MAC-SCC: A Medium Access Control Protocol with Separate Control Channel for Reconfigurable Multi-hop Wireless Networks

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Abstract—In this paper, we propose a novel Medium Access Control protocol with a Separate Control Channel (MAC-SCC) to increase the channel efficiency and address the unfairness and instability problems of IEEE 802.11 MAC protocol. In MAC-SCC, the available bandwidth is partitioned into two channels: a data channel and a control channel, each associated with a network allocation vector (NAV). To reduce hardware complexity, the station transmits or receives on one channel only at any given time. In the network employing MAC-SCC, the next data frame can be pre-scheduled during the current data transmission via the separate control channel, and thus reducing the frame collision probability and the bandwidth wasted during backoff. Moreover the use of the separate control channel helps to achieve fair medium access and solve the instability problem resulted from frequent link failures. The optimal bandwidth partitioning between the two channels is analyzed via a statistical model, which shows 10% bandwidth for the control channel and 90% bandwidth for the data channel. The performance of MAC-SCC is quantified via extensive simulations in both a stand-alone simulator developed by using PARSEC and a comprehensive network simulator called QualNet with whole protocol stack. Our results show that MAC-SCC can effectively reduce the link failure probability, achieve fair medium access when running multiple TCP sessions, and yield a throughput gain up to 60% under high traffic load.

Index Terms—Bandwidth partitioning, channel efficiency, MAC-SCC, medium access control, mobile ad hoc network, network allocation vector, performance evaluation.

I. INTRODUCTION

RECONFIGURABLE multi-hop wireless network consists of a collection of self-configured nodes that act both as hosts and as routers, and communicate with each other via wireless links without the intervention of a centralized controller [1]. With the unmatched flexibility to support the communication of mobile users, the reconfigurable multi-hop wireless network has become increasingly popular in the past few years. At the same time, however, several challenges, such as Quality of Service (QoS), efficient routing and medium access control (MAC), need to be addressed in order to enable efficient communication in such reconfigurable multi-hop wireless networks. In this paper, we focus on the MAC protocol that are employed to resolve contentions for accessing the shared medium. It has been shown in [2] that MAC protocols can significantly affect the overall performance of the multi-hop wireless networks. The hidden station [3] is a main problem of the medium access control in multi-hop wireless networks. A hidden station is a node that is close to the receiver but outside the transmission range of the sender. Such node can not detect the ongoing transmission, and thus it may send out control or data frames and interfere the reception at the receiver. To alleviate the hidden station problem, the Request To Send (RTS)/Clear To Send (CTS) mechanism has been developed and standardized in IEEE 802.11 Distributed Coordination Function (DCF) [4].

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Fig. 1 (a) illustrates a simple network topology composed of 4 nodes. As shown in Fig. 1 (b), when source S1 has data to send to node D1, it first senses the medium. If the medium is idle during an interval of DIFS (DCF InterFrame Space), S1 sends an RTS frame. Upon receiving RTS successfully, D1 responds with a CTS after an interval of SIFS (Short InterFrame Space). On receiving the CTS, S1 sends the data frame, and D1 will accordingly respond with an ACK. There is a duration field in any valid frames to indicate the period reserved for data transmission. On receiving a valid frame, a node updates its Network Allocation Vector (NAV), which is a timer used to indicate the duration of channel occupancy. If the source (e.g., S2 in Fig. 1 (b)) detects the channel busy based on either physical medium sensing or NAV, it has to defer its RTS transmission. More specifically, S2 starts its backoff timer, which decreases only after the medium becomes idle for an interval of DIFS, and sends RTS when the timer expires. The initial value of the backoff timer is uniformly distributed in the contention window whose size is exponentially increased with the number of retransmissions.

While IEEE 802.11 MAC protocol is employed widely in wireless local area network and ad hoc networks, it has been shown that the basic RTS/CTS approach may result in several problems as listed below.

1) Channel efficiency: The channel efficiency of the IEEE 802.11 MAC protocol may be reduced dramatically when the traffic load is high. As can be seen from Fig. 1 (b), a certain amount of time is used for signaling only, and in particular, the
entire bandwidth is wasted during backoff. In wireless local area networks, where all nodes are within the transmission range of each other, the RTS/CTS frames are assumed not to collide with data frames, because every node maintains a NAV such that one node does not send RTS/CTS during the data transmission of another node. But this assumption is not valid in reconfigurable multi-hop environments due to the hidden station problem, and accordingly a large number of signaling frames may experience multiple collisions. Under high traffic load, multiple retransmissions may fail, leading to exponentially increased backoff time and further decreased channel efficiency.

2) Link failure and instability problem: Worse yet, the node may even falsely report a link failure. For example, in a simple network with the string topology shown in Fig. 2, when node $D$ has data to send to node $E$, it sends an RTS. Assuming an omnidirectional antenna for transmission, then both nodes $C$ and $E$ will receive the RTS frame. As a result, node $C$ will defer its transmission (if any) and node $E$ replies with a CTS. After receiving CTS, node $D$ can send the data frame. However, since node $B$ cannot receive the RTS or CTS frames, it assumes that there is no on-going transmission. If node $B$ has data to send to node $C$, it will send out an RTS. But node $C$ cannot receive this RTS correctly because of the interference from node $D$, and thus will not reply to node $B$. After timeout, node $B$ will backoff for a period of time before retransmitting the RTS frame. If node $D$ is sending several long back-to-back TCP data packets, the channel will be kept busy, and thus multiple consecutive attempts to transmit an RTS frame from node $B$ may fail. When failing seven times (a default value defined in IEEE 802.11 standard) to receive the CTS from node $C$, node $B$ will quit and falsely report a link failure. In such a case, upper layers will initiate certain recovery schemes (e.g., re-routing), likely resulting in a long end-to-end delay. During route discovery, TCP throughput is about zero, leading to the instability problem as reported in [5].

