Cooperative Multi-Channel MAC Protocols for Wireless Ad Hoc Networks

by

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ABSTRACT

Today, many wireless networks are single-channel systems. However, as the interest in wireless services increases, the contention by nodes to occupy the medium is more intense and interference worsens. One direction with the potential to increase system throughput is multi-channel systems. Multi-channel systems have been shown to reduce collisions and increase concurrency thus producing better bandwidth usage. However, the well-known hidden- and exposed-terminal problems inherited from single-channel systems remain, and a new channel selection problem is introduced.

In this dissertation, Multi-channel *medium access control* (MAC) protocols are proposed for *mobile ad hoc networks* (MANETs) for nodes equipped with a single half-duplex transceiver, using more sophisticated physical layer technologies. These include *code division multiple access* (CDMA), *orthogonal frequency division multiple access* (OFDMA), and diversity.

CDMA increases channel reuse, while OFDMA enables communication by multiple users in parallel. There is a challenge to using each technology in MANETs, where there is no fixed infrastructure or centralized control. CDMA suffers from the near-far problem, while OFDMA requires channel synchronization to decode the signal. As a result CDMA and OFDMA are not yet widely used.

Cooperative (diversity) mechanisms provide vital information to facilitate communication set-up between source-destination node pairs and help overcome limitations of physical layer technologies in MANETs.

In this dissertation, the Cooperative CDMA-based Multi-channel MAC (CCM-MAC) protocol uses CDMA to enable concurrent transmissions on each channel. The Power-controlled CDMA-based Multi-channel MAC (PCC-MAC) protocol uses transmission power control at each node and mitigates collisions of control packets on the control channel by using different sizes of the spreading factor to have different processing gains for the control signals. The Cooperative Dual-access Multi-channel MAC (CDM-MAC) protocol combines the use of OFDMA and CDMA and minimizes channel interference by a resolvable *balanced incomplete block design* (BIBD).

In each protocol, cooperating nodes help reduce the incidence of the multi-channel hidden- and exposed-terminal and help address the near-far problem of CDMA by supplying information.

Simulation results show that each of the proposed protocols achieve significantly better system performance when compared to IEEE 802.11, other multi-channel protocols, and another protocol CDMA-based.

To my Lord.

I am nothing without you.

To my family, Seohyun, Chaejun, and Myungsoon,

And my parents, Byungchan and Minja.

You have always been there through the hard times.

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INTRODUCTION

1.1 Motivation

There are many situations in which mobile wireless users cannot count on the aid of a centralized architecture for connectivity. Some examples include combat missions, search and rescue operations, and natural disasters. A *mobile ad hoc network* (MANET) is a self-configuring network of mobile devices connected by wireless links. It enables wireless communication among mobile users without the aid of a fixed infrastructure or a central controller, such as in cellular networks. Each node in a MANET is free to move independently in any direction. Therefore, its links to other nodes may change frequently. MANETs support wireless communication through the dynamic infrastructure constructed by the mobile users themselves. Such a capability creates challenges at all levels of the network protocol stack and, as a result, there has been significant research activity in the past decades, especially at the transport [4, 8, 12, 76], network [5, 7, 13, 18], and *medium access control* (MAC) layers [14, 31, 51, 62, 78]. In this dissertation, we focus our research on MAC protocols for MANETs.

In all networks with a broadcast channel, all nodes share the medium; a wireless network is one example using a broadcast channel. Therefore, accessing the medium is a fundamental problem, and the main job of a MAC protocol is to coordinate the access to the medium. Contention occurs when multiple nodes compete for access to a channel. A collision occurs when the transmissions of two or more nodes overlap in time. How effectively a MAC protocol manages contention and minimizes collisions impacts the network performance.

A great many MAC protocols have been proposed. The MAC protocols for MANETs can be classified broadly into two categories: Contention based [41, 47, 51] and schedule based [40, 58, 66]. Schedule based protocols can avoid contention and collisions by scheduling transmit and receive periods but have strict time synchronization requirements which is difficult in MANETs. The contention based protocols do not have any time synchronization requirements and can more easily adjust to topology changes as nodes move, join or leave the network. Here, our focus is on contention based protocols.

The most widespread wireless MAC protocol is a *carrier sense multiple access with collision avoidance* (CSMA/CA) protocol used in the IEEE 802.11 standard with a single channel. The unique aspects of this protocol are that it randomly defers packets in the backoff domain to reduce the number of collisions in the network, and that only one node in each contention region of the network can transmit as the others would cause potential interference and packet loss [21]. However, there are many drawbacks of this protocol; one of the more prominent is declining performance in heavily loaded networks since bandwidth is wasted in resolving collision, and backoff contributes to increasing in delay. Therefore, improving performance throughput is one of the major challenges in MANETs.

Multi-channel systems which have the potential to increase system throughput [39, 50, 65, 69], are a rapidly growing research area. Indeed, the IEEE 802.11 standard for wireless *local area networks* (LANs) [16] provides multiple channels available for use. The IEEE 802.11b physical layer (PHY) has 14 channels, $5\,MHz$ apart in frequency [16]. However, to be non-overlapping, the frequency spacing must be at least $30\,MHz$. Channels 1, 6 and 11 are typically used for communication in current implementations, and thus we have 3 channels for use. IEEE 802.11a provides 12 channels, 8 in the lower part of the band for indoor use and 4 in the upper part for outdoor use [1]. The change from a single channel to a multi-channel system was a breakthrough in itself because using a multi-channel system supports some performance advantages by reducing collision and enabling more concurrent transmissions, thus producing better bandwidth usage even with the same aggregate capacity. However, theoretically, splitting a channel into smaller sub-channels does not increase capacity in general. For example, using 1 channel W bandwidth, the capacity of a network which is time shared by 2 node pairs is: $C_1 = W \log_2(1 + \frac{P_r}{N_O W})$ based on Shannon's equation [60]. Here, P_r is the received power, and N_O is the noise spectral density. Using 2 narrower channels each of W/2 bandwidth, two senders can each have a capacity of $C_2 = \frac{W}{2} \log_2(1+\frac{\frac{P_r}{2}}{N_O \frac{W}{2}})$ which is exactly half of C_1. Therefore, the per sender share of the capacity remains the same even though in practice, the use of multiple channels has some performance benefits such as parallel transmission and low delay in a dense network. In other words, the throughput of MAC protocol exploiting multi-channel may be bounded by the bandwidth assigned. By the limited bandwidth, the capacity of network to support many nodes is limited as well.

Several MAC protocols are proposed that use multiple channels to improve throughput [24, 27, 41, 49, 65]. In these MAC protocols, several methods are applied to address problems occurring in multi-channel systems, such as power control [27, 37], node cooperation [32, 41], synchronization of transmission time by beaconing [65]. Some protocols require multiple transceivers at each node [20, 24, 74] which is expensive in terms of hardware. However, it is not easy to design a MAC protocol exploiting multiple channels. Now, a sender and receiver must both agree upon a channel for communication; this is the channel selection problem. In addition, the well-known hidden and exposed terminal problems of single channel systems still remain in a multi-channel setting. Without addressing the problems, optimal efficiency cannot be achieved from a multi-channel system. Also, the limitation on throughput bounded by bandwidth should be in concern.

