A Cooperative CDMA-Based Multi-channel MAC Protocol for Ad Hoc Networks

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Abstract. In this paper we present CCM-MAC, a cooperative CDMA-based multi-channel *medium access control* (MAC) protocol for multi-hop wireless networks. The protocol mitigates the multi-channel hidden and exposed terminal problems through cooperation from overhearing neighbours. By accounting for the multiple access interference obtained through cooperation, it also addresses the near-far problem of CDMA. We provide an analysis of the maximum throughput of CCM-MAC and validate it through simulation in Matlab. A significant improvement in network throughput is achieved over IEEE 802.11 and another multi-channel MAC protocol.

1 Introduction

Most wireless LANs are single channel systems. However, as the number of nodes communicating increases, systems with a single channel suffer declining performance. Contributing to the problem are the well-known hidden and exposed terminal problems. To combat these problems there is growing interest in multi-channel systems. Indeed, the IEEE 802.11 standard [1] already has multiple channels available for use. The IEEE 802.11a physical layer has 12 channels, 8 for indoor and 4 for outdoor use. IEEE 802.11b has 14 channels, 5 MHz a part in frequency. To avoid channel overlap, the channels should have at least 30 MHz guard bands; typically, channels 1, 6 and 11 are used for communication.

In a multi-channel system, the transmitter and receiver must both use an agreed upon channel for communication. This introduces a channel coordination problem. As well, the *hidden* and *exposed terminal* problems remain in the multi-channel setting. Figure 1(a) shows a communication between nodes A and B in progress on channel 1. Suppose that C chooses channel 2 to communicate with D. When A and B complete their transmission, neither has overheard the negotiation of channel 2 between C and D. As a result, a collision might happen if A then chooses channel 2 on which to communicate with B.

Figure 1(b) illustrates the exposed terminal problem in a multi-channel setting. Suppose that there are three channels and two of them are in use by nodes

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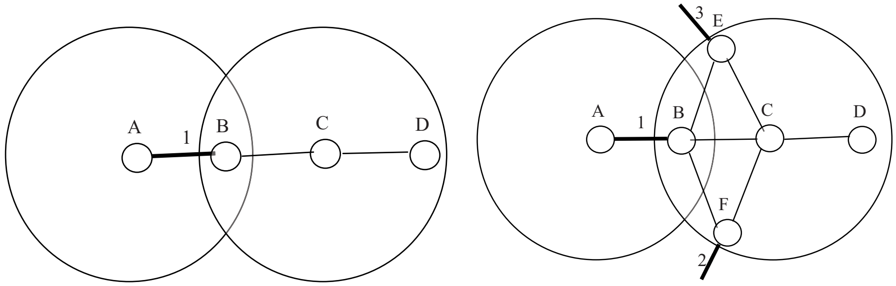


(a) Hidden terminal (b) Exposed terminal

Fig. 1. The multi-channel hidden and exposed terminal problems

E and F. If nodes B and C want to communicate with nodes A and D, respectively, there is a free channel available. However, both B and C are in the transmission range of E and F. Even though both transmitters could use the same channel, one transmitter will delay its transmission. Without resolving the multi-channel hidden and exposed terminal problems, the optimal efficiency that can be derived from multiple channels can not be achieved.

In this paper, we propose a cooperative CDMA-based multi-channel MAC protocol for *mobile ad hoc networks* (MANETs). It uses *code division multiple access* (CDMA) technology on each channel and a cooperative mechanism to mitigate these problems. The idea of node cooperation is inspired from the CAM-MAC protocol of Luo et al. [2]. It is a simple idea: the reason the hidden and exposed terminal problems happen is because nodes lack knowledge about channel usage. Idle nodes that overhear channel negotiation may help other nodes make informed decisions.

CDMA has a very high spectral efficiency, i.e., it can accommodate more than one user on a channel. While CDMA is widely used in cellular systems there are some difficulties in applying CDMA to MANETs. The *near-far* problem takes place because a signal from a closer source is much stronger than from a source far away. Figure 2 shows a receiver R_2 of T_2 also in the transmission range of T_1. Since T_1 is closer (in terms of distance), its signal drowns out the signal of T_2. In cellular networks this is solved by the base station controlling the power to equalize the signals; this is not viable in MANETs where there is no centralized control. Cooperation is also used to mitigate the near-far problem in our proposed protocol.

