A Multi-channel MAC Protocol with Novel Channel Selection for Ad Hoc Networks

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ABSTRACT

In wireless ad hoc networks, the medium access control (MAC) protocols that are based on a single-channel model will suffer from serious collisions when network traffic load is high. Moreover, the hidden/exposed terminal problems will become serious. In this paper, we present an efficient multi-channel MAC protocol to increase network performance. The proposed protocol has the following features: (1) A dedicated control channel is used to negotiate and collect channel usage information among nodes. (2) A counter-based channel selection strategy is used to balance channel load and reduce contentions and collisions among nodes. (3) A local negotiation strategy is used to reduce the channel re-negotiation overhead during data retransmissions.

1: INTRODUCTIONS

Since transmissions in wireless networks must rely on a common radio medium, the medium access control (MAC) protocol becomes important. A MAC protocol is addressed to potential contentions and collisions on the communication medium. MAC protocols can be mainly classified into two categories: single-channel model and multi-channel model. In the single-channel model, all nodes operate on the single common channel for communication. In the multi-channel model, the overall bandwidth is divided into several non-overlapping channels and every node can operate at any one of the channels for communication.

In the wireless ad hoc network, when the MAC protocol is based on the single-channel model, serious collisions may occur when network traffic tends to saturation. Also, the hidden/exposed terminal problems may become more serious so as to reduce the channel utilization and throughput. To relieve these problems, using multiple channels is one approach and has several advantages. First, the throughput can be increased. Second, multiple transmissions in the same interference range can be distributed to different channels, which can reduce contentions and collisions. Third, a higher degree of quality of service can be supported and the fairness between transmission pairs can be achieved [4].

Many protocols based on the multi-channel model have been proposed [1][6][11][13][15][18]. Although the multi-channel scheme can provide higher performance than the single-channel one, there are still some challenges such as the multi-channel hidden terminal problem [6] and the deafness problem [13][14]. An appropriate channel selection is also an essential issue in the multi-channel environment. In this paper, we propose an efficient multi-channel MAC protocol to increase network performance.

This paper is organized as follows. Section 2 gives the related work. Section 3 shows our design. The performance evaluation is shown in Section 4. We draw conclusions in Section 5.

2: RELATED WORK

We review the related problems in single-channel and multi-channel environments, respectively. Also, we introduce two multi-channel MAC protocols that will be compared in this paper.

The hidden terminal and exposed terminal problems are two traditional problems in the single-channel environment. A hidden terminal is a node within the range of the receiver, but out of the range of the sender. A hidden terminal may initiate a transmission which results in a collision at the receiving node of the ongoing transmission. An exposed terminal is a node within the range of the sender, but out of the range of the receiver. Since an exposed terminal can not transmit when the sender is transmitting, this will lead to low throughput.

The IEEE 802.11 standard [5] uses the exchange of RTS/CTS packets, which carries the NAV (Network Allocation Vector) information to claim the channel reservation for a certain time period, to avoid the hidden terminal problem. However, this mechanism is ineffective in combating with the exposed terminal problem.

To relieve these problems, using multiple channels is one approach. The main idea of multi-channel MAC protocols is to distribute network traffic into different channels so as to increase the network aggregate throughput. Although a multi-channel MAC protocol can provide some benefits, there are some issues that need to be concerned.

In the multi-channel environment, if a node is equipped with only one half-duplex transceiver, this node can only activate on a particular channel but can not hear any communication taking place on a different channel. This presents two problems: the multi-channel hidden terminal problem [6] and the deafness problem [13][14].

The multi-channel hidden terminal problem is similar to the conventional hidden terminal problem but happens when doing channel switches. The deafness problem arises when a sender attempts to communicate with a receiver that is already engaged in another communication on a different channel. This will cause the sender several transmission retries.

