics. For quantitative evaluations of the MAC protocol, it is usual that the ideal (PHY) characteristics are assumed [15]–[18]. Actually, all the MAC protocols discussed in this paper are independent of the PHY characteristics. Obviously, the quantitative throughput decreases as bit errors due to PHY characteristics increase. The qualitative characteristic relationships among the MAC protocols, however, do not vary according to the PHY characteristics.

In addition, it is assumed that there is no hidden node in the network at the assumption 2. When there are hidden nodes in the network, the throughput is degraded due to the frame collisions due to the hidden nodes. The degradation is, however, limited because all the protocols use RTS/CTS handshakes, which are effective for avoiding hidden-node problems. Therefore, the assumption 2 is also valid and effective for simplifying the network situations.

#### 4.1 RTS-Frame Transmission Probability

RTS frames are retransmitted until a DATA-frame is transmitted successfully. In the McMAC-CG, the value of CW is reset when the retransmission number is over  $m$  like IEEE802.11 DCF [15]. From [15] the average slot number of backoff counts for one DATA-frame-transmission success is

$$U = \sum_{j=0}^{\infty} p^j W_i, \text{ for } i = j \bmod m$$

$$= \sum_{i=0}^m W_i \frac{p^i}{1 - p^{m+1}}, \quad (1)$$

where  $p$  is the RTS-frame transmission failure probability, which is obtained in Sect. 4.2. Additionally,  $W_i$  is the CW value for  $i$ -th retransmission, which is expressed as

$$W_i = \begin{cases} \frac{2^i(CW_{min} + 1)}{2}, & \text{for } i \leq m' \\ \frac{CW_{max} + 1}{2}, & \text{for } m' < i \leq m \end{cases}, \quad (2)$$

where  $CW_{min}$  and  $CW_{max}$  are the initial and maximum values of the CW, respectively, and  $m$  is the retransmission limit number. An RTS frame is transmitted when the backoff counter becomes zero. The frame-transmission probability

is

$$\tau = \frac{\sum_{j=0}^{\infty} p^j}{U} = \frac{1}{(1-p)U}. \quad (3)$$

Therefore, the probability that at least one node attempt to transmit an RTS frame in a certain group is expressed as

$$p_t = 1 - (1 - \tau)^{N_c}, \quad (4)$$

where  $N_c$  is the expected value of node number in a control channel of the group, which are expressed in Sect. 4.3. By using  $p_t$ , the average time of backoff count decrement for one frame transmission success, which includes carrier-sensing time is obtained from

$$\Omega = (1 - p_t)\sigma + p_t(1 - p)T_{r_s} + p_t p T_{r_f}, \quad (5)$$

where  $T_{r_s} = DIFS + RTS + SIFS + CTS$  and  $T_{r_f} = DIFS + RTS$  are the necessary times for RTS/CTS handshake and RTS-frame transmission failure, respectively, and  $\sigma$  is the system slot time. Additionally,  $DIFS$  is the duration of the distributed inter frame space (DIFS),  $SIFS$  is the duration of the short inter frame space (SIFS), and  $RTS$  and  $CTS$  are the transmission times of an RTS and CTS frames, respectively.

#### 4.2 RTS/CTS Handshake Failure Probability

It is seen from protocol operation explained in Sect. 3 that the RTS/CTS handshake is in success with full satisfactions that (1) the DATA-reception node is in the same group, (2) the DATA-reception node is in the control channel of the same group, and (3) no RTS-frame collision occurs.

The probability that a DATA-reception node is in the different group from a DATA-transmission node is expressed as

$$p_{r(1)} = 1 - \frac{\frac{N}{G} - 1}{N - 1}, \quad (6)$$

where  $N$  and  $G$  are the node number and the group number, respectively. The probability that a DATA-reception node communicates with another node in a DATA channel is obtained as

$$p_{r(2)} = \frac{(N - 1) - (N_c G - 1)}{N - 1}$$

$$= \frac{N - N_c G}{N - 1}. \quad (7)$$

In (7),  $(N - N_c G)$  expresses the number of nodes, which are not on the control channel.