The rest of paper is organized as follows. §2 reviews related work on multi-channel MAC protocols, CDMA, and cooperative mechanisms. §3 introduces our CCM-MAC protocol and describes how it mitigates the multi-channel hidden and exposed terminals problems and the near-far problem in CDMA through node cooperation. §4 analyzes the throughput achievable by CCM-MAC. Using

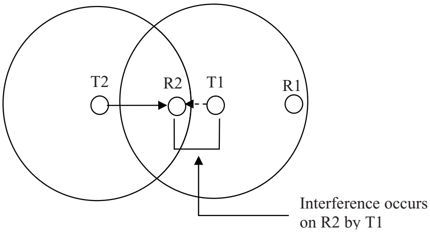


Fig. 2. The near-far problem of CDMA in MANETs

Matlab, we present simulation results comparing our protocol to IEEE 802.11, and the MMAC-CC multi-channel protocol in §5. Finally, in §6, we conclude.

2 Related Work

2.1 Multi-channel MAC Protocols

Some multi-channel MAC protocols use a control channel to coordinate channel selection. Of those without a control channel, [3,4] are equipped with single-transceiver. Lo et al. [3] uses CSMA on multiple-channels. N nodes compete to select one channel from M available; a channel is randomly chosen from the free channel list acquired by sensing at the transmitter. Zhou et al. [4] propose a multi-frequency MAC protocol for wireless sensor networks. It uses multiple frequencies to transmit or receive, and senses the carrier signal on all of frequencies rather than using a handshake. For nodes equipped with multiple transceivers, Nasipuri et al. [5] propose a multi-channel MAC protocol for multi-hop wireless networks that uses power-based channel selection. Both transmitter and receiver monitor all channels and select one that has the lowest signal power. In [6], a "soft" channel reservation is made, meaning a node prefers a channel on which it was last successful. This protocol uses as many transceivers as channels, and is therefore expensive in terms of the hardware required. A power-saving multi-radio multi-channel MAC protocol for WLANs is proposed by Wang et al. [7]. This protocol divides time intervals into three phases so that it can estimate the number of active links, negotiate channels, and then transmit data.

Some multi-channel MAC protocols using a dedicated control channel use one transceiver. Shi et al. [8] introduce the asynchronous multi-channel coordination protocol for WLANs. The control channel uses IEEE 802.11 DCF. Each node maintains a channel table and a variable indicating the channel it prefers. So et al. [9] uses a beacon signal to make periodic transmissions and give contention window time to all nodes which hear a beacon. Nodes then negotiate with each neighbour for a channel. The dynamic channel assignment with power control protocol, proposed by Wu et al. [10], expects the best channel to be the one for which another transmitter located the farthest distance from the transmitter is in use; they check signal power on transmitter side only.

Other protocols that use a control channel use multiple transceivers. Jain et al. [11] include free channel information in the handshake in a protocol that uses as many transceivers as channels. Wu et al. [12] propose a multi-channel MAC protocol with on-demand dynamic channel assignment. Each node uses two half-duplex transceivers, and each transceiver is used on a dedicated channel.

2.2 CDMA in Multi-hop Wireless Networks

Garcia-Luna-Aceves et al. [13] propose a method to assign codes in a dynamic multi-hop wireless network. Using neighbour information embedded in the handshake a unique orthogonal code is found. This protocol does not address the exposed terminal problem, or the near-far problem.

Muqattash et al. [14] propose a CDMA-based power controlled MAC protocol for MANETs. They address the near-far problem by using power control among the nodes. To obtain information about the power strength of the neighbour nodes, each node is equipped with multiple transceivers.

2.3 Node Cooperation

Cooperative mechanisms are becoming increasingly important in wireless networks with the potential to enhance system performance. More common in cellular networks (see, for example, [15]), cooperation is still largely unexplored in MAC protocols for MANETs. From the system point of view, since a node has limitations in terms of its antenna, power, cost and hardware, it is infeasible to use MIMO technology. Cooperative communication explores the benefits of multi-user environment by creating a virtual MIMO system.

Liu et al. [16] propose a cooperative MAC protocol for WLANs. The feature of CoopMac is to use a variety data rates on each channel. If the direct path between source and destination has low SNR, then using an intermediate cooperative node that relays the packet may be effective. A cooperative asynchronous multi-channel MAC protocol (CAM-MAC) is proposed by Luo et al. [2]. In CAM-MAC, the transmitter and receiver obtain channel usage information from idle neighbours after the handshake. Many problems remain, such as the hidden terminal problem, cooperative node selection, and control packet collision.