To overcome these problems in multi-channel environments, the related work has shown two broad mechanisms: (1) the use of a dedicated control channel [2][3][8][10][11][15][16], and (2) the use of a common control period [6][7][9][19] to do negotiations. In the first mechanism, one control channel is dedicated to exchange control packets for negotiations. The remaining available channels are called data channels. The common control period is a fixed period of time during which each upcoming sender/receiver pair comes to a common channel for negotiations. Two representative protocols: DCA [15] and MMAC [6] are introduced below.

The Dynamic Channel Assignment (DCA) protocol was proposed in [15], which is based on the dedicated control channel scheme. This protocol uses one transceiver which permanently listens to the dedicated control channel for negotiations, and another transceiver that can switch between data channels for data exchanges. In DCA, a data channel that is idle on both the sender and receiver sides is selected for subsequent data exchanges. The major drawbacks of the DCA scheme are the control channel saturation problem [6] and the channel negotiation overhead. In DCA, when total bandwidth offered to the network is fixed, the control channel saturation problem takes place. Serious contentions cause the control channel a bottleneck and an inefficient usage of data channels. Since DCA employs per-packet negotiations, if one packet fails to be delivered on the data channel, the sender has to contend for the control channel and re-negotiate with the receiver again. This will increase the control channel overhead when the channel error is high.

The MMAC protocol enables mobile nodes to use multiple channels by switching channels dynamically with only one transceiver. It solves the multi-channel hidden terminal problem by asking all nodes to listen to a common channel periodically. In MMAC, the channel usage is organized into beacon intervals each of which is consisted of a channel negotiation interval (called ATIM window) and a data transmission interval. The ATIM window is a time duration during which all nodes have to listen to the default common channel and do negotiations. The major drawback of the MMAC scheme is the requirement of time synchronization among all nodes, which might become an overhead in an ad-hoc environment. Also, the packet delivery delay might be long, since any data transmission can only take place in the data transmission interval.

3: NOVEL CHANNEL SELECTION SCHEME

In this section, we give an overview of our proposed Novel Channel Selection (NCS) protocol. In NCS, the data exchange has two phases. In the first phase, a sender contends for the control channel and selects an appropriate data channel to be used. Then, the sender exchanges the CRTS-CCTS packets with the receiver on the control channel. The CRTS and CCTS packets are modified from the RTS and CTS packets, respectively, and carry the information of the selected channel number. In the second phase, the four-way handshake mechanism is exploited by following the sequence RTS-CTS-DATA-ACK on the selected data channel.

Before describing the protocol in details, we first summarize our assumptions.

- All available channels have the same bandwidth. Nodes have prior knowledge of how many channels are available and how to switch to a particular channel given the channel number.
- Each node is equipped with two half-duplex transceivers, one transceiver is assigned to a dedicated control channel for negotiations, and the second transceiver is switched between the remaining data channels for data transmission.
- Each node maintains a counter for each data channel, which records the number of times that the data channel has been selected by neighbors for data transmissions. This information can be collected on the dedicated control channel.

3.1: DESIGN OVERVIEW

Our proposed protocol has the following features:

- Dedicated control channel strategy

Since nodes can use one dedicated transceiver to listen to the control channel permanently, nodes can collect the channel usage information and negotiate with other nodes at any time.

- Counter-based channel selection strategy

This strategy attempts to balance traffic load on different channels. For each data channel, each node will count the number of source-destination pairs that have selected the data channel for data transmission by overhearing CRTS and CCTS packets. We will select the one with the lowest count when doing each channel selection.

- Local negotiation strategy

This strategy attempts to reduce channel negotiation overhead on the control channel. If the data transmission on the selected data channel is failed, a sender need not re-negotiate with the receiver on the control channel again. The sender can just initiate the retransmission process on the same data channel immediately.

