On Channel Selection Strategies for Multi-Channel MAC Protocols in Wireless Ad Hoc Networks

Ian Wormsbecker   Carey Williamson
Department of Computer Science, University of Calgary
2500 University Drive NW, Calgary, AB, Canada T2N 1N4
Email: {ianw,carey}@cpsc.ucalgary.ca

Abstract— **Multi-channel Medium Access Control (MAC) protocols have recently been proposed to improve the performance of the Transmission Control Protocol (TCP) in IEEE 802.11 wireless ad hoc networks. This paper uses *ns-2* network simulations to study the impact of channel selection techniques on multi-channel MAC protocol performance, particularly for the Bi-directional Multi-Channel MAC protocol. Three channel selection strategies are studied: Random, Lowest Channel First, and Soft Channel Reservation. The simulation results identify four distinct scenarios in which data channel frame losses can occur. Among the channel selection strategies evaluated, the Soft Channel Reservation technique is the most effective for the *missed reservation* problem. This channel selection strategy reduces link-layer data frame losses and provides higher TCP throughput compared to the other channel selection approaches.**

Keywords: Wireless ad hoc networks, multi-channel MAC protocols, ns-2 network simulation

I. INTRODUCTION

The IEEE 802.11 standard is widely used by a broad range of wireless communication devices. This standard defines how these devices communicate at the physical and link layers.

The TCP/IP (Transmission Control Protocol/Internet Protocol) protocol suite is typically used to provide transport-layer and network-layer services on top of the IEEE 802.11 link-layer protocol. This approach allows wireless devices to integrate seamlessly with existing networks.

TCP performs well when used with highly reliable link-layer protocols in wired networks [1]. However, wireless networks, especially ad hoc networks, are prone to link-layer errors from the characteristics of the wireless medium.

TCP can perform poorly when the underlying network uses the IEEE 802.11 protocol [9]. Excessive retransmission attempts, transient link-layer failures, and fairness problems can lead to poor network performance [3], [4], [6], [8], [11], [22]. TCP's congestion control and retransmission mechanisms do not work well with IEEE 802.11, especially in multi-hop networks, which rely on intermediate nodes to forward packets from a source to a destination. Multi-hop wireless ad hoc networks cause many adverse interactions between the IEEE 802.11 protocol and TCP [6], [7], [13], [20].

Several researchers have proposed *multi-channel* MAC protocols to improve TCP performance over IEEE 802.11 multi-hop networks. Using multiple channels at the physical layer allows multiple nodes to transmit and receive data concurrently, without interfering with each other. However, multi-channel protocols exhibit a *missed reservation* problem [13], [19], similar to the well-known *hidden terminal* problem.

This paper studies the role of *channel selection* in multi-channel MAC protocols. The specific research questions addressed are the following:

- Can careful channel selection alleviate the missed reservation problem?
- What are the impacts of channel selection strategies on TCP-level performance?

We use the *ns-2* network simulator [2] to answer these questions, on a simple chain network topology. Three different channel selection strategies are studied, namely Random, Lowest Channel First, and Soft Channel Reservation.

There are two main contributions in this paper. First, we show that there are actually *four* (rather than one) different link-layer frame loss scenarios that can occur with multi-channel MAC protocols. Among these four, the missed reservation problem is the most prevalent. Second, we show that the channel selection strategies differ with respect to these loss scenarios. Among the channel selection strategies evaluated, the Soft Channel Reservation technique is the most effective for the missed reservation problem. This channel selection strategy significantly reduces link-layer data frame losses compared to the other channel selection approaches, and provides slightly higher TCP throughput.

The rest of this paper is organized as follows. Section II provides some background material on IEEE 802.11 wireless ad hoc networks, and prior work on multi-channel MAC protocols. Section III describes our simulation model, and the experimental methodology for our work. Section IV presents the simulation results. Section V concludes the paper.

II. BACKGROUND AND RELATED WORK

A. MAC Protocols

The physical-carrier-sensing mechanism of the IEEE 802.11 MAC protocol is called the Distributed Coordination Function (DCF). It uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to reduce the likelihood that overlapping transmissions occur.

The IEEE 802.11 MAC protocol also supports Request-To-Send/Clear-To-Send (RTS/CTS). This virtual-carrier-sensing mechanism can reduce the chance of collisions caused by hidden terminals. A transmitting node with a large data frame to send first transmits a short RTS control frame to the intended destination. To grant permission to send, the destination node transmits a CTS frame back. Any other node that overhears the RTS/CTS exchange knows to defer access to the wireless channel for the NAV (Network Allocation Vector) time duration specified in the RTS/CTS frames. Once the NAV elapses, the channel is available for access again by any node.

A Multi-Channel MAC (MCMAC) protocol extends the IEEE 802.11 MAC to use multiple physical-layer channels. With more than one channel, throughput gains are possible by allowing multiple transmissions to occur simultaneously. Because these simultaneous transmissions occur on different wireless channels, frame collisions are reduced. Experiments have shown that IEEE 802.11b WLAN technology can use up to 4 channels concurrently [15]. The IEEE 802.11a and 802.11g standards provide even more channels.

Although many variants of MCMAC protocols exist [10], [16], [17], [18], [19], our work considers a generic model of the multi-channel MAC protocols found in the literature [13]. The protocol uses $K > 1$ physical layer channels, where one channel is a control channel, and the remaining $K-1$ channels are data channels. Each node has a single transceiver, which is tunable to any of the physical channels.