3) Unfairness problem: Due to the binary backoff algorithm, IEEE 802.11 MAC protocol also results in unfairness problem among multiple TCP sessions [5], [6]. Assuming that the transmission range of a node only covers the immediate neighbor nodes and there are two TCP sessions in the network shown in Fig. 2: Session 1 with one hop from node $C$ to node $B$ and Session 2 with two hops from node $D$ to node $F$. Clearly, node $C$ and node $D$ will contend for the channel. In IEEE 802.11, however, node $C$ has a much higher probability to win contention for channel access, because of the following two reasons. First, since session 2 involves two hops, node $D$ can transmit for no more than 50% of the session period (due to the contention with node $E$). Thus, only about 50% data frames of Session 1 experience channel contention. On the other hand, every data frame of Session 2 has to contend for the channel. Second, the IEEE 802.11 backoff algorithm favors the last successful transmission. More specifically, the station (e.g., node $C$) that just completes a successful transmission always uses the minimum contention window, leading to a short backoff time and high probability of winning channel contention. As a result, Session 2 is shut down with a throughput about zero.

In this paper, we propose a novel MAC protocol using a separate control channel (MAC-SCC) to address the above problems in IEEE 802.11. In MAC-SCC, the available bandwidth is partitioned into two channels: a data channel and a control channel, each associated with a network allocation vector (NAV). To reduce hardware complexity, the station transmits or receives on one channel only at any given time. In the network employing MAC-SCC, the next data frame can be pre-scheduled during the current data transmission via the separate control channel, and thus reducing the frame collision probability and the bandwidth wasted during backoff. Moreover the use of the separate control channel helps to achieve fair medium access and solve the instability problem resulted from frequent link failures. The optimal bandwidth partitioning between the two channels is analyzed via a statistical model, which shows 10% bandwidth for the control channel and 90% bandwidth for the data channel. The performance of MAC-SCC is quantified via extensive simulations in both a stand-alone simulator developed by using PARSEC and a comprehensive network simulator called QualNet with entire protocol stack. Our results show that MAC-SCC can effectively reduce the link failure probability, achieve fair medium access when running multiple TCP sessions, and yield a throughput gain up to 60% under high traffic load.
The rest of this paper is organized as follows. The related work is discussed in Section II. The proposed MAC-SCC protocol is described in Section III. The simulation results are presented in Section IV. Finally, Section V concludes the paper.

II. RELATED WORK

Various MAC protocols have been proposed to improve the performance of the basic RTS/CTS scheme. MACAW [6], [7] uses an RTS-CTS-DS-DATA-ACK handshake sequence and a different backoff algorithm to achieve high channel utilization and fair channel access. As discussed in [6], however, MACAW cannot solve the unfairness problem completely, especially in the situation as shown in Fig. 2. Efficient MAC protocol with power control are proposed in [8], [9] in order to reduce the interference and improve system throughput. In [10]–[12], the authors propose MAC protocols for the wireless network deploying directional antennas to improve channel efficiency via spatial reuse. [13] proposes a dynamic channel assignment scheme, where the channels are assigned to the nodes dynamically so that the same channels are not used by the nodes which are within two hops. [14] proposes to combine different MAC protocols in order to adapt to dynamic network conditions.

In this paper, we focus on the use of multiple channels, which is an effective way to enhance MAC protocol efficiency and may be applied together with other techniques (such as, dynamic channel assignment scheme, the use of directional antennas and/or power control) as well. Several existing multichannel MAC protocols for multihop wireless networks are discussed as follows.

The dual busy tone multiple access (DBTMA) is proposed in [15]. To further alleviate the hidden station problem and reduce the collision probability, extra hardware is deployed to support two outband busy tones: one indicating data transmission and the other indicating data reception. The carrier sense is done by detecting these two busy tones. DBTMA without MAC layer acknowledgement uses RTS-CTS-DATA handshake sequence. The error recovery relies on the high layer protocol, such as TCP. [16] enhances DBTMA by combining power control with RTS/CTS-based and busy tone-based approach to increase channel efficiency.

[17] proposes a multi-channel carrier sense multiple access (CSMA) protocol, where the total available bandwidth is divided into \( N \) narrow-band sub-channels. The RTS/CTS mechanism is not used. Instead, an idle sub-channel is selected randomly for data transmission. [18] further improves the multi-channel protocol by maintaining a list of free sub-channels at each node. The available sub-channel with the highest channel quality is chosen for data transmission. A receiver-based multi-channel MAC protocol is proposed in [19], where each mobile node is assigned with a channel to receive data packets. The maximal matching algorithm is employed to improve the channel efficiency and network throughput. [20] presents a receiver-initiated channel-hopping with dual polling (RICH-DP) protocol, where the total bandwidth is divided into a number of subchannels and the nodes hop among the subchannels by following the same sequence. If a node is involved in data transmission or reception, it stays in the currently used subchannel until the data transmission is finished. Otherwise it hops to the next channel after a short dwell time.

Similar to [17]–[20], the total available bandwidth is divided into a number of narrow-band sub-channels in [21]. But one sub-channel is reserved for control (i.e., transmitting RTS/CTS messages). Reserving control channel can significantly reduce the collision probability of data channel, because control packets are usually very short. Each node senses the medium and builds a free-channel list. This list is embedded in the RTS frame of the transmitting node. The receiving node can accordingly choose the channel which is free for both of them. Clearly, the RTS/CTS frames need the extra field/bytes to accommodate the free-channel list. In addition, it is assumed in [21] that multiple packets on different channels can be received simultaneously, which may increase hardware cost. A similar idea is used in [22]–[24] and further enhanced in [25] with power control. [26] proposes to employ two control channels, one for RTS/CTS and the other for ACK, respectively, in order to improve data channel reuse ratio.