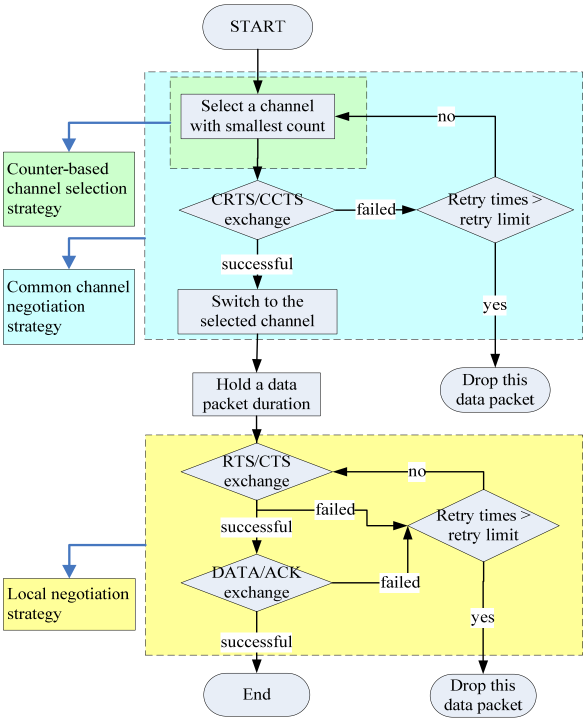

Figure 1: Flow chart.

3.2: PROTOCOL OPERATIONS

The detailed operations of the NCS scheme are described as follows:

Step 1: When a sender has packets to send, it needs to transmit a CRTS packet to the receiver on the control channel. The sender will check its counter and will select the channel with the lowest count. The selected channel number is embedded in the CRTS packet.

- If the control channel is in free status, the sender can immediately transmit the CRTS packet.
- If the control channel is in busy status, the sender will transmit the CRTS packet after the backoff process.

Step 2: Upon the successful reception of this CRTS packet, the receiver will confirm its data transceiver status, and then will increase the counter of the selected channel by one.

- If the data transceiver is in free status, the receiver replies a CCTS packet which carries the same selected channel number as the sender on the control channel and then switches its data transceiver to the selected channel.
- If the data transceiver is in busy status, the receiver replies the currently used data channel number by the CCTS packet to the sender.

Step 3: When the sender receives the CCTS packet, it switches its data transceiver to the selected data channel that indicated by the CCTS packet. Then, a four-way handshake procedure by following the RTS-CTS-DATA-ACK sequence is initiated after waiting for a data packet duration.

Step 4: If the receiver successfully receives the data packet on the data channel, it transmits an ACK packet to complete the whole transmission process. If the sender fails to receive an ACK packet, it will wait for timeout and will execute the backoff process, and then will initiate a retransmission process on the same data channel.

Step 5: Other nodes in the vicinity of the transmission pair will increase their counters of the selected channel by one upon the reception of the CRTS or CCTS packet on the control channel.

Figure 1 shows the flow chart of the above operations. The holding of a data packet duration means that a sender has to wait for a time duration the length is equal to the time to transmit a data packet of maximal size. This holding is for avoiding possible collision after switching to the new channel.

In Step 2, we check whether the receiver is currently communicating with another node. If yes, the receiver's data transceiver becomes busy. In this case, the receiver can only communicate with other nodes on the currently used channel.

Figure 2 shows an example scenario where nodes P and Q do negotiations by exchanging the CRTS/CCTS packets and select channel 2 as the data channel.

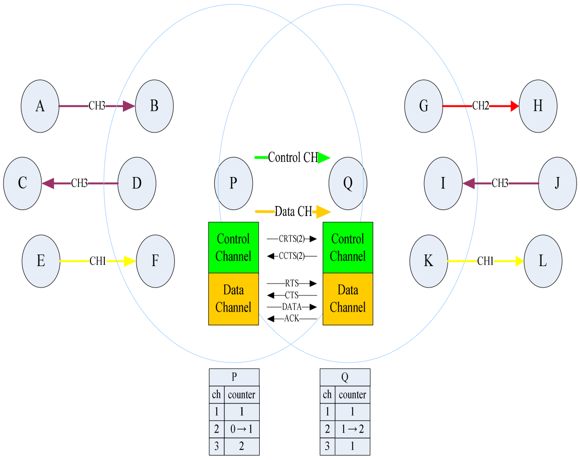

Figure 2: An example scenario.

