A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks *

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Abstract

The wireless mobile ad hoc network (MANET) architecture has received a lot of attention recently. This paper considers the access of multiple channels in a MANET with multi-hop communication behavior. We point out several interesting issues when using multiple channels. We then propose a new multi-channel MAC protocol, which is characterized by the following features: (i) it follows an "on-demand" style to assign channels to mobile hosts, (ii) the number of channels required is independent of the network topology and degree, (iii) it flexibly adapts to host mobility and only exchanges few control messages to achieve channel assignment and medium access, and (iv) no clock synchronization is required. Compared to existing protocols, some assign channels to hosts statically (thus a host will occupy a channel even when it has no intention to transmit)[4, 12, 14], some require a number of channels which is a function of the maximum connectivity[4, 10, 12, 14], and some necessitate a clock synchronization among all hosts in the MANET[14, 24]. Extensive simulations are conducted to evaluate the proposed protocol.

1 Introduction

A *mobile ad-hoc network (MANET)* is formed by a cluster of mobile hosts without the infrastructure of base stations. The applications of MANETs appear in places where predeployment of network infrastructure is difficult or unavailable (e.g., fleets in oceans, armies in march, natural disasters, battle fields, festival field grounds, and historic sites). A working group called MANET [1] has been formed by the Internet Engineering Task Force (IETF) to stimulate research in this direction. Issues related to MANET have been studied intensively [10, 13, 17, 18, 22, 23, 24, 25].

A *MAC (medium access control)* protocol is to address how to resolve potential contention and collision on using the communication medium. Many MAC protocols have been proposed for wireless networks [5, 9, 15, 16, 20, 19], which assume a common channel shared by mobile hosts. We call such protocols *single-channel MAC protocols.* A standard that has been widely accepted based on the single-channel model is the IEEE 802.11 [2]. One common problem with such protocols is that the network performance will degrade quickly as the number of mobile hosts increases, due to higher contention/collision.

One approach to relieving the contention/collision problem is to utilize multiple channels. With the advance of technology, empowering a mobile host to access multiple channels is already feasible. We thus define a *multi-channel MAC protocol* as one with such capability. Using multiple channels has several advantages. First, while the maximum throughput of a single-channel MAC protocol will be limited by the bandwidth of the channel, the throughput may be increased immediately if a host is allowed to utilize multiple channels. Second, as shown in [3, 22], using multiple channels will experience less *normalized propagation delay* per channel than its single-channel counterpart, where the normalized propagation delay is defined to be the ratio of the propagation time over the packet transmission time. Therefore, this reduces the probability of collisions. Third, since using a single channel is difficult to support quality of service (QoS), it is easier to do so by using multiple channels.

Here, we use "channel" upon a logical level. Physically, a channel can be a frequency band (under FDMA), or an orthogonal code (under CDMA). How to access multiple channels is thus technology-dependent.

A multi-channel MAC typically needs to address two issues: *channel assignment (or code assignment)* and

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medium access. The former is to decide which channels to be used by which hosts, while the later is to resolve the contention/collision problem when using a particular channel. There already exist many related works [4, 6, 7, 8, 10, 12, 14, 21, 22, 24, 11, 26]. References [4, 6, 8, 12, 21] are for channel assignment in a traditional packet radio network, and thus may not be appropriate for a MANET, which has mobility. Two IEEE 802.11-like protocols are proposed in [7, 26], which separate control traffic and data traffic into two distinct channels. However, this is a special case because only one data channel is allowed. A scheme based on *Latin square* is proposed in [14], which assumes a TDMA-over-FDMA technology. The channel assignment is static, and to achieve TDMA, a clock synchronization is necessary (which is difficult, especially for a large-scale MANET). Furthermore, a number of transceivers which is equal to the number of frequency bands is required, which is very costly. The protocol in [11] also assigns channels statically. It is assumed that each host has a polling transceiver and a sending transceiver. The polling transceiver hops from channel to channel to poll potential senders. Once polled, an intending sender will use its sending transceiver to transmit its packets. How to assign channels to mobile hosts is not addressed in that work. The drawbacks include long polling time and potential collisions among polling signals. The protocol [10] assigns channels to hosts dynamically. It mandates that the channel assigned to a host must be different from those of its two-hop neighbors. To guarantee this property, a large amount of update messages will be sent whenever a host determines any channel change on its two-hop neighbors. This is inefficient in a highly mobile system. Further, this protocol is "degree-dependent" in that it dictates a number of channels of an order of the square of the network degree. So the protocol is inappropriate for a crowded environment.