Several approaches have been proposed recently to apply the multiple channel MAC schemes on existing IEEE 802.11 channels. In [27], the authors propose to reserve one IEEE 802.11 channel for signaling and use the other channels for data transmission. Five control frames (two RTS frames, two CTS frames, and a Probe frame) are involved in channel reservation for each data frame. [28] proposes to apply multi-channel MAC protocol on three non-overlapped IEEE 802.11b channels and focuses on solving the multi-channel hidden station problem. In order to further improve channel efficiency, [29] proposes to employ three half-duplex transceivers that can reduce the channel switching delay.

Note that, all of the above multi-channel MAC protocols [17]–[26] share several problems compared with our proposed MAC-SCC protocol. First, to implement multi-channel protocols, the wireless network interface card (NIC) needs to scan all channels. The more channels are employed, the more complex and expensive is the protocol implementation. If multiple NICs are used, the cost is even higher. In contrast, MAC-SCC only maintains two channels (no matter how much bandwidth is used by the network), thus significantly reducing the hardware complexity and cost. Second, the multi-channel protocols have a low peak transmission rate and may potentially waste the channel bandwidth. More specifically, each pair of wireless terminals can be assigned with only one channel for communication, even when there are many other idle channels. As a result, the communication delay is long, compared with MAC-SCC where each data frame is transmitted over the entire data channel, whose bandwidth may be (theoretically) equivalent to the sum of all data channels in the multi-channel protocols. Third, in most multi-channel protocols, all channels have the same bandwidth. One channel is used for control while the other channels are for data transmission. It is not clear whether the control channel will be overloaded or its bandwidth may be wasted.

In this paper, we present a solid traffic analytic model. The bandwidth partitioning in MAC-SCC is based on our analytic results, which allocates appropriate amount of bandwidth to
the control channel and the data channel, respectively.

III. PROPOSED MAC-SCC PROTOCOL

In this section, we first introduce the proposed MAC-SCC protocol. Then, we discuss the optimal bandwidth partitioning between the control channel and the data channel. Finally, we discuss and compare MAC-SCC with several related protocols.

A. Protocol Description

1) Protocol Overview: The basic idea of our proposed MAC-SCC protocol is described as follows while the details will be discussed later in this section. In MAC-SCC, the entire bandwidth into two subchannels (e.g., by using two frequency bands or two time slots or two orthogonal codes): CH a that is primarily used for data transmission and CH b that is used for signaling, with bandwidth \( W_d \) and \( W_s \) (\( W_d \gg W_s \)), respectively. When a source node initializes data transmission, it senses \( CH \ a \) first. If \( CH \ a \) is idle, similar to that in IEEE 802.11, a RTS-CTS-DATA-ACK handshake sequence is applied on \( CH \ a \) for channel reservation. If \( CH \ a \) is busy, \( CH \ b \) is used to schedule the next data transmission. As shown in Fig. 1 (c), nodes \( S_2 \) and \( D_2 \) can exchange the RTS and CTS frames on \( CH \ b \), even when node \( S_1 \) is sending a data frame to node \( D_1 \) on \( CH \ a \). In other words, the contention of next channel access is resolved during the transmission of the current data frame. As soon as the current data transmission finishes, the next data frame (from \( S_2 \) to \( D_2 \)) can be transmitted by following an SRTS-SCTS-DATA-ACK handshake sequence, where SRTS and SCTS are simplified RTS and simplified CTS, respectively. As we can see, the channel reservation in MAC-SCC is in sharp contrast to IEEE 802.11 MAC protocol, where \( S_2 \) has to defer sending RTS until the medium becomes idle for interval equal to the sum of DIFS and a random backoff time, during which the entire bandwidth is wasted.

2) Frames and Channels: In addition to RTS, CTS, DATA and ACK, two extra frames, SRTS and SCTS, are employed in MAC-SCC. The SRTS and SCTS frames include only three fields: \textit{frametype}, \textit{duration} and \textit{checksum}. They are employed to address the potential hidden station problem due to the use of two channels. More specifically, the RTS and CTS transmitted on \( CH \ b \) (e.g. by \( S_2 \) and \( D_2 \) in Fig. 1) may not be received by the nodes (e.g. \( S_1 \) and \( D_1 \) in Fig. 1) that are currently sending or receiving on \( CH \ a \) because of the hardware limitation. As a result, \( S_1 \) and \( D_1 \) don’t update their NAV and may become hidden stations when \( S_2 \) sends data frame to \( D_2 \). In order to avoid such hidden station problem (i.e. to block any possible transmission from \( S_1 \) to \( D_1 \)), SRTS and SCTS are transmitted on \( CH \ a \) before the transmission of data frame.