All channels are assumed to have *identical* physical-layer characteristics (i.e., transmission rate, signal-to-noise ratio, bit error rate). While this assumption may not be realistic, the purpose of our study is to see the effects (if any) of the channel selection strategies applied to the set of available channels. For this purpose, identical channels are sufficient. This assumption also simplifies the simulation model and the interpretation of the simulation results.

In a multi-channel MAC protocol, a channel negotiation phase must occur on the control channel prior to a node transmitting data to another node. During this phase, the two nodes involved in the data transmission must agree on a data channel to use. Once a data channel has been selected, the nodes switch to that channel for actual data transmission.

The channel negotiation phase functions similarly to the regular IEEE 802.11 MAC, with a few small exceptions. In order to facilitate channel selection, the RTS and CTS frames each have an additional field. In the RTS frame, a bitmask field represents the sender's set of available data channels. In the CTS frame, a field specifies the selected channel on which data transmission should occur.

Other nodes learn about channel selections when they overhear the RTS/CTS exchange. This reduces the chance that multiple nodes select the same data channel. Each node maintains a NAV timer for every channel, moving a busy channel back to the available channel list upon NAV expiration.

The Bi-directional Multi-Channel MAC Protocol (Bi-MCMAC [13]) extends the MCMAC protocol to allow one data frame exchanged *in each direction* following a *single* RTS/CTS/CRN handshake. The extra control frame for Channel Reservation Notification (CRN) is broadcast by the sender to advise neighbours of the channel selection and cumulative NAV duration.

Like the MCMAC Protocol, Bi-MCMAC uses K physical channels, with one used for control, and the rest used as data channels. Where it differs from the MCMAC, however, is that during the data transmission phase, the two nodes have the option of each transmitting a data frame, therefore providing a bi-directional frame exchange mechanism. This approach improves the efficiency of TCP transfers, which require the movement of TCP data packets and TCP ACK packets in opposite directions through the wireless ad hoc network [13].

B. Multi-Channel Hidden Terminal Problem

One problem that can arise with multi-channel MAC protocols is a variant of the hidden terminal problem. The multi-channel hidden terminal problem occurs when a node is busy transmitting or receiving on a data channel when a neighbouring node initiates a channel reservation handshake on the control channel. Because a node is active on a data channel, it is unable to learn of the channel its neighbour selected and, in turn, may inadvertently choose the same channel when it begins its next data exchange.

One possible solution to the multi-channel hidden terminal problem is to use multiple network transceivers. This solution allows a node to listen on the control channel and all data channels at the same time. However, using multiple transceivers increases the cost and complexity of the wireless devices, and may not be practical for small devices such as a PDA or sensor modules. For these reasons, our study assumes each node has a single network transceiver capable of half-duplex communication.

Channel selection can also help alleviate this problem. By carefully selecting data channels, the likelihood of the multi-channel hidden terminal problem may be reduced. Furthermore, scarce wireless resources may be used more efficiently under different channel selection strategies, leading to improved TCP performance. The channel selection approach is the main focus of our paper.

C. Related Work

Fu *et al.* [6] have proposed two techniques for improving TCP performance in multi-hop wireless networks. They argue that TCP acheives the highest throughput when it operates with a congestion window specifically tailored to the length of the chain. In particular, they propose a congestion window of $\frac{h}{4}$ where h is the number of hops in the chain network. They introduce two mechanisms to improve TCP performance: Distributed Link-layer RED (LRED), and adaptive pacing. By using these methods, they improved TCP throughput by 5% to 30% for different network topologies.

Nasipuri and colleagues have extensively studied multi-channel protocols in wireless networks [10], [16], [17], [18]. They first examined a multi-channel system that requires listening on all physical channels [10], [18]. When a frame needs to be sent, the transmitting node selects the channel with the lowest interference. They also compared a "soft reservation" channel selection scheme with a random channel selection scheme, attributing the superiority of soft reservation schemes to the ability to "reserve" a channel for data transmission for every node. Next, they used the control-and-data channel model and the RTS/CTS mechanism to allow the receiving node to select the channel with the best signal-to-noise ratio [10]. They extended this mechanism to include dynamic channel selection, which attempts to maximize the signal-to-noise ratio at the receiver, and reduce the interference with neighbouring nodes [17]. This scheme increases the average throughput of all nodes.

Vaidya and colleagues propose a multi-channel MAC protocol that solves the multi-channel hidden terminal problem using temporal synchronization [19]. Nodes negotiate data channels for use during an "ATIM period" that occurs at specified intervals. Any nodes that do not negotiate a channel for use must wait for the next interval in order to transmit data. Their results show increased throughput for Constant Bit Rate (CBR) traffic. They attribute this advantage to the elimination of the multi-channel hidden terminal problem. Although the proposed protocol requires only one transceiver at each node, global timing issues add to the complexity.

Another technique for improving multi-hop wireless network performance is *power control*, which reduces the interference range for a given transmission. Jung *et al.* [12] propose a multi-channel MAC protocol with power control that improves wireless network performance. However, their protocol requires two transceivers: one to listen constantly on the control channel, and one to transmit on a data channel.