3.3: ENHANCED MODE

Although NCS can efficiently balance channel load and can reduce negotiation overhead on the control channel, it still suffers from bandwidth waste on the control channel. In some cases, the dedicated control channel may become less congested than other data channels.

Hence, we propose an improvement on NCS by enabling the control channel to transmit data too when the available channel number is small. Mostly, the enhanced-NCS scheme is similar to the original one, such as the counter-based channel selection and local negotiation strategies. The different between these two schemes is the extra utilization of the control channel. In the enhanced-NCS scheme, when the control channel is selected by the sender for data transmission, the sender initiates a normal RTS/CTS exchange with the receiver.

We will show the performance improvements through the simulations.

4: PERFORMACE EVALUATION

We use the CSIM [17] language to write our simulation programs for evaluating the performance of our proposed protocol. We mainly compare our scheme with the DCA and MMAC protocols. Besides, the comparisons of the Original-NCS and Enhanced-NCS schemes are also addressed.

4.1: SIMULATION MODEL

We consider a fully connected topology where all nodes are within the radio range of each other. Each traffic flow is generated by the Poisson distribution. The bandwidth model in our simulation is based on the fixed channel bandwidth model, where each channel has a fixed bandwidth. Since IEEE 802.11b/g in the 2.4GHz band offers three non-overlapping channels, we assume that the default channel number is three. The major parameter settings in our simulation are listed in Table 1.

Parameters	Items	Values
input parameters	#Station	10-80 (default 80)
	#Channel	2-10 (default 3)
system parameters	Channel rate	2 Mbps
	Bit error rate	1.00E-04
	simulation time	60 sec
	ATIM length	20 ms
	Beacon interval	80 ms
	Slot time	20 us
	SIFS	10 us
	DIFS	50 us
	CW max	1023
	CW min	15
	Retry limit	6
	MAC header	24 bytes
	Control packet	20 bytes
	Data packet	1024 bytes

Table 1: Parameter Settings.

In the simulation, we use the following metrics to measure the performance of each protocol.

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

$$Avgerage\_Delay = \frac{Total\_Packet\_Delay}{No\_Successfull\_Packets}$$

$$Drop\_Rate(\%) = \frac{No\_Drop\_Packets}{No\_Total\_Generated\_Packets}$$

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

4.2: SIMULATION RESULTS

Figure 3 shows the throughputs of different protocols as the number of stations (sender nodes) increases. The network load becomes heavy when the number of stations is large. When the network load is low, all protocols perform similarly. As network load grows to near saturation, Enhanced-NCS performs significantly better than DCA as well as MMAC. This is because the bandwidth of the control channel is fully utilized by the proposed strategy. Since there are only 3 channels are available, both Original-NCS and DCA use one channel for channel negotiations and other 2 channels for data transmissions.

The throughput is dependent on the channel decision strategy. DCA has to concern with each channel state and then agrees with a free channel before data transmission. The results in complex channel negotiations and ineffective reservation when data transmissions fail on the selected data channel. Our proposed protocol which uses the counter-based channel selection can simplify the channel decision and can balance channel load on the network.

Besides, when data transmission fails on the selected data channel, the NCS-based schemes can use the local negotiation strategy to reduce the channel renegotiation overhead on the control channel. The simulation result shows that this strategy can get performance improvement over DCA.

As compared with MMAC, MMAC uses all 3 channels for data transmissions which results in better performance than Original-NCS and DCA. But it suffers the penalty on the ATIM windows size, which results in lower throughput than Enhanced-NCS.