3 The CCM-MAC Protocol

In this section we describe our *Cooperative CDMA-based Multi-channel MAC* (CCM-MAC) protocol. The basic channel selection mechanism is similar to that used in MMAC-CC [17]. There is one control channel and N data channels. Control packets are transmitted on the control channel using a common code; this allows nodes in transmission range to overhear the channel negotiation. Data packets are transmitted on a data channel, with each node using its unique code which is orthogonal to all other codes. Thus, CCM-MAC combines both the advantages from using multiple channels and from CDMA.

3.1 Channel Negotiation in CCM-MAC

CCM-MAC uses a handshake for channel negotiation. In addition to the usual *request-to-send* (RTS), *clear-to-send* (CTS), and *acknowledgment* (ACK) packets, three additional control packets are used: *decided-channel-to-send* (DCTS) is used to indicate the channel selected, *information-to-inform* (ITI) is used by an overhearing node to aid the transmitter or receiver in its decision, and *confirm* (CFM) to inform neighbours of the receiver of the channel selected.

Figure 3 shows an example of channel negotiation in CCM-MAC. In this example node B has a packet to transmit to node C. If the control channel is idle, B transmits an RTS to C. Node C returns a CTS to B containing a list of free channels at B. Suppose that there is a node A that overhears only the RTS, and a node D that overhears only the CTS. Then, node A sends an ITI to B with information about the channel state around B, and simultaneously, node D sends an ITI to C with information about the channel state around C. (In this example, the ITI do not collide).

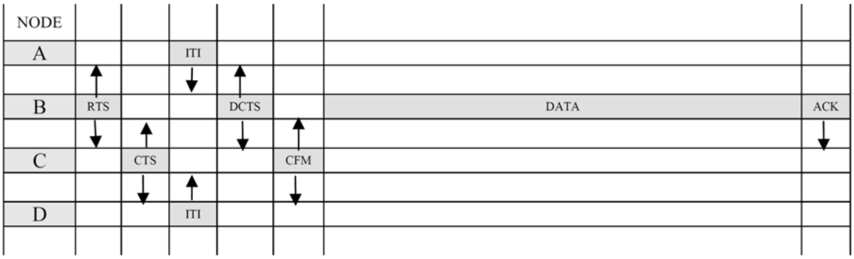


Fig. 3. Example of channel negotiation in CCM-MAC

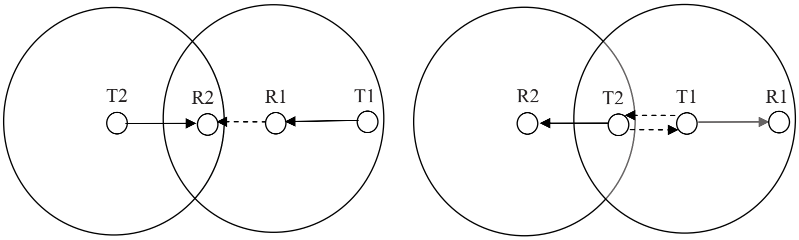
Using the information contained in the CTS and the ITI, B selects a channel and sends its choice in a DCTS to node C. At the same time, the node A overhears the channel selection and stores this information together with duration information. On receiving the DCTS, if the selected channel is available on the receiver side, C returns a CFM to node B to confirm the choice. In this way, neighbours of the destination also overhear and store the channel selection and duration information. Finally, on receipt of the CFM, B transmits the data packet to C. If the data transmission is completed successfully, C transmits an ACK to node B *on the data channel*.

Recall that all the control packets in CCM-MAC are transmitted using a common code. It is possible that several nodes overhear an RTS/CTS exchange and may want to cooperate in the channel negotiation. Here, we take advantage of the *capture effect* of CDMA. This allows a node to demodulate the strongest signal of those transmitted. Therefore, we assume a node receives the ITI from its closest cooperating neighbour; this node also provides the most accurate information to node x since its transmission range overlaps that of x the most.

For CCM-MAC to mitigate the near-far problem of CDMA, the cooperating neighbours must provide additional information to allow a node to decide whether it may add another transmission onto a channel with existing communications. This is discussed next.