III. EXPERIMENTAL METHODOLOGY

A. Simulation Model and Assumptions

The *ns-2* network simulator [2] was used for all simulations in this study. The File Transfer Protocol (FTP) model is used at the application layer to provide an infinite supply of data to TCP for transmission. We use the TCP NewReno model [5] with Delayed ACKs enabled, and a TCP maximum segment size of 1024 bytes. All simulations were run for 300 seconds to achieve steady-state results for TCP throughput.

A static chain topology is used for all experiments. While simple, this topology is adequate to demonstrate the link-layer contention issues that occur between nodes in multi-hop ad hoc networks, and the benefits of multi-channel MAC protocols.

The chain length was varied from 2 to 16 nodes. An N-chain topology has N-1 hops that a packet must traverse from the sender to the receiver. The 2-node scenario has direct connectivity between the sender and the receiver. Each node is 250 m from its neighbour(s). The wireless transmission range is 250 m, while the interference range is 500 m.

Figure 1 shows an example with 4 nodes. The two endpoints of the chain are the TCP sender and the TCP receiver. The intermediate nodes in the chain are forwarding nodes only; they do not generate any traffic of their own. TCP data is transmitted in the forward direction, with TCP acknowledgments transmitted in the reverse direction.

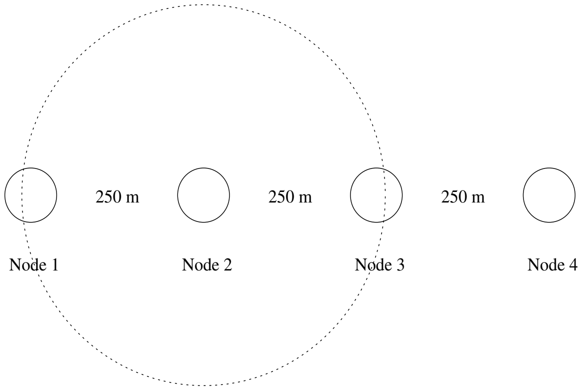


Fig. 1. Example Chain Topology for ns-2 Simulations

A static routing protocol called NOAH (NO Ad Hoc routing) was used to define routes at simulation startup [21]. NOAH is a wireless routing module for *ns-2* that only supports direct communication between adjacent wireless nodes. Using NOAH permits a cleaner analysis of the MAC protocols without the presence of anomalies from route discovery delays or broadcast storms.

The wireless channel model extends the *ns-2* channel model to support multiple physical-layer channels [13]. The center frequency of the control channel is 2.412 GHz, while the data channels are centered at 2.427 GHz, 2.447 GHz, and 2.462 GHz. For simplicity, we assume that there is no inter-channel interference (since the channels are well-separated), and that all channels have identical physical properties. Each channel has a fixed transmission rate of 1 Mbps.

B. Channel Selection Strategies

Channel selection is the responsibility of the receiving node for a given data transmission. The node making the channel selection receives from the transmitting node a list of channels that the sender thinks are available. This information is compared with the list of channels that the receiving node thinks are available. By intersecting these two sets, the node identifies the candidate channels that both nodes believe are available. Using this information, and a channel selection algorithm, a channel for data transmission is chosen.

We consider three channel selection strategies:

- *Random* channel selection is used as a baseline channel selection strategy. This technique simply selects a channel uniformly at random from the set of available channels. With random selection, traffic should be balanced across all data channels.
- The *Lowest Channel Available* strategy assumes that the channels are numbered, and simply selects the lowest numbered channel that is available.
- The *Soft Channel Reservation* strategy uses "soft state": each node remembers the channel on which it most recently had a successful transmission. By utilizing a channel that was successful previously, it is hoped that this channel is still available. Furthermore, neighbouring nodes may favour disjoint data channels for short periods of time before choosing a new channel. If the channel that

was last used successfully is not available, two possible solutions exist. One solution is to choose an available channel randomly. Another solution is to select the lowest numbered channel that is available.

C. *Performance Metrics*

Multiple metrics are used in the simulation experiments to measure performance:

- *TCP Throughput*: TCP throughput is calculated as the number of successfully delivered data bytes from the TCP source to the TCP destination per unit time. This metric is expressed in kilobits per second (kbps). A higher throughput value indicates better performance.
- *MAC-layer Collisions*: MAC collisions are calculated as the number of unicast MAC-layer frames that are lost due to interference from competing transmissions. The types of frames susceptible to collisions are RTS, CTS, Data, and ACK frames. CRN frames are broadcast and are therefore not included in this metric. A lower value of this metric indicates better protocol performance.
- *Data Channel Losses*: The data channel loss count represents the number of link-layer frame losses that contained TCP Data, TCP ACK, or MAC ACK frames. These frames are transmitted on data channels only. A lower loss count is better.

IV. RESULTS

A. *Overview*

Figure 2 compares the TCP throughput results using the IEEE 802.11 MAC protocol, the Multi-Channel MAC (MCMAC) protocol, and the Bi-directional Multi-Channel MAC protocol (Bi-MCMAC). The MCMAC and the Bi-MCMAC protocols both use the Soft Channel Reservation strategy, with three data channels and one control channel. These parameter choices are consistent with current IEEE 802.11b technology [15]. For reference purposes, the results for the single-channel IEEE 802.11 MAC protocol are also shown.

There are two general trends evident in Figure 2 when comparing the three MAC protocols. First, throughput decreases as chain length increases, which is consistent with other findings in the literature [6], [13], [14]. When chain length increases, data packets must traverse the chain one hop at a time. This hop by hop transmission reduces throughput. Second, the Bi-MCMAC protocol provides better performance than both the MCMAC and IEEE 802.11 MAC protocols for all chain lengths. Again, this finding is consistent with those in the literature [13]. The bi-directional mechanism improves protocol efficiency by reducing the number of control frames required to transmit data packets.

