Performance of multichannel wireless ad hoc networks

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Abstract: This paper addresses the design of Medium Access Control (MAC) protocols for wireless ad hoc networks that derive benefits from using multiple orthogonal channels for data transmission. Each node is assumed to have a single half-duplex transceiver that can dynamically select the best channel for transmitting data. We show that even with the same total bandwidth, multichannel MAC protocols can improve the throughput due to two factors – reduction of the number of backoffs during channel access, and increase of the probability of success of transmitted data packets by selecting channels to minimise co-channel interference. We propose multichannel MAC protocols with signal-power based channel selection for achieving these goals and present performance results that show that the proposed protocols can provide significantly higher throughput than that obtained by using the IEEE 802.11 MAC.

Keywords: ad hoc networks; Medium Access Control (MAC); multichannel MAC; dynamic channel selection.

Reference to this paper should be made as follows: Nasipuri, A. and Das, S.R. (2006) 'Performance of multichannel wireless ad hoc networks', *Int. J. Wireless and Mobile Computing*, Vol. 1, Nos. 3/4, pp.191–203.

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1 Introduction

Despite the tremendous amount of research on Medium Access Control (MAC) protocols for ad hoc wireless networks, the network capacity continues to be its primary limitation. The IEEE 802.11 MAC is the most popular established standard for wireless LANs that is applied to these networks (IEEE Standards Department, 1997). Currently, 802.11b compliant network interfaces use a single DS/SSMA channel and one radio per node. To reduce contention amongst a number of users on the shared channel, the 802.11 MAC uses a combination of carrier sensing, random backoffs and an optional channel reservation scheme using an exchange of control packets. Numerous studies have shown that this design has significant disadvantages under heavy traffic, which are exacerbated in dense networks or under situations requiring a number of concurrent transmissions in the same region. The main factors responsible for such performance degradation are the isotropic nature of signal propagation and the exponential path loss characteristics in the wireless medium. Some of the well known problems arising out of these are the hidden terminal and exposed terminal problems, which have been investigated thoroughly (Tobagi and Kleinrock, 1975).

In recent years, a significant amount of attention has been directed to the possibility of improving the throughput by using multiple orthogonal channels that can be shared by all the nodes in the network. Although wireless ad hoc networks do not have centralised control or access points that can perform channel allocation, appropriately designed MAC protocols can allow the transmitting nodes to *dynamically* select distinct channels in the same neighbourhood to reduce the possibility of destructive interference. Several multichannel MAC protocols have been proposed with this objective (Jain et al., 2001; Nasipuri and Das, 2000; So and Vaidya, 2004; Wu et al., 2002; Zheng and Zhang, 2003), which provide significant improvement in the average network throughput in comparison to single channel protocols, even if the same total channel bandwidth is used. Multichannel MAC protocols can also provide a framework to support QoS in ad hoc networks. The study of multichannel MAC protocols is also important from the perspective of resource utilisation in wireless LANs. The physical layer specifications of IEEE 802.11b as well as 802.11a define multiple channels, of which several can be used simultaneously without causing interference to one another. This additional bandwidth is wasted when all transmissions are performed on the same channel. Hence, efficient mechanisms for utilising multiple channels for improving the throughput in mobile ad hoc networks is an important issue.

In this paper, we explore the advantages of performing random access over a set of orthogonal channels, any one of which can be selected for data packet transmission. We show that performance improvement can be achieved even if the same bandwidth is segregated into multiple channels. We then explore a number of dynamic channel selection schemes for multichannel MAC protocols that use signal-power measurements for improving the probability of successful packet transmissions. The primary research contributions of this paper can be summarised as follows:

- We show that segregating a given transmission bandwidth into multiple channels can provide advantages in random channel access due to two reasons. Firstly, the availability of multiple channels reduces the probability of backoffs even when all nodes are using a single transceiver in half-duplex mode. Secondly, the existence of multiple channels provide a mechanism to implement dynamic channel selection algorithms to select the best channel for data transmission, thereby improving the probability of successful reception of transmitted packets.
- We propose multichannel MAC protocols that dynamically select the best amongst a set of free channels based on co-channel interference considerations. We show that the best results are obtained by the channel selection mechanism that tries to maximise the Signal-to-Interference Ratio (SIR) at the intended receiver while maintaining a low SIR at other active receivers in its vicinity.
- We present extensive performance evaluations to illustrate the quantitative merits of using multiple channels and signal-power based dynamic channel selection schemes.

2 Background and motivation

In this section, we motivate our work by presenting some background information on the IEEE 802.11 MAC and discussing the fundamental advantages and concerns of using multiple channels assuming that the total available bandwidth is kept unchanged.

Our approach is to investigate the theoretical advantages of random access using multiple orthogonal wireless channels in a multihop network scenario. Orthogonal channels may be created by frequency, time or code division, however, the implementation is not an issue here. The IEEE 802.11 physical layer standard already has multiple channels defined in all the specifications. For instance, the 802.11b physical layer has 14 CDMA channels of which three (channels 1, 6 and 11) are non-overlapping and may be simultaneously used to carry 11 Mbps of traffic on each (IEEE Standards Department, 1997). Similarly, 802.11a provides eight orthogonal channels at 54 Mbps per channel (IEEE 802.11a Working Group, 1999). Standard-compliant 802.11 wireless LAN radios operate on only one channel at any given time. The additional capacity is intended for infrastructured wireless LANs, where multiple non-overlapping channels can be used by adjacent access points. However, needs for higher end-to-end throughputs in multihop ad hoc networks have led to the interest in using multiple channels within the non-infrastructured or ad hoc networking mode as well. Future implementations of the MAC may allow dynamic channel selection over the existing orthogonal channels to take advantage of the extra bandwidth available in addition to the increased efficiency of multichannel random access protocols that we address in this paper.

2.1 IEEE 802.11 distributed coordination function

The MAC layer specification in 802.11 for non-infrastructured wireless LANs uses a scheme that is known as *Carrier-Sense Multiple Access with Collision Avoidance* (CSMA/CA) with an optional channel reservation scheme that uses a four-way handshake between sending and receiving nodes. These two methods constitute the *Distributed Coordination Function* (DCF), which is designed to provide distributed coordination amongst asynchronous nodes for sharing a common channel for communication.

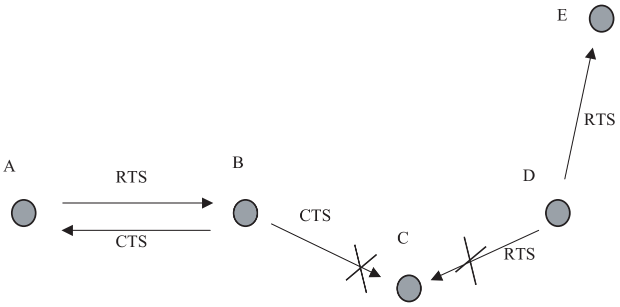
The basic CSMA/CA scheme relies on two techniques to avoid collisions amongst contending nodes: *carrier sensing* and *random backoffs*. Before transmitting a data packet, the sender senses the carrier to determine if the channel is free from other transmissions in its neighbourhood. The data packet is transmitted if the channel is observed to be free for a period of time exceeding a *Distributed Interframe Space* (DIFS). If the channel is found busy, it retransmits the packet after a slotted random backoff period that is counted over the subsequent period of time in which it senses the channel to be free. The backoff period is chosen to be B times a backoff slot duration, where B is an integer that is chosen uniformly in $[0, \mathrm{CW} - 1]$ and CW is the length of the contention window. If a data packet is received correctly, the receiving node transmits an ACK packet after a *Short Interframe Space* (SIFS). If an ACK is not received within the stipulated time period, the sender attempts to transmit the data packet again following the same procedure. Starting with the smallest CW value of $\mathrm{CW}_{\mathrm{min}}$, with every subsequent retry attempt the value of CW is doubled until it reaches the maximum value of $\mathrm{CW}_{\mathrm{max}}$. The parameters $\mathrm{CW}_{\mathrm{min}}$ and $\mathrm{CW}_{\mathrm{max}}$ are specified by the standard, for example, 32 and 1024, respectively, for 802.11 CDMA channels (IEEE Standards Department, 1997). The adaptive backoff period is designed to account for variations of the congestion in the network.