Since \( CH \ a \) and \( CH \ b \) have different bandwidth, the same frame needs different time to be transmitted on these two channels. To facilitate our discussion, we denote \( T^{a}_{\text{data}} \), \( T^{a}_{\text{ack}} \), \( T^{a}_{\text{rts}} \), \( T^{a}_{\text{cts}} \), \( T^{b}_{\text{data}} \), \( T^{b}_{\text{ack}} \), \( T^{b}_{\text{rts}} \), and \( T^{b}_{\text{cts}} \) to be the time to transmit a data frame, an ACK frame, an SRTS frame, an SCTS frame, an RTS frame, and a CTS frame on \( CH \ a \), respectively, while denote \( T^{b}_{\text{rts}} \) and \( T^{b}_{\text{cts}} \) to be the time to transmit an RTS and a CTS frame on \( CH \ b \), respectively. Each node maintains two NAVs, \( NAV^a \) and \( NAV^b \) for \( CH \ a \) and \( CH \ b \), respectively. The values of \( NAV^a \) and \( NAV^b \) are always decreasing if they are larger than zero. Updating the NAVs is similar to that in IEEE 802.11. More specifically, the frame header includes a duration field with a value \( t_{\text{duration}} \) to indicate the time interval that \( CH \ a \) is to be reserved for data transmission. When sending an RTS on \( CH \ a \), \( t_{\text{duration}} = T^{a}_{\text{data}} + T^{a}_{\text{ack}} + T^{a}_{\text{cts}} + 3SIFS \); When sending an SRTS on \( a \), \( t_{\text{duration}} = T^{a}_{\text{data}} + T^{a}_{\text{ack}} + 3SIFS \); When sending a CTS or an SCTS on \( CH \ a \), \( t_{\text{duration}} = T^{a}_{\text{data}} + T^{a}_{\text{ack}} + 2SIFS \); When sending an RTS or a CTS on \( CH \ b \), \( t_{\text{duration}} = T^{b}_{\text{data}} + T^{b}_{\text{ack}} + T^{a}_{\text{cts}} + T^{a}_{\text{data}} + T^{a}_{\text{ack}} + 4SIFS \).1

Upon receiving RTS or CTS on \( CH \ a \) or \( CH \ b \), a node updates its \( NAV^a \) or \( NAV^b \) as to be discussed next in Section III-A.3. The RTS and CTS frames also include a defer time field to indicate the amount of time (\( t_{\text{defer}} \)) taken before the node can send or receive data on \( CH \ a \). In addition, similar to that in the IEEE 802.11 standard, when the medium is busy or collision occurs, a node starts a backoff timer, which has an initial random value and decreases when the channel becomes idle for an interval of DIFS.

Note that, although two channels are used, a node is not required to transmit and/or receive on \( CH \ a \) and \( CH \ b \) simultaneously. More specifically, when a node is transmitting on one channel, it doesn’t receive any frame at the same time. When a node is not transmitting, it listens to different channels depending on its NAVs (as summarized in Table I). When both \( NAV^a \) and \( NAV^b \) are greater than zero or \( NAV^a = NAV^b = 0 \), the node monitors both channels. However, it only receives on one channel upon a frame arrival. When \( NAV^a > 0 \) and \( NAV^b = 0 \), the node listens to (and receives frames on) \( CH \ b \) only. Table II summarizes the frames transmitted on the two channels. The RTS and CTS frames can be transmitted on either \( CH \ a \) or \( CH \ b \), while SRTS, SCTS, DATA, and ACK frames can be transmitted on \( CH \ a \) only.

3) Detailed Description: The MAC-SCC protocol is discussed in details as follows, with the major steps summarized in Fig. 3. In Step 1, the source \( S \) first senses the medium. If both \( CH \ a \) and \( CH \ b \) are idle, it means there is no on-going data transmission. In order to reduce the delay for signaling, the RTS frame is sent on \( CH \ a \), which has higher bandwidth. If \( CH \ a \) is busy while \( CH \ b \) is idle, \( S \) constructs an RTS frame with \( t_{\text{defer}} = NAV^a \) to indicate that \( S \) cannot send

\begin{table}[h]
  \centering
  \caption{Listening of Two Channels}
  \begin{tabular}{|c|c|}
    \hline
    NAV values & Channels \\
    \hline
    \( NAV^a = 0 \) & \( NAV^b = 0 \) & \( CH \ a \) and \( CH \ b \) \\
    \hline
    \( NAV^a > 0 \) & \( NAV^b = 0 \) & \( CH \ b \) \\
    \hline
    \( NAV^a > 0 \) & \( NAV^b > 0 \) & \( CH \ a \) and \( CH \ b \) \\
    \hline
  \end{tabular}
\end{table}

\begin{table}[h]
  \centering
  \caption{Usage of Two Channels}
  \begin{tabular}{|c|c|}
    \hline
    Frame Types & Channel \\
    \hline
    RTS-CTS & \( CH \ a \) or \( CH \ b \) \\
    \hline
    SRTS-SCTS & \( CH \ a \) \\
    \hline
    DATA-ACK & \( CH \ a \) \\
    \hline
  \end{tabular}
\end{table}

1To simplify the protocol description, we assume \( CH \ a \) and \( CH \ b \) use the same interface spaces (DIFS and SIFS). But different values can be used for \( CH \ a \) and \( CH \ b \) with minor modifications.
1. Source S sends RTS:
   When a node S has data to send to a node D, it first
   senses CH a and CH b.
   If both CH a and CH b are idle for a period of DIFS
   S sets t_{defer} = 0;
   t_{duration} = T_{cts} + T_a^{data} + T_{ack} + 3SIFS
   S sends RTS on CH a;
   Else if only CH b is idle for a period of DIFS
   S sets t_{defer} = NAV^a;
   t_{duration} = T_{scts} + T_a^{data} + T_s^{ack} + 3SIFS
   S sends RTS on CH b;
   Else
   S starts a backoff timer and sends RTS
   on CH b when it times out.
   Endif

3. Source S receives CTS and sends data:
   If S receives CTS (let t' = t_{defer} obtained from CTS)
   If S receives CTS on CH a
   t_{duration} = t_{duration} - T_a^{data} - SIFS
   S sends data frame after SIFS;
   Else
   t_{duration} = T_{scts} + T_a^{data} + T_s^{ack} + 3SIFS
   S sends SRTS frame after t' - T_{cts} + SIFS;
   Endif
   Else
   S starts a backoff timer and sends RTS on
   CH b when it times out.
   Endif