On very short chain topologies (i.e., 2 or 3 nodes), the multi-channel MAC protocols show no performance advantage. With only 2 or 3 nodes in the network, there is never more than one data frame transmission in progress at a time. As a result, the multi-channel MAC protocols are no more effective than the IEEE 802.11 MAC protocol.

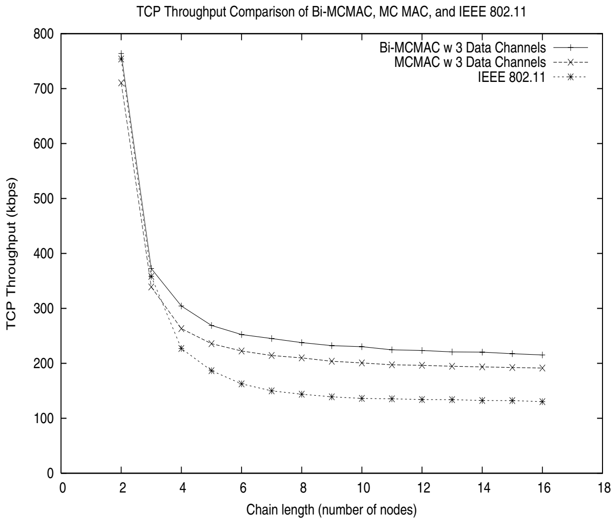


Fig. 2. TCP Throughput vs. Chain Length for Different MAC Protocols

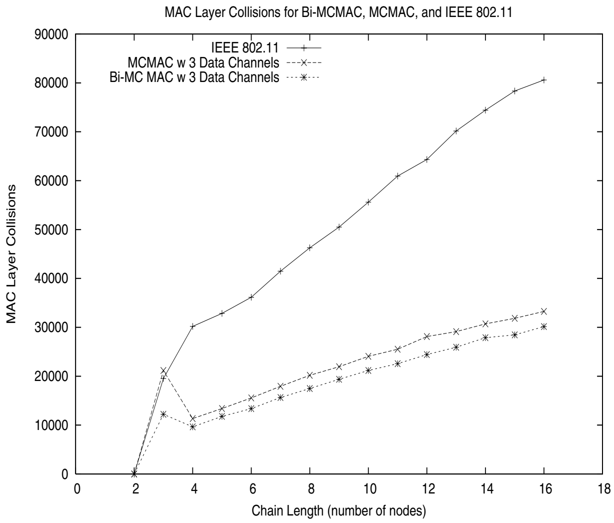


Fig. 3. MAC-layer Collisions vs. Chain Length for Different MAC Protocols

For a 3-node chain, all three MAC protocols experience a throughput drop of about 50%, compared to the 2-node case. The primary reason is that packets must traverse two hops from the sender to the receiver, instead of one. A secondary reason is contention between the sending node transmitting TCP data packets in the forward direction and the receiving node transmitting TCP ACK packets in the reverse direction. This contention results in collisions during the RTS/CTS handshake. While the 2-node case has no MAC-layer collisions (see Figure 3), the 3-node case has many collisions. These collisions reduce the effective utilization of the data channels for transmitting TCP packets. Although there are MAC-layer collisions on the control channel, Figure 4 shows that there are no data channel frame losses for any of the MAC protocols in the 3-node case.