The RTS-frame from a certain node is collided when at least one of the other nodes start to transmit an RTS frame simultaneously. The RTS-frame collision probability is expressed as

$$p_{r(3)} = 1 - (1 - \tau)^{N_c - 1}. \quad (8)$$

From (6)–(8), the RTS/CTS handshake failure probability is

$$p = 1 - \prod_i^3 (1 - p_{r(i)}). \quad (9)$$

#### 4.3 Expected Value of Node Number on Control Channel

By using  $\Omega$  in (5) and  $U$  in (1), the average time, in which a node is on the control channel, for one DATA-frame transmission success is

$$T_b = \Omega U. \quad (10)$$

On the other hand, a node is on the DATA channel when the node transmits or receives a DATA frame. Therefore, an average time, in which a node is on a DATA channel for one DATA-frame transmission success, includes DATA-frame transmission and reception times. From the assumption 7, it can be stated that the DATA-frame transmission opportunity is the same as the DATA-frame reception opportunity. Therefore, the average time can be obtained from

$$T_d = 2T_{d_s}, \quad (11)$$

where  $T_{d_s} = SIFS + DATA + SIFS + ACK$  is the necessary time for DATA-frame communication. By using  $T_b$  and  $T_d$ , the probability that a node is on the DATA channel is expressed as

$$p_d = \frac{T_d}{T_b + T_d}, \quad (12)$$

The expected value of node number on each control channel is can be expressed by using  $p_d$  as

$$N_c = \frac{N(1 - p_d)}{G}. \quad (13)$$

#### 4.4 Network Throughput

From the assumption 9, each node spends  $(T_b + T_d)$  for one DATA-frame transmission success. Namely, the maximum network throughput is expressed as

$$S = \frac{NP}{T_b + T_d}, \quad (14)$$

where  $P$  is the DATA payload size. The network throughput can be obtained by solving (1)–(13) for  $T_b$ ,  $\tau$ ,  $p_{r(1)}$ ,  $p_{r(2)}$ ,  $p_{r(3)}$ ,  $N_c$ , and  $T_d$ .

The analytical expression of the maximum throughput is a function of system parameters including the group number. Therefore, it is possible to derive the optimal group number for obtaining the highest maximum throughput with low computation cost by using the analytical expression.

### 5. Performance Evaluations

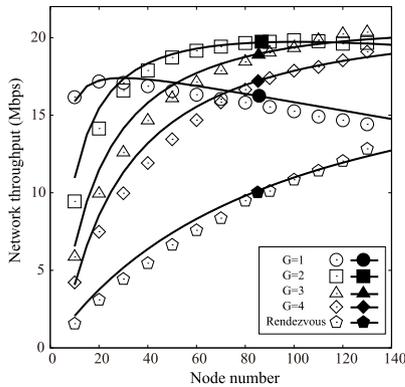
The effectiveness of the McMAC-CG and the validity of the analytical expressions are evaluated by carrying out simulations. Additionally, the optimal group number and contention-window sizes were predicted from analytical expressions. Table 1 gives the environmental parameters,

**Table 1** Environmental parameters.

Basic rate	6 Mbps
Data rate	48 Mbps
DIFS	34 $\mu$ s
SIFS	16 $\mu$ s
Payload size	512 bytes
RTS frame size	20 bytes
CTS frame size	14 bytes
ACK frame size	14 bytes
MAC Header	24 bytes
PHY Header	16 bytes
minimum CW size ( $CW_{min}$ )	15
maximum CW size ( $CW_{max}$ )	1023
maximum number of retransmissions ( $K$ )	7
Number of channels ( $\Gamma$ )	12
Slot time ( $\sigma$ )	9 $\mu$ s
channel hopping interval	900 $\mu$ s
Simulation time	30 s
Simulation number	20

which basically follow those in IEEE 802.11a [14]. In each simulation,  $N$  nodes are located randomly. All the nodes are in the carrier-sensing area one another. 12 channels are available in simulations, which is the same environment in [11]. All the network nodes can generate DATA frames following the Poisson distribution and circulates among groups every 900  $\mu$ s. The DATA-reception node is selected randomly. RTS, CTS, R-CTS, and ACK frames are transmitted at the basic rate. Every simulations are executed for 30 second in simulation time and obtained data during from 10 s to 30 s are used for evaluations. Data at the beginning of 10 second is wasted as a transient data. All the plots are average values for 20 simulation results. Though it is omitted to show the detailed expressions, the analytical expressions of multiple rendezvous protocol for saturation condition can be also obtained.