In cellular networks, the various spread spectrum methods such as *code division multiple access* (CDMA) and *orthogonal frequency division multiple access* (OFDMA) are adopted on physical access layer [6] to improve channel capacity. In CDMA, each user is assigned a unique code that is pairwise orthogonal. It supports more than one communication on a channel at a time until the channel is saturated [73]. CDMA employs spread-spectrum technology and a special coding scheme to allow multiple nodes over the same physical channel where each node occupy the entire available bandwidth. Therefore, it supports more than one communication on a single channel simultaneously without any collision. In addition, when a transmission power control is combined with CDMA, it improves the advantage of CDMA we can achieve because by power control mechanism, each user can control transmission range so as not to interfere on-going communication which is in original transmission range as well as not to break the orthogonality of the signal. While CDMA increases channel reuse ratio, OFDMA supports differentiated quality of service by assigning a different number of sub-carriers to different users [19, 35]. OFDMA employs multiple closely spaced sub-carriers, but the sub-carriers are divided into groups of sub-carriers. Each group is named a sub-channel. OFDMA enables either transmission or reception of multiple packets to/from multiple users concurrently [72].

While widely used in cellular systems, there are two major challenges to adopt these technologies in MANETs. One is the near-far problem of CDMA, which occurs when a signal from a closer sender is much stronger than from a sender farther away [60]. The other is the channel synchronization problem of

OFDMA. When the sub-channels are not synchronized between a transmitter and receiver, the receiver cannot decode the signal because it cannot detect the signal. Instead, the receiver recognizes the signal as noise. In cellular or infrastructure based network environments these problems are solved by the central controller (base station) controlling the transmission power to equalize the signals in CDMA, or assigning well organized channel group to each user in OFDMA.

These solutions are not feasible in MANETs where there is no central controller that has complete understanding of the network topology, which would be able to manage all nodes at once. As a result, OFDMA and CDMA are not yet widely used in ad hoc networks. There are some proposed MAC protocols for MANETs using CDMA [15,25,67] and OFDMA [33,71]. But the focus is on taking advantage of using spread spectrum mechanisms without concern of the near-far problem of CDMA as well as on resource allocation algorithms in terms of power, bit, and subcarriers in the time domain and do not provide MAC solution. Both the near-far problem of CDMA and the channel synchronization problem of OFDMA cannot be ignored when these technologies are adopted into MANETs.

1.2 Contributions of this Dissertation

Motivated by the various challenges mentioned here, we propose several multi-channel MAC protocols for ad hoc networks in which each node is equipped with a single half-duplex transceiver, exploiting node cooperation, transmission power control, and spread spectrum mechanism [43, 45, 46]. The two major contributions of this dissertation are: 1) to enable MAC protocols to use the physical access schemes such as CDMA and OFDMA effectively in MANETs, and 2) to improve network throughput. Specifically, the contributions of this dissertation in more detail are as follows:

We proposed multi-channel MAC protocols for MANETs that allow nodes to transmit in parallel on distinct channels. Moreover, using a dedicated channel for the exchanges of control messages helps solve the channel selection problem and reduce data packet collision.

To enable MAC protocols to use the physical access schemes the key issues are to resolve the near-far problem and the channel synchronization problem.

Node cooperation is used to collect the information about channel usage and to inform neighbouring nodes of the information collected. Transmitters can make a better decision about what channel to select based on the information obtained from cooperating nodes. The near-far problem of CDMA is mitigated with the help of cooperating nodes to facilitate communication set-up and with the transmission power control mechanism that adjusts transmission power at each node to reduce interference power which may disturb on-going communications. Also, it may mitigate multi-channel hidden- and exposed-terminal problems as well as near-far problem, which occur due to lack of knowledge of channel usage. In this sense, node cooperation is key for effective use of CDMA and OFDMA. We use clustering network to address the channel synchronization problem of OFDMA. Also, a resolvable balanced incomplete block design (BIBD) is used to define channel groups; this minimizes interference among groups used in adjacent clusters. The multi-channel hidden- and exposed-terminal problems are solved when the communicating pair are affiliated with the same cluster, and mitigated otherwise.

By adopting physical access technologies, such as CDMA and OFDMA, which have high spectral efficiency, channel utilization is improved. In addition, we use the transmission power control which may increase the channel reuse ratio. The transmission power control combined with CDMA increases the number of concurrent transmissions compared to using transmission power control alone. Also, it decreases interference effectively and as a result, improves network throughput. We also use variable spreading factors on the control channel to increase the channel reuse ratio and to reduce the near-far problem. Using different spreading factors, each node produces different spreading degree of the signal for the packets on the control channel. This reduces effectively the incidence of the near-far problem than using the same spreading factor, and enhances the advantage of using CDMA.

The result of simulations show that our proposed protocols [43, 45, 46] achieve a significantly better performance throughput and delay among several other protocols including one that uses multiple channels. They also, show competitive or slightly better throughput and delay than CDMA-based MAC protocol for nodes equipped with multiple transceivers.

1.3 Organization of this Dissertation

The rest of this dissertation is organized as follows. In Chapter 2, an overview of related work is described. We give an overview of MANETs and 802.11 standard, and review the related work on protocols that use multiple channels, node cooperation, transmission power control, and spread spectrum. The details of our proposed protocols [43, 45, 46] and the performance evaluation of each protocol are presented in Chapters 3, 4, and 5. In Chapter 3, a cooperative CDMA-based multi-channel MAC (CCM-MAC) protocol is introduced. A power controlled CDMA-based multi-channel MAC (PCC-MAC) is presented in Chapter 4. In Chapter 5, a cooperative dual access multi-channel MAC (CDM-MAC) protocol is described. Finally, in Chapter 6, we conclude and propose the future research directions.

BACKGROUND AND RELATED WORK

In this chapter, we first give an overview of mobile ad hoc networks (MANETs) in Section 2.1 since all the protocols reviewed here including those proposed in this dissertation, are for MANETs. In Section 2.2, we describe the IEEE 802.11 standard protocol, as it is the most commonly used MAC protocol for wireless networks. Related work on multi-channel MAC protocols is presented in Section 2.3. Node cooperation mechanisms and its use in wireless networks are discussed in Section 2.4. Transmission power control is reviewed in Section 2.5. Finally, related work on the use of spread spectrum techniques is presented in Section 2.6.

2.1 Overview of MANETs

A *mobile ad hoc network* (MANET) is an autonomous collection of mobile nodes that communicate over bandwidth constrained wireless links as shown in Figure 1, where S is a source node and D is a destination node. It enables mobile nodes to communicate with each other through wireless links without any help of a fixed infrastructure or a central controller (base station).

The nodes are free to move randomly and organize themselves arbitrarily. The strength of the connection between the nodes can change rapidly in time or even disappear completely. Nodes can appear, disappear and re-appear as time goes on. Thus, the network's topology may change rapidly and unpredictably over time and, in spite of this, the network connections should be maintained if possible.