3.2 Mitigating the Near-Far Problem

There are two factors to consider for the near-far problem in MANETs. One is the *distance* between nodes.[1] The other is the communication mode (transmit or receive) of a node. Figure 4 shows two transmitters T_1 and T_2 and their corresponding receivers R_1 and R_2. In Figure 2, since R_2 is close to T_1 the signal from T_2 may interfere with the signal from T_1. Therefore, the data transmission between T_2 and R_2 may fail. However, in Figure 4 the near-far problem does not occur; each receiver is far enough away from the other transmitter.



(a) Interference among receivers

(b) No interference among receivers

Fig. 4. Example of interference and no interference between receivers in CDMA

If each node knows the distance to and communication mode of the nodes around it the near-far problem may be avoided. In CCM-MAC cooperating neighbours may provide this information. Not only may a cooperating neighbour help with channel usage information, it can also estimate the distance between the neighbour and transmitter (or receiver) by checking the signal strength. This helps in the channel selection. If the distance to a neighbour with an ongoing transmission is too close, and it is in a different communication mode, by selecting a different channel from that of the ongoing transmission, the near-far problem can be avoided.

In this way, a transmission may be added to a channel with an ongoing transmission if it does not cause interference. Otherwise, another channel (if available) is selected. This makes effective use of the multiple channels, and supports high spatial reuse ratio in the system as more nodes may transmit data concurrently.

3.3 Mitigating Multi-channel Hidden/Exposed Terminal Problems

Figure 5 gives an example scenario to illustrate how CCM-MAC mitigates the multi-channel hidden and exposed terminal problems. Suppose that nodes A and

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[1] We assume all nodes use the same signal power.

B are communicating. Node C can initiate data transmission at the same time since it is out of the transmission range of A. But C is hidden to A and could cause a collision at B. This problem is solved by the CCM-MAC handshake. Through the ITI and CFM packets, node C can measure distance information, and obtain channel information to make an informed decision for channel selection to avoid the hidden terminal problem.

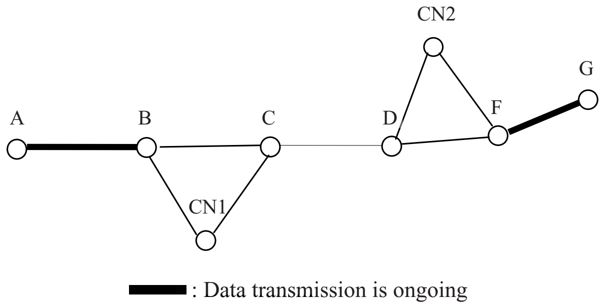


Fig. 5. Example for CCM-MAC mitigating the hidden and exposed terminal problems

There may be some situations in which not enough information is available to make a channel selection. Consider Figure 5 again, and assume that node C and D complete a transmission. Even though C and D may know that nodes B and F are in their respective transmission range, they may not know which channels are in use or the communication mode of each node. As a result, it may cause a hidden terminal problem. In CCM-MAC, cooperating neighbours are again the key to the solution.

In this case, node C sends an RTS to D. When D and any neighbour of C receive the RTS, they estimate their distance to node C by calculating the signal power using

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} \frac{(4\pi f d)^2}{c^2} \tag{1}$$

where P_t is the signal power at the transmitting antenna, P_r is the signal power at the receiving antenna, c is the speed of light, λ is the carrier wavelength, f is the frequency, and d is the propagation distance between antennas.

Meanwhile, D compares the distance between C and D and D and F and determines a free channel list which it includes, along with the distance estimate, in the CTS back to C. The cooperating neighbours CN_1 and CN_2 each transmit an ITI to nodes C and D, respectively, with the following information: the identifier of the node with an ongoing transmission (B and F, respectively), an estimate of the distance between the communicating pair (the distance between A and B, and F and G, respectively), and channel usage information.

In this example, the distance between B and C and D and F is too close, while nodes A and F are relatively far from nodes B and G. Therefore, the communication between C and D should not use the same channel as A and B or F and G to avoid the near-far problem.

The argument for the exposed terminal problem is very similar.

4 Analysis of the Maximum Throughput of CCM-MAC

Unlike technologies such as TDMA and FDMA in which the capacity is fixed and easily computed, CDMA does not have a fixed capacity. A CDMA system can accommodate more users on one channel because it has a very high spectral efficiency. As the number of users increases, the interference increases and the *signal to noise ratio* (SNR) decreases. If the SNR falls below a threshold, the channel is saturated, and no more users are allowed onto the channel. Therefore, the capacity of a CDMA system depends on the number of concurrent users.