A "degree-independent" protocol called *multichannel-CSMA* protocol is proposed in [22]. Suppose that there are n channels. The protocol requires that each mobile host have n receivers concurrently listening on all n channels. On the contrary, there is only one transmitter which will hop from channel to channel and send on any channel detected to be idle. Again, this protocol has high hardware cost, and it does not attempt to resolve the hidden-terminal problem due to lack of the RTS/CTS-like reservation mechanism. A *hop-reservation* MAC protocol based on very-slow frequency-hopping spread spectrum is proposed in [24]. The protocol is also degree-independent, but requires clock synchronization among all mobile hosts, which is difficult when the network is dispersed in a large area.

In this paper, we propose a new multi-channel MAC protocol which can be applied to both FDMA and CDMA technology. The protocol requires two simplex transceivers per mobile host. Based on an RTS/CTS-like reservation mechanism, our protocol does not require any form of clock synchronization among mobile hosts. It dynamically assigns channels to mobile hosts in an "on-demand" fashion and is also a degree-independent protocol. Both the channel assignment and medium access problems are solved in an integrated manner with light control traffic overhead. Observations are given to explain under what condition our multi-channel MAC protocol can outperform its single-channel counterpart. Simulation results are presented. The results also indicate that using our protocol will experience less degradation when the network is highly loaded.

2 Concerns with Using Multiple Channels

The purpose of this section is to motivate our work. We will show that care must be taken if one tries to directly translate a single-channel MAC (such as IEEE 802.11) to a multi-channel MAC. To start with, we will introduce a multi-channel MAC protocol based on a static channel assignment strategy. Then several interesting observations with using multiple channels, as opposed to using single channel, will be raised.

2.1 SM: A Simple Multi-channel Protocol

Below, we present a simple multi-channel MMAC protocol, which we cal *SM*. The protocol uses a static channel assignment, and on each channel the transmission follows IEEE 802.11. We assume that there are an arbitrary number of hosts in the MANET, but the system only offers a fixed number, n, of channels. Each mobile host is equipped with a half-duplex transceiver Thus, when $n = 1$, this converges to the IEEE 802.11 Standard.

In SM, channels are assigned to mobile hosts in a random, but static, manner. One simple way is to use hosts' IDs (e.g., IP address or network card's MAC address). Supposing that channels are numbered 0, 1, ..., $n-1$, we can statically assign channel $i = ID \bmod n$ to host ID . The basic idea is: when a host X needs to send to a host Y, X should tune to Y's channel. Then, X follows IEEE 802.11 [2] to access the medium.

2.2 Some Observations

Below, we make some observations associated with the above SM protocol. Two traditional problems in a single-channel system are the *hidden-terminal* and *exposed-terminal* problems, as illustrated in Fig. 1. In Fig. 1(a), when host A is sending to B, because host C can not sense the signals from A, it is likely that C's transmission activity will be overheard by B and thus destroy B's receiving activity. In Fig. 1(b), host A is sending to B. Later, host C intends to send to host D, but since C can sense A's

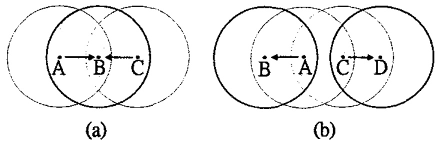

Figure 1: (a) the hidden-terminal problem, and (b) the exposed-terminal problem.

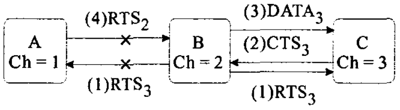

Figure 2: The problem of missing RTS in a multi-channel MAC. (The leading number on each message shows the message sequence; the subscript shows the channel on which the corresponding message is sent.)

signals, C will wait until A's transmission activity terminates. In fact, the communications from A to B and from C to D can happen concurrently.

We would like to know how these problems affect the SM protocol, which has multiple channels. As shown below, the hidden-terminal problem will become more serious, the exposed-terminal problem will become less serious, and some new problems may appear.