5. Destination D receives SRTS and sends SCTS:
   If D receives SRTS on CH a
   t_{duration} = t_{scts} - T_a^{data} - SIFS
   D sends SCTS frame after SIFS;
   Endif

7. Destination D receives DATA and sends ACK:
   When D receives DATA successfully, it sends
   an ACK to S on CH a.

2. Destination D receives RTS and sends CTS:
   If D receives RTS successfully
   If D receives RTS on CH a
   D sets t_{defer} = 0;
   t_{duration} = t_{cts} - T_a^{data} - SIFS
   D replies with CTS on CH a after SIFS;
   Else
   If NAV^b = 0 (let t' = t_{defer} obtained from RTS)
   D sets t_{defer} = max(t' - SIFS - T_{rts}^b, NAV^a);
   t_{duration} = t_{cts} + SIFS
   D replies with CTS on CH b after SIFS;
   Endif
   Endif

4. Other nodes update their NAV:
   If receiving a frame on CH a
   If NAV^a < t_{duration} NAV^b = t_{duration}
   Endif
   Else If receiving a frame on CH b
   If NAV^b < t_{duration} + t_{defer}
   NAV^b = t_{duration} + t_{defer}
   Endif

6. Source S receives SCTS and sends DATA:
   If S receives SCTS on CH a
   t_{duration} = t_{scts} - T_a^{data} - SIFS
   S sends data frame after SIFS;
   Endif

8. For other nodes, Converting NAV^b to NAV^a:
   If NAV^a == 0 and NAV^b > 0
   NAV^a = NAV^b; NAV^b = 0;
   Endif

Fig. 3. The major steps in MAC-SCC. (Note that, we use t_{frame} to represent the duration field in the received frame, where frame could be RTS, CTS, SRTS, SCTS, DATA or ACK. Similarly, t_{defer} is used to represent the defer field in the received frame, where frame could be RTS or CTS.)

data frame during the interval, and sends RTS on CH b. If
both CH a and CH b are busy, S backs off for a random time
and then sends RTS on CH b.

In Step 2, if destination D receives RTS on CH a suc-
cessfully, it sets t_{duration} of CTS to be the duration for
completing the data transmission (i.e., T_a^{data} + T_s^{ack} + 2SIFS)
and responds with a CTS on CH a after SIFS. Otherwise, if
D receives RTS on CH b and its NAV^b is 0, it sets t_{defer} to
be the interval that either S cannot send or receive data
frames (i.e., t_{scts} - SIFS - T_{rts}^b) or D cannot send or
receive data frames (i.e., NAV^a). Then D sets t_{duration} of
CTS to be the time to complete the next data transmission
(T_a^{data} + T_s^{ack} + T_{scts} + T_{scts} + 4SIFS). Finally, D sends
CTS on CH b.

In Step 3, when S receives CTS on CH a, it updates
t_{duration}, and sends data frame. When S receives CTS on CH b,
it sends SRTS frame after the deferred time. If S cannot
receive CTS, it assumes collision occurred and backs off for
a random time before sending another RTS on CH b.

In Step 4, upon receiving a valid frame, other nodes, which
are neither the source nor the destination, update their NAV^a
or NAV^b based on the duration field. Note that, after setting
NAV^b, the signaling on CH b is forbidden for a period until
the current data transmission is finished (as shown in Step 8).
In other words, CH b is used to schedule the next data frame
only (but not the third data frames or beyond in the future),
because to schedule additional data frames (other than the
next one) increases the complexity but does not help improve
channel efficiency noticeably.

In Step 5, destination D responds with SCTS after it receives
SRTS. In step 6, source S sends the data frame after it receives
SCTS. As shown in Step 7, D responds with an ACK frame
after it receives the data frame successfully. Finally, in Step
8, when NAV^a becomes 0 and NAV^b > 0, it means the
current data transmission is over, and the next data frame is
ready to be sent. The node sets NAV^a = NAV^b, which is the
duration for the next data transmission, and sets NAV^b = 0
free up CH b for sending control frames.

B. Optimal Bandwidth Partitioning

One important design issue in MAC-SCC is bandwidth par-
tioning. More specifically, one needs to decide the minimum
amount of bandwidth ($W_s$) to be allocated for the control channel such that there is a high probability ($1 - \varepsilon$ where $\varepsilon$ is a small value) that at least one RTS/CTS pair for the next data frame succeeds during the transmission of the current frame. The bandwidth for CH a ($W_d = W - W_s$ where $W$ is the total bandwidth), on the other hand, should be as large as possible to achieve high peak data rate.

For analytical tractability, we ignore the hidden station problem in the following discussion. As a result, the probability of a successful RTS ($P_s$) equals the probability that no arrivals occur during the propagation and medium sense delay ($\tau$) [30]. In addition, since the SRTS and SCTS frames are free of collision, they are considered as part of data frame in our analysis. Assume that RTS arrival is Poisson distributed with an average rate of $\lambda$, the probability that an RTS can be received correctly without collision is:

$$P_s = e^{-\tau\lambda}. \quad (1)$$

Let $k$ be the number of retry needed to achieve a success probability of $1 - \varepsilon$, i.e., $(1 - e^{-\tau\lambda})^k < \varepsilon$, then,

$$k > \frac{\log(\varepsilon)}{\log(1 - e^{-\tau\lambda})}. \quad (2)$$

Denote $l_{data}$, $l_{ack}$, $l_{rts}$ and $l_{cts}$ to be the length for data frame, ACK frame, RTS frame and CTS frame, respectively. The time for data transmission on CH a is

$$T_A = \frac{l_{data} + l_{ack}}{W_d} + SIFS. \quad (3)$$

Assume the RTS frames have an exponential increase of backoff time after each collision. More specifically, the backoff time after the $i$th collision is $2^i \frac{l_{rts}}{W_s}$. Accordingly, the time for successfully exchanging RTS/CTS frames after $k$ attempts on CH b is

$$T_B = \sum_{i=0}^{k-1} 2^i \frac{l_{rts}}{W_s} + l_{cts} \frac{l_{cts}}{W_s} + SIFS \quad (4)$$