The carrier sensing mechanism relies on comparing the power of the detected carrier signal on the channel to the carrier-sense threshold T_{CS}. To minimise packet collisions due to the hidden terminal problem, it is recommended to use a T_{CS} value for which the carrier sensing range is approximately twice as much as its radio range. However, increasing the carrier sensing range also increases the effect of the exposed terminal problem and essentially reduces spatial reuse of the wireless channel.

The channel reservation option provides an additional mechanism for reducing the hidden terminal problem without having to use a high carrier sensing range. With this option, the sending and receiving nodes exchange two short control packets, known as the *Request-To-Send* (RTS) and the *Clear-To-Send* (CTS) packets, respectively, before initiating a data packet transmission. If the receiver correctly receives the RTS packet, it replies by sending a CTS, thereby confirming that adequate conditions exist for data transmission. This serves as a 'virtual' carrier sensing at the location of the receiver from that at the sender. Neighbouring nodes that receive either the RTS or the CTS or both are required to delay their transmissions for a period of time specified in the corresponding packet. This duration is maintained in a variable known as the *Net Allocation Vector* (NAV) in each node. The duration of silencing period specified by the RTS is equal to the time by which the sender expects to receive the ACK packet and the corresponding duration specified by the CTS packet is the time until which the receiver expects the data packet transmission to be over. This results in the sending and receiving nodes to reserve the channel until the end of data packet transmission cycle.

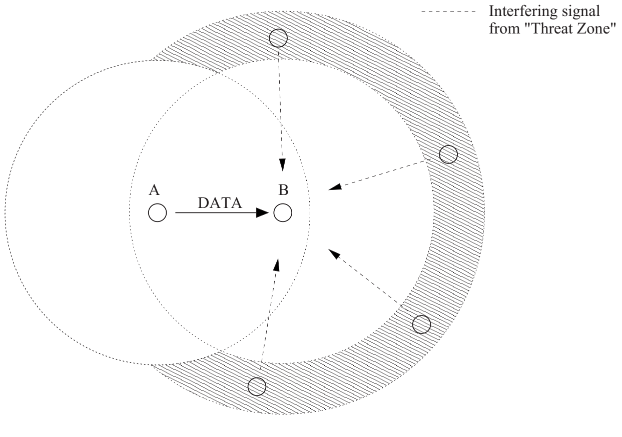
However, the DCF with the RTS/CTS option may still fail to eliminate data packet collisions due to multiple reasons. One reason is the failure in receiving transmitted RTS and CTS packets by a neighbour due to a 'busy' state or collisions with other control packets. An unsuccessfully received control packet by *any* neighbour of two communicating nodes opens up the possibility of loss of the data packet due to a subsequent transmission from the neighbour. This phenomenon is illustrated in Figure 1, where node C fails to receive the CTS packet from B due to a collision with another RTS packet from D and becomes a potential source of destructive interference for the data packet being received by B.

Figure 1 Illustration of scenario where RTS–CTS may not silence transmissions from a hidden terminal



Note that a packet collision in wireless is technically equivalent to the Signal-To-Interference-Plus-Noise Ratio (SINR) of the received packet falling below the minimum SINR threshold ($\mathrm{SINR}_{\mathrm{min}}$) required for correct detection at the receiver. This can occur due to a number of reasons. Wireless networks use frequency reuse, where multiple transmissions occur on the channel simultaneously from sources that are sufficiently far apart. Before initiating any data transmission, the carrier sensing mechanism attempts to make sure that the existing co-channel interference from other transmissions on the channel is safe for the current transmission to be successful. However, once a transmission has started, inaccurate carrier sensing and failure to detect the transmission by a nearby node can cause it to initiate another transmission that can cause the ongoing reception to fail. This can happen even if the interfering node is outside the radio range or the carrier sensing range of the nodes engaged in communication. An illustration of this phenomenon is shown in Figure 2, where the SNR of the data packet received by B from A is greater than $\mathrm{SINR}_{\mathrm{min}}$ initially when all other nodes in the network are silent. However, nodes located in the 'threat zone' marked by the shaded area may not be able to detect this data transmission, since they are outside receiving distance of B and hence, would not have received the CTS packet from B. If any of these nodes start transmitting during the packet transmission from A to B, the *total SINR of the packet* being received by B may fall below $SINR_{\mathrm{min}}$ causing the packet to be decoded incorrectly. Such packet loss due to interference can occur frequently due to the combined interference from a large number of out-of-range transmissions at a receiver.

Figure 2 Illustrations of packet loss due to out-of-range transmissions



For ease of explanation, we will distinguish between these two causes of packet loss by calling them *primary* (as in Figure 1) and *secondary* (as in Figure 2) collisions, respectively. Primary collisions are caused by transmissions from neighbouring nodes that are within the radio range of the receiver, that is, hidden terminals, whereas secondary collisions are caused by the (collective) interference from transmissions outside the radio range of the receiver.

2.2 Random access with multiple channels

The primary advantage of using multiple channels in a wireless network is that it provides a mechanism for multiple concurrent transmissions amongst independent source-destination pairs in a given region. Consequently, *both primary and secondary collisions may be reduced by spacing out transmissions over channels as well as over time*, thereby introducing an additional dimension for controlling interference.

Although this is intuitive, the advantages of adding dynamic channel selection to a MAC protocol similar to 802.11 DCF requires some extra thought. This is because increasing the number of channels with the same total bandwidth reduces the bandwidth per channel. When N channels are used and the available bandwidth is equally divided amongst all channels, the average number of packets transmitted per channel may be inversely proportional to N but the packet transmission time increases by a factor of N. In the following, we discuss the ramifications of these on the two crucial factors that determine the average throughput of packet transmissions in a multihop wireless network:

1. the probability that a contending node gains access to a channel for transmitting its packet and
2. the probability that the transmitted packet is received correctly.

2.2.1 Probability of channel access

We develop an analytical model for deriving the channel access probability in a CSMA-based wireless packet network using N channels. This analysis is similar to that presented in Kamerman and Whitehead (1994), with the additional consideration of multiple channel transmission. We assume an infinite number of nodes that are uniformly distributed in a given area, where all nodes can hear one another. Packet arrivals are uniformly distributed in the area and is assumed to follow a Poisson process. Let the packet transmission time be normalised to one time unit when $N = 1$. Hence, with N channels, the packet transmission time is N time units. A new packet is transmitted if there is at least one free channel at the time of its arrival. The channel selection mechanism is not an issue for calculating the channel access probability as long as it assigns a unique channel from the set of free channels. In the event that no channels are free, the packet is deferred for transmission at a latter time. We assume that carrier sensing is ideal and all nodes in the area can detect the number of free channels without error. Propagation delays and carrier sensing times are assumed to be zero.