- *Missing RTS:* In Fig. 2, host B initiates a communication with C using C's channel 3. Host A later intends to communicate with B and thus sends an RTS on channel 2. Since B is busy in sending, this RTS will not be heard by B. Furthermore, since A can not sense the carrier from B (on channel 3), multiple RTSs may be sent at a *short* period of time until the maximal number of retrials expires. On the contrary, in a single-channel MAC, the carrier from B can be detected by A and thus A will inhibit its next RTS unless the common carrier is free. Thus, A's RTS has a higher chance to succeed in a single-channel MAC.
- *Missing CTS:* In Fig. 3, similar to the earlier scenario, B initiates a communication with C on channel 3. Later on, host D wants to send to C and initiates an RTS on channel 3, thus destroying C's receiving activity. This is similar to the hidden-terminal problem. However, in a single-channel MAC, this RTS will be prohibited by C's earlier *CTS*. Unfortunately, in a multi-channel MAC, C's earlier CTS may not be heard by D because D will tune its transceiver to channel 3 only after there is a transmission need. Thus, using CTS is less effective in a multi-channel MAC as opposed to that in a single-channel MAC. In addition, as shown in the right-hand part of Fig. 3, even if D's intending receiver is E instead of C, as long as E's channel is the same as C's, C's receiving activity will still be destroyed. Hence, the hidden-terminal problem will become more serious unless sufficient care has been taken. If it is guaranteed that no two hosts within a distance of two hops will use the same channel to send (such as [4, 10]), this problem can be eliminated.

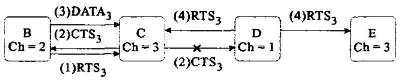

Figure 3: The problem of missing CTS in a multi-channel MAC.

3 Our MAC Protocol

This section presents our multi-channel MAC protocol, which we call *DCA (dynamic channel assignment).* We first describe our channel model. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. Each data channel is equivalent and has the same bandwidth. The purpose of the control channel is to resolve the contention on data channels and assign data channels to mobile hosts. Data channels are used to transmit data packets and acknowledgements. Each mobile host is equipped with two half-duplex transceivers. Control transceiver will operate on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels. Data transceiver will dynamically switch to one of the data channels to transmit data packets and acknowledgements.

Each mobile host, say X, maintains the two data structure. One is $CUL[\ ]$, the other is FCL. $CUL[\ ]$ is called the *channel usage list.* Each list entry $CUL[i]$ keeps records of when a host neighboring to X uses a channel. $CUL[i]$ has three fields: $CUL[i]$*.host* is a neighbor host of X, $CUL[i]$*.ch* is a data channel used by $CUL[i]$*.host*, and $CUL[i]$*.rel_time* is when channel $CUL[i]$*.ch* will be released by $CUL[i]$*.host*. Note that this CUL is distributedly maintained by each mobile host and thus may not contain the precise information. FCL is called the *free channel list*, which is dynamically computed from CUL.

The main idea of our protocol is as follows. For a mobile host A to communicate with host B, A will send an RTS (request-to-send) to B carrying its FCL. Then B will match this FCL with its CUL to identify a data channel (if any) to be used in their subsequent communication and reply a CTS (clear-to-send) to A. On receiving B's CTS, A will send a RES (reservation) packet to inhibit its neighborhood from using the same channel. Similarly, the CTS will inhibit B's neighborhood from using that channel. All these will happen on the control channel. Finally, a data packet will be transmitted on that data channel.

The complete protocol is shown below. Table 1 lists the variables/constants used in our presentaiton.

1. On a mobile host A having a data packet to send to host B, it first checks whether the following two

Table 1: Meanings of variables and constants used in our protocol.

T_{SIFS}	length of short inter-frame spacing
T_{DIFS}	length of distributed inter-frame spacing
T_{RTS}	time to transmit an RTS
T_{CTS}	time to transmit a CTS
T_{RES}	time to transmit a RES
T_{curr}	the current clock of a mobile host
T_{ACK}	time to transmit an ACK
NAV_{RTS}	net. allocation vector on receiving an RTS
NAV_{CTS}	net. allocation vector on receiving a CTS
NAV_{RES}	net. allocation vector on receiving a RES
L_d	length of a data packet
L_c	length of a control packet (RTS/CTS/RES)
B_d	bandwidth of a data channel
B_c	bandwidth of the control channel
τ	maximal propagation delay

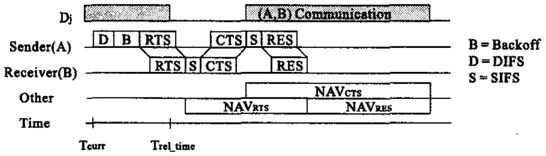

Figure 4: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

conditions are true:

a) B is not equal to any $CUL[i].host$ such that

$$CUL[i].rel\_time > T_{curr} + (T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS}).$$

If so, this means B will still be busy (in using data channel $CUL[i].ch$) after a successful exchange of RTS and CTS packets.

b) There is at least a channel D_j such that for all i:

$$(CUL[i].ch = D_j) \Longrightarrow (CUL[i].rel\_time \leq T_{curr} + (T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS})).$$

Intuitively, this is to ensure that D_j is either not in the CUL or in CUL but will be free after a successful exchange of RTS and CTS packets. (Fig. 4 shows how the above timing is calculated.)