The optimal bandwidth partitioning should allow RTS/CTS on CH b to complete before the end of the current data transmission on CH a. Let $T_A = T_B$, we can obtain the optimal value of the division of bandwidth ($D$),

$$D = \frac{W_d}{W_s} = \frac{l_{data} + l_{ack}}{2^{k-1} (l_{rts} + l_{cts})}. \quad (5)$$

Plugging typical values for the parameters in the above equations, we can have an observation on the bandwidth partitioning. As discussed in [4], we assume $l_{rts} = 20$ bytes, $l_{ack} = l_{cts} = 16$ bytes, and $\tau = 10$ $\mu$s. In addition, we consider IP traffic with an average size of $l_{data} \approx 1500$ bytes, $\lambda = 800$/sec and $\varepsilon = 10^{-5}$. According to Equations (1)-(5), we arrive at $D \approx 9.99$ or $W_s \approx 0.09 W$. In other words, CH b needs about 9% of the total bandwidth to ensure an RTS success probability of $1 - 10^{-5}$.

C. Further Discussion

1) Comparison with Single Channel MAC Protocols:

   Compared with typical MAC protocols with a single channel, the use of a separate control channel in MAC-SCC may increase the implementation cost. However, our study shows that such cost increase is very limited. We address this issue in two folds. First, we discuss it from the point of view of bandwidth cost and efficiency. Note that, while MAC-SCC employs two subchannels, it doesn’t require additional bandwidth. In our performance evaluation, we assume that the same bandwidth is available for MAC-SCC and IEEE 802.11 networks. The latter uses all bandwidth as a single channel, while the former divides the total available bandwidth into two subchannels. Our results show that, with the same total bandwidth, MAC-SCC achieves higher channel efficiency and fairness. Second, we discuss this problem from the point of view of implementation cost. In MAC-SCC, the transceiver needs to operate on two channels. However such tunable transceiver shall have a complexity similar to the current IEEE 802.11 devices, which is already tunable with a limited switching delay (usually about 100s) [4]. Note that, such delay has no significant impact on our MAC-SCC protocol. More specifically, if the data channel (i.e., CH A) is idle, all frames (RTS, CTS, DATA, and ACK) are transmitted on CH A only. Thus there is no channel switching at all. Only when CH A is busy, the stations need to transmit the control frames on CH B first, and then switch to CH A for data transmission, which results in about 100s delay. Note that however, since ongoing transmission on CH A is very likely to last for much longer than 100s, the channel switching delay will not lead to the waste of bandwidth on CH A. Therefore, we believe that the tunable transceiver can be developed for MAC-SCC with a similar cost compared with the ones currently used in IEEE 802.11 devices. Other possible increase in software complexity, e.g., due to the maintenance of two NAVs, shall be very limited as we have observed in our simulation.

2) Comparison with Other Multi-Channel MAC Protocols:

   Table III summarizes the features of our proposed MAC-SCC protocol and compares it with several representative multi-channel MAC protocols, such as DBTMA [15] and multi-channel MAC [21], as well as the popular IEEE 802.11 MAC protocol [4]. DBTMA achieves excellent channel efficiency. At the same time, however, it needs extra hardware to enable the busy tones. Additionally, DBTMA is not efficient at error recovery, since it has no ACK in MAC layer and completely relies on transport layer protocol to recovery errors.

   Both MAC-SCC and multi-channel MAC protocol can achieve good channel efficiency under high traffic load. But multi-channel protocol requires simultaneous transmission/reception, resulting in complex and costly hardware implementation. Although the multi-channel scheme with $N$ subchannels allows multiple concurrent transmissions, the peak rate of each node is decreased to $1/N$, because one node usually uses one sub-channel for data transmission. The performance of multi-channel protocols depends on node density. If the number of nodes in the transmission range is less than $N$, some channel bandwidth is wasted.

In addition, any existing multi-channel MAC protocol with
a control channel [15], [21], [22] maintains only one NAV. The control channel is used by the nodes to compete for the current transmission alone. In contrast, our proposed MAC-SCC protocol maintains two NAVs respectively for the data channel and the control channel, as discussed in Section III. The transmission of the next data frame can be pre-scheduled during the current data transmission via the separate control channel, and thus reducing the frame collision probability and the bandwidth wasted during backoff. Moreover, the usage of the separate control channel helps to achieve fair medium access and solve the instability problem resulted from frequent link failures.

IV. SIMULATION AND DISCUSSION

We have done extensive simulations to evaluate the performance of the proposed MAC-SCC protocol, in terms of throughput, link failure probability, and fairness. We first implement MAC-SCC as a stand-alone protocol using PARSEC [31] to verify its correctness and effectiveness. Then, we implement MAC-SCC in QualNet [32] to study its performance in the whole protocol stack.

A. Stand-alone Simulation in PARSEC

We have implemented MAC-SCC by using PARSEC and studied it as a stand-alone protocol without interaction with other network layer protocols. We simulate 25 and 50 static nodes uniformly distributed in a circle with a diameter of 500 m. Each node has a default transmission range of 250 m. The parameters defined in the IEEE 802.11 standard, such as the length of SIFS, DIFS, propagation delay, and control frames, are adopted in this simulation (as listed in Table IV). We consider Internet traffic with an average packet length of 1500 bytes, and the data frame length can be calculated accordingly. The packet arrival is a Poisson process with a variable average rate. The traffic load (G) is defined to be the number of frames per frame time [33]. The total available bandwidth is assumed to be 11 Mbps.