Figure 7 shows the network throughput in the saturation state as a function of the node number for fixed group number. It can be confirmed from Fig. 7 that the predicted maximum throughput from analytical expressions agree with simulation results quantitatively, which shows the validity of the analytical expressions. In the single control channel protocol, namely for  $G = 1$ , the network throughput decreases as node number increases. This is because the RTS-frame collision probability increases as node number increases. Conversely, the network throughput of the multiple rendezvous protocol increases as the node number increases. This is because the pair number increases with increase in the node number. It is seen from Fig. 7 that the network throughput increases as node number increases in the McMAC-CG, namely  $G \neq 1$ . By applying the grouping, the control channel congestions are mitigated. The network throughput decreases as group number increases for small node number regions. This is because the overhead for meeting a receiver increases as group number increases. When the node number is larger than 110, however, the network throughput for  $G = 3$  is higher than that for  $G = 2$ . This is because the control-frame collision problem is not ignored for  $G = 2$  in this region and the control channel increment is effective for mitigat-



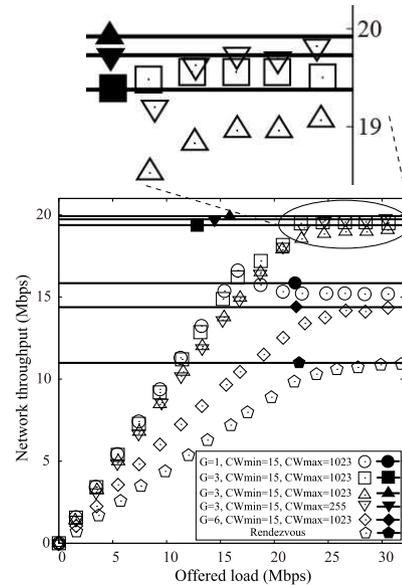
**Fig. 7** Simulation results (plots) and analytical prediction (lines) of network throughput as a function of node number for fixed group number.

ing the frame collisions. It is also seen from Fig. 7 that the proposed protocol can obtain high network throughput compared with the multiple rendezvous protocol. This is because the overhead for meeting a receiver decreases as group number decreases. The control-frame collisions increase with the decrease in the group number, while the time to meet a receiver decreases with the increase in the group number. It can be stated that there is a trade-off relationship between the control-frame collision reduction and meeting probability enhancement against group number variation. Namely, there is an optimal group number, which depends on the node number. It is seen from Fig. 7 that the network throughput can be predicted accurately from the analytical expressions.

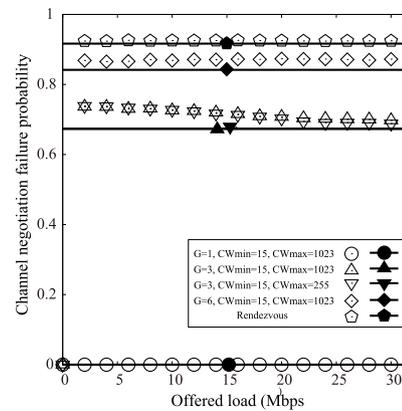
Figure 8 shows the network throughput as a function of the offered load obtained from simulations and the maximum throughput obtained from analytical expressions for  $N = 100$  and the fixed group number and CW values. The throughput of the single control channel protocol for  $G=1$  is higher than those of McMAC-CG for  $G=2$  at light offered load. It is seen from Fig. 8 that the throughput for  $G=2$  is, however, higher than that for  $G=1$  in the range of  $OL > 17$  Mbps. This is because control-frame collision probability for  $G=1$  increases rapidly, which can be confirmed from Fig. 10. It is seen from Fig. 8 that the network throughputs of the McMAC-CG are higher than that of both the single control channel protocol and multiple rendezvous protocol in the range of heavy offered load because of the RTS-frame collision reduction and meeting probability enhancement effects.

Not only the group number but also the CW size effects can be evaluated from the analytical expressions. Namely, the optimal combination of  $G$ ,  $CW_{min}$ , and  $CW_{max}$  for maximizing the network throughput can be predicted from analytical expressions. It can be confirmed from Fig. 8 that the highest saturation network throughput is obtained for  $[G, CW_{min}, CW_{max}] = [3, 15, 255]$ . The simulation results show the same results as the analytical predictions.

Figure 9 shows the meeting failure probability as a function of the offered load obtained from simulations and those in saturation conditions predicted from analytical expressions for  $N = 100$ . The meeting failure probability is defined as the probability that a DATA-reception node is in the



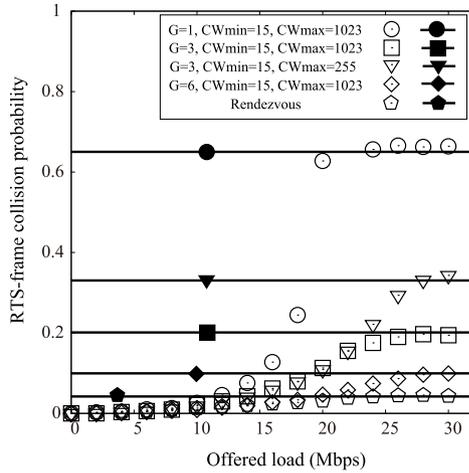
**Fig. 8** Network throughput as a function of the offered load obtained from simulation (plots) and maximum throughput obtained from analytical expressions (lines) for  $N = 100$  and fixed group number and CW sizes.