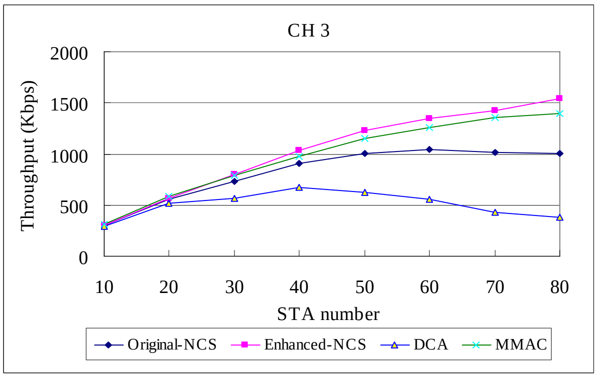

Figure 3: Throughput vs. Number of stations.

Figure 4 shows the average packet delays of different protocols as the network load increases. As can be seen, MMAC shows a higher delay in our simulation due to the ATIM window. Nodes have to wait for the ending of the current ATIM window, and then start transmitting data packets. When the network size becomes large, not every transmission pair can finish channel negotiations during the ATIM window. These nodes have to wait for the next ATIM window. This will also postpone the packet delivery.

As compared with DCA, our proposed Original-NCS suffers from higher contentions when network size is large. The reason is that only two available channels can be used for data transmission, and Original-NCS uses extra RTS/CTS packets to prevent the hidden terminal problem on the data channel. This will cause a higher packet delay than DCA. Enhanced-NCS can relieve this problem, because all of the available channels are able to transmit data packets. This can reduce the contentions on each of available channels and performs the similar delay with DCA.

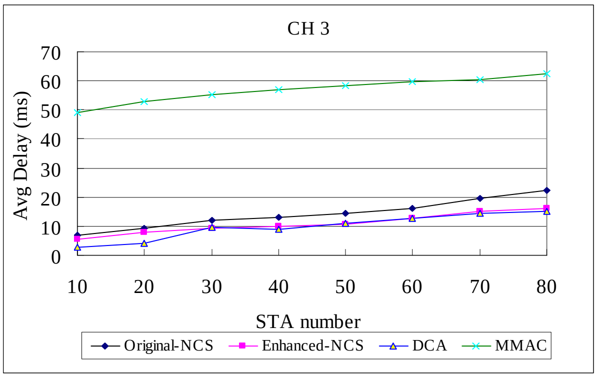

Figure 4: Average Delay vs. Number of stations.

Figure 5 compares the drop rates of the protocols. The drop rate is used to evaluate the reliability of protocols, which is directly proportional to the traffic load of the network. The higher drop rate represents the lower reliability of the scheme. As can be seen, Enhanced-NCS has the lowest drop rate among all protocols. DCA suffers from a highest drop rate because of serious contentions on the dedicated control channel.

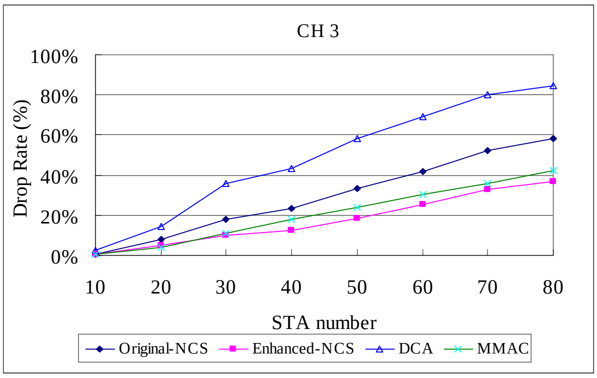

Figure 5: Drop Rate vs. Number of stations.