With these, we derive the probability that a randomly chosen *test packet* arriving in the network is transmitted, that is, not deferred. Define:

λ = the rate of total arrivals of packets in the area

λ_t = rate of transmitted packets in the area

$p_d(N)$ = probability that a test packet arriving in the area has to defer

Hence, the rate of transmission of all packets in the area is given by

$$\lambda_t = (1 - p_d(N))\lambda \tag{1}$$

Since the length of a transmitted packet is N time units, the rate of arrival of packets that cause the test packet to defer (i.e. the rate of packet transmission over N time units) is

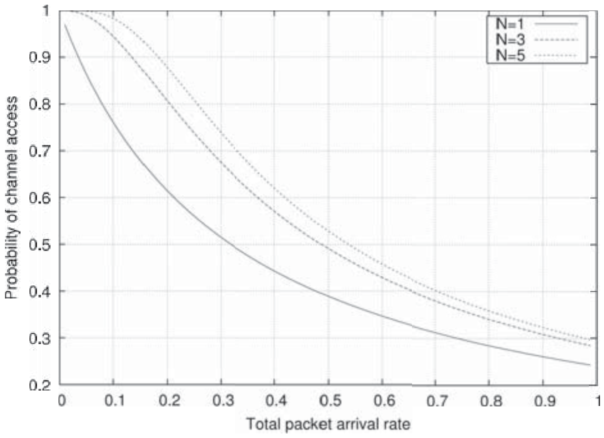
$$\lambda_N = N\lambda_t = N(1 - p_d(N))\lambda \tag{2}$$

The test packet will be deferred if at least N packets are transmitted in the previous N time units, thereby occupying all channels. Hence, under equilibrium conditions, we have

$$\begin{aligned} p_d(N) &= \sum_{i=N}^{\infty} \frac{e^{-\lambda_N}\lambda_N^i}{i!} \\ &= 1 - \sum_{i=0}^{N-1} \frac{e^{-\lambda_N}\lambda_N^i}{i!} \end{aligned} \tag{3}$$

For any chosen N and an arrival rate λ, the probability that a test packet will be deferred $p_d(N)$ may be calculated by numerically solving Equations (2) and (3) together. We plot the probability of transmission of an arriving packet $(1 - p_d(N))$ for $N = 1, 3$ and 5 channels versus total packet arrival rate in Figure 3. The importance of these results is that it indicates that under ideal carrier sensing conditions, the probability of gaining access to any one of N available channels with a fixed aggregate capacity in a CSMA network increases with N. However, the rate of improvement reduces when N gets larger.

Figure 3 Analytical channel access probabilities for 1, 3 and 5 channels in a CSMA network



2.2.2 Probability of successful transmission

The above model represents an idealistic CSMA network with multiple channels that allows us to estimate the gain in channel access probability only. Extending this analysis to evaluate the probability of success of the transmitted packet is complex, as it depends on the locations of the transmitter and the receiver nodes as well as the interfering nodes. Accurate calculation of the probability of success will also depend on the channel selection scheme used in the network. Hence, we discuss the issue qualitatively here and verify them later using discrete-event network simulations.

When all transmissions are performed on the same channel using a random access protocol such as 802.11, the scope of secondary collisions cannot be eliminated. This is because a node that intends to transmit can only detect an ongoing transmission in the network by physically sensing the carrier (which is tested positive when it is within the carrier sensing range of the transmitter) or by correctly receiving an RTS or CTS packet. However, a node located outside the carrier sensing range and hence the radio range, of the transmitter would not be able to detect the transmission. Since secondary collisions occur due to transmissions from outside the radio range of a receiver, single channel MAC protocols suffer from this problem.

The use of multiple channels provide a mechanism for reducing secondary collisions in the following way. Assume that each node can sense the carrier signal strengths on all channels and compare them to determine the channel that is clearest, that is, has the lowest carrier signal-power. Assuming that the wireless channel is symmetrical and isotropic, this would also be the channel on which the nearest node using the channel is located farthest. Hence, choosing the clearest channel for data transmission from a set of free channels reduces the probability of secondary collisions by maintaining the largest margin for accommodating additional co-channel interference. We elaborate on this issue in the next section while describing specific signal-power-based channel selection schemes.

3 Dynamic channel selection schemes

Channel selection based on signal-power measurements can be performed in a number of ways. In this section, we describe several signal-power-based channel selection schemes to improve the probability of success of data transmissions in an ad hoc network. We first state the assumptions that differentiate the conditions under which multichannel MAC protocols can be implemented over that used by the traditional 802.11 standard:

- N non-overlapping data channels are available, of which one is devoted for the transmission of control packets (RTS and CTS) only and the remaining channels are used for transmitting data. The data channels have identical bandwidths, which may be different from that of the control channel. N is assumed to be much smaller than the number of nodes in the network. Typically, it is assumed that $N < 10$, whereas the number of nodes in an ad hoc network may be much higher.
- Each node has a single half-duplex transceiver that can operate on any of the N channels. It is assumed that a node can transmit or receive on only one channel at any given time. In idle state, that is, when not transmitting or receiving data, all nodes continuously monitor the control channel for incoming RTS and CTS packets. When a data packet is to be transmitted or received, the MAC can dynamically select the channel that is to be used by the network interface card.
- Each node is capable of sensing the carriers on all channels. Carrier sensing is performed sequentially over all channels to identify the free and busy channels and also to measure and compare the carrier signal strengths on all the channels. The channel switching time is of the order of a few microseconds (Wu et al., 2002) which is negligible compared to packet transmission times.

We now describe some channel selection schemes based on signal-power measurements.

3.1 Transmitter based channel selection

We first explore a scheme where the channel selection is based on the clearest channel detected at the transmitter. When a node has a packet to transmit, it senses the carrier on all the data channels and ranks all free channels in increasing order of carrier signal strengths. It transmits this ordered *free-channel list* over the RTS packet to the intended receiver. If the receiver receives the RTS, it performs carrier sensing over all the data channels listed in the free-channel list and removes any channel from the list that it finds busy. It then selects the first channel in the free-channel list and sends this information to the transmitter over a CTS packet. Both the RTS and CTS are transmitted over the control channel. The receiver then tunes to the selected data channel and waits for the data packet. Upon receiving the CTS packet, the transmitter initiates data packet transmission over the selected data channel. If there is no channel that is free at the transmitter as well as the receiver, the transmitter retries the transaction by sending another RTS packet after a backoff delay.

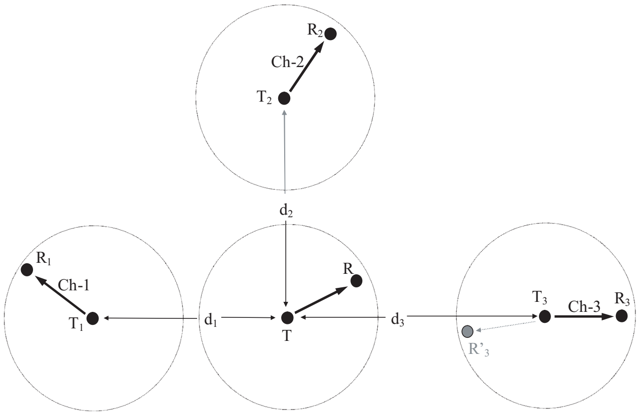
To gain a better understanding of the effects of this channel selection scheme, we refer to an example scenario illustrated in Figures 4. Assume that there are only three data channels, which are being used by the node pairs $T_1 - R_1$, $T_2 - R_2$, and $T_3 - R_3$, respectively, when a new packet is to be transmitted from T to R. Since $d_1 < d_2 < d_3$, T would detect the lowest carrier signal strength on channel-3. Hence, it would select channel-3 for transmitting its packet to R. This is intended to achieve two objectives:

1 the resulting interference caused by T to R_3 (which is the only other receiver that is receiving in channel-3) is expected to be smaller than what it would have caused to either R_1 or R_2 if channel 1 or 2 were chosen, respectively

2 the SINR of the received packet at R is expected to be highest on channel 3.