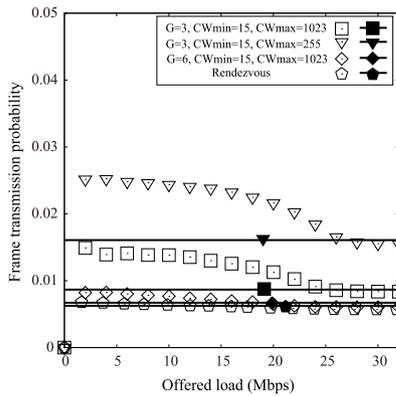
**Fig. 9** Meeting failure probability as a function of the offered load from simulations (plots) and that in the saturation condition from analytical expressions (lines) for  $N = 100$  and fixed group number and CW sizes.

different channel from a DATA-transmission node when the transmission node transmits an RTS frame. It is seen from Fig. 9 that the meeting failure probability of the McMAC-CG increases with the increase in the group number. This is because it takes long time for DATA-transmission node to be in the same group as DATA-reception node. Obviously, the multiple rendezvous protocol provides the highest meeting failure probability. The analytical predictions of the negotiation failure probability also agree with simulation results quantitatively.

Figure 10 shows the RTS-frame collision probability as a function of the offered load for  $N = 100$ . The node number of the channel with RTS/CTS handshake is the smallest in the multiple rendezvous protocol. Therefore, the lowest RTS-frame collision probability can be obtained in the multiple rendezvous protocol. It is seen from Fig. 10 that the



**Fig. 10** RTS-frame transmission failure probability induced by frame collisions as a function of the offered load obtained by simulation and analytical one in saturation state for fixed group number and CW sizes.



**Fig. 11** Frame transmission probability as a function of the offered load from simulations (plots) and that in the saturation condition from analytical expressions (lines) for  $N = 100$  and fixed group number and CW sizes.

RTS-frame collision probability increases as the group number of the McMAC-CG decreases. It can be confirmed from Figs. 9 and 10 that there is a trade-off relationship between the control-frame collision reduction and meeting probability enhancement against group number variation. The positive factor, which is the reduction of the frame collisions, is stronger than the negative one, which is the increase in meeting failure in the McMAC-CG compared with the single control channel protocol. The positive factor, which is the increase in meeting success in the McMAC-CG, is stronger than the negative one, which is the increase in the frame collisions, compared with the multiple rendezvous protocol. Therefore, the McMAC-CG achieves higher network throughput than both the single control channel protocol and the multiple rendezvous one.

Figure 11 shows the frame transmission probability as a function of the offered load for  $N = 100$ . It is seen from Fig. 11 that the frame transmission probability decreases as the offered load increases because of the RTS-frame collisions. When RTS-frame collisions and/or

CW value increase, the transmission probability decreases. It is also seen that the frame transmission probability of  $[G, CW_{min}, CW_{max}] = [3, 15, 255]$  is the highest in all the combinations in Fig. 11, which agree with the parameter set for the highest throughput as shown in Fig. 7.

## 6. Conclusion

This paper has proposed McMAC-CG for multi-channel ad-hoc networks. In McMAC-CG, all the channels are divided into some groups and each group has a control channel. Network nodes circulate among the groups like the multiple rendezvous protocol and channel negotiations are carried out on the control channel of the group like the single control channel protocol. The control-frame collision probability decreases as the group number increases. On the other hand, the expected time to meet a receiver decreases as the group number decreases. Therefore, there is a trade-off relationship between frame-collision probability reduction and meeting probability enhancement against the group number variation. The protocol characteristics can be comprehended analytically with some assumptions, which is also an important contribution of this paper. By using the analytical expressions, optimal parameter set including group number can be predicted. In practical network, it is necessary to establish how to share the optimal group number information among network nodes, which should be addressed in the future.

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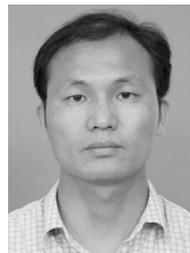
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