A Multichannel CSMA MAC Protocol for Multihop Wireless Networks

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Abstract *We describe a new carrier–sense multiple access (CSMA) protocol for multihop wireless networks, sometimes also called ad hoc networks. The CSMA protocol divides the available bandwidth into several channels and selects an idle channel randomly for packet transmission. It also employs a notion of "soft" channel reservation as it gives preference to the channel that was used for the last successful transmission. We show via simulations that this multichannel CSMA protocol provides a higher throughput compared to its single channel counterpart by reducing the packet loss due to collisions. We also show that the use of channel reservation provides better performance than multichannel CSMA with purely random idle channel selection.*

1 Introduction

We consider multihop wireless networks where there is no cellular infrastructure (such as base stations). Nodes communicate via multihop wireless links. Nodes can be mobile and dynamic routing protocols are used to establish routes between a pair of communicating nodes. In literature, terms such as packet radio networks or *ad hoc* networks have also been used to describe such networks. Such networks are very useful in military and other tactical applications such as law enforcement, emergency rescue or exploration missions, where cellular infrastructure is unavailable or unreliable. There is considerable interest in using ad hoc networks in commercial applications as well where there is a need for ubiquitous communication services without the presence of a fixed infrastructure.

A central challenge in the design of Medium Access Control (MAC) protocols for such wireless networks has been to reduce the impact of the so-called *hidden terminal* problem [4], where a source cannot hear the transmission from another, distant source and starts transmission assuming the medium to be free, while the transmitted packets collide at the receiver that may hear the transmissions from both sources. A reservation based mechanism using request–to–send/clear–to–send (RTS/CTS) packets [4, 3] is commonly used to address this problem. This solution is also adopted in the new IEEE standard 802.11 [5] for wireless LANs. Several other, more recent, protocols also use some form of RTS/CTS exchanges. Examples include FAMA [6], GAMA [13], CARMA [7], etc. However, the RTS and CTS packets themselves are broadcast packets sent using carrier sensing at the sender and can collide at the receiver(s) due to the hidden terminal problem. Even though the RTS and CTS packets are usually short, the problem can be severe at high loads.

Even if RTS/CTS exchanges were free from ill, all packet transmissions in a multihop wireless network cannot solely rely on RTS/CTS exchanges. These include broadcast transmissions frequently used by the dynamic routing protocols. Such transmissions are intended to reach *all* neighbors. For example, broadcast floods are used to update routing tables of all nodes in a portion of the network (e.g., link-state or distance vector protocols [10]) or to discover new or alternate routes (e.g., on-demand protocols [9, 15]). Such transmissions cannot use channel reservation and must depend on a pure CSMA technique [11] for channel access.

Our goal in this paper is to investigate a new multiple–channel CSMA protocol that can reduce the effect of the hidden terminal problem. The protocol selects channels dynamically and employs a "soft" channel reservation. The idea is somewhat similar to frequency-division multiple access (FDMA) schemes used in cellular systems. The major difference is that there is no central infrastructure and thus the channel assignment is done in a distributed fashion via carrier sensing much as in a traditional CSMA scheme. Use of carrier sensing to perform channel assignment also distinguishes it from the traditional *broadcast scheduling* problem [18, 17] in a spatially disperse packet radio network, where channel assignment is performed via a central control or via additional message communication and synchronization. None of them are viable in an ad hoc setting.

2 Multichannel CSMA Protocol

Multiple channel CSMA protocols are not entirely new. They were shown to be more efficient than their single channel counterparts in wired LANs [2]. Packet transmission over multiple random access channels in wireless networks was also explored in [16], where multi-channel slotted ALOHA [1] was analyzed. A multichannel MAC protocol was presented in [8] for application in a class of ad hoc networks termed as *Reconfigurable Wireless Networks*. Some protocols have been proposed for wireless LANs [14, 19] where each host is allowed to transmit in a unique frequency channel. However, there has not been any demonstration of improved throughput of wireless networks by breaking up the available wireless medium into several channels and using a suitable access protocol for reducing the probability of collisions, which is the goal of this paper.