We note, however, that Transmitter-Based Channel Selection (TBCS) may not meet these objectives in all cases. For instance, if R_3 was located at the position indicated by R_3' in Figure 4, T would still select channel 3 for transmission, but the resulting interference to R_3' would possibly be greater than what it would have caused to R_1 or R_2 had it chosen channel 1 or 2, respectively. This problem arises because the transmitter-based clearest channel selection scheme estimates the *distances from active transmitters but not the receivers*. The transmitter-based channel selection scheme may also fail to select the channel that can provide the maximum SINR at the intended receiver. For instance, the clearest channel at R in Figure 4 is likely to be channel 1, as the farthest active transmitter from R is T_1.

Figure 4 Example illustrating channel selection based on the clearest channel at the transmitter

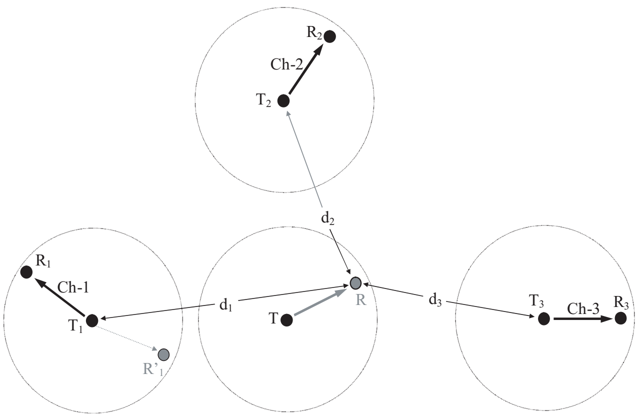


3.2 *Receiver-based channel selection*

One of the ways to achieve the best SINR at the receiver is to select the clearest channel that is detected *by the receiver*. This can be implemented in the following manner. The transmitter uses an RTS packet to send its list of free channels to the intended receiver. If the receiver receives the RTS, it performs carrier sensing over all channels and selects the channel included in the transmitter's free-channel list that has the lowest carrier signal strength *at its own location*. The receiver includes this channel number in the CTS packet that it sends to the receiver and simultaneously tunes to that channel awaiting the data packet. The other elements of this scheme are the same as in the TBCS scheme.

This protocol allows each transmitter–receiver pair to select the channel that has the smallest interference at their respective receivers. Hence the probability of collisions is expected to be minimised using this channel selection process. However, this channel selection scheme also has a drawback – it does not consider the interference that would be caused by a new transmitter to receivers *that are already active*. An example to illustrate the possible effect is shown in Figure 5. This is the same scenario as in Figure 4, but here we depict the distances from all active transmitters to R instead of T. Since here $d_1 > d_2 > d_3$, it is expected that under isotropic propagation conditions the carrier signal strength at R will be smallest on channel 1. Hence, Receiver-Based Channel Selection (RBCS) would select channel 1. This appears to be the desired solution under the described scenario, where the closest active receiver on channel-1, R_1, is located sufficiently far from T. However, the transmission from T might generate significant interference to R_1 if it was located at R_1' instead. Note that RBCS chooses channel 1 irrespective of the location of R_1 as its channel selection is based on the distances from the active transmitters to R. However, if R_1 was in the latter position, the transmission from T on channel 1 could cause significant interference to it, possibly resulting in the loss of the packet that it is receiving.

Figure 5 Example illustrating channel selection based on the clearest channel at the receiver and the associated problem



3.3 *Cooperative Channel Selection (CCS)*

The concepts behind TBCS and RBCS were discussed in our early work in (Jain et al., 2001; Nasipuri and Das, 2000). We now describe a new multichannel MAC protocol that attempts to solve the problems experienced by TBCS and RBCS and meets both the objectives described in Section 3.1. This channel selection scheme is 'cooperative' in the sense that it aims to minimise the amount of interference from new transmitters to currently active receivers while selecting the best channel for their own transmissions. The main hurdle for achieving this is to implement a mechanism by which a transmitter can estimate the amount of interference that it would cause to an active receiver on that channel. We propose the use of *receiver-initiated busy-tones* to serve this purpose. Busy-tones are narrow out-of-band tones that were previously proposed to serve as a mechanism for neighbours of active receivers to know about an ongoing transmission (Deng and Haas, 1998; Tobagi and Kleinrock, 1975). Here, we consider the use of busy-tones on all data channels. An active receiver transmits a busy-tone on the channel as long as it is receiving data. The idea is for the transmitter to check the strengths of busy-tones from active receivers to estimate the amount of interference it would cause to them and the receiver to use carrier sensing on the data channels to determine the clearest data channel for receiving.

The details of this protocol are as follows. When a node has a data packet to send, it first transmits an RTS packet to the receiving node on the control channel with a list of free data channels available for transmission. Here, free channels are those for which the busy tone signals lie below the carrier-sensing threshold. This list is sorted in ascending order of the signal powers of the busy tones and embedded in the RTS packet. Upon successful reception of the RTS packet, the receiver node creates its own free-channel list by sensing the *carrier signals* on the data channels. This list is also sorted in ascending order of signal strengths. If there are channels that are included in the free-channel list sent by the transmitter as well as that obtained at the receiver, the receiver selects the *best common channel* by going down the lists and selecting the first channel that is common to both. In case of a tie, the best channel from the receiver's list gets preference. The receiver then sends this channel information in the CTS packet and switches to the chosen data channel to receive the data. If it does not receive the data within a certain period, it reverts to idle mode and continues monitoring the control channel.

4 Performance evaluation

We now present performance results of the proposed multichannel MAC protocols, obtained from computer simulations. These simulations are performed using the RFMACSIM simulator, which is a discrete-event simulator that has accurate wireless physical layer and the IEEE 802.11 MAC implementations (Puig, 1993). Additional modifications were incorporated into RFMACSIM to simulate the TBCS, RBCS, and the CCS multichannel MAC protocols. In addition, a multichannel MAC that uses *Random* Channel Selection (RCS) is also implemented, that is, one in which the data channel is randomly chosen from the set of channels that are free both at the transmitter as well as the receiver, determined through the RTS-CTS exchange over the control channel. The performances of these multichannel MAC protocols are compared to that of a single channel 802.11 MAC under identical conditions.

4.1 Network model

Table 1 lists the parameters used in all MAC implementations. Traffic is considered to be uniformly distributed over the whole network, with each node generating data packets according to a Poisson process. The destination of a generated packet is selected randomly from the set of neighbours of the node in which the packet is generated.

Table 1 Parameter values used in simulations

Parameter	*Values used*
Transmit power	25 dBm
Carrier-sense threshold	-90 dBm
Noise floor	-110 dBm
Minimum SIR	10 dB
Data packet size	1000 bytes
RTS packet size	10 bytes
CTS packet size	10 bytes
SIFS	10 μs
DIFS	60 μs
Total bandwidth	2 Mb/sec

4.2 Optimisations

The basic framework of the multichannel MAC protocols described above follow the same principles as the IEEE 802.11 MAC. This includes the mechanisms followed for carrier sensing, backoffs and access retries. However, there are several aspects in the implementation of the multichannel MAC protocols that warrant reviewing these mechanisms and the corresponding parameters used.