Note that the transmission times of control/data frames on different channels are different. Let $L$ be the frame transmission time in the single channel scheme (i.e., in the IEEE 802.11). In MAC-SCC, the time for transmitting the frame on $CH_a$ is $(D + 1)/D \times L$, while the time for transmitting the frame on $CH_b$ is $(D + 1) \times L$. In this simulation, the main performance metric is the system throughput, which is defined as the amount of successful data transmission measured by the percentage of the maximal bandwidth (11 Mbps). We also consider the link failure probability as discussed in Section II and study the optimal bandwidth partitioning.

1) Optimal bandwidth partitioning: Fig. 4 shows the system throughput with different bandwidth partitionings under various traffic loads. With an increase in bandwidth for $CH_b$, it takes less time to transmit RTS/CTS on $CH_b$ and accordingly has a higher probability to succeed. But since the bandwidth of $CH_a$ is decreased, data transmission then takes a longer time. This tradeoff has been studied by simulation. As we can see, the optimal value of $D$ is about 10, verifying the analytic results discussed in Section III-B. The control channel (or the data channel) becomes the bottleneck when $D \gg 10$ (or $D \ll 10$). In the following discussion, $D = 10$ is used as

<table>
<thead>
<tr>
<th>TABLE III</th>
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<tr>
<td>COMPARISON OF MAC-SCC, DBTMA, MULTI-CHANNEL PROTOCOL AND IEEE 802.11</td>
</tr>
<tr>
<td>Features</td>
</tr>
<tr>
<td>Channels</td>
</tr>
<tr>
<td>Optimal channel partitioning</td>
</tr>
<tr>
<td>Simultaneous transmission/ reception</td>
</tr>
<tr>
<td>NAV</td>
</tr>
<tr>
<td>Pipelined channel reservation</td>
</tr>
<tr>
<td>MAC-ACK</td>
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<tr>
<td>Handshake sequence</td>
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<tr>
<td>Fairness</td>
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<tr>
<td>Stability</td>
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<tr>
<td>Channel efficiency</td>
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</table>

<p>| TABLE IV  |</p>
<table>
<thead>
<tr>
<th>SIMULATION PARAMETERS (I)</th>
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<tbody>
<tr>
<td>RTS Length</td>
</tr>
<tr>
<td>CTS Length</td>
</tr>
<tr>
<td>SRTS Length</td>
</tr>
<tr>
<td>SCTS Length</td>
</tr>
<tr>
<td>ACK Length</td>
</tr>
<tr>
<td>Average Data Frame Payload Length</td>
</tr>
<tr>
<td>DIFS</td>
</tr>
<tr>
<td>SIFS</td>
</tr>
<tr>
<td>Propagation Delay</td>
</tr>
<tr>
<td>Total Bandwidth</td>
</tr>
</tbody>
</table>

![Fig. 4. Optimal Bandwidth Partitioning.](image)
2) Throughput: The throughput of MAC-SCC and the basic RTS/CTS scheme for a network with 25 nodes are depicted in Fig. 5. In the basic RTS/CTS scheme, the system throughput decreases rapidly with the increase of $G$, because under a heavy traffic load, the collision probability is high, and the long backoff time results in low channel efficiency. In MAC-SCC, since the next data transmission can be scheduled on $CH_b$ even when $CH_a$ is busy, the collision probability and the backoff time are reduced. The proposed MAC-SCC is more robust under a heavy traffic load and can maintain a high throughput with up to 60% gain, when compared with the basic RTS/CTS approach. Similar experimental results are obtained when we simulated 50 nodes, each with a transmission range of 150 m.

3) Link failure probability: Fig. 6 shows the link failure rate (reported to the upper layer) as a function of traffic load. As discussed in Section II, the IEEE 802.11 MAC protocol reports a link failure after seven consecutive RTS attempts fail, to the upper layer, which in turn starts a recovery procedure, e.g., to discover a new route. Clearly, frequent link failures may result in a large amount of recovery overhead. As shown in Fig. 6, MAC-SCC significantly reduces the link failure rate, because when $CH_a$ is busy, the node can still send control frames on $CH_b$ and avoid multiple RTS retransmissions due to the lack of responses from the receiving node.

B. Comprehensive Simulation in QualNet

QualNet [32] is a commercial network simulator with the whole protocol stack (from physical layer to application layer). In order to implement MAC-SCC in QualNet, we have modified the IEEE 802.11b physical layer model to enable two subchannels. The new MAC-SCC protocol is added into the protocol stack, following our discussion in Section III. The results obtained from our simulation are discussed as follows.

1) Fairness among TCP sessions: In order to study the fairness problem among TCP sessions, we first adopt a string topology similar to that used in [5] (see Fig. 7). The nodes are equally spaced. The distance between two adjacent nodes equals to the nodal transmission range. Thus, an end-to-end connection usually spans over multiple hops. For example, if a packet is sent from node 1 to node 5, it must go through 4 hops to reach its destination. We simulated two FTP sessions: Session 1 with one hop from node 1 to node 2 and Session 2 with multiple hops. The destination of Session 2 is always node 3, while the source varies from nodes 4, 5, 6 to 7, resulting in 1, 2, 3 or 4 hops, respectively. Each FTP session starts at the first second of our simulation and transmits 2000 data frames that are generated by using tcplib, a library for realistic TCP/IP network traffic generation [34]. Fig. 8 (a) and (b) show the throughput of these two FTP sessions running on IEEE 802.11 and MAC-SCC, respectively.