We extend the concept presented in [2] to the wireless scenario to design a new multi-channel CSMA scheme that provides "soft" channel reservation. In [2], it is shown that for a wired LAN with N channels, use of carrier sensing to randomly select one of the idle channels for transmission has a throughput advantage that increases with N. This is attributed to the reduction of the normalized propagation delay per channel, which is defined as the ratio of the propagation time over the packet transmission time. The bandwidth per channel decreases with larger N, thereby decreasing the normalized propagation delay. Hence, the probability of multiple stations sensing the channel to be idle and choosing to transmit at mutually overlapping times, decreases with N. This, in turn, reduces the probability of collisions.

However, wireless networks follow a different mechanics than wired networks. Here, lower channel bandwidth and faster propagation speed typically result in a much smaller normalized propagation delay as compared to wired networks. Collisions, however, occur for a very different reason. Signal strength reduces with distance and thus it is possible that some nodes in the network cannot hear each other sufficiently well, the signal strength being below the carrier–sensing threshold. This causes transmitting nodes to be "hidden" from other transmitting nodes, but still can cause sufficient interference at the receiver for packets to be lost due to collisions. Signal strengths at the transmitter and receiver being different, the transmitter is never in a position to detect collisions. In addition, the combination of even weak signals from many transmitters can raise the overall interference high enough to cause collisions. One of our goals in the paper is to demonstrate that in spite of these differences, multichannel CSMA protocols can reduce collisions significantly in wireless networks, *albeit* for a different reason than wired nets. We also design a new mechanism to do channel reservation, which provides additional benefits.

Our scheme breaks up the total available bandwidth into N non–overlapping channels, where N may be much smaller than the number of hosts. The channels may be created in the frequency domain (FDMA) or code domain (CDMA), though we will use frequency domain in our description in this paper. Due to the absence of network-wide synchronization in such networks, we assume that TDMA is not used. The radio transmitter and receiver at every host are assumed to be able to operate in any one of these channels. Note that each channel has a bandwidth of W/N, where W is the total available bandwidth for communication. Typically, a transmitter tries to reuse the channel it used in its last successful transmission. In case this "reserved" channel is busy (determined by carrier sensing) or the most recently used channel resulted in an unsuccessful transmission, another free channel is selected at random. A back-off and retry strategy is employed in case there is no free channel.

The detailed protocol operations are now described. The protocol is described as a multichannel variation of the basic CSMA/CA (CSMA with collision avoidance) protocol used in the IEEE 802.11 standard [5] for wireless LANs.

1. Each node monitors the N channels continuously, whenever it is not transmitting. It detects whether or not the total received signal strength (TRSS) in the channels are above or below its sensing threshold (ST). The channels for which the TRSS is below the ST, are marked as IDLE. The time at which the TRSS dropped below ST is noted for each channel. These channels are put on a `free_channel` list. The rest of the channels are marked as BUSY.

2. At the start of a protocol cycle, i.e., when a packet arrives from the traffic generator:

   (a) If the `free_channel` list is empty, the node waits for the first channel to be IDLE. Then it waits for a period called the Long Interframe Space (LongIFS), and it waits further for a random access backoff period before transmitting the packet. It is required that the channel remains IDLE during this period.

   (b) If the `free_channel` list is not empty, the node checks if the channel that it used successfully in the most recent past, `last_channel`, is included in the list. If the `last_channel` is IDLE, then the node chooses this channel for data transmission in the current protocol cycle. Else, the node randomly selects a channel from the `free_channel` list using a uniform random number generator.

3. Before actually transmitting the packet the node checks to see whether the TRSS on the chosen channel has remained below ST for at least a LongIFS period.

   (a) If not, the node initiates a backoff delay after the LongIFS.