4.2.1 Optimising the control channel bandwidth

Having a separate control channel brings up the issue of determining its optimum bandwidth to maximise bandwidth utilisation. The optimum solution would provide sufficient control channel bandwidth to minimise the contention amongst RTS and CTS packets while leaving enough channel capacity for the data channels. This depends on a number of parameters that include the data and control packet lengths, the node density, traffic and the total channel bandwidth. Under the chosen parameters, we determined using computer simulations that the optimum solution under heavy traffic conditions for reasonably uniform node distributions (such as the grid topology) is approximately 0.1 times the total bandwidth. Some of these results are presented in the next section.

4.2.2 Optimising NAVs

A related design issue when using a separate control channel is the modification of the NAV parameter, which is used to keep neighbouring nodes from transmitting when a data transmission is in progress. In single-channel 802.11 MAC, when a node receives an RTS packet that has a different destination, it sets is NAV to $\mathrm{NAV_{RTS}} =$ CTS duration + Data frame duration + ACK duration + $3 \times$ SIFS + $3 \times$ propagation time after the RTS is received. Similarly, on receiving a CTS packet, a node sets its NAV to $\mathrm{NAV_{CTS}} =$ data frame duration + ACK duration + $2 \times$ SIFS + $2\times$ propagation time. Since RTS and CTS transmissions cannot interfere with data in the proposed multichannel framework, these parameters need to be modified to:

$$\begin{aligned}\mathrm{NAV_{RTS}} &= \text{CTS duration} + \text{SIFS}\\ &\qquad + \text{propagation time}\\ \mathrm{NAV_{CTS}} &= 0\end{aligned}$$

4.2.3 Optimising the backoff parameters

Another issue concerns the backoff parameters, that is, the minimum and maximum backoff window sizes and the backoff slot period, used for calculating the random backoff periods during access retries. Backoffs are required when the carrier on the control channel is found to be high (implying that the channel is in use) during the transmission of a control packet. Since data packet transmission times are higher for multichannel MAC protocols (due to the reduction of the bandwidth per data channel, under the same aggregate bandwidth assumption), these parameters also depend on N. The optimum values of these parameters have also been found experimentally to maximise the throughput in the grid network topology. The results are given in Table 2.

Table 2 Optimised backoff parameters for the grid network

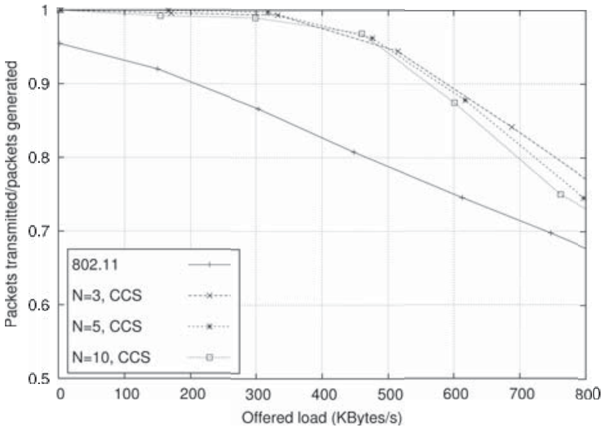
No. of data channels	*Slot time (μs)*	*Minimum window size (slots)*	*Maximum window size (slots)*
2	25	8	1024
4	15	128	1024
9	10	256	1024

Note that the above optimisations have been performed only with the objective of obtaining meaningful performance comparisons of the various MAC protocols presented in this paper. Hence, the primary concern was to determine how they depend on N under the same set of MAC parameters. The complete evaluation of the optimisation criteria under different network settings or traffic patterns is beyond the scope of this paper. Some related work on this issue on single channel 802.11 networks may be found in Scalia and Tinnirello (2004) and Anastasi (2003).

4.3 *Performance in a grid network*

We first evaluate the average performance of CCS, RBCS, TBCS, RCS and the 802.11 MAC, all using an aggregate bandwidth of 2 Mbps in an ad hoc network of 225 nodes, placed in a 15 × 15 grid. The internode spacing was taken as 180 m, which resulted in 36 neighbours per node. The offered load was varied by changing the average Poisson arrival rate in all nodes. The resulting ratio of transmitted packets over offered packets for varying number of channels is plotted in Figure 6. These results were identical for all the multichannel protocols using the same N. Hence only the results for CCS are shown in the figure. We note the ratio of transmitted packets are appreciably higher using multiple channels, as predicted by our analysis in Section 2.2. Differences between the assumptions used in the simulation model and that used for analysis, such as finite number of nodes and the use of control packets, possibly account for the differences in the quantitative gains obtained with different N.

Figure 6 Fraction of offered data packets that are transmitted using various protocols in a 225 node grid network



The probability of collisions of transmitted data packets depends on N as well as the channel selection scheme. In Figure 7, we plot the fraction of data packet collisions obtained with different number of channels for all the multichannel protocols and compare them with that obtained with the 802.11 protocol. We note that use of multiple channels with random channel selection does not reduce the probability of collisions. The number of collisions using TBCS is comparable to that in 802.11, while both RBCS and CCS has lower number of collision when the number of channels is greater that 5. CCS provides the lowest number of collisions. The resulting throughputs are plotted in Figure 8. We observe that while random channel selection performs worse than 802.11, the throughput using all three signal-power-based channel selection schemes is better than that of 802.11 when either 5 or 10 channels are used. RBCS performs better than TBCS and CCS provides the best performance. A comparison of the throughputs obtained from all four channel selection schemes using 10 channels is shown in Figure 9. CCS provides the highest throughput, whose peak value is nearly 40% higher than that obtained using 802.11.