In the multi-channel CCM-MAC protocol, there is one dedicated control channel and N data channels; CDMA is used on each channel. A common code is used on the control channel, while each user transmits data packets using a unique orthogonal code on a data channel.

To compute the throughput of the CCM-MAC protocol we use a *transmission frame*. A transmission frame is the time required for the CCM-MAC handshake, the transmission of the data packet, followed by the acknowledgment.

The time $T_{Handshake}$ for a pair of nodes to complete a handshake requires each control packet in the handshake to be transmitted:

$$T_{Handshake} = T_{RTS} + T_{CTS} + T_{ITI} + T_{DCTS} + T_{CFM}.$$

The maximum number of pairs of nodes H_{max} to complete the handshake successfully when noise is not considered is given by:

$$H_{max} = \frac{\frac{D}{B} + T_{ACK}}{T_{Handshake}}$$

where D is the size of the data packet, and B is the bandwidth of each channel. Therefore the throughput of CCM-MAC is given by

$$Throughput(\text{CCM-MAC}) = \frac{H_{max} \times D}{\frac{D}{B} + T_{ACK}}. \tag{2}$$

However, if H_{max} is more than the channel can support, then it may not be possible for all of the node pairs completing the handshake to communicate. Therefore, we must determine the maximum number of users that can communicate concurrently on one channel.

Similar to Van Rooyen et al. [18] and Turin [19], the received signal Y_{pi} of the ith user in the pth symbol period is given as:

$$\begin{aligned} Y_{pi} &= \sqrt{E_s}(x_{pi} + \eta_i) + \eta_{pi} \\ &= \underbrace{\sqrt{E_s}x_{pi}}_{signal} + \underbrace{(\sqrt{E_s}\eta_i + \eta_{pi})}_{noise}. \end{aligned} \tag{3}$$

Here, E_s is the energy per symbol, x_{pi} is the data of the ith user in the pth symbol period, η_i is the *additive white Gaussian noise* (AWGN) with zero mean that the ith user experiences from other active users, and η_{pi} is the noise the ith user experiences during the pth symbol period.

The output SNR for the ith user's signal may be expressed by the ratio of signal and noise power from (3) as

$$\begin{aligned}\alpha_{pi} &= \frac{E[\sqrt{E_s} x_{pi}]^2}{E[(\eta_i + \eta_{pi})^2]} \\ &= \frac{E_s}{E[\eta_i^2] + 2E[\eta_i, \eta_{pi}] + E[\eta_{pi}^2]}\end{aligned} \tag{4}$$

since the user's signal $x_{pi} = \pm 1$, i.e., is a data bit denoted by ±1. The value of $E[\eta_i, \eta_{pi}]$ is zero because the mean of the AWGN is zero. $E[\eta_{pi}^2]$ is $\frac{N_0}{2E_s}$ where N_0 is the noise spectral density [18].

Following Pursley [20], $E[\eta_i^2] \approx \frac{K-1}{3N_c}$, where K is the number of users considering noise and N_c is the number of chips per bit or processing gain. Substituting this approximation into Equation (4) yields an approximate expression for the SNR:

$$\begin{aligned}\alpha_{pi} &= \frac{E_s}{\frac{K-1}{3N_c} + \frac{N_0}{2E_s}} \\ &\approx \left(\frac{K-1}{3N_c} + \frac{N_0}{2E_s}\right)^{-1}\end{aligned} \tag{5}$$

since E_s is a constant.

In this system model, all nodes transmit with the same power level and the received power from each node is also the same. Rearranging Equation (5) to obtain an expression for K, the maximum number of users considering noise, gives:

$$K = 3N_c \left(\frac{1}{\alpha_{pi}} - \frac{N_0}{2E_s}\right) + 1 \tag{6}$$

where N_c, the number of chips per bit or processing gain is T/T_c, where T_c is the duration of the chip pulse.