Before examining the results, let us first discuss the “ideal” fairness between two TCP sessions: Session 1 with one hop and Session 2 with $k$ hops (as shown in Fig. 7). If the two sessions run individually, their throughputs are $S$ and $S/k$, respectively.
When they run simultaneously and the MAC protocol is perfectly fair, their throughput should be \((k - 1 + 0.5) \times S/k\) and \(0.5 \times S/k\), respectively, because Session 2 has \(k\) hops and interferes with Session 1 only at the last hop. More specifically, \((k - 1)/k\) of total traffic in Session 1 will not be interfered by Session 2. For remaining \(1/k\) of total traffic, we can assume half of it will be transmitted successfully if the MAC protocol is fair. On the other hand, all traffic of Session 2 will experience contention. The ideal throughput results are depicted in Fig. 8(a) (shown as "Expected Session 1" and "Expected Session 2"). From Fig. 8(a), we clearly observe the unfairness problem of IEEE 802.11, in which Session 2 with more than one hop is almost shut down completely. When Session 2 has one hop only, although the average throughput of Session 2 is about the same as that of Session 1, our simulation exhibits that the channel might be dominated randomly by either Session 1 or Session 2. In a sharp contrast, when MAC-SCC is employed, the throughput of the two sessions (given in Fig. 8(b)) shows almost ideal fairness and is very close to the expected results of the perfectly fair protocol (as illustrated in Fig. 8(a)), signifying that MAC-SCC can effectively relieve the unfairness problem of IEEE 802.11.

We have also studied the scenarios with more than two TCP sessions. Specifically, the results obtained from three typical scenarios (see Figs. 9(a)-9(c)) are presented here. Scenario 1 contains three TCP sessions: two 1-hop sessions and one 2-hop session; Scenario 2 contains four TCP sessions: two 1-hop sessions and two 2-hop sessions; Scenario 3 contains eight TCP sessions, four 1-hop sessions and four 2-hop sessions. For each scenario, three different seeds are used in simulation. The
results of Scenario 1 are shown in Fig. 10, where “I1”, “I2”, and “I3” stand for IEEE 802.11 with seed 1, 2, and 3, respectively while “M1”, “M2”, and “M3” stand for MAC-SCC with seed 1, 2, and 3, respectively. As can be seen, the 2-hop session is almost shut down completely when IEEE 802.11 protocol is employed. The throughput is dominated randomly by one of the two 1-hop sessions. In contrast, MAC-SCC shows perfect fairness (as we have discussed earlier), where the 1-hop sessions have almost the same system throughput, while the 2-hop session has about half of the throughput of 1-hop sessions. Scenarios 2 and 3 (see Fig. 11 and Fig. 12) also show a similar trend. With more TCP sessions, the interference
among the nodes become more significant. As a result, the above simple analysis on perfect fairness no longer holds. As we can see from the figures, however, MAC-SCC do improve the fairness effectively compared with IEEE 802.11 protocol.

2) UDP throughput: In order to study the throughput of UDP running over MAC-SCC, we simulate 50 nodes that are randomly distributed in a square area of $250m \times 250m$. The transmission range of a node is $250m$ and thus most nodes are within the transmission range of each other. The packet length is exponentially distributed with an average length of 512 bytes. We simulated 6 TRAFFIC-GEN sessions in the application layer. The start time, the end time, and the default packet interval time of each session are shown in Table V. We vary the traffic load by multiplying the default packet interval time of all sessions with a scalar equal to 1, 0.5, 0.4, 0.3, 0.2, 0.1, respectively. We define the normalized traffic load as we discussed earlier.

<table>
<thead>
<tr>
<th>Session</th>
<th>Start(s)</th>
<th>End(s)</th>
<th>Interval(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>100</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>82.49</td>
<td>199</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>91.39</td>
<td>248</td>
<td>0.008</td>
</tr>
<tr>
<td>5</td>
<td>107.8</td>
<td>274</td>
<td>0.011</td>
</tr>
<tr>
<td>6</td>
<td>107.8</td>
<td>274</td>
<td>0.011</td>
</tr>
</tbody>
</table>

3) Bandwidth Partitioning: In our earlier analysis and stand-alone simulations, we have assumed that the packet arrival at MAC layer is a Poisson process. This however, may not be true due to various applications and the cross-layer interactions, which may consequently affect the channel partitioning. To evaluate the impact of traffic on channel partitioning, we simulate 50 nodes that are randomly distributed in a square area of $250m \times 250m$. The nodes have a transmission range of $250m$. Six variable bit rate (VBR) applications are simulated in the application layer. The start time, the end time, and the default packet interval time of each session are shown in Table V. The packets are with average length of 1500 bytes and sent at variable rate which is a function of $interval \times scalar$. The system throughput with different bandwidth partitioning are shown in Fig. 13. As we can see, the system with bandwidth partition of 10 always yield optimal or near-optima results. We have also carried out simulations under other traffic patterns, such as FTP and TRAFFIC-GEN traffic. We observe that the system always reaches the highest throughput when the division of bandwidth ($D$) is between 8 and 12.

V. CONCLUSION

We have proposed a novel Medium Access Control protocol with a Separate Control Channel (MAC-SCC). In MAC-SCC, the available bandwidth is partitioned into two channels: a data channel and a control channel, each associated with a network allocation vector (NAV). To reduce hardware complexity, the station transmits or receives on one channel only at any given time. The performance of MAC-SCC is quantified via extensive simulations in both a stand-alone simulator developed by using PARSEC and a comprehensive network simulator called QualNet with whole protocol stack. Our results show that MAC-SCC can effectively reduce the link failure probability, achieve fair medium access when running multiple TCP sessions, and yield a throughput gain up to 60% under high traffic load, when compared with the basic RTS/CTS scheme.

REFERENCES


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