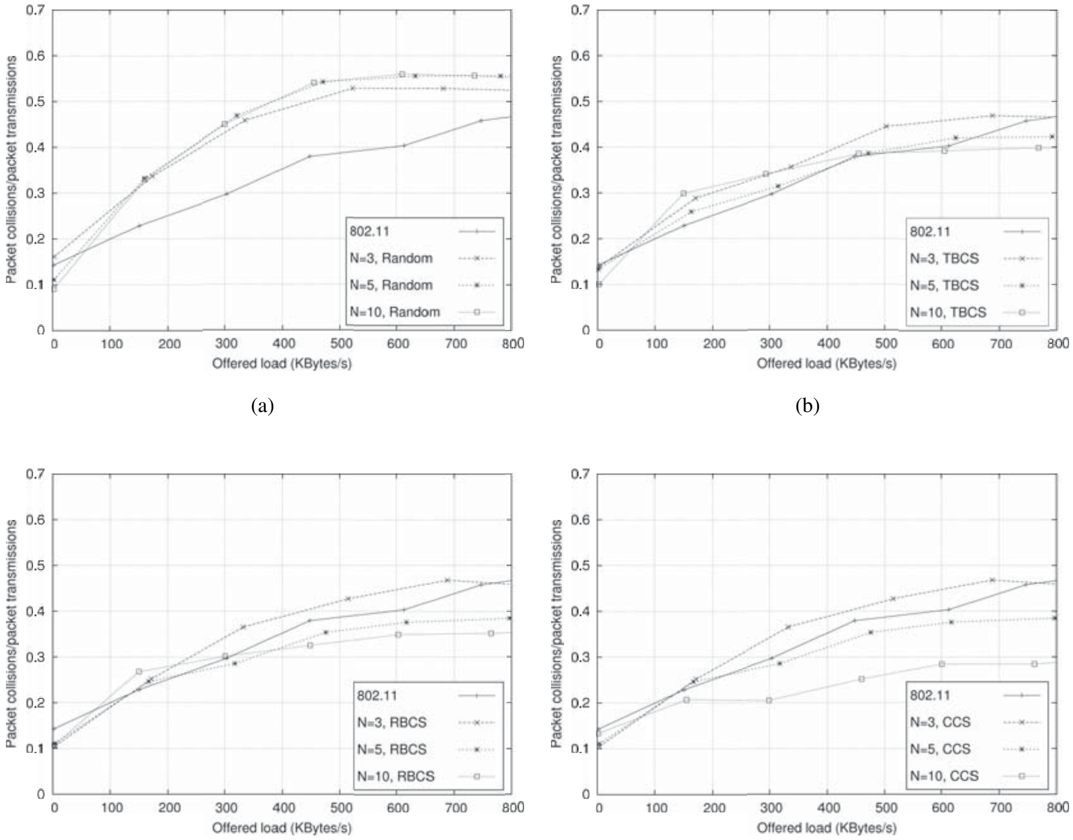
Figure 10 shows the variation of the throughput obtained with CCS under different control channel bandwidths. In Figure 10(a), the variation of the throughput obtained at an offered load of 750 kB/s is plotted for three, five and 10 channels in the grid topology described above with 180 m grid spacing. To demonstrate the effects under a different network density, we show the same results obtained with a grid spacing of 120 m in Figure 10(b). The total bandwidth is maintained constant for all cases. With 120 m grid spacing, each node has 68 neighbours and the aggregate network throughput is lower than that obtained with 180 m grid spacing. However, for all cases the peak throughput is observed to occur when the control channel uses approximately 10% of the total bandwidth.

4.4 *Performance in multipath routing*

Although the performance results discussed above are expected to be similar irrespective of the routes used for multihop communication (as long as there are a large number of nodes independently contending for data transmission in a given region), we consider a specific routing pattern for which the results are expected to be different – that used for multipath routing. Multipath routing has been demonstrated to have a great potential to improve performance of ad hoc networks by providing traffic diversity. These protocols maintain multiple paths between a source and destination nodes that can carry data traffic simultaneously in a load-balanced fashion (Lee and Gerla, 2001; Marina and Das, 2001; Nasipuri et al., 2001). In addition to providing fault tolerance in a dynamically changing ad hoc network of mobile nodes, it can also allow multipath forwarding where data packets are forwarded on multiple routes concurrently to improve the end-to-end throughput. One of the key issues for implementing multipath forwarding is the phenomenon called *route coupling* (Pearlman et al., 2000), which is the problem where multipath routes fall within the same radio neighbourhood causing difficulty of these routes to be used at the same time. Here, we demonstrate that the use of multichannel MAC protocols greatly reduces this route coupling problem.

Consider the network model depicted in Figure 11, where a source node (S) is routing data packets to the destination (D) over five parallel multihop paths, each of five hops. The same transmission power of 25 dBm as before is assumed but the distance between nodes on adjacent paths is reduced to 100 m to increase the effect of route coupling. We plot the end-to-end packet delivery ratio, that is, the ratio of the number of packets received at D over that generated at S, versus the offered load for 802.11 and CCS with $N = 3$ and 5 channels in Figure 12. The results show significant

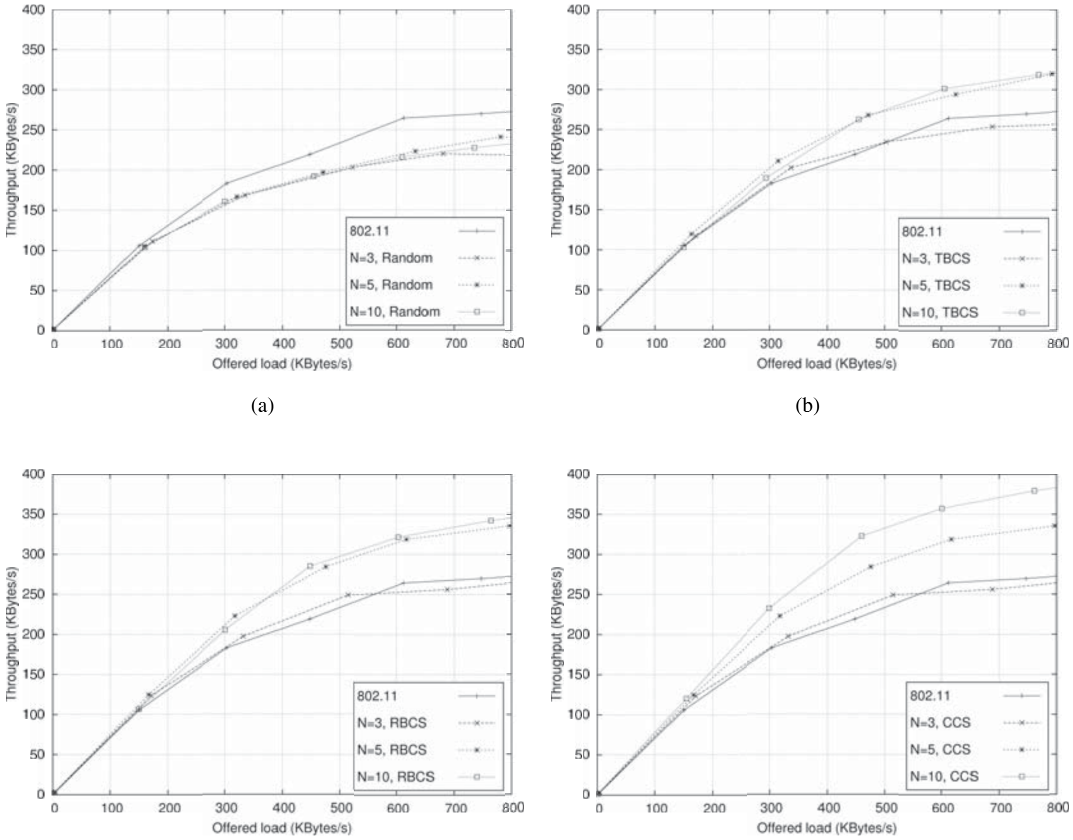
Figure 7 Fraction of data packets that are lost due to collisions (a) random channel selection; (b) TBCS; (c) RBCS and (d) CCS



(a) (b)

(c) (d)

Figure 8 Throughput obtained for different number of channels using (a) random channel selection; (b) TBCS; (c) RBCS and (d) CCS



(a) (b)

(c) (d)

improvements achieved using CCS over the single channel 802.11 MAC in this scenario. The primary reason is that CCS removes coupling by dynamically selecting orthogonal channels for transmission.