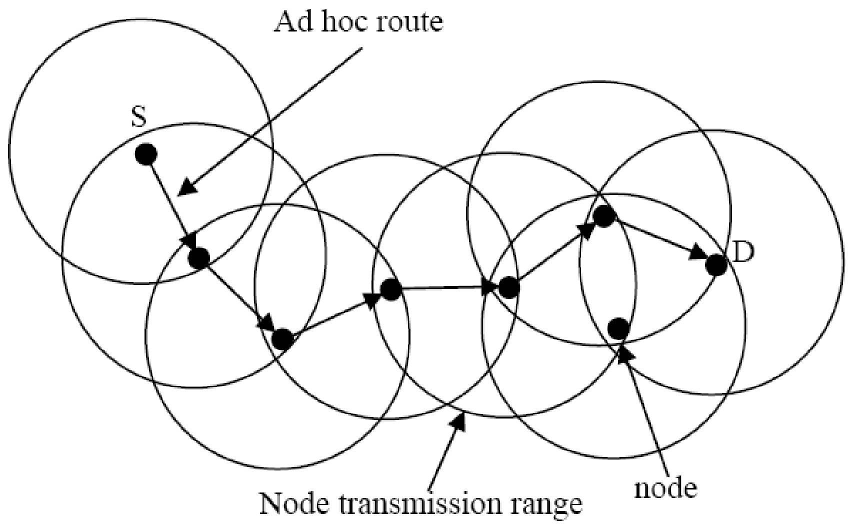
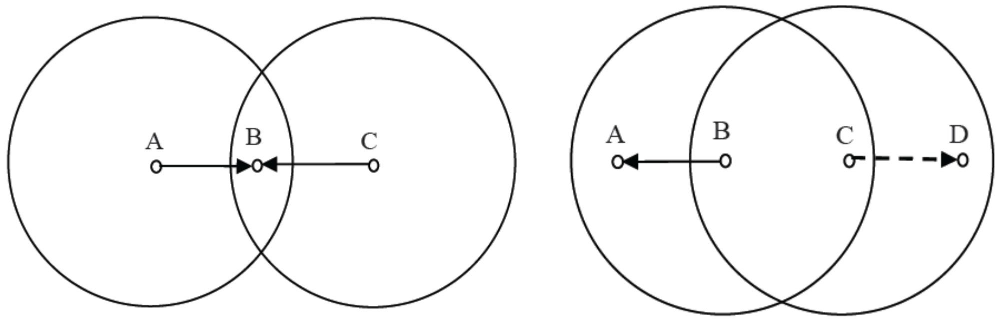


Fig. 1. An ad hoc wireless network.

The network is decentralized, where all network activity including organizing the network and delivering messages must be executed by the nodes themselves, *i.e.,* routing functionality is incorporated into mobile nodes. By the local broadcast nature of wireless channel, a node's transmission is received by all nodes within one hop transmission range. In general, a MANET consists of many nodes that are not all within one hop transmission range of each node, and a packet must traverse multiple hops to reach its destination as in Figure 1. Since the MANET features fully distributed network management [59] and dynamic link change between nodes, each node must gather and maintain enough information about network topology so that it can make independent decisions about how to route data through the network to any destination. Thus, message routing is a challenging problem in MANETs.

In addition, since all the individual nodes in a MANETs share a common wireless transmission medium via distributed mechanisms, the transmissions among competing nodes must be coordinated by the *medium access control* (MAC) protocol. The MAC protocol coordinates transmissions from different nodes in order to minimize/avoid collisions. This main issues that should be considered while designing a MAC protocol for MANETs are bandwidth efficiency, and the hidden- and exposed-terminal problems [23, 26]. Since the radio spectrum is limited, the bandwidth available for communication is very limited. Consider Figure 2, which shows examples of hidden- and exposed-terminal problems with a single channel system. The hidden-terminal problem refers to the collision of packets at a receiving node due to simultaneous transmission of those nodes that are not within the direct transmission range of the sender, but are within the transmission range of the receiver. A collision occurs when the transmission of two nodes overlaps in time [63]. Figure 2 (a) shows an example of A and C hidden from each other.

In this figure, both nodes A and C have a data packet to send to node B. Node A is sending a data packet to node B. Now suppose that node C initiates a data transmission to node B. It is possible because node C is out of the transmission range of node A and cannot sense the signal of node A. In this case, the data packets from both nodes A and C collide at node B.



(a) Hidden terminal problem. (b) Exposed terminal problem.

Fig. 2. The hidden and exposed terminal problems in a single channel.

Figure 2(b) shows an example of the exposed terminal problem. The exposed terminal problem occurs when a node is prevented from sending packet due to a neighbouring transmitter. In Figure 2(b), suppose that both nodes B and C have a data packet to send to node A and D, respectively, and that node B negotiates access to the channel using a CSMA-based protocol. At this time, node C defers its transmission because it senses the transmission of node B. However, since node A is out of the transmission range of node C, the signal from the node C would not interfere with the reception at the node A.

The hidden- and exposed-terminal problems cause bandwidth to be wasted. When two nodes that are hidden from each other transmit a packet to the same receiver, if the packets collide at the receiver, they each back off for some time. The bandwidth is wasted during the backoff period. When two nodes are exposed to each other, even though they could transmit concurrently, one of the transmitters postpones its transmission. As a result spatial reuse is limited.

Therefore, the MAC protocol for MANETs should be designed in such a way that the scarce bandwidth is utilized in an efficient manner and the hidden- and exposed-terminal are reduced effectively. However, determining viable channel access in a decentralized environment where multiple nodes compete for access to the channel is not an easy problem. Thus, MAC is also a fundamental problem in MANETs.

2.2 Overview of IEEE 802.11 Protocol DCF and its Inherent Problems

The IEEE 802.11 *distributed coordination function* (DCF) is a fully distributed scheme based on *carrier sense multiple access with collision avoidance* (CSMA/CA) [21]. In a CSMA/CA based protocol, node A wishing to transmit a packet to node B has to first listen to the channel for a *distributed interframe space* (DIFS) time so as to check for any activity on the channel. If node A senses any activity on the channel, it defers its transmission and follows an exponential backoff algorithm. If there is no activity sensed on the channel, node A transmits a *request to send* (RTS), which include the source, destination, and the duration of following transaction (*i.e., the packet and the respective ACK*). If the RTS is received by node B, it responds with a *clear to send* (CTS), which includes the same duration information. If the CTS is not received by node A, node A will retransmit the RTS based on an exponential random backoff algorithm. On receipt of the CTS, node A transmits the data packet to node B. If the data transmission is completed successfully, node B transmits an *acknowledgement* (ACK) to node A. If node A does not receive the ACK, it will retransmit the data packet until it gets acknowledged or thrown away after a given number of retransmissions. All other nodes receiving either the RTS and/or the CTS, will set their *network allocation vector* for the given duration to reduce the probability of a collision in both the sender's A and receiver's B area.