On longer chain topologies (e.g., 4 nodes or more), the

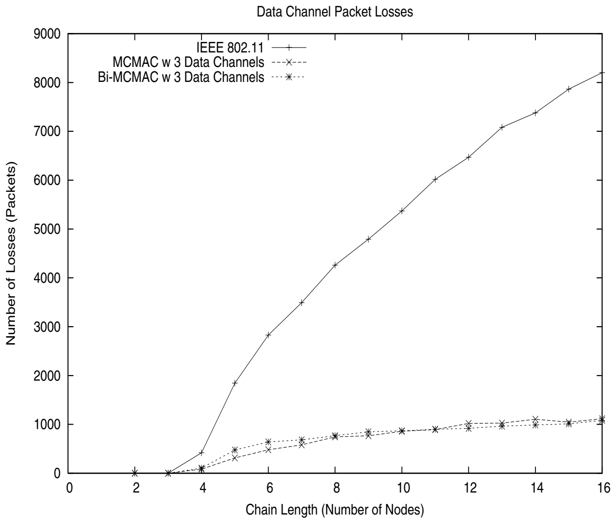


Fig. 4. Data Channel Losses vs. Chain Length for Different MAC Protocols

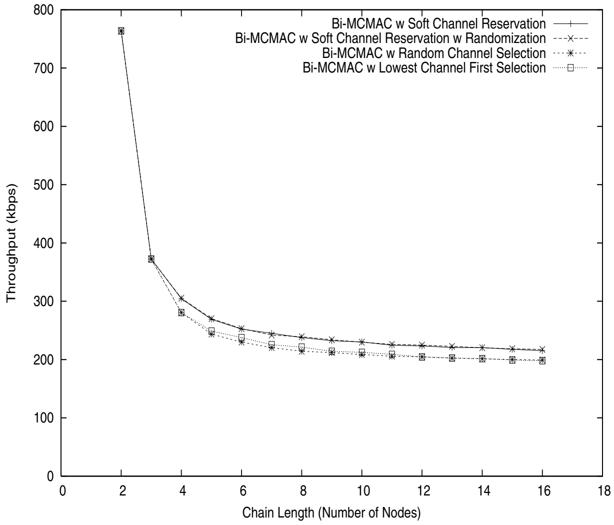


Fig. 5. TCP Throughput vs. Chain Length for Channel Selection Strategies

multi-channel MAC protocols in Figure 2 show greater throughput advantages over the IEEE 802.11 MAC protocol. The two multi-channel MAC protocols have higher throughput since they allow two nodes to transmit concurrently on different data channels. For example, Node 1 can send to Node 2 while Node 3 is communicating with Node 4, as long as they select different data channels. The IEEE 802.11 MAC protocol, however, does not allow this spatial reuse: Node 3 cannot transmit because of the exposed node problem [6]. As a result, the IEEE 802.11 protocol experiences more than twice as many MAC-layer collisions as the multi-channel MAC protocols (see Figure 3).

For chain lengths beyond 4 nodes, a gradual reduction in throughput occurs for all three MAC protocols. The multi-channel MAC protocols maintain a consistent advantage over the IEEE 802.11 MAC protocol, because of the extra channel resources available. The Bi-MCMAC protocol consistently outperforms the MCMAC protocol.

B. *Effect of Channel Selection*

Next, the different channel selection techniques were evaluated using the Bi-MCMAC protocol, which offers the best performance. Three data channels, as well as the control channel, were used for all simulations.

Figure 5 shows the TCP throughput results for Random channel selection, Lowest Channel Available, and Soft Channel Reservation both with and without randomization. Figure 6 shows the corresponding data channel frame losses for these same techniques.

For short chain lengths (2 or 3 nodes) the throughput results are identical for all channel selection techniques. Since at most one data channel is in use at a time, the method for selecting this channel is irrelevant.

For a chain topology with 4 or more nodes, the Soft Channel Reservation technique shows a 10% TCP throughput advantage compared to Random or Lowest Channel First channel selection. This throughput advantage is consistent across all scenarios studied. The reason for this improvement is apparent in Figure 6: the Soft Channel Reservation technique significantly reduces data channel frame losses.

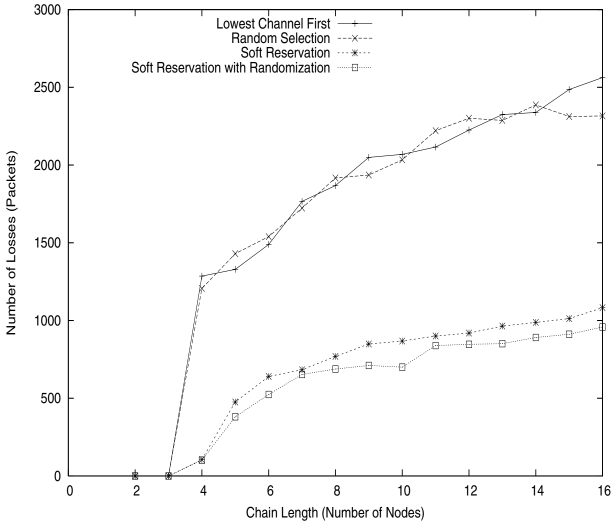


Fig. 6. Data Channel Losses vs. Chain Length for Channel Selection Strategies

The Soft Channel Reservation technique consistently maintains a lower data channel loss rate as the chain length increases. This reduction occurs because the channel selection technique reduces the effects of the multi-channel hidden terminal problem. The next section examines this behaviour in more detail.

C. *Data Channel Loss Scenarios*

Detailed analysis of our simulation results shows that there are actually *four* distinct data channel loss scenarios that occur with multi-channel MAC protocols. While one of these scenarios, namely the multi-channel hidden terminal problem, has been documented in the literature, the other three (to the best of our knowledge) have not been described. This section explores all four of these scenarios in detail.

The four loss scenarios are illustrated in Figure 7. For simplicity, we consider only the 4-node chain topology. Node 1 is the TCP source and Node 4 is the TCP destination. The simulation examples presented in Figure 7 are protocol timing diagrams. The horizontal axis represents time, while the vertical axis portrays activity on the control and data channels for each node. Horizontal lines represent frame transmissions.

The four loss scenarios are explained as follows:

1) Missed Reservation: The first data channel loss scenario is known in the literature as the *missed reservation* problem. In general, a node is busy transmitting or receiving on a data channel when a neighbouring node initiates a channel reservation handshake. Because a node is active on a data channel, it is unable to learn of the channel its neighbour selected and, in turn, may choose the same channel when it begins its next data exchange.

Figure 7(a) displays an example of this loss scenario extracted from the simulation trace files. Node 3 and Node 4 perform an RTS/CTS/CRN handshake exchange at time 259.705 and begin communicating on data channel 3. Node 2 is aware of their channel selection because it received the CRN from Node 3. Node 1 and Node 2 then perform an RTS/CTS/CRN handshake exchange later at time 259.707, choosing data channel 2 for their exchange. However, when Node 2 sent the CTS, Node 3 was unable to receive it because it was in a data exchange with Node 4 on channel 3. Node 3 has missed the channel reservation. When Node 3 and Node 4 conclude their current data exchange at time 259.715, they perform a new RTS/CTS/CRN handshake at time 259.716 to begin another data exchange. Unfortunately, Node 3 believes that data channel 2 is available, and advertises it in the RTS frame that it sends to Node 4. Node 4 happens to choose data channel 2, leading to a data channel loss (X).