Figure 9 Comparison of throughput using 10 channels using various MAC protocols and the single channel 802.11 MAC

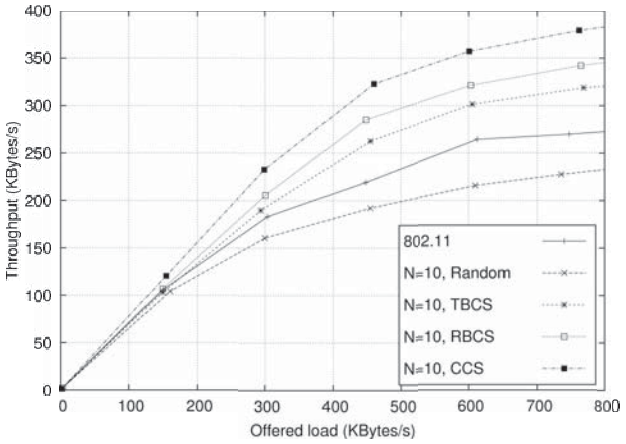
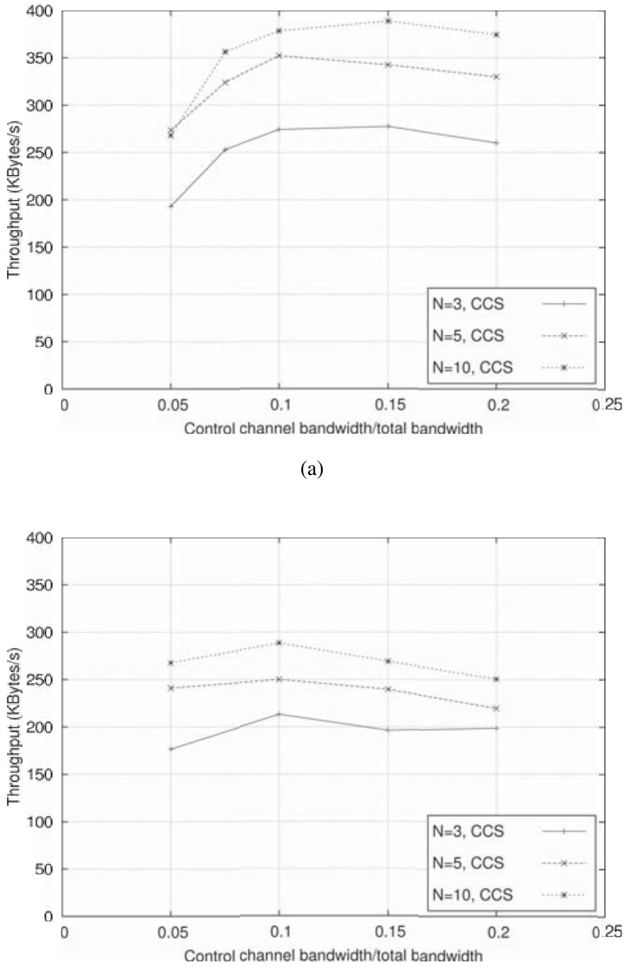


Figure 10 Variation of throughput with control channel bandwidth at a constant offered load. The results in (a) are obtained in a grid network with 180 m grid spacing and those in (b) are obtained when the grid spacing is reduced to 120 m



(a)

(b)

Figure 11 Five path topology

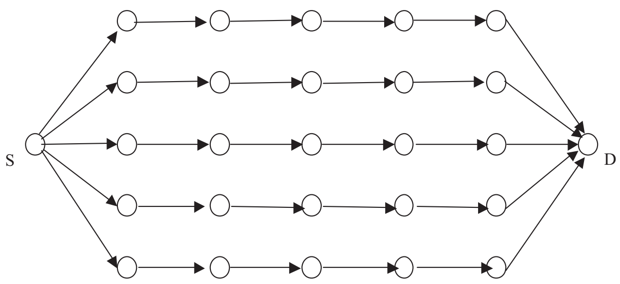
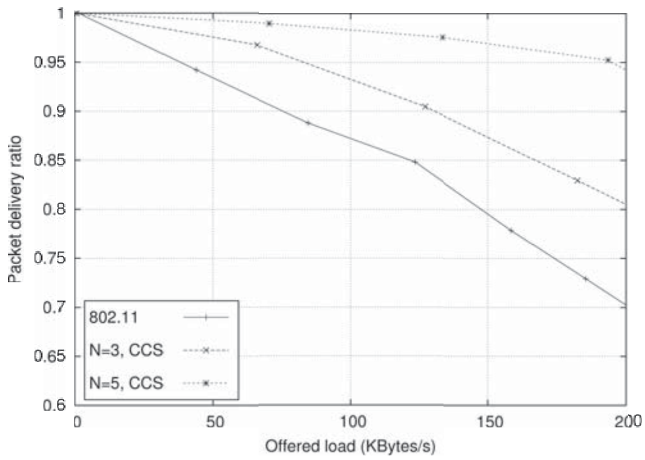