However, since our protocol is designed for operation in a multi-hop wireless network, it may be that the received power for each receiver is different. The SNR in this case, following Van Rooyen et al. [18], is

$$\alpha_0 = \frac{3N_c P}{\frac{N_0}{T_c} + \sum_{j=1}^{K} \left(\frac{d_{is}}{d_{ij}}\right)^{\beta} P} \tag{7}$$

where the first term of the denominator N_0/T_c is the Gaussian noise power in the chip-rate bandwidth, and the second term is the interfering power component expressed as a sum of the interference induced by all other active nodes. This equation assumes that the transmit power of all nodes is equal, but that each is at a different distance from receiver node i. Here d_{is} is the distance between node i and the source node s, d_{ij} is the distance between node i and active node j, P is the transmit power, and β is the propagation law exponent (normally equal to 4). The inter-node powers are scaled by the distance d_{ij}. Using Equations (5) and (7) a value for K, the maximum number of users with noise, is derived.

Finally, by Equations (2), (3), and (5), the throughput of CCM-MAC in the best case is

$$Throughput(\text{CCM-MAC}) = \frac{M \times D}{\frac{D}{B} + T_{ACK}} \tag{8}$$

where

$$M = \begin{cases} H_{max} & \text{if } H_{max} < K \times N \\ H_{max} \times N & \text{if } H_{max} > K \times N \end{cases}.$$

5 Protocol Evaluation in Matlab

We use Matlab to simulate CCM-MAC, IEEE 802.11, and the MMAC-CC multi-channel MAC protocol [17].

For IEEE 802.11 the channel bandwidth is $2\,Mbps$. For CCM-MAC, that bandwidth is shared among a control channel and three data channels; the bandwidth of each channel is $500\,Kbps$. For MMAC-CC the bandwidth is shared equally among four channels.

A random grid topology, similar to [14], is used. M mobile users are placed in an area of $1000 \times 1000\,m^2$. The square is split into M smaller squares. The location of a mobile user is selected uniformly at random within each of these squares. The random way point model is used for mobility, with a user speed that is uniformly between zero and $2\,m/s$.

Every user is a source of packets. For each generated packet, the destination is randomly selected from one of the one-hop neighbours. Each node generates packets according to a Poisson process with rate λ, with the same rate used for all nodes. Table 1 shows other parameters of the simulation; these correspond to realistic hardware settings [21].

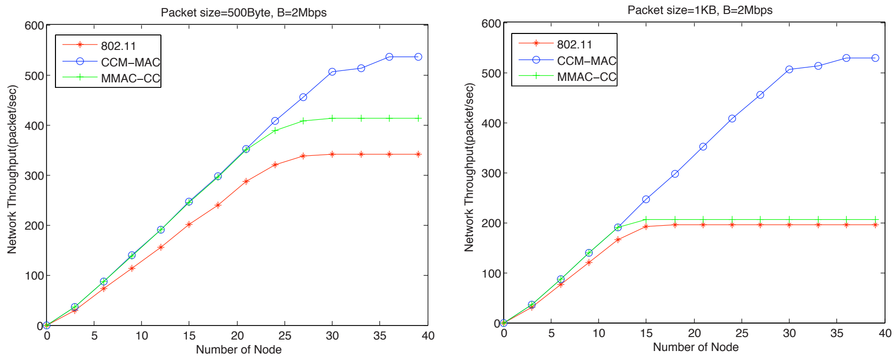
Table 1. Simulation parameters

Frequency	$2.4\,GHz$
IEEE 802.11 data rate	$2\,Mbps$
CCM-MAC data rate	$1.5\,Mbps$
CCM-MAC control channel rate	$500\,Kbps$
MMAC-CC channel rate	$500\,Kbps$
Transmission power	$20\,dBm$
Processing gain	$11\,chips$
SNR threshold	$15\,dB$
Reception threshold	$-68\,dBm$
Carrier-sense threshold	$-74\,dBm$
Interference threshold	2.78 [18]

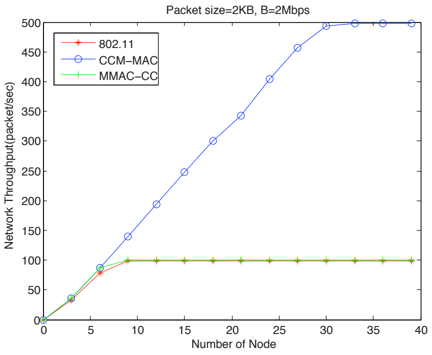
5.1 Simulation Results

Figure 6 shows throughput as a function of increasing node density, for increasing packet sizes. The throughput of MMAC-CC is always higher than IEEE 802.11, and the throughput of CCM-MAC is always higher than MMAC-CC. This can be interpreted as the advantage that using a multi-channel protocol brings over a single channel, and then the advantage that CDMA brings over and above using multiple channels.