   (b) If yes, then the node initiates transmission immediately, without further delay.

4. Any backoff is canceled immediately if the TRSS on the chosen channel goes above the ST at any time during the backoff period. When TRSS again goes below ST a new backoff delay is scheduled.

5. After the end of a successful transmission (as indicated by an acknowledgement) `last_channel` is set to the channel used. Else `last_channel` is undefined and a random channel will be chosen from the `free_channel` list for the retransmission.

When the number of channels, N, is sufficiently large, the above protocol tends to "reserve" a channel for data transmission for every node. This channel reservation technique minimizes occasions when two contending transmissions happen to choose the same channel. On the other hand, the flexible nature of soft reservation allows for using other free channels. It is expected that hosts will tend to dynamically select free channels in a mutually exclusive fashion so as to enable parallel, interference–free transmission. Even in heavy traffic conditions, when the number of channels may not be sufficient for conflict–free transmissions, the chance of collisions will be reduced because of persistence of every node to use a "reserved" channel for itself.

3 Simulation Model

We developed an event driven simulator particularly suited for MAC layer performance evaluations for wireless networks. The simulator uses a network of n^2 wireless nodes, placed in a $n \times n$ square grid. In the data we present, the nodes are stationary. Traffic is Poisson with a random source node with a randomly chosen destination located within its radio range. The radio range is determined using the transmitter power, a propagation or path loss model and the signal sensing threshold (ST). An indoor propagation model is used to evaluate the path loss between a given pair of nodes. It uses a piecewise log-log function in which the dB path loss is assumed to vary linearly with the log of the distance between the source and the destination. Multipath fading is simulated as a separate loss component, generated randomly for each packet transmission and is assumed to remain constant for the duration of the packet.

Each time a node commences or ends transmition, the simulator evaluates the received signal strength (RSS) in the chosen channel at each node location. Two components of the RSS are computed at each non-transmitting node for every channel: (a) the strength of the desired signal, and (b) the total signal strength (obtained by summing the RSS contributions from all nodes currently transmitting packets in that channel). From the two basic RSS components, an interference RSS component is computed as the difference between the total and desired signal strengths. The desired RSS and the interference RSS yield a signal-to-interference ratio (SIR). The SIR is recomputed for every receiving node every time there is a change in the RSS on the corresponding channel. A packet is assumed to be received correctly, whenever the SIR stays above the specified minimum SIR threshold for the *entire* duration of the packet. This essentially implements a "power capture" model.

In our experiments, we considered two types of receiver operations. In the first, the receiver is assumed to be able to receive only one packet at a time. This receiver, which we will call the *single user* (SU) receiver, receives only the first incoming packet, subject to the usual capture model, and drops any overlapping packet. In the second type, we assume a *multiuser* (MU) receiver, which can receive multiple packets simultaneously as long as they are received on separate channels and each meet the power capture constraints. Multiuser receivers have been studied extensively for CDMA in [12].

4 Simulation Results

We ran simulations to measure the throughput in the network. Separate runs were done for different number of channels, all with the same total bandwidth W. The parameters used for the simulation are shown in Table 1.

With these parameters, the maximum number of neighbors (nodes that are within transmission range) for any node in the network is found to be 13. Throughput curves were obtained for both the single user and multiuser receiver models using the multichannel CSMA protocol with soft reservation for N=1, 5, 10, and 20 channels. These are shown in Fig. 1. Also plotted in Fig. 1 are the throughput curves for a multichannel CSMA protocol *without* channel reservation, where the source simply picks a channel at *random* from the set of idle channels. Note that for the single-user receiver with channel reservation, the throughput increases from N=1 to N=5. The improvement is negligible for more channels. With the multiuser receiver with channel reservation, the throughput increases through 20 channels. As expected, the throughput for the multiuser receiver is higher than that for the single-user receiver for the same number of channels.