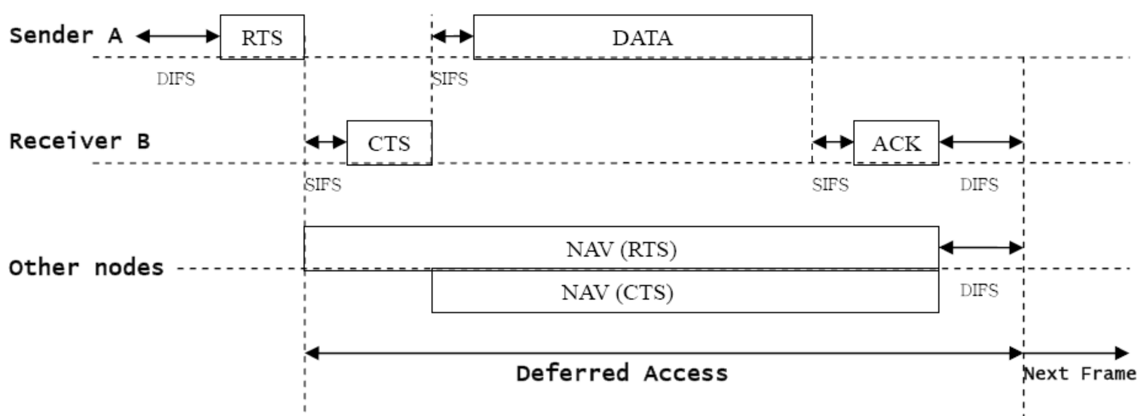


Fig. 3. Handshake of the IEEE 802.11 protocol.

Figure 3 shows the sequence of the handshake of the IEEE 802.11 protocol. The *short interframe space* (SIFS) and *distributed interframe space* (DIFS) are types of interframe spacing (time intervals) between packets. The IFSs provide priority levels for accessing the channel. The SIFS is the shortest of the interframe spaces and is used after RTS, CTS, and DATA packets to give the highest priority to CTS, DATA and ACK, respectively.

IEEE 802.11 relies on physical carrier sensing and is known to suffer from the hidden- and exposed-terminal problems [21].

2.3 Multi-channel Systems

It is now well known that wireless networks with a single channel are fraught with significant capacity problems [17, 39, 44, 50]. Due to the broadcast nature of wireless transmissions – resulting in interference – only one transmission can occur in a physical neighbourhood. In recent years several diversity techniques have been used to get around this fundamental limitation. One such diversity technique now being widely studied is to use multiple channels. Using multiple channels in MAC protocols for wireless ad hoc networks has mainly been studied with the objectives to reduce contention in the network and to improve the performance through parallel transmission [39, 50, 51, 65, 69, 80].

Figure 4 is example showing the benefit of using multiple channels. In this figure, there are three pairs of communicating nodes. Let the packet arrival times at node A, C, and E be denoted by T_A, T_C, and T_E, respectively. If all transmissions are performed on a single channel, node C and E will find the channel busy at the times of their packet transmissions and have to backoff for random time intervals before they are eventually transmitted. On the other hand, if three channels, are available and each node is able to find a free channel

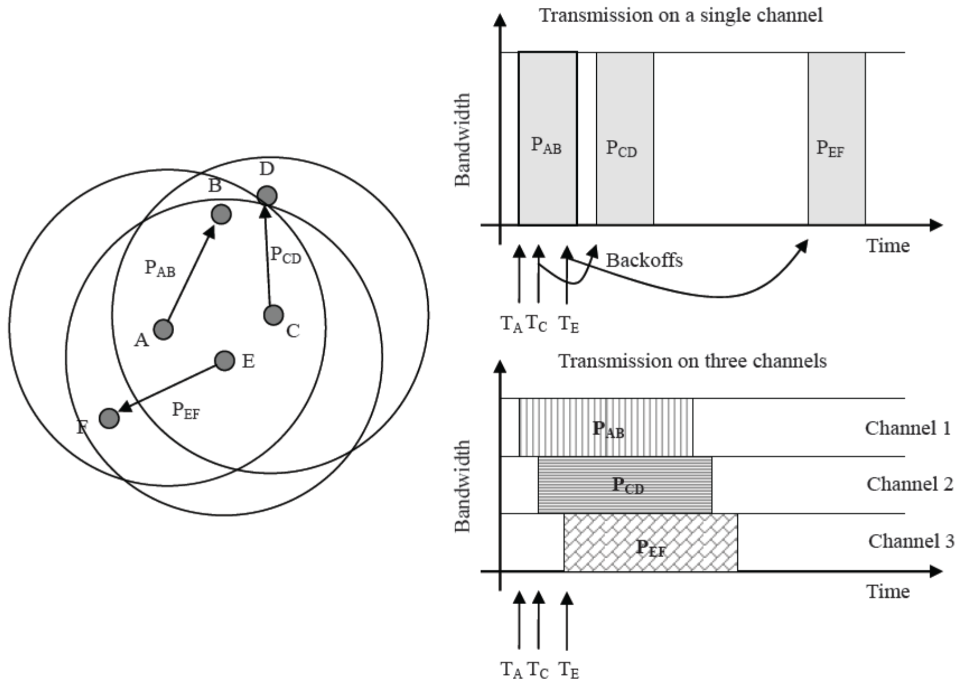
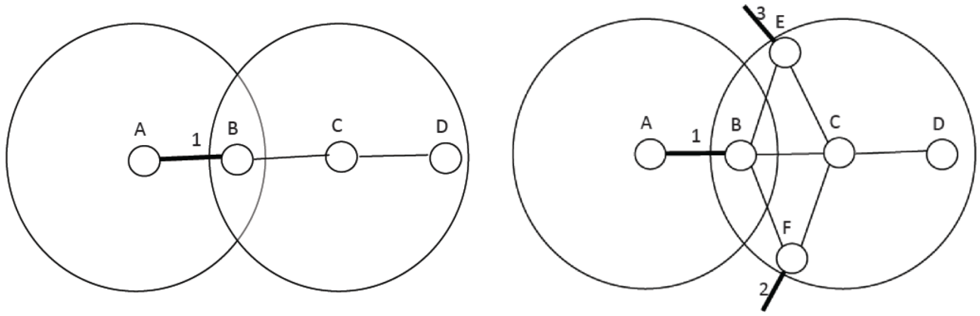


Fig. 4. Single channel vs. Multiple channels.

for its transmission, there would be no need for backoffs. As shown in Figure 4, with multiple channels, the time to transmit is larger than on a single channel since the bandwidth is less. However, the time to complete all transmissions can be shorter than resolving backoff. Hence, the average channel utilization and throughput in this scenario is better with three channels instead of one, even if the same aggregate channel capacity is used in both cases. This is primary advantage of using multiple channels in a wireless network.

However, it also brings a new channel selection problem. In multi-channel systems, the overall bandwidth is divided into several non-overlapping channels and every node operates on any one of the channels for communication.



(a) Hidden terminal problem. (b) Exposed terminal problem.

Fig. 5. The hidden and exposed terminal problems in multi-channel systems.

If a node is equipped with only one half-duplex transceiver, when this node activates on a particular channel it cannot hear any communication taking place on a different channel. Therefore, a sender and receiver must both agree upon a channel for communication.

Moreover, there still exist the hidden- and exposed-terminal problems inherited from the single channel systems. Consider Figure 5, which shows the examples of hidden- and exposed-terminal problem in multi-channel systems. Figure 5(a) shows a communication between nodes A and B in progress on channel 1. Now suppose that nodes C and D select channel 2 for communication. When nodes A and B complete their transmission, neither has overheard the negotiation of channel 2 by nodes C and D, assuming each has a single half-duplex transceiver. As a result, a collision occurs on channel 2 if A then negotiates it for communication with B.

Figure 5(b) illustrates the exposed terminal problem in a multi-channel setting. Suppose that the system has three channels and that channels 2 and

3 are in use by nodes E and F (to destinations not shown in the figure). Suppose also that nodes B and C have packets queued for transmission to nodes A and D, respectively. There is a free channel (channel 1) available; nodes B and C may even know this information because they are both in the transmission range of nodes E and F. However, assuming the use of a *carrier sense multiple access* (CSMA) based protocol, only one of B or C uses channel 1 for communication, while the other defers its transmission.

The change from a single channel to a multi-channel system provides some performance advantages with the same aggregate capacity. However, since the channel selection, the hidden- and exposed-terminal problems exist in a multi-channel system, the optimal efficiency that can be derived from multiple channels cannot be achieved. Therefore, these problems should be tackled to improve performance in a multi-channel MAC protocol.

2.3.1 Multi-Channel MAC Protocols

We classify the protocols as whether there is a dedicated control channel, and how many transceivers are in use.

Some multi-channel MAC protocols use a control channel for channel selection. Of those that do not use a control channel, some protocols [39, 65, 69, 80] assume that nodes are equipped with a single-transceiver. So and Vaidya [65] use a beacon signal to make periodic transmissions and give contention window time to all nodes that hear the beacon. Nodes then negotiate with each neighbour for a channel. Figure 6 shows the processing of channel negotiation

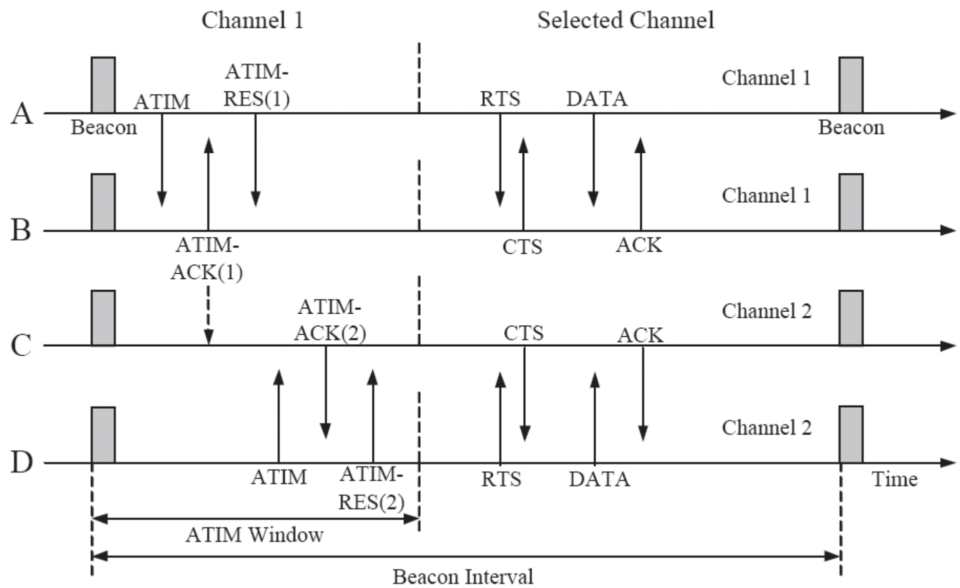


Fig. 6. Processing of channel negotiation and data exchange.

and data exchange in their protocol. During the *ad hoc traffic indication messages* (ATIM) window, A sends an ATIM to B and B replies with ATIM-ACK indicating to use channel 1. This ATIM-ACK is overheard by C, so channel 1 is moved to the low state (low preference) in C's *preferable channel list* (PCL). When D sends an ATIM to C, C selects channel 2. After the ATIM window, the two communications (between A and B, and C and D) can take place simultaneously.

Zhou et al. [80] propose a multi-frequency MAC protocol. It uses multiple frequencies to transmit or receive, and senses the carrier signal on all frequencies rather than using a handshake. Lo et al. [39] use 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.

Tzamaloukas et al. [69] propose a receiver-initiated channel hopping scheme (RICH). The RICH protocol is based on simple polling by the receiver. The nodes of a frequency-hopping network must agree on when to hop. A common frequency-hopping sequence is assumed by all the nodes, so that nodes listen on the same channel at the same time. Nodes perform a receiver initiated collision avoidance handshake to determine which communication pair should remain in the present hop to exchange data, while all other nodes continue hopping using the common hopping sequence. The dwell time for a frequency hop in RICH need be only as long as it takes for a handshake to take place. A node ready to poll any of its neighbours sends a *ready to receive* (RTR) control packet over the current channel hop specifying the address of the intended sender and the polling node's address. If the RTR is received successfully by the polled node, that node starts sending data to the polling node immediately and over the same channel hop, and all other nodes hop to the next channel. When the transmission of data is completed, the sender and receiver re-synchronize to the current channel hop. If either multiple RTRs are sent during the same channel hop, or the polled node has no data to send to the polling node, the polling node does not receive any data a round-trip time after sending its RTR and must rejoin the rest of the network at the current channel hop.

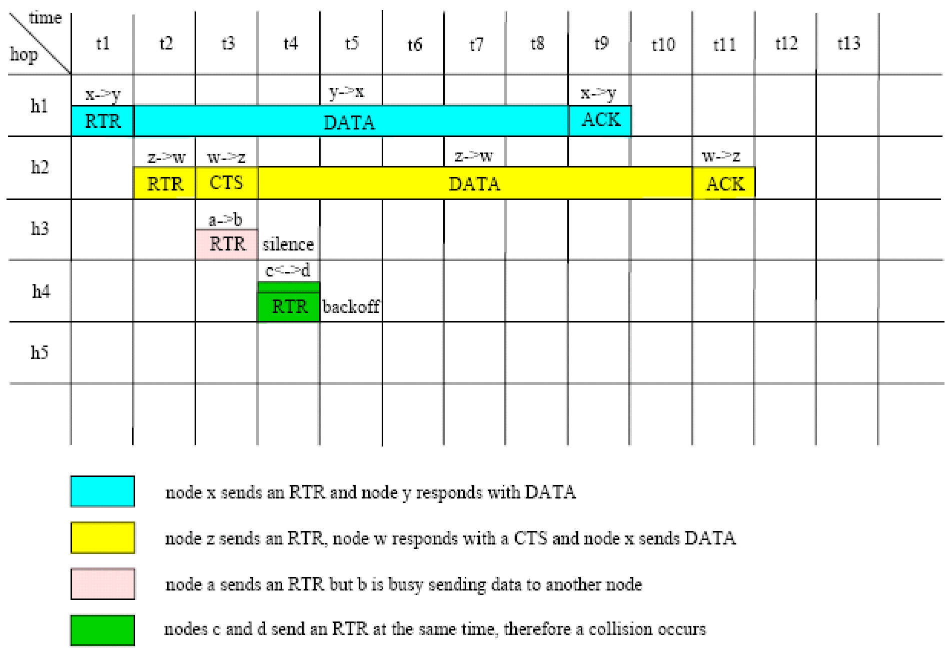


Fig. 7. Processing of RICH.

Figure 7 illustrates the operation of RICH. In this figure, all the nodes start at time t_1 on channel h_1. At time t_2 the nodes hop to h_2, and so on. Node x sends an RTR to node y and node y responds with data over the same channel at time t_1. Notice that there is a probability of $\frac{1}{N-1}$ that node y has data for x, where N is the number of nodes in the network. While x and y, stay on channel h_1 until y has finished sending its data, all the other nodes hop to h_2. At time t_2 another node z sends an RTR to node w, but now it is the case that w does not have a data packet for z; therefore, w sends a CTS enabling z to send any data to w. At time t_4 node z starts sending its data to w. Again, nodes z and w stay on channel h_2 until z finishes sending its data, while the other nodes hop to h_3. At time t_3, node a sends an RTR to node b but node b is busy transmitting data to another node. Therefore, node b does not receive the RTR and at time t_4 there is silence. In this case, node a continues to hop with the other nodes to channel h_4. At time t_4 nodes c and d send an RTR and therefore a collision occurs. Both nodes have to backoff and try to send an RTR at a later time.

For nodes equipped with multiple transceivers, Kyasanur et al. [34] propose routing and interface assignment in a multi-channel multi-interface wireless network. It considers the scenario when the number of available interfaces is less than the number of available channels or vice versa. It uses a static interface assignment that fixes one interface on a channel when there are more interfaces than channels. Dynamic interface assignment, where each interface can switch from one channel to another, and hybrid interface assignment, which combines static and dynamic assignment, are used when there are fewer interfaces than channels. In Nasipuri et al. [49, 51] and Zhang et al. [79] proposed each node can listen to all channels concurrently and choose the one that has the lowest signal power. These protocols require as many transceivers as channels. Adya et al. [2] propose a multi-radio unification protocol for IEEE 802.11 wireless networks. It uses a probe message to estimate channel quality and when a channel is chosen, it splits data over multiple radios, which elevates spectrum usage.

Some multi-channel MAC protocols using a control channel use only one transceiver. The dynamic channel assignment with power control protocol, proposed by Wu et al. [75], expects the best channel to be the one in use by another sender located the farthest distance away; they check signal power on the transmitter side only. Similarly, Nasipuri et al. [50] propose a multi-channel MAC protocol with cooperative channel selection (MMAC-CC). In the MMAC-CC, control packets except ACK, and data and ACK packets are transmitted on the control channel and on the data channel, respectively. When a node has a data packet to send, it first sends an RTS containing the free channel list obtained by sensing the carrier signal on data channels. When the RTS is received by a receiver, the receiver creates its own free channel list by sensing the carrier signal on data channels. Then, the receiver selects best common channel for both the transmitter and receiver and sends this channel information in the CTS packet. Based on this channel information, the transmitter selects a channel and initiates data transmission. While the receiver is receiving a data packet, it sends busy-tones on the data channel in use. It helps other transmitters to make their free channel lists.

Of those that use a control channel, some protocols assume that nodes are equipped with multiple transceivers. At one extreme, Jain et al. [24]

use as many transceivers as channels, and include free channel information in the handshake. Wu et al. [74] propose a multi-channel MAC protocol with on-demand dynamic channel assignment. Each node uses two half-duplex transceivers, and each one is used on a dedicated channel. Hung et al. [20] propose a multi-channel MAC protocol, called Dynamic Private Channel (DPC), that uses dynamic channel allocation for ad hoc networks. It uses multiple transceivers for control and data channels. Each node obtains channel usage information by overhearing the handshake.

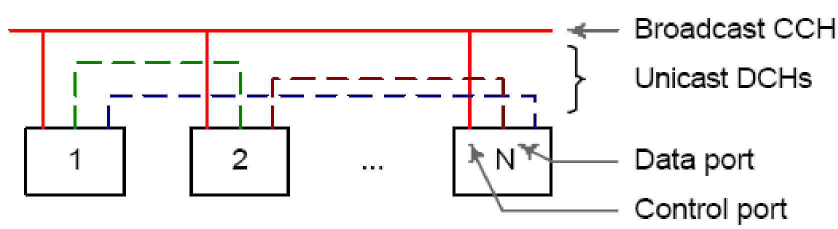


Fig. 8. Multi-channel system used in DPC.

Figure 8 shows the multi-channel system for their protocol. Each DPC node is equipped with $N_I + 1$ transceivers, where $N_I = 1$. There is one broadcast control channel (CCH) and multiple unicast data channels (DCHs). The CCH is shared by all nodes. Therefore, transmission on the CCH will be heard by all nodes within transmission range of the sender. Access to this channel is contention-based. When a node X requests a channel for communicating with another node Y, one of the free DCHs is assigned to the pair (X,Y) for a limited duration T_d. The request of a DCH is performed through the CCH and is coordinated in a distributed manner where all nodes participate. If a node X has a data packet to send to node Y, X will initiate the setup process by sending an RTS to Y through the CCH. Before sending out the RTS, node X chooses a free DCH and includes the channel information in the RTS. When Y receives the RTS, it checks if the channel chosen by X is acceptable. If so, it returns a *reply* to RTS (RRTS) to node X with the same channel information. Otherwise, Y suggests another channel and puts the new channel information in the RRTS. When the channel negotiation comes to an end, both nodes tune one of their transceivers to the selected DCH. The data exchange begins with Y sending out a CTS to X. At the end of T_d or when (X,Y) does not need the channel anymore, the DCH will become free again.

2.4 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, [77]), cooperation is still largely unexplored in MAC protocols for MANETs. Cooperation is the process of working or acting together. The notion of cooperation takes full advantage of the broadcast nature of the wireless channel and creates spatial diversity, thereby achieving an improvement in system robustness, capacity, delay, a significant reduction in interference, and an extension of coverage range [32,38,41,42]. Even though cooperation can be used in wireless networks in many different ways, we focus on cooperation at the MAC layer where idle nodes that overhear transmissions participate in the protocol. The cooperating nodes help facilitate the communication between the active node pair, *i.e.*, the sender/receiver pair.

Luo et al. [41] propose a cooperative asynchronous multi-channel MAC (CAM-MAC) protocol as shown in Figure 9. In this figure, suppose a communication session is to be established between node A and B but these nodes have insufficient knowledge of the channel usage to select a safe (collision-free) channel. This channel usage information can potentially be acquired from idle neighbours (nodes C, D, E) if they maintain such information. Therefore, rather than selecting channels independently, nodes C, D and E help nodes A and B in making a good decision. In CAM-MAC, cooperating nodes help both transmitter and receiver with channel selection.

Ivanov et al. [22] propose a cooperative multi-channel MAC protocol that avoids redundant channel blocking (CAM-MAC ARCB) through virtual topology inferencing. This is an extended version of CAM-MAC [41]. This protocol tries to solve one drawback of CAM-MAC. When information of selected channels is propagated to distant nodes it can prevent nodes from using the specific channel even if the nodes using that channel are not in range. This is called the *redundant channel blocking* (RCB) problem. Figure 10 illustrates the RCB problem. In these figures, suppose that all nodes are equipped with a half-

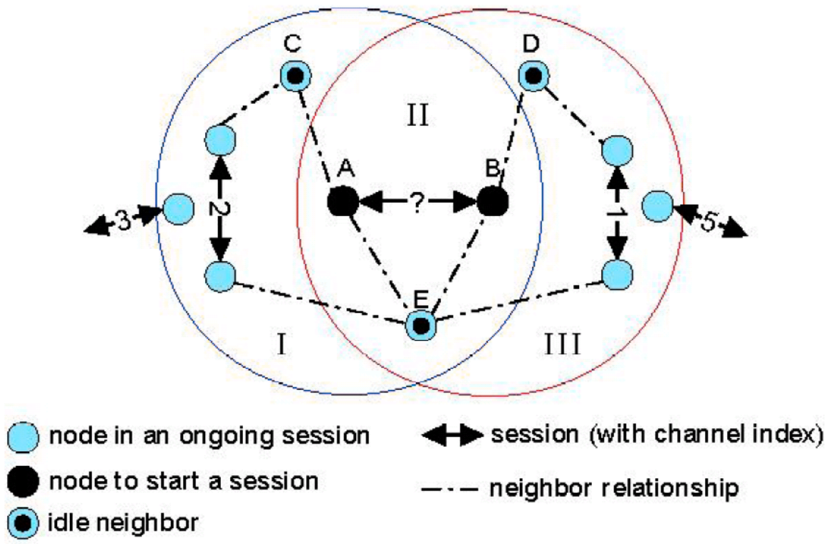
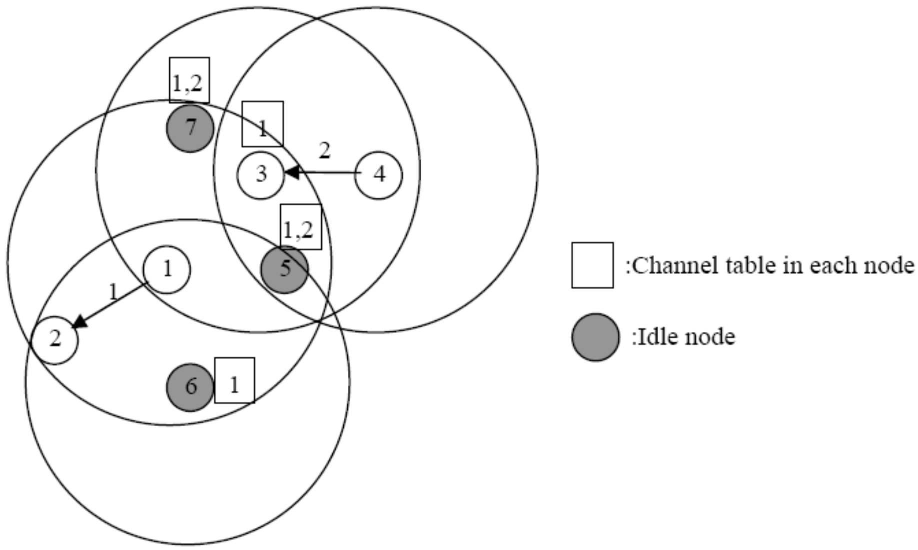
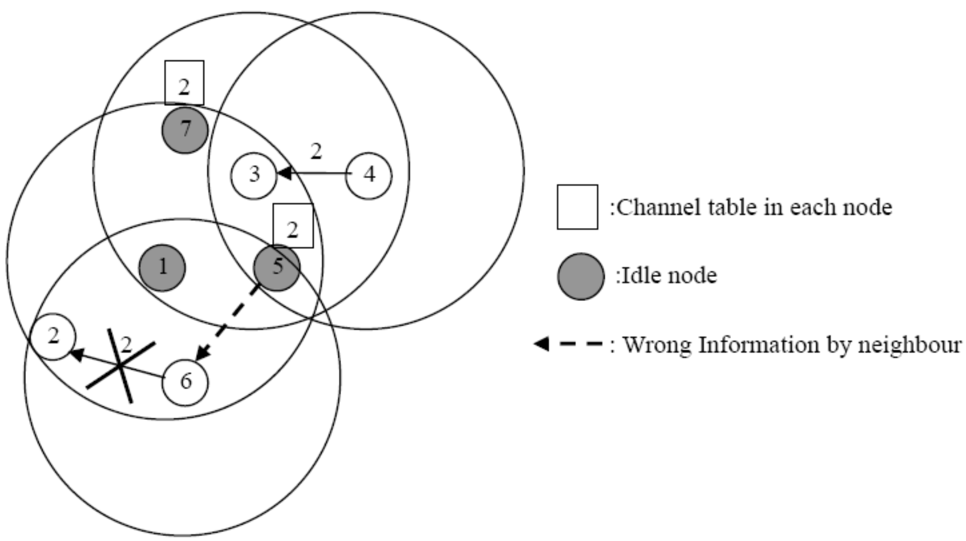


Fig. 9. Observation of CAM-MAC.

duplex transceiver. As shown in Figure 10(a), the channel usage information of channel 1 being used by nodes 1 and 2 is overheard by nodes 3, 5, 6 and 7, which are in the transmission range of node 1. Therefore, when nodes 3 and 4 select a channel for their communication, they choose channel 2 to avoid an overlap of channel. The information about channel 2 being used by nodes 3 and 4 is overheard by nodes 5 and 6, which are in the transmission range of nodes 3 and 4. Consider Figure 10(b). When node 6 would like to transmit data and begins negotiation, node 6 will not be able to use channel 2 even though it is out of the transmission range of nodes 3 and 4. This occurs because when node 6 begins negotiation, node 5 immediately prevents node 6 from using channel 2 even if nodes 6 and 2 are out of transmission range of nodes 3 and 4.



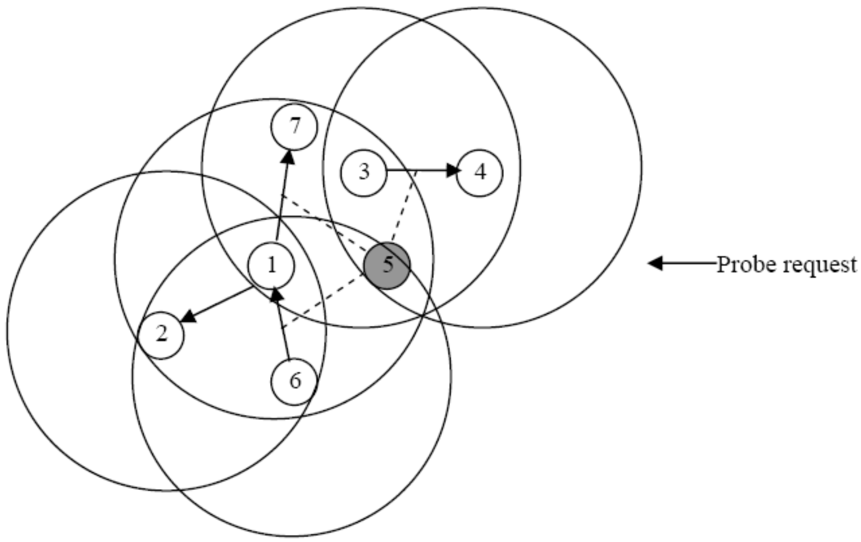
(a) Channel usage information while nodes 1 and 4 are communicating with their receivers



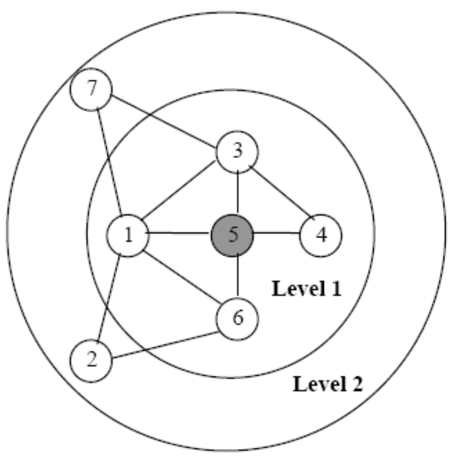
(b) Node 6 begins negotiation with 2, but it is blocked by 5

Fig. 10. Redundant channel blocking (RCB) problem.

To address the RCB problem, in the CAM-MAC ARCB protocol, a node not only determines the channels that are used in its neighbourhood, but also determines the surrounding topology. Figure 11 shows the solution mechanism. In Figure 11(a), node 5 listens to the negotiation process of its neighbours. During the negotiation process, each source node transmits a probe request which contains the source and destination address, and the channel being requested. Node 5 then categorizes the different source and destination addresses as either level 1 or level 2 neighbours, and creates a virtual topology knowledge of surrounding nodes as shown in Figure 11(b). Level 1 neighbours of node j are the nodes in one-hop range of node j while level 2 neighbours of node j are the nodes in two-hop range of node j. When node j overhears a control packet from a source node, it checks virtual topology table. If there is no node address of the source node on level 1 in the virtual topology table, it stores the node address of the source node on level 1. The numbers in brace on level 1 are addresses of destination nodes stored when node j directly overhears a responding control packet from the destination nodes. If node j overhears a control packet only from a source node but not from the destination node, it stores the destination address included in a control packet from the source node on level 2 in the virtual topology table. This leads to each node containing two tables, which is the table of virtual topology (Figure 11(c)), and the table of channels used by the neighbouring nodes (Figure 11(d)). Based



(a) Node 5 sensing neighbours probe request



(b) Virtual topology

Nodes in level 1	Nodes in level 2
3{1,4}	7
4{3}	
6{1}	2
1{3,6}	2,7
⋮	⋮

(c) Virtual topology table by node 5

Source node	Destination node	Channel
3	4	2
1	2	1
⋮	⋮	⋮

(d) Channel table of node 5

Fig. 11. Mechanism of CAM-MAC ARCB.

on this information, when nodes 6 and 1 negotiate to use channel 2, it will be blocked by node 5. However, when nodes 6 and 2 negotiate to use channel 2, it will not be blocked by node 5.

2.5 Power-Control in MAC Protocols

Power control in MAC protocols for MANETs has been studied with the objectives to reduce power consumption and to improve channel reuse [9, 27, 37, 57, 75]. Since our focus is on power control for improving spatial reuse, we discuss the use of power control for this objective. The idea is to use power control to increase the number of concurrent transmissions in the network.

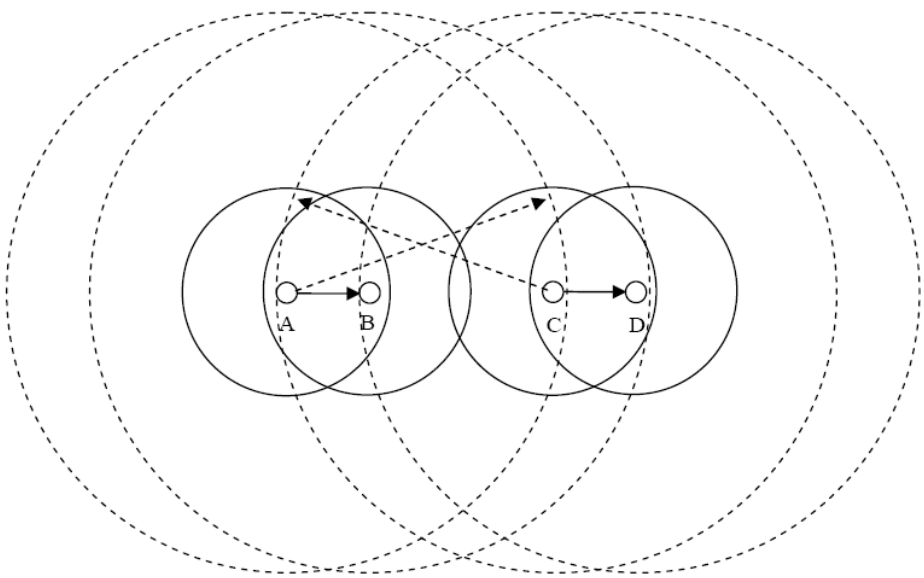


Fig. 12. Changing number of concurrent transmissions by different transmission power.

Consider Figure 12, where the solid and dotted circles represent the transmission range of a node transmitting at low and at high transmission power, respectively. Suppose that nodes A and C have a packet to transmit to nodes B and D, respectively.

There are two different scenarios according to the interference model. First, based on the *protocol interference model*, if nodes A and C transmit at high power at the same time, the two transmissions compete for access to the channel; only one pair is successful while the other is not. On the other hand, if both nodes A and C use low transmission power the two transmissions do not interfere each other and can take place concurrently.

Second, based on the *physical model* of interference, even though both nodes A and C transmit at high power at the same time, both of them may be successful if the ratio of the received signal strength and the sum of the interference caused by nodes sending simultaneously, plus noise is above a certain threshold on nodes B and D. This *Signal to Interference plus Noise Ratio* (SINR) is defined as :

$$SINR = \frac{P_r}{P_{thermal} + P_{mai}}. \tag{1}$$

where P_r is the received signal power, $P_{thermal}$ is thermal noise power, and P_{mai} is multiple access interference power. In Equation (1), transmission power affects both P_r and P_{mai}. Therefore, the proper use of transmission power may improve network capacity.

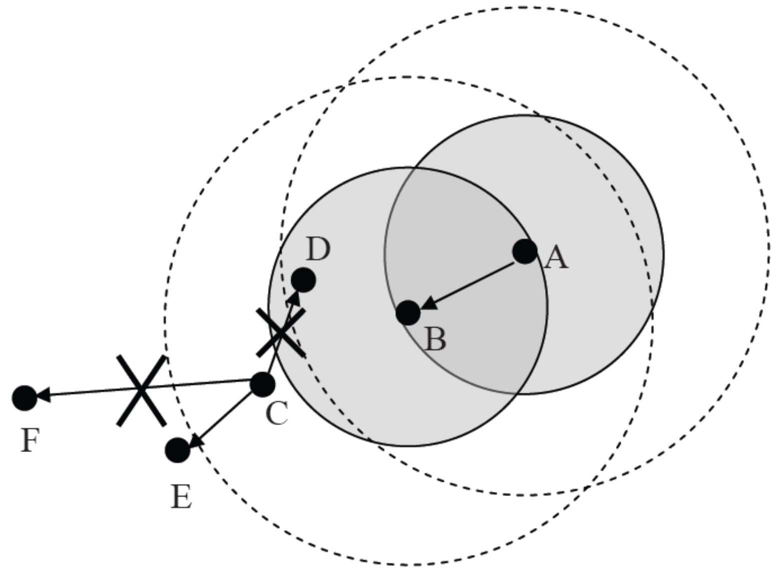


Fig. 13. Power control mechanism of DCA-PC protocol.

Wu et al. [75] propose a dynamic channel assignment protocol with power control (DCA-PC). Figure 13 shows the power control mechanism of DCA-PC protocol. In this figure, the areas bounded by dotted circles represent the transmission ranges of the control packets from nodes A and B. The circles in gray are the transmission ranges of A's data packet and B's ACK packet, respectively. In the DCA-PC protocol, each node is equipped with two transceivers. One is for the control channