A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks

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Abstract- **In this paper, we propose a CSMA-based medium access control protocol for multihop wireless networks that uses multiple channels and a dynamic channel selection method. The proposed protocol uses one control channel and N data channels, where N is independent of the number of nodes in the network. The source uses an exchange of control packets on the control channel to decide on the best channel to send the data packet on. Channel selection is based on maximizing the signal-to-interference plus noise ratio at the receiver. We present performance evaluations obtained from simulations that demonstrate the effectiveness of the proposed protocol.**

1 INTRODUCTION

A multihop wireless network (also called ad hoc network [10]) is a collection of mobile data terminals (nodes) equipped with wireless transceivers that form an autonomous network without the help of any fixed networking infrastructure. A node can transmit data packets to other nodes who are within its radio range. In order to transmit packets to a node outside the range, the network uses a multihop store-and-forward routing. Such networks received considerable attention in recent years in both commercial and military applications due to its attractive properties of building a network on the fly and not requiring any pre-planned infrastructure such as base stations or a central controller.

In an ad hoc network nodes transmit packets in an unsynchronized fashion. The medium access control (MAC) protocol [5] is responsible for coordinating access to the shared radio channel minimizing conflicts. However, the design of random channel access schemes is a considerably more difficult task in wireless than in wireline networks. This is due to the fact that in the wireless medium, the signal strength decays with distance causing the medium characteristics to be highly location-dependent. Hence, traditional "listen-before-transmit" mechanisms such as CSMA (carrier-sense multiple access) [7] does not work very well as the channel state might be different at the receiver from what is estimated at the transmitter. This gives rise to the so-called "hidden terminal problem" [13], where two nodes that do not hear each other transmit packets to a common receiver, and packets collide at the receiver.

To overcome this problem, random channel access protocols in wireless LANs often use channel reservation techniques by exchanging short "request-to-send" (RTS) and "clear-to-send" (CTS) control packets before the data packet is sent [6]. This effectively performs a "virtual carrier sensing" at the receiver by letting the sender know whether the channel state at the receiver is conducive for packet reception. In addition, the channel is temporarily reserved for the data packet transmission since neighbors of the receiver who receive the CTS may defer transmission at least for the duration of data transmission. The duration can be included in the RTS/CTS packets. IEEE Standard 802.11 for wireless LAN [3] essentially uses this handshaking technique for asynchronous data transfer (called the *distributed coordination function* or DCF). The standard, however, augments this technique with an ACK packet to be transmitted from the receiver back to the sender at the end of the data packet – following on the idea from [1]. In addition to the RTS-CTS-data-ACK handshake, the 802.11 DCF employs a carrier-sense multiple access with collision avoidance (CSMA/CA) technique. The idea here is that the channel is always sensed before any transmission. If the channel is sensed busy, the sender waits until the channel is idle and then goes through a random backoff period before retrying. The random backoff period ensures fairness among contending transmissions.

The above access protocol on a single channel is prone to inefficiencies at heavy loads, since with increasing traffic there is a higher wastage of bandwidth from collisions and backoffs. Collisions can occur among the control packets (such as RTS and CTS). And since backoff delays are unsynchronized, medium can be idle if all contending nodes are in backoff. In addition, any node hearing RTS or CTS must defer at least until the end of the entire exchange (i.e., until end of ACK). This means that concurrent transmissions cannot take place when two senders hear each other, even though the respective receivers do not hear any node other than their respective senders (the so called "exposed terminal problem"). This is because each sender need to be able to receive control packets (CTS and ACK) correctly, which may see interference from the data packet from the

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other sender.

The rest of the paper is organized as follows. In section 2, we explain the motivation behind multichannel CSMA protocols. In section 3, our multichannel protocol with receiver-based channel selection is described. Section 4 presents simulation results. Section 5 describes related work. Conclusions are presented in section 6.

2 MOTIVATING MULTICHANNEL PROTOCOLS

The use of multiple channels may provide some performance advantages in reducing collisions and enabling more concurrent transmissions and thus better bandwidth usage even with the same aggregate capacity. Multichannel protocols allow a number of nodes in the same neighborhood to transmit concurrently on different channels without interfering with one another. Carrier sensing can be coupled with an efficient channel selection mechanism to pick the clearest channel for transmission. If multiple channels are formed on the basis of multiple CDMA codes, a receiver may also receive multiple signals from different sources at the same time. Due to these advantages, a number of multichannel MAC protocols have been explored for multihop wireless networks (see the related work in section 5). Based on the way multiple channels are used, these protocols may be broadly classified into two classes. The first class assumes a separate channel for every node in the network, formed on the basis of individual CDMA codes. Transmissions may be transmitter-oriented (in which each node transmits using its own code) or receiver-oriented (in which all transmissions made to the same receiver use the same code). The second class of multichannel protocols do not assume dedicated channels for every node. Instead, the available bandwidth is assumed to be divided into a number of channels whose number is smaller than the number of nodes. A node may transmit and receive on any channel. There are some advantages of using a smaller number of shared channels over unique channels for every node in the mobile ad hoc network. For example, this does not require every node to know the whole set of codes used in the network that can increase the design complexity significantly.

In this paper, we propose a new multichannel MAC protocol that belongs to the second class of protocols described above. The available bandwidth is divided into one control channel and a predefined number of data channels which is fewer than the number of nodes. The idea is to isolate the control packets from data in the wireless medium and exploit spatial reuse of the data channels with a MAC protocol that employs distributed channel selection. We propose a new channel selection mechanism by which a sender uses an RTS-CTS dialog with the receiver to select a channel for sending the data packet. The clearest channel is chosen based on the interference power sensed at the receiver. The main objective of the protocol is to distribute the packet transmissions over time and channels so as to maximize bandwidth utilization. We derive the optimum bandwidth partition between the control and traffic channels and also the optimum number of channels to maximize the aggregate throughput. Performance evaluations of the proposed MAC protocol are presented using extensive computer simulations.

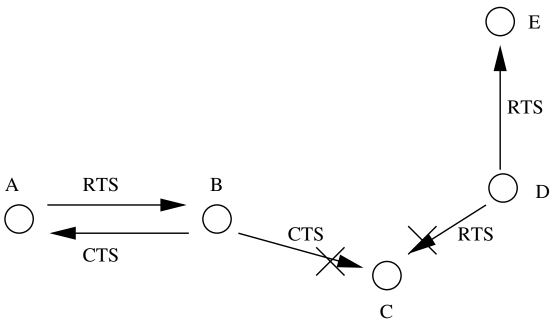


Figure 1: Example situation where a hidden terminal **C** misses the CTS packet from **B** due to collision with an RTS packet from **D**. This makes **C** unaware of the transmission from **A** to **B**.

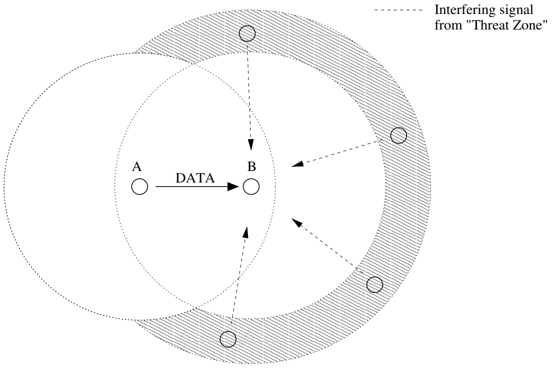


Figure 2: Illustration of the "threat zone" for the receiver **B** which is receiving a data packet from **A**. Several transmissions from nodes lying in the shaded area can tip the total interference power at **B** over the acceptable limit, and prevent capture of packet from **A**.

2.1 Some Preliminaries

As mentioned above, RTS-CTS based handshaking protocol is able to avoid hidden terminal problems at low load by sensing the carrier at the receiver. However, this scheme, suffers from problems at high loads. First, the RTS packets themselves are prone to the hidden terminal problem. Even though these packets are small, collisions do occur at high load, and delay is introduced by the successive retry attempts each after a longer backoff. Thus, the channel access efficiency for the control packets is also an important concern. Second, various factors can cause a hidden terminal to fail to receive a CTS packet correctly. This may result in a collision between the data packet and an RTS packet from the hidden terminal. For instance, the CTS packet may not be received by a hidden terminal due to a collision with another RTS packet (see Figure 1). This may also happen if a node that is just outside the radio range of a receiver during the CTS transmission, moves within range while the receiver is receiving the data packet. Lastly, and perhaps most importantly, in wireless networks there is a "threat zone" consisting of a region just outside the nominal radio range of a receiver from where other transmissions can largely affect its packet reception even though they are out of range. Nodes lying in the "threat zone" will not be able to detect the CTS from the receiver but will contribute to the interference power at the receiver. Hence, as shown in Figure 2, if a significant number of nodes in the shaded region start transmitting while **B** is receiving the data packet, then the combined interference can add up to disrupt its reception.

We propose a multichannel MAC protocol that addresses these problems. For convenience, our protocol augments the 802.11 DCF using the following channel structure:

1. A separate channel is maintained for transmission of control packets. This channel is shared by all nodes for transmitting RTS and CTS packets. Since these packets rely on CSMA alone and are prone to the hidden terminal problems, use of a separate control channel will eliminate the probability of interference between control and data packets. An appropriately chosen bandwidth for the control channel can minimize collisions amongst control packets.
2. The remaining bandwidth (which will be the major part) is divided into N traffic channels to be used for data packets only. A node can transmit and receive on any of these channels. Assuming that traffic is equally distributed in these channels, there will always be a *best* channel for receiving a data packet at the receiver. This will be the channel in which the signal to interference-plus-noise ratio (SINR) at the receiver is expected to be the maximum, i.e. the clearest channel at the receiver before data transmission. The receiver informs the sender about its channel selection via the CTS packet. The optimum number of traffic channels may depend on the network environment such as connectivity density and traffic.

The remainder of this paper is organized as follows. We describe the details of the proposed multichannel MAC protocol with receiver-based channel selection (RBCS) in section 3. In section 4, we evaluate the performance of RBCS in comparison with IEEE 802.11 DCF MAC using a detailed simulation in *ns-2* [4]. Finally, in section 5, we discuss some related work followed by concluding remarks in section 6.

3 PROTOCOL DESCRIPTION

Before we describe the protocol, we summarized our assumptions:

- The total available bandwidth W is divided into $N+1$ non-overlapping frequency bands, one control channel and the rest data channels.
- The bandwidth of the control channel, W_c, is determined off-line and fixed. Each of the data channels has a bandwidth of $\frac{W-W_c}{N}$.
- Nodes can simultaneously sense carrier on all the channel for incoming transmissions.
- Nodes are equipped with half-duplex radios, so that they can either receive or transmit at a time but not both.
- Nodes can transmit and receive on all channels. However, at a given time, only one packet can be transmitted on any channel. But, multiple packets can be received at different channels at the same time.

We now describe the proposed multichannel MAC protocol with receiver-based channel selection (RBCS). Since this is an extension of the RTS-CTS-data-ACK based control handshaking in IEEE standard 802.11, we only emphasize the multichannel RBCS aspects. The rest of the protocol operations is identical — such as channel sensing, interframe gaps, random backoff procedures etc.

1. When a node has a packet to send, it transmits a RTS packet to the receiving node in the control channel.
    (a) Before transmitting RTS, the sender senses the carrier on all the data channels and builds a list of free data channels available for transmission. Free channels are those for which the total received power is below carrier-sensing threshold. This list is embedded in the RTS packet of the sending node.
    (b) If the free-channel list is empty, the node enters backoff and re-attempts transmission of the RTS packet after the expiry of backoff.
    (c) Unlike 802.11, other nodes receiving the RTS on the control channel defer their transmissions only until the duration of CTS and *not* until the duration of ACK. This is because data and ACK are transmitted in a data channel and cannot interfere with other RTS/CTS transmissions. This encourages more parallel transmissions.
2. Upon successful reception of this RTS packet, but before actually transmitting the CTS packet, the destination node creates its own free-channel list by sensing the carrier on all data channels. It then compares this free-channel list with that contained in the RTS packet.
    (a) If there are free channels in common, the destination selects the *best* common channel as the channel with the least received power according to its own sensing and sends this channel information in the CTS packet.

   (b) If no common free channels are available, the destination refrains from sending a CTS. The source then times out and retries after back off.

3. When the sending node receives the CTS packet, it transmits the data packet on the data channel indicated in the CTS. Thus, the data is transmitted on a channel that is free on both sender and receiver, and also the clearest at the receiver.
4. Other nodes in the vicinity of the destination node, upon receiving the CTS packet on the control channel, refrain from transmitting on the data channel indicated in the CTS for the duration of the entire transfer (including ACK). Until such time, this data channel is not considered free regardless of its received power level.
5. If the destination successfully receives the data packet on the data channel, it transmits an ACK packet on the same data channel. If the source fails to receive an ACK, it times out and enters back off.

4 PERFORMANCE EVALUATION

In this section we present simulation results comparing performance of the original 802.11 DCF single channel protocol and its multi-channel RBCS counterpart as presented above. These include the throughput and delay performance, and evaluation of the optimum bandwidth of the control channel (W_c), and the optimum number (N) of data channels.

4.1 Simulation Model

All the results are based on simulations using a modified version of the *ns-2* network simulator from USC/ISI/LBNL [4], with wireless extensions from the CMU Monarch project [2, 11]. The extensions provide a wireless protocol stack with a complete implementation of the IEEE 802.11 standard and a two-ray ground reflection radio propagation model. The radio interface model approximates the first generation WaveLan radio interface [15] with a 2Mbps nominal bit rate and a nominal transmission range of 250 meters using an omnidirectional antenna.

In our experiments, we have considered the wireless medium to be noiseless and error-free. Thus the packet losses are either due to collisions at the destination caused by other interfering transmissions or because the destination is not available for receiving the transmitted packet (i.e., it is already in transmit mode). The simulation model also implements a "power capture" model, where a receiver can successfully receive one packet even when there are competing transmissions being heard. If the signal power of any one packet is sufficiently exceeds the sum of the others, this packet may be captured and the rest counted as collisions.

We used two different stationary network models in our simulations. The first model consists of 100 nodes arranged in a 10 × 10 grid (see Figure 3), with a grid spacing of 175 meters. The second model consists of 225 nodes placed in a 15 × 15 grid with grid spacing of 125 meters. We also consider a mobile network model, which consists of 100 mobile nodes in a 2500m × 2500m area. The nodes move independently of one another, with random speeds that are uniformly distributed between 0-20 m/s. The mobility pattern is based on the *random waypoint* model [2]. Here, each node is always moving towards a randomly chosen destination point in the network. After reaching this location, the node pauses for a fixed *pause time* before moving again to a different location. Note that small pause times then indicates more mobile networks.

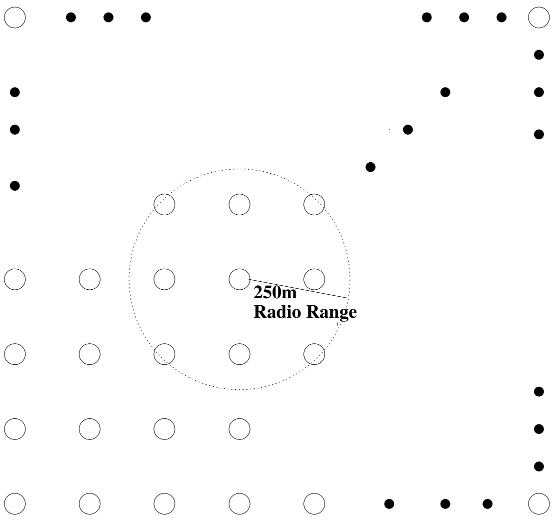
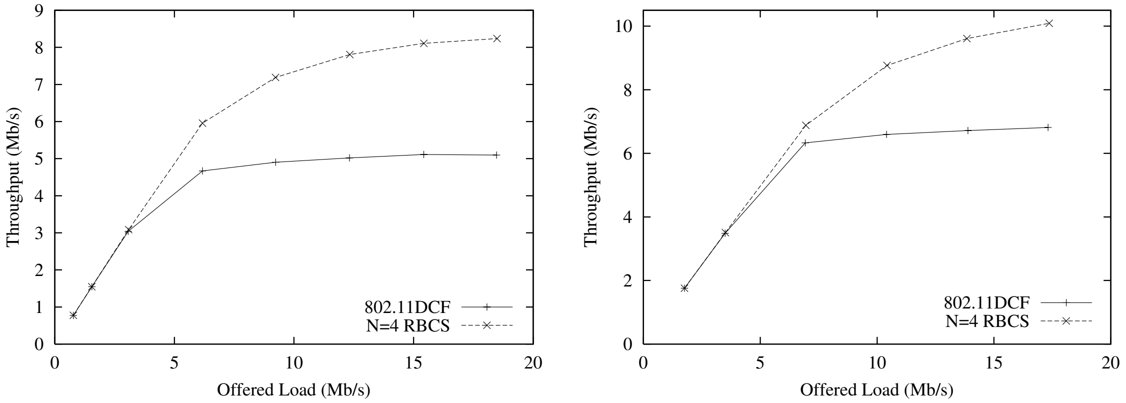


Figure 3: Grid network of 100 nodes, 10x10 grid with 175m grid size

For all network models, traffic is generated according to independent Poisson processes at every node with identical mean arrival rates which is varied to change the offered load. A neighboring node (within radio range) is chosen randomly as the receiver. The results using the mobile network model are based on the average of three different randomly generated mobility scenarios. For all simulations, a fixed packet size of 1.5KB is used. All simulations are run for a duration of simulated 500 seconds.

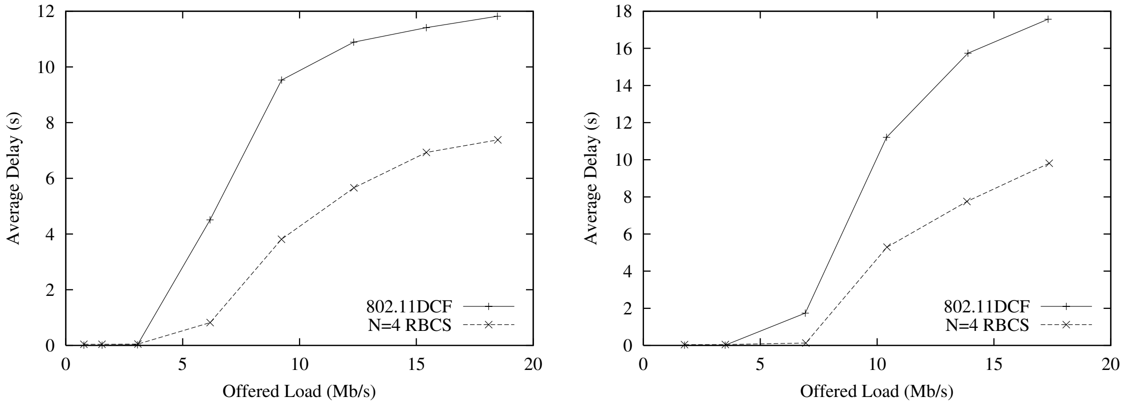
4.2 Throughput and Delay Performance in Static Network

First, we compare the throughput and delay performance of multi-channel RBCS against single channel 802.11 on the static grid models. Figure 4(a) and (b) show how throughput varies with increasing offered load for the two MAC protocols. Offered load is measured by the aggregate data generated by the applications in Mb/s over all nodes. The corresponding throughput refers to the total amount of data that is successfully delivered in Mb/s. Results show an improvement of up to 50% by using the proposed RBCS



(a) 100 nodes

(b) 225 nodes



(c) 100 nodes

(d) 225 nodes

Figure 4: Throughput and average packet delay of RBCS and IEEE 802.11 DCF for static grid networks.

MAC over 802.11. This is more significant at heavy load conditions when the contention for the channel is high.

In Figure 4 (c) and (d), we plot the average packet transmission delay experienced in the two static network models. Note that the use of multiple channels increases the individual packet transmission times as the bandwidth per channel is inversely related to the number of channels. However, the average packet delay is still significantly smaller in multichannel as there are fewer packet collisions and hence fewer retransmissions, particularly at high loads. At very small traffic loads, when no retransmissions are necessary, the packet delay using multichannel is higher than that of the IEEE 802.11 DCF because of higher packet transmission times as packet transmission times dominate. This effect is not seen clearly because of the scales used in the plots.

4.3 Control Channel Bandwidth

To derive an optimum bandwidth for the control channel, we perform simulations to obtain the throughput for different fractional bandwidths alloted to the control channel at the same offered load. This is done for each value of N. The results, plotted in Figure 5, indicate that for smaller values of N, a higher fractional bandwidth for the control channel works better. However, the difference between cases with 10 and 20 % bandwidth alloted to the control channel is very small. Hence, for our simulations we have fixed the W_c to be 10% of the total bandwidth W.

4.4 Optimum Number of Channels

Our earlier experience with various multichannel MAC protocols [9, 8] has indicated that with an increasing num-

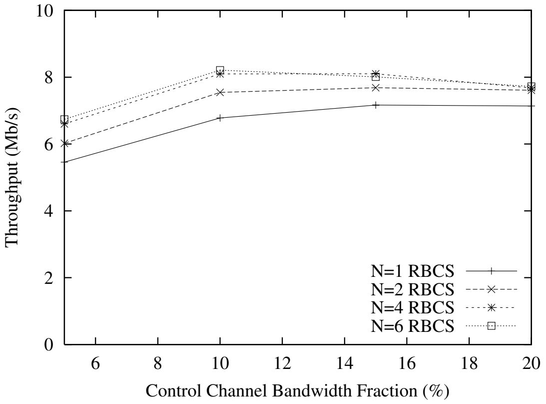


Figure 5: Variation of the peak throughput of an ad hoc network with 100 nodes with different percentage bandwidth alloted to the control channel (W_c/W).

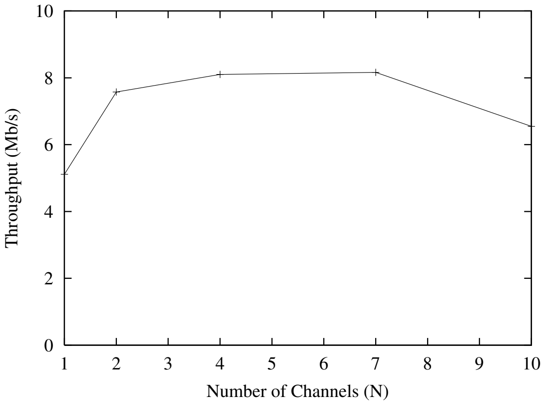


Figure 6: Variation of the peak throughput of an ad hoc network with 100 nodes with the different numbers of channels.

ber of channels there is a trade-off between the reduced level of interference and the frequency of unsuccessful transmission because of the receiver being busy. With increasing number of channels the packet transmission times increase and hence nodes are found to be busy more often. This implies that for a given set of network parameters, there is an optimum value of N which gives the maximum gain in the overall throughput. Figure 6 illustrates the variation of the peak throughput of the network with N. For the static network model of 100 nodes, the best performance with the RBCS protocol is achieved with 4 to 7 channels.

Note also that our simulation model currently considers an idealized system. The problem of cross-channel intereference has been ignored. In reality, some bandwidth will be wasted in provisioning guard bands between channels, and such wastage will increase with the number of channels.

4.5 Effect of Mobility

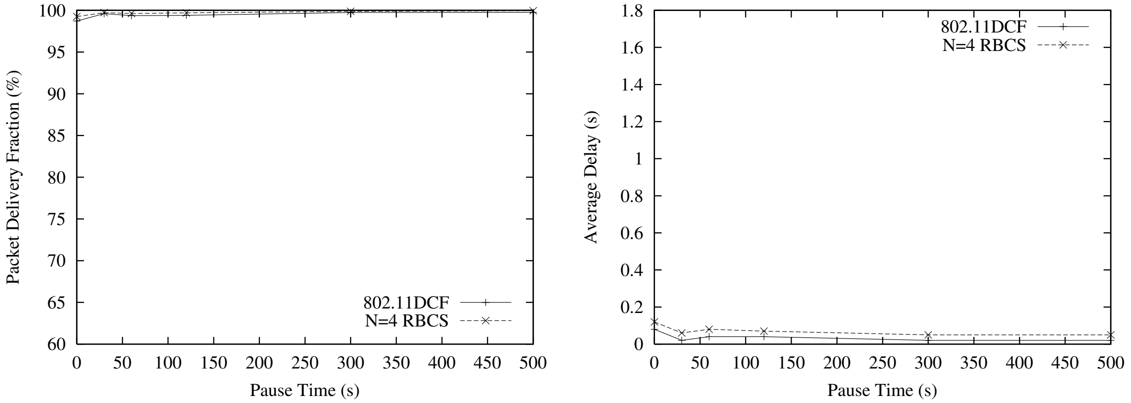
Finally, we demonstrate the effect of introducing mobility in the network which makes the situation somewhat more challenging for channel access. In Figure 7, we compare the packet delivery fraction and packet delay of RBCS and 802.11 DCF at low, medium, and high offered loads. We note that the average packet delay is higher for the RBCS protocol, possibly due to the higher packet transmission times and a small number of retransmissions required under the prevailing network conditions. We note here that in our chosen model, a node can transmit in only one channel at a time. Thus, the multichannel protocol is inherently at a disadvantage as any node always transmits with a much lower bit rate compared to the single channel protocol. If we use radios capable of transmitting on multiple channels concurrently (similar to ADSL modems using multicarrier modulations), then this delay disadvantage will go away. This is a topic of our future work. Observe however, that the packet delivery fraction remains higher for RBCS against 802.11 DCF because of the inherent property of RBCS to avoid collisions.

5 RELATED WORK

The benefits of using multiple channels and distributed channel selection methods in wireless random access was previously presented by Nasipuri et al. in [9], where a "soft" channel reservation protocol was studied. The protocol gave preference to the channel that was used for the last successful transmission. In a more recent work, Nasipuri and Das [8] extended the idea of multichannel CSMA by using interference power measurements on various channels on the sender side as the selection criteria. In both the papers, the authors have evaluated the multichannel MAC over the basic CSMA protocol for only "static" networks. RTS-CTS handshaking was not studied.

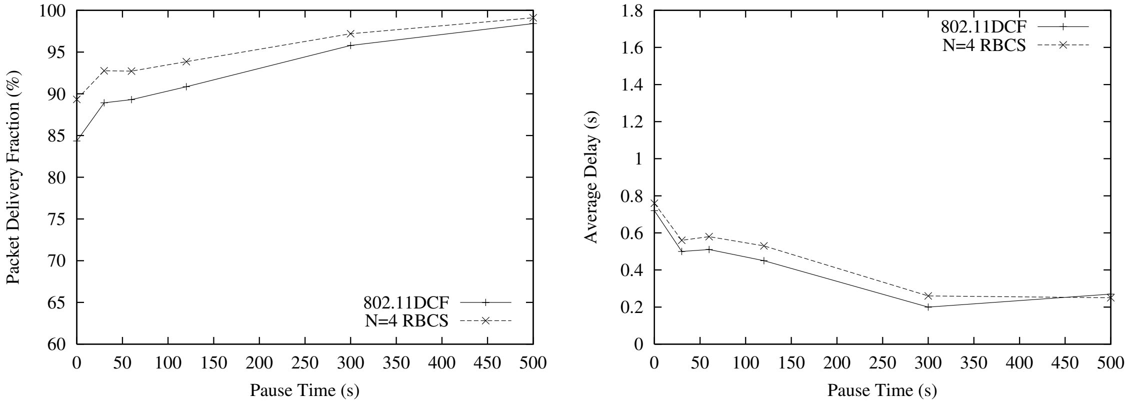
The use of a separate control channel has been studied in [12, 14]. In [12] the authors used unique spreading codes for each node. The identity of the receiver is communicated to a sender through the CTS on the common control channel. Tseng et al. studied a multichannel MAC protocol with a common pool of data channels and one control channel [14]. Their channel selection was based on a randomly selected channel from the set of channels that are free both at the source and the receiving nodes. The destination informs the source about the channel selection using the CTS packet and the source broadcasts another reservation packet to inform all its neighbors about the selected channel.

Compared to the above, our work here attempts to use the best (clearest) channel among the set of traffic channels that are free both at the source and the receiver nodes. This is the channel where packet loss is least likely to occur due to collision. Also, the use of a separate control channel eliminates interference between data and control packets and often shorter defer periods.



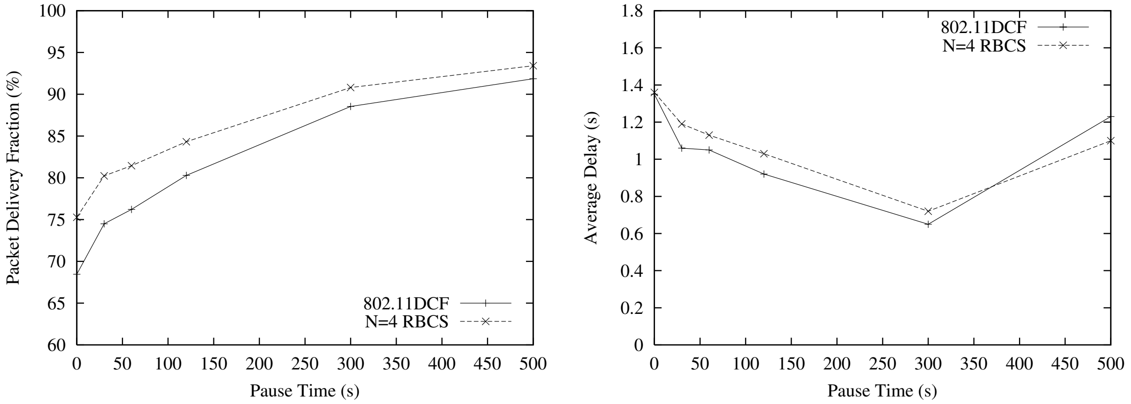
(a) 100 nodes, low load (4 pkt/s)

(b) 100 nodes, low load (4 pkt/s)



(c) 100 nodes, medium load (6 pkt/s)

(d) 100 nodes, medium load (6 pkt/s)



(e) 100 nodes, high load (8 pkt/s)

(f) 100 nodes, high load (8 pkt/s)

Figure 7: Packet delivery fraction and average delay comparision of RBCS with IEEE 802.11 DCF for 100 nodes mobile network.

6 CONCLUSIONS

We have presented a multichannel MAC protocol with a receiver-based channel selection (RBCS) mechanism for wireless multihop networks. By the use of short reservation packets over the control channel, RBCS makes use of the receiver-side channel state information to select the best channel at the sender, that reduce collisions at the receiver. Using a detailed simulation model in *ns-2*, we have evaluated the performance of the multichannel RBCS MAC in comparision with the IEEE 802.11 DCF. The multichannel RBCS is implemented as an extension of 802.11 for a fairer comparison. Simulation results demonstrate performance improvements for the multichannel protocol both in terms of lower delay and higher throughput in static grid networks where possibility of interference from hidden terminals are high. In dense mobile networks we still observe improvements in delivery fraction that translates to throughput improvements. However, there is a slight degradation in delay performance due to higher packet transmission times in multichannel. We expect that this degradation can be removed by transmitting multiple packets at multiple channels at the same time. We will explore this option in the future.

7 ACKNOWLEDGMENTS

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