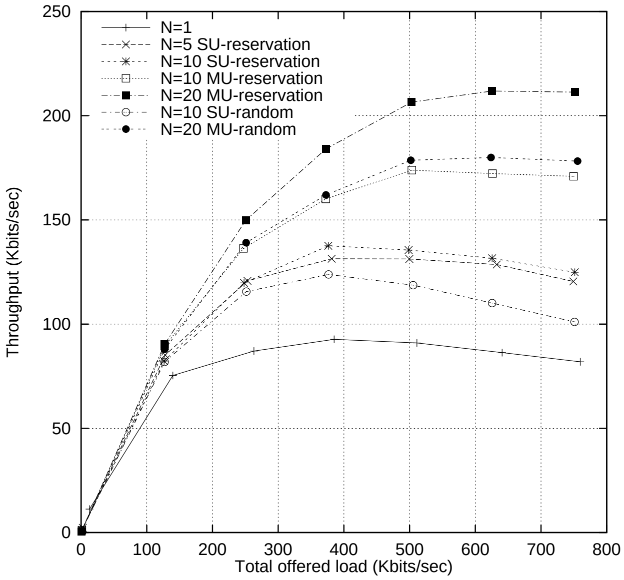

Figure 1: Throughput performance of a 225 node network configuration with parameters as given in Table 1.

The throughput with multichannel CSMA using the random channel selection scheme is also better than that of the single channel scheme. However the performance is poorer than the multichannel schemes using "soft" channel reservation. This shows the benefit of channel reservation.

Fig. 2 gives further insight into the performance of the multichannel MAC protocols by showing the breakdown of

Table 1: Parameters used for the simulations in Fig. 1

Parameter	Values used
No. of nodes	225
Grid size	200 m
Transmitter power	35 dBm
Signal sense threshold (ST)	10 dBm
Minimum SIR	10 dBm
Packet size	5000 bytes
Long IFS	40 μsec
Total bandwidth	1 Mb/sec

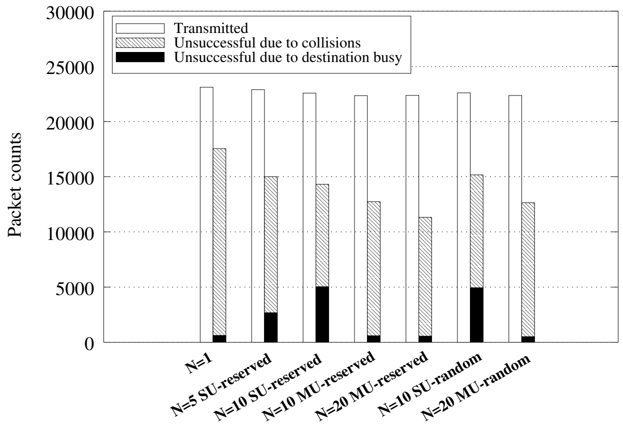

Figure 2: Packet counts for the 4th simulation points of the plots in Figure 1.

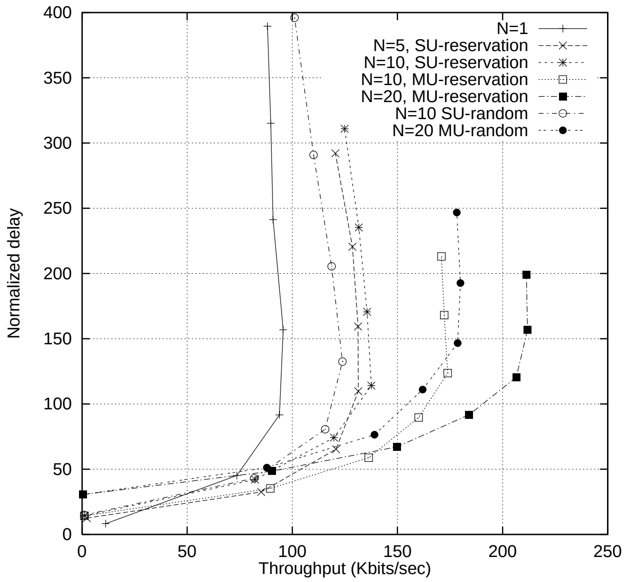

Figure 3: Delays of the MAC protocols considered in Fig. 1, normalized to the transmission time of a packet over a single channel. The average normalized retransmission delay δ is taken as 50.