As the packet size increases, the gap in throughput between CCM-MAC and, IEEE 802.11 and MMAC-CC, increasingly widens. In Figure 6, for 500 *byte* packets and 36 nodes, the throughput of CCM-MAC is 1.3 times higher than MMAC-CC, and the throughput of MMAC-CC is 1.2 times higher than IEEE 802.11. For 1 *Kbyte* packets and 36 nodes, the throughput of CCM-MAC is now 2.5



(a) 500 *byte* packets (b) 1 *Kbyte* packets

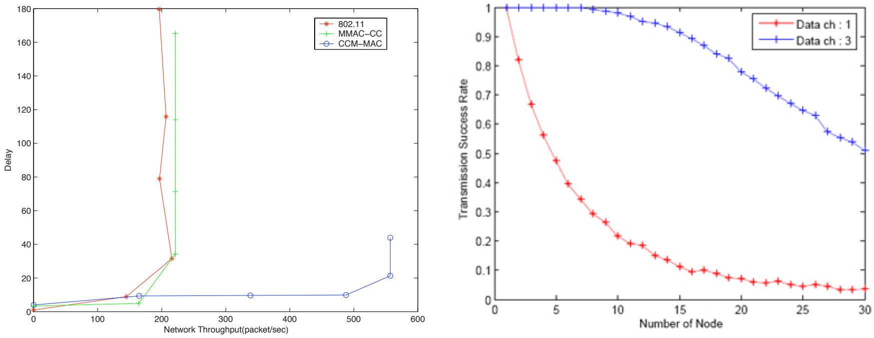


(c) 2 *Kbyte* packets

Fig. 6. Throughput as a function of node density

times higher than MMAC-CC, while the throughput of MMAC-CC is now only 1.1 times higher than IEEE 802.11. For 2 *Kbyte* packets, CCM-MAC is 4.9 times higher than the throughput of the other two protocols, which are essentially the same after 12 nodes. As well, the advantage CDMA becomes more pronounced in sparser networks as the packet size increases. For 500 *byte*, 1 *Kbyte*, and 2 *Kbyte* packets the CDMA advantage becomes evident at about 24, 12, and 6 nodes in the network.

In CCM-MAC, the duration of handshake is fixed. However, the total negotiation cycle for all pairs depends on the actual packet transmission time. This is because the first pair of nodes gain access to the control channel for channel negotiation as soon as they complete packet transmission. Hence, the larger the packet size, the more chances for other node pairs to complete their handshake resulting in a larger number of nodes that can be transmitting simultaneously; this increases the overall system throughput.



(a) Throughput vs. average delay

(b) Success rate

Fig. 7. Throughput delay curve, and probability of successful packet transmission

We also measured the average packet delay in CCM-MAC, MMAC-CC, and IEEE 802.11. The average delay D is the time elapsed in transmitting one data packet using the entire system bandwidth. Following Kleinrock and Tobagi [22], the delay is given by

$$D = \left(\frac{G}{S} - 1\right) \times R, \text{ where } R = N + 2a + \alpha + \delta \qquad (9)$$

where G is the offered traffic, S is throughput, and N is the number of channels. R is the sum of the packet transmission time, the round trip propagation delay, the transmission time for the acknowledgment (α), and the average retransmission delay (δ). We assume that ACK transmission and propagation delay time is so small that we can ignore their contribution to delay.

We assume that each protocol has same value of δ. Figure 7(a) shows that the average delay for CCM-MAC remains stable at the higher traffic loads. At low traffic loads, IEEE 802.11 and MMAC-CC have a slightly better delay because both procotols have a wider bandwidth than CCM-MAC for each channel. Figure 7(b) shows how the probability of successful packet transmission in CCM-MAC for one and three data channels for increasing node density. It is not surprising that the probability of successful transmission increases as the number of available channels increases.

6 Conclusion

In this paper we presented CCM-MAC, a cooperative CDMA-based multichannel MAC protocol for ad hoc networks. It addresses the near-far problem of CDMA through multiple access interference, and mitigates the hidden and exposed terminal problems in multi-channel systems, both through cooperation. At high loads, and in denser networks, the protocol shows a significant improvement in throughput as well as lower delay than IEEE 802.11 and MMAC-CC.

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