Among the channel selection strategies studied, both Random and Lowest Channel Available are susceptible to this loss scenario. Because a channel selection is made with incomplete information, and without considering past channel usage, there is a non-zero probability that the nodes select a busy channel.

The Soft Channel Reservation technique alleviates the data channel losses associated with this scenario. Because the Soft Reservation technique prefers using the last channel successfully used (if available), neighbouring nodes tend to favour disjoint data channels over short time periods. Thus fewer data channel losses occur.

2) Missed CTS: The second data loss scenario is the result of a node missing a CTS frame transmitted between two other nodes, because it was busy receiving an RTS frame from another neighbour. Later, this node uses the same data channel as the node whose CTS it missed.

This data loss scenario is depicted in Figure 7(b) with an example extracted from the simulation traces. Node 1 begins an RTS/CTS/CRN handshake with Node 2 at time 343.152 by sending its RTS. An instant later, Node 4 attempts a separate RTS/CTS/CRN handshake with Node 3 by sending an RTS frame. While Node 4 is transmitting, Node 2 begins transmitting the CTS to Node 1 with the data channel it selected for use. For Node 3 to learn of the channel selected, it must overhear this frame. However, Node 3 is currently receiving the RTS frame from Node 4. Node 3 therefore misses the CTS frame informing it of the channel chosen by Node 1 and Node 2 for their data transmission. In addition, the initial RTS frame that Node 4 sent is not received by Node 3, because of interference. Node 4 performs backoff, and retries the RTS. The new handshake attempt at time 343.154 is successful. However, Node 3 does not know which channel Node 1 and Node 2 are using. In the example illustrated, Node 3 selects the same data channel that Node 1 and Node 2 are using, corrupting the transmission.

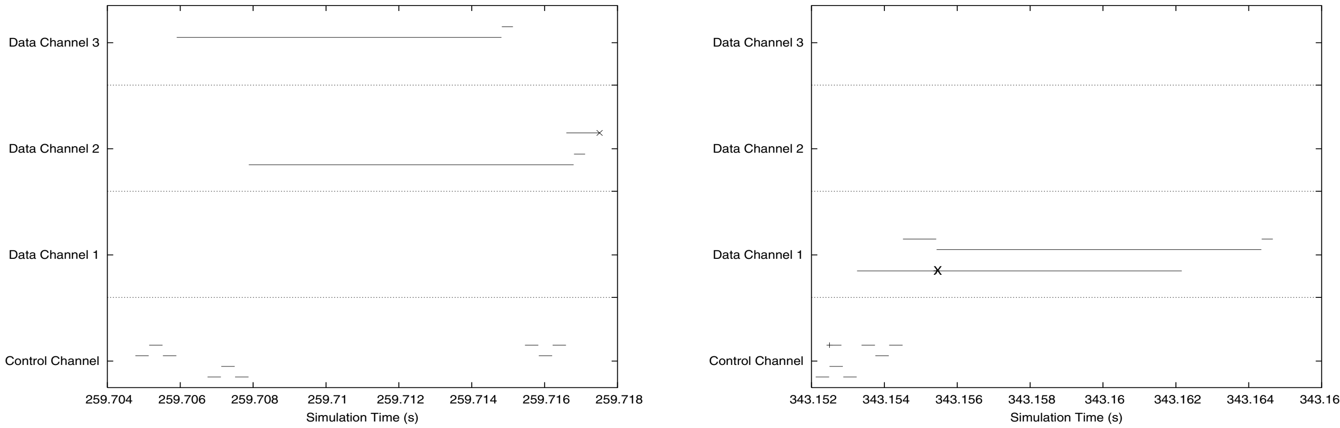
All of the channel selection techniques are susceptible to data channel losses from this scenario. However, missing a CTS frame does not always lead to a data channel loss. For example, with Random channel selection, the probability that Node 3 selects the busy data channel is $\frac{1}{D}$ for D data channels. Furthermore, if Node 2 and Node 3 had used different data channels during their previous transmissions, Soft Channel Reservation would favour their previous channels, avoiding a data channel loss. However, regardless of the channel selection technique used, losses can always occur in this scenario. If even one node is unaware of a channel selection, its list of available channels may include an occupied channel.

3) Missed CRN: The third data channel loss scenario is a complex scenario that initially starts with a node missing a CRN frame, due to a collision with an RTS frame. The result is a node not knowing the data channel chosen by its neighbour.