Figure 6 presents the comparisons of protocols when varying the number of available channels. We use the maximum 80 stations to evaluate the channel number effect. When the available channel is small, Enhanced-NCS performs better than other protocols. This is because the control channel can be used as a data channel, which results in higher throughput than other ones. DCA adopts the per-packet reservation mechanism. When a packet is failed on the data channel, DCA has to do renegotiation on the control channel, which causes higher contentions on the control channel. When the available channel is small, this phenomenon will become more serious.

As compared with DCA, Original-NCS uses the local negotiation strategy when packet deliveries are failed on the data channel. This feature can reduce the overhead of the control channel. In MMAC, all nodes have to finish channel negotiations within the ATIM window. Since the ATIM window size is fixed, the number of nodes which can successfully finish negotiations is limited. In other words, increasing the number of available channels is not helpful on the throughput, because the throughput of MMAC depends on the ATIM window size.

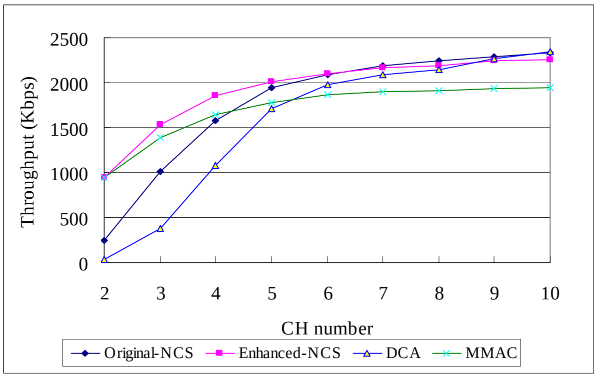

Figure 6: Throughput vs. Number of channels.

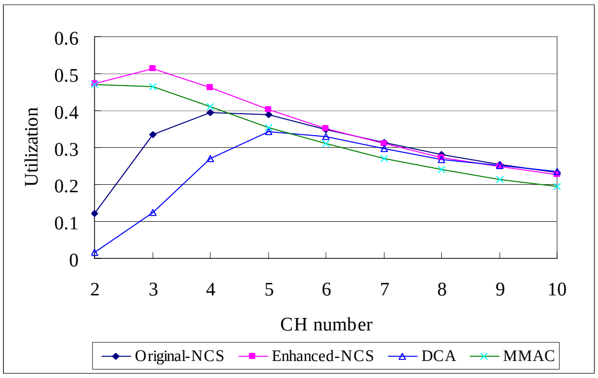

Figure 7: Utilization vs. Number of channels.

Figure 7 compares the utilizations of protocols when varying the number of available channels. As can be seen, Enhanced-NCS achieves higher utilization than other protocols with the same traffic load. This is because both control and data channels can be fully utilized for data transmissions. Nodes in MMAC are equipped with only one transceiver, and hence this causes a limitation on the channel utilization when available channel number is small. In DCA, the control channel is only used for channel negotiations. When the available channel number is small, the control channel overhead will seriously effect the utilization. Our proposed

Original-NCS adopts the local negotiation strategy can bring better utilization than DCA.

5: CONCLUSIONS

In this paper, we have presented a multi-channel MAC protocol that utilizes multiple channels to improve throughput in wireless networks. To overcome the multi-channel hidden terminal and deafness problems, our proposed NCS scheme is based on the dedicated control channel technique. In our proposed NCS protocol, we address three strategies to increase the performance. First, we propose a counter-based channel selection strategy to balance channel load and reduce contentions and collisions among nodes. Second, we propose a local negotiation strategy to alleviate the drawback of the channel renegotiation overhead when data transmissions fail. Third, we propose a strategy that enables the control channel for data transmissions to increase the utilization of this channel. The comparisons between DCA, MMAC, and NCS are given and discussed. In particular, we show that our NCS scheme can achieve higher throughput and channel utilization than DCA and MMAC.

Our future work will involve more simulations and deeper analyses of these protocols. We will consider the impact of the routing algorithms (such as AODV, DSR) and study the capacity influenced by different network models as pointed out in [12].

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