Then A puts all D_j's satisfying condition b) into its FCL. Otherwise, A must wait at step 1 until these conditions become true.

2. Then A can send a $RTS(FCL, L_d)$ to B, where L_d is the length of the yet-to-be-sent data packet. Also, following the IEEE 802.11 style, A can send this RTS only if there is no carrier on the control channel in a T_{DIFS} plus a random backoff time period. Otherwise, it has to go back to step 1.

3. On a host B receiving the $RTS(FCL, L_d)$ from A, it has to check whether there is any data channel $D_j \in FCL$ such that for all i:

$$(CUL[i].ch = D_j) \Longrightarrow (CUL[i].rel\_time \leq T_{curr} + (T_{SIFS} + T_{CTS})).$$

If so, D_j is a free channel that can be used. Then B picks any such D_j and replies a $CTS(D_j, NAV_{CTS})$ to A, where

$$NAV_{CTS} = L_d/B_d + T_{ACK} + 2\tau.$$

Then B tunes its data transceiver to D_j. Otherwise, B replies a $CTS(T_{est})$ to A, where T_{est} is the minimum estimated time that B's CUL will change minus the time for an exchange of a CTS packet:

$$T_{est} = \min\{\forall i, CUL[i].rel\_time\} - T_{curr} - T_{SIFS} - T_{CTS}.$$

4. On an irrelevant host $C \neq B$ receiving A's $RTS(FCL, L_d)$, it has to inhibit itself from using the control channel for a period

$$NAV_{RTS} = 2T_{SIFS} + T_{CTS} + T_{RES} + 2\tau.$$

This is to avoid C from interrupting the RTS → CTS → RES dialogue between A and B.

5. Host A, after sending its RTS, will wait for B's CTS with a timeout period of $T_{SIFS}+T_{CTS}+2\tau$. If no CTS is received, A will retry until the maximum number of retries is reached.

6. On host A receiving B's $CTS(D_j, NAV_{CTS})$, it performs the following steps:

a) Append an entry $CUL[k]$ to its CUL such that

$$\begin{aligned} CUL[k].host &= B \\ CUL[k].ch &= D_j \\ CUL[k].rel\_time &= T_{curr} + NAV_{CTS} \end{aligned}$$

b) Broadcast $RES(D_j, NAV_{RES})$ on the control channel, where

$$NAV_{RES} = NAV_{CTS} - T_{SIFS} - T_{RES}$$

c) Send its DATA packet to B on the data channel D_j. Note that this steps happens in concurrent with step b).

On the contrary, if A receives B's $CTS(T_{est})$, it has to go back to step 1 at time $T_{curr}+T_{est}$ or when A knows that there is a newly released data channel, whichever happens earlier.

7. On an irrelevant host $C \neq A$ receiving B's $CTS(D_j, NAV_{CTS})$, C updates its CUL. This is the same as step 6a) except that

$$CUL[k].rel\_time = T_{curr} + NAV_{CTS} + \tau.$$

On the contrary, if C receives B's $CTS(T_{est})$, it ignores this packet.

8. On a host C receiving $RES(D_j, NAV_{RES})$, it appends an entry $CUL[k]$ to its CUL such that:

$$\begin{aligned} CUL[k].host &= A \\ CUL[k].ch &= D_j \\ CUL[k].rel\_time &= T_{curr} + NAV_{RES} \end{aligned}$$

9. On B completely receiving A's data packet, B replies an ACK on D_j.

To summarize, our protocol relies on the control channel to assign data channels. Because of the control channel, the deadlock problem can be avoided. For the same reason, the missing RTS/CTS and the hidden-terminal problems will be less serious.

4 Experimental Results

We have implemented a simulator to evaluate the performance of our DCA protocol. We mainly used SM as a reference for comparison. Also, note that when there is only one channel, SM is equal to IEEE 802.11. The parameters used in our experiments are: physical area = 100 × 100, transmission range $r = 30$, $DIFS = 50\mu sec$, $SIFS = 10\mu sec$, backoff slot time = $20\mu sec$, control packet length $L_c = 300$ bits, max. no. of retrials to send an RTS = 6. A data packet length L_d is a multiple of L_c. 200 hosts were generated randomly in a physical area. Packets arrived at each mobile host with an arrival rate of λ packets/sec. For each packet arrived at a host, we randomly chose a host at the former's neighborhood as its receiver.