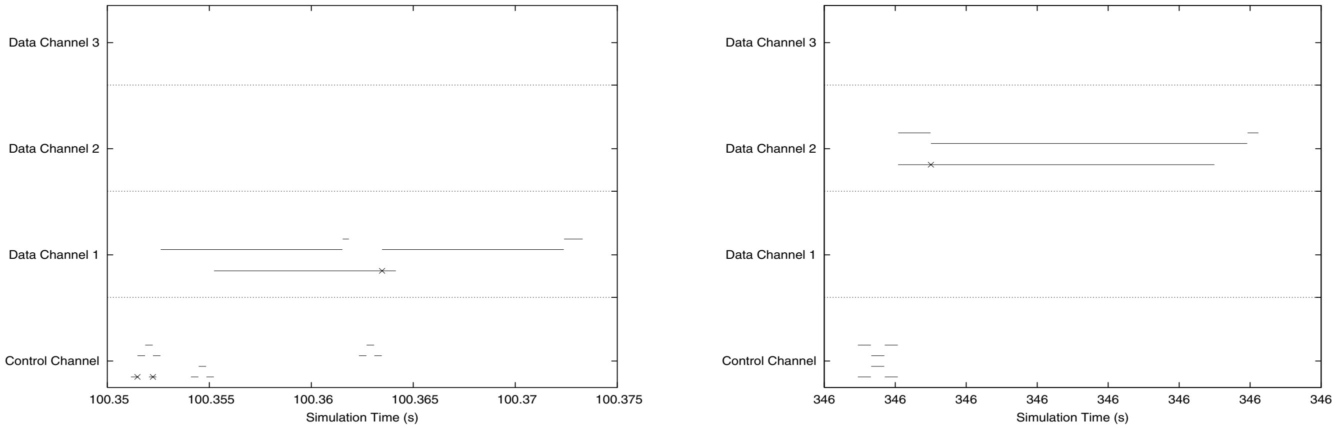
Figure 7(c) shows an example of this scenario from the simulation trace files. Node 1 and Node 3 both send RTS frames near time 100.351, destined to Node 2 and to Node 4, respectively. The RTS destined for Node 2 is interfered with by the RTS being transmitted to Node 4, resulting in a collision at Node 2. Node 4, however, receives the RTS destined for it, since Node 4 is outside the interference range of Node 1.

While Node 1 is waiting to resend its RTS, Node 4 transmits a CTS frame to Node 3, with data channel 1 as the selected channel. Node 3 transmits a CRN frame to inform its neighbours about the channel selected. While Node 3 is sending the CRN frame, the timer at Node 1 expires, and Node 1 retransmits its RTS to Node 2 at time 100.353. A collision results at Node 2, since it concurrently receives the CRN from Node 3 and the RTS from Node 1. After the CRN has been broadcast, Node 3 and Node 4 tune to data channel 1 to commence transmission of a TCP data packet to Node 4.

Node 1 times out again and resends its RTS to Node 2. This time, because Node 3 and Node 4 are now using a data channel, Node 2 can respond with a CTS. However, Node 2 is unaware that Node 3 and Node 4 are currently using data channel 1. Node 2 decides to use channel 1. Node 1 and Node 2 tune to channel 1 and begin their data transmission. Once Node 3 and Node 4 finish their transmission, they will attempt to select a data channel for a subsequent transmission.



(a) Missed Reservation (b) Missed CTS



(c) Missed CRN (d) Simultaneous Handshake

Fig. 7. Examples Illustrating Four Different Data Channel Loss Scenarios

Because they were transmitting on the data channel when Node 2 transmitted the CTS specifying channel 1, they do not know that channel 1 is in use. Node 3 and Node 4 select data channel 1, and begin transmitting data. Unfortunately, Node 2 is receiving data from Node 1 on that channel. When Node 3 begins transmitting, Node 2 receives corrupted data.

Although this scenario is similar to the missed reservation problem, there is a subtle difference in the events leading to the data frame loss. Due to the missed CRN, Node 2 inadvertently selects the same channel that it would have known was unavailable had it received the CRN. The first loss scenario was the result of a node using the *data* channel at the time of channel selection, whereas this scenario is the result of a missed CRN while listening on the control channel.

4) Simultaneous Handshake: The fourth data channel loss scenario is the result of a simultaneous handshake between two pairs of nodes. This simultaneous handshake results in neither pair of nodes being aware of which data channel the other pair has selected.

Figure 7(d) shows an example of this problem, as extracted from the simulation trace files. Node 1 and Node 4 both decide to transmit at the same time, and begin the RTS/CTS/CRN handshake. Given that the interference range of these nodes does not extend beyond 2 hops, Node 2 and Node 3 are able to receive the RTS. Simultaneously, Node 2 and Node 3 respond to the RTS with a CTS frame, and their channel selection. Again, due to the interference range not extending beyond 2 hops, the CTS frames are received correctly.

The channel selections made by Node 2 and Node 3 were performed without knowledge of the channel that the other node selected. Therefore, a data channel collision is possible. In this example, both pairs selected the same data channel for their exchange, and a data channel loss occurs. Node 4 begins by transmitting a short TCP ACK packet to Node 3, while Node 1 simultaneously transmits a long TCP Data packet to Node 2. The TCP ACK packet is received successfully by Node 3. However, when Node 3 begins to transmit a large TCP Data packet back to Node 4 using the bi-directional mechanism, Node 2 is within Node 3's interference range. This corrupts the TCP Data sent from Node 1 to Node 2.

All of the channel selection techniques are susceptible to this loss scenario. However, the Lowest Channel Available technique may experience more data losses. Because neither pair of nodes knows the data channel chosen by their neighbour, they will both choose the lowest data channel available, resulting in a frame collision.

TABLE I

PREVALENCE OF DATA CHANNEL LOSS SCENARIOS

Loss scenario	Count
Missed Reservation	21
Missed CTS	6
Missed CRN	2
Simultaneous Handshake	1

Random channel selection has a lower chance of collision than Lowest Channel Available. Both nodes making the channel selection decision do so independently. The collision probability is $\frac{1}{D}$ for D data channels.