all packets transmitted. This data correspond to middle points from Fig. 1. The total number of "unsuccessful" transmissions is largest for the case N=1 and decreases successively from left to right for the protocols with channel reservation. Packet transmissions are unsuccessful due to primarily two reasons - the "destination busy" situation, and due to "collisions". A single user receiver is busy whenever it is transmitting or receiving a packet on any channel. A multiuser receivers is unavailable only when it is currently transmitting or receiving on the same channel on which the new incoming packet is transmitted. "Collisions" occur when the received SIR falls below the required minimum SIR threshold.

Note that with the single user receiver, the number of packets unsuccessful due to the destination busy condition increases with N. This is attributed to the fact that the bandwidth-per-channel decreases with increasing N, causing the nodes to take proportionately longer times for transmission and reception. However, it is important to note that collisions *decrease* with increasing N using the proposed soft reservation protocol. Note that between the cases N=1 and N=5 with reservation, the reduction of collisions is greater than the increase in unsuccessful transmissions due to a busy destination. This benefit is lost, however, beyond $N = 5$. On the other hand, since the multiuser receiver can receive multiple packets concurrently, it loses fewer packets due to the destination busy condition. With random channel selection, collision counts are higher than that with channel reservation. This is due to the situations where hidden transmitters are choosing the same idle channel in the absence of any reservation. This possibility is reduced with channel reservation.

We next estimate the average packet transmission delay using the multichannel CSMA protocol. In our simulations, acknowledgements of successful packet reception and retransmission of unsuccessful packets is not yet implemented. Thus, we evaluate the average delay in successful packet transmission by following the ideas presented in [11]. The average packet delay D, normalized to the time for transmission of one packet using the whole bandwidth, is determined from

$$D = (G/S - 1) \times R + N + a \tag{1}$$

where G is the offered load, S is the corresponding throughput, R is the normalized average delay between successive retransmissions, and a is the normalized propagation time. R depends on the packet transmission time, the round trip propagation delay between the source and the destination, the transmission time of the acknowledgement packet (α), and the average retransmission delay (δ). Hence

$$R = N + 2a + \alpha + \delta \tag{2}$$

For our scenario we assume a to be negligibly small and exclude it from our calculations. Also, for simplicity we assume that the acknowledgement packets are much smaller than the data packets and that they are sent over an ideal channel with negligible delay. Hence, we use $R = N + \delta$, where we consider a fixed average retransmission delay for all N to assess the performance of the multichannel protocols. Using the offered load (G) and corresponding throughputs (S) from in Fig 1, we use Eq. 1 to derive the average transmission delays for each protocol. These are shown in Fig. 4. Note that the average delay is higher for the multichannel protocols at low traffic loads. This is due to the smaller bandwidth per channel with higher N. However, the delay is lower at high traffic loads, as the number of retransmissions is smaller compared to the single channel case.

5 Conclusions

We have demonstrated that distinct advantages in throughput can be gained in a CSMA protocol by segregating the available bandwidth into multiple channels, and using the carrier sense information for selecting idle channels with a "soft" channel reservation. This reservation based scheme performs better than a multichannel scheme with random selection of idle channels. This performance advantage is in spite of the lower per channel bandwidth. However, a large number of channels may cause an unacceptably high packet transmission time. This in turn affects the throughput for single user receivers and the average delays for both single and multiuser receivers. Our simulation shows that a handful of channels works very well. Our future work will focus on more elaborate performance evaluation with a focus on the determination of the optimal number of channels.

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