In our simulation, both of the earlier bandwidth models are used. There are two performance metrics:

$$Throughput = \frac{\text{Packet\_Length} * \text{No\_Successful\_Packets}}{\text{Total\_Time}}$$

$$Utilization = \frac{\text{Packet\_Length} * \text{No\_Successful\_Packets}}{\text{Total\_Time} * \text{No\_Channels}}$$

Each control and data channel is of the same bandwidth. If the fixed-channel-bandwidth model is assumed, each channel's bandwidth is 1 Mbits/sec. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbits/sec.

In this experiment, we change the number of channels to observe its effect. Fig. 5 shows the result under the fixed-channel-bandwidth model. We observe that the throughput of SM will increase as more channels are used. Similar to SM, the throughput of our DCA increases as more channels are used, but will saturate at round 11 channels, after which points using more channels is of little help. As comparing these two protocols, we see that below the saturation point (11 channels), DCA can offer significantly more throughput than SM. However, with more than 11 channels, DCA will be less efficient than SM. This is because the control channel is already fully loaded and can not function well to distribute data channels to mobile hosts.

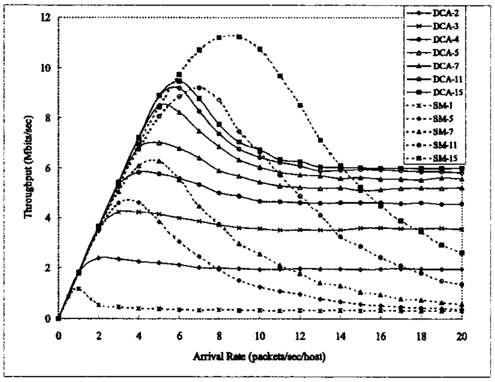

Figure 5: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

Another point to be made is that at high load, DCA will suffer less degradation than SM. There are two reasons. The first reason is that DCA separates control from data channels. In 802.11-like protocols, an RTS/CTS dialogue is not guaranteed to be heard by all neighboring hosts due to collision. Thus, any "innocent" host who later initiates an RTS/CTS will corrupt others' on-going data packets (an analysis on this can be found in [7]). Separating control and data channels will relieve this problem. The second reason is that DCA uses multiple data channels. Using multiple data channels can further reduce the possibility of data packet collisions incurred by incorrect RTS/CTS/RES dialogues (by "incorrect", we mean that some of the RTS/CTS/RES packets are collided/corrupted at some hosts, making them mistakenly choose the same data channel at the same time; a larger number of data channels will dilute such probability).

Fig. 6 shows the same simulation under the fixed-total-bandwidth model. We see that the utilization of SM decreases as more channels are used. This is perhaps because of the short of flexibility in static channel assignment. On the contrary, the best utilization of our DCA appears at around 4 channels. The peak performance is about 15% higher than SM-1 (i.e., IEEE 802.11). Also, at high load, our DCA will suffer less degradation than SM. With more channels, our DCA will degrade significantly.

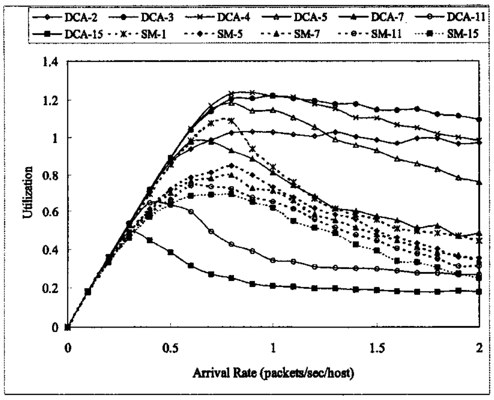

Figure 6: Arrival rate vs. utilization under the fixed-total-bandwidth model with different numbers of channels.

5 Conclusions

We have proposed a new multi-channel MAC protocol based on an on-demand channel assignment concept. The number of channels required is independent of the network size, degree, and topology. There is no form of clock synchronization used. These features make our protocol more appropriate for MANETs than existing protocols. We solve the channel assignment and medium access problems in an integrated manner in one protocol. Simulation results have justified the merit of our protocol under both bandwidth models. Another noticeable discussion in this paper is the missing-RTS, missing-CTS, which may behave differently in a multi-channel environment as opposed to a single-channel environment.

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