Figure 12 Packet delivery ratio in a multipath routing scenario

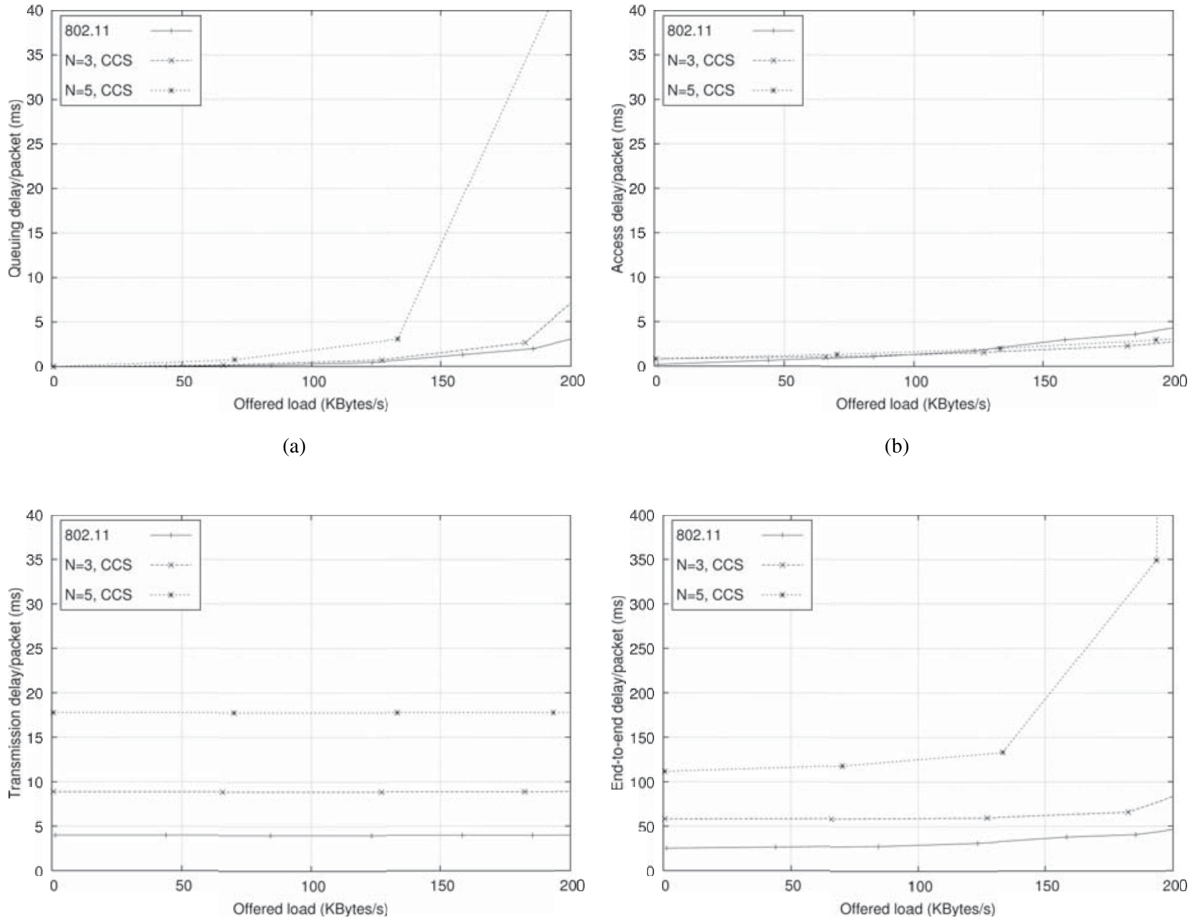


The corresponding MAC layer packets delays are plotted in Figure 13. We note that the access delays (i.e. average time spent gaining medium access) are small for all multichannel schemes. However, both the queueing delay (i.e. average time spent in the queue from the time the packet was generated until access is attempted) and the transmission delays (i.e. time spent in transmission) are higher for the CCS multichannel MAC protocol. The transmission delay depends on the channel bandwidth and hence increases with N. It does not depend on the offered load. The final end-to-end delays of packets that successfully traverse the multihop routes are plotted in Figure 13(d), which shows that *on a packet basis* CCS produces longer delays, which increases with N and is higher at heavy loads. This is the expected result that is caused by the reduction of bandwidth per channel with increasing values of N. It must be noted that all delays presented in Figure 13 represent those obtained at the MAC layer, which is different from the end-to-end delay that would be experienced in the application layer. The end-to-end delay in the application layer would also depend on retransmissions of packets dropped at the MAC layer, in which the multichannel CCS MAC provides a significant advantage over single-channel 802.11 MAC.

5 Related work

Many related work have explored the benefits of using multiple channels in ad hoc networks. Early work on this concept include the multichannel MAC protocol proposed in Lopez-Rodriquez and Perez-Jimenez (1999), where the

Figure 13 Delay performance of multichannel MAC with multipath routing



(a) (b)

(c) (d)

nodes identify channel usage in their neighbourhood by carrier sensing and exchange this information during data transmission. The first free channel is selected for data transmission. A multichannel MAC protocol that uses a polling mechanism to schedule data transmissions based on the exchange of usage tables was presented in Haas (1997). The multichannel MAC with 'soft reservation' presented in Nasipuri et al. (1999) tries to restrict channel usage for each node on the same channel whenever possible, thereby reducing contention during channel access. Our earlier work presented in Nasipuri and Das (2000) and Jain et al. (2001) introduced the idea of using signal-power measurements (either at the transmitter or the receiver) on free channels for dynamic channel selection. Wu et al. (2000) proposed a multichannel Dynamic Channel Assignment (DCA) MAC that assumes the use of two transceivers per node. Nodes can monitor the control channel for RTS and CTS packets simultaneously while exchanging data on any one of *n* data channels. RTS and CTS packets are used to exchange free channel information amongst a pair of communicating nodes and a randomly selected free channel is used for data transmission. In the sequel (Wu et al., 2002), the authors include power control to the DCA protocol. In Zheng and Zhang (2003), the authors propose an opportunistic multichannel MAC that uses the RTS packet to also act as a 'pilot signal' for channel estimation. The RTS packet is transmitted on all channels to allow the receiver to estimate the best channel for data transmission. This protocol assumes that the physical layer is capable of multirate data transmission. The receiver determines the optimum transmission rate from channel estimation and sends this information back to the transmitter over the CTS packet on the chosen channel. The authors suggest that this protocol can be implemented using only two transceivers per node, one for data transmission on any chosen channel and the other for listening to all other channels. A multichannel MAC protocol that provides differentiated services over multiple channels is proposed in Choi et al. (2003). This protocol also considers negotiation over a common control channel but assumes that only one transceiver is used in each node. Each node maintains channel usage tables that includes channel-related information for all data channels. Channel selection is based on data packet lengths (considered variable), priorities and data channel availability. The multichannel MAC proposed in So and Vaidya (2004) uses only one transceiver per node. It proposes to use time synchronisation using beacon signals and Ad Hoc Traffic Indication Messages (ATIM) at the start of all beacon intervals to exchange Preferable Channel Lists (PCL). Channel selection is aimed to balance the channel load as much as possible.

Along with the development of multichannel MAC protocols, some work has also been reported on evaluation of the capacity of CSMA based MAC protocols using multiple data channels and dynamic channel selection (Li et al., 2003a,b). The theoretical guaranteed throughput depends on a number of parameters that include the topology, the packet loss rate and the aggregate bandwidth. However, the authors show that for medium network sizes (100–300 nodes) with a 2 Mbps channel rate, multichannel MAC protocols can theoretically achieve more than nine times the throughput capacity as can be achieved by using a single channel protocol.

As opposed to the multichannel MAC protocols presented in Wu et al. (2000, 2002) and Choi et al. (2003) the protocols considered in this paper operate with only one transceiver per node. Although all transceivers are assumed to be tunable to any of the available channels, the assumption of a single transceiver per node removes the possibility of a node operating on multiple channels at the same time. The protocols presented here derive advantage from distributing transmissions on multiple orthogonal channels in an intelligent way, so that the average probability of collisions is reduced. Furthermore, as opposed to the assumptions in So and Vaidya (2004), we consider that same available bandwidth is divided into N channels. Hence the improvement obtained in the throughput from the multichannel protocols presented here is due to the effectiveness of the channel selection algorithm only and not from utilising additional bandwidth.

6 Conclusion

The usage of multiple orthogonal channels provides benefits in an ad hoc wireless network by allowing multiple concurrent transmissions in the same region. It creates a framework for reducing contention in random channel access by allowing contending transmitters to distribute their transmissions over channels as opposed to using random backoffs over a single shared channel. A direct advantage achieved with this framework is the improvement in the channel access probability, which effectively reduces the number of backoffs experienced by contending transmitters.

A second advantage of using multiple channels is the reduction of secondary data collisions caused by out-of-range transmitters. This can be achieved by transmitting data packets on the channel that has the highest tolerance to co-channel interference. Channel selection may be implemented by signal-power measurements on all data channels that are free at the time of transmission. This paper explores these advantages and presents several options of signal-power based channel selection schemes. Finally, we present a multichannel MAC with collaborative channel selection that successfully derives benefits from these advantages. Numerical results are presented from analysis and simulations to evaluate these advantages.

The proposed multichannel MAC protocols involve some additional hardware complexity. Firstly, it requires the presence of multiple orthogonal channels with each node having the capability of carrier sensing over all channels by sequentially switching over all channels. This is not a severe limitation due to the existence of multiple channels in current wireless standards and the possibility of short channel switching times in currently available interfaces. The proposed multichannel MAC with CCS also requires the implementation of out-of-band busy tone signals on all channels, which might cost some additional bandwidth. However, as pointed out in Tobagi and Heinrock (1975) and Deng and Haas (1998), the channel overhead for busy tones is small (less than 10%). This additional overhead may be justified due to the superior performance achieved by this protocol.

Future directions in the usage of multiple channels in wireless LANs include investigations on multiple network interface cards operating on multiple channels (Adya et al., 2003). While this scheme has the same objective of exploiting the available spectrum for deriving higher bandwidths, usage of multiple interface cards would require modification of the link layer without affecting the MAC.

Acknowledgements

The work reported in this paper has been partially supported by the NSF grants ANI-9973147 and ANI-0308631. The authors thank Jun Zhuang, Nitin Jain and Jai Mondhe, for their invaluable help with programming and simulations.

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