The susceptibility of Soft Channel Reservation to this scenario depends on the previous channel selection decisions. If both nodes have previously transmitted a data frame on the same channel, loss can occur. However, because a node tends to favour its recent channel, this is unlikely to occur.

We have estimated the prevalence of the four data channel loss scenarios in our simulation experiments. The simulation run with 4 nodes produced 1,206 data channel losses (for Random channel selection). Rather than analyze all of these losses manually, we selected 30 data channel losses at random from the trace, and analyzed them individually to classify each.

The results from the manual analysis are summarized in Table I. The missed reservation problem is the most common data channel loss scenario, occurring about 70% of the time. The simultaneous handshake scenario is the least frequently observed. These results indicate that the performance advantages of the Soft Channel Reservation technique come from its ability to alleviate the missed reservation problem.

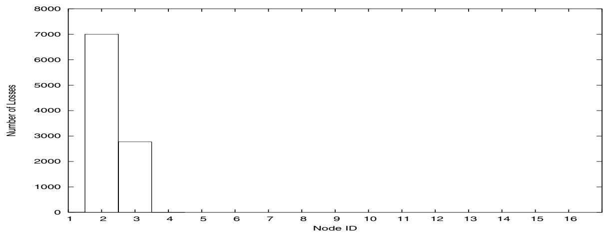
D. Loss Profile

Our final analysis studies the relative location of the data channel loss events within the chain network topology. We refer to this analysis as the "loss profile" for the chain topology. Simulation experiments were analyzed with 4, 10, and 16 nodes using both Random channel selection and Soft Channel Reservation.

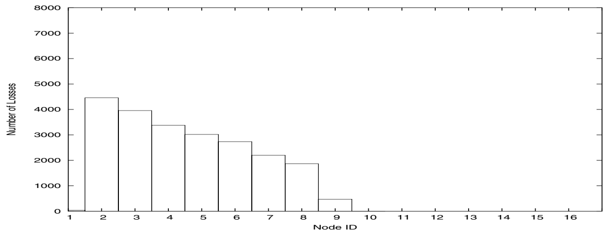
The simulation results show that more losses occur near the TCP sender at the start of the chain. This phenomenon is similar to that reported by Fu *et al.* [6]. That is, if the TCP congestion window size is larger than that required to sustain the steady-state throughput of the chain topology, then the TCP source tends to inject packets into the network too quickly, creating excessive contention early in the chain.

Figure 8 displays the number of losses occurring at each node for the Soft Channel Reservation technique. Results for Random channel selection are qualitatively similar, and are omitted for space reasons.

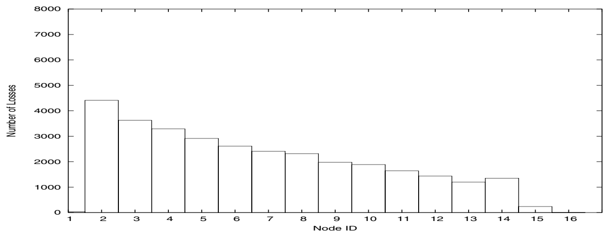
Regardless of the channel selection technique or the chain length, the node experiencing the most frame losses is the second node in the chain (Node 2). This phenomenon occurs since the TCP sender, Node 1, attempts to inject data into the network at a faster rate than can be maintained. Node 1 continually attempts to transmit RTS frames to Node 2, while Node 3 attempts to transmit RTS frames to Node 4. Node 4 can receive the latter RTS frames, however RTS frames sent from Node 1 to Node 2 collide with RTS frames being transmitted by Node 3. Because the RTS frames are transmitted on the control channel, the channel selection technique does not help to resolve this contention.



(a) 4 Nodes



(b) 10 Nodes



(c) 16 Nodes

Fig. 8. Loss Profile for Soft Channel Reservation

One final observation is an interesting "echo" effect evident in the 16-node scenario. That is, a node near the end of the chain experiences more losses than the nodes on either side of it. This effect is due to contention with RTS frames being transmitted from Node 16 to Node 15, so as to transmit TCP ACK packets back to the TCP source. These RTS frames collide with RTS frames being transmitted from Node 14 to Node 15, for sending TCP data to the destination. This effect was not evident on the 4-node and 10-node chains.

V. SUMMARY AND CONCLUSIONS

This paper presents a detailed study of the effect of channel selection strategies on the performance of multi-channel MAC protocols, using *ns-2* network simulation. The paper identifies four distinct data channel loss scenarios that can occur with multi-channel MAC protocols, and studies the effectiveness of three channel selection strategies (Random, Lowest Available Channel, and Soft Reservation) in dealing with these problems.

The simulation results show that the multi-channel hidden terminal problem has a measurable impact on TCP performance. The channel selection technique used, however, can alleviate data frame losses. Using Soft Channel Reservation results in 10% TCP performance improvement versus Random channel selection for long chain topologies. This improvement is the result of fewer data channel losses for the Soft Channel Reservation technique. Soft Channel Reservation avoids the most prevalent of the four data channel loss scenarios observed, namely missed reservations, thereby reducing the effect of the multi-channel hidden terminal problem.

Future work will consider larger and more realistic network topologies, which may have even greater channel contention, as well as the issue of node mobility, which may reduce the hysteresis advantages of Soft Channel Reservation. Channel scheduling strategies for heterogenous rate networks and wireless mesh networks are also on our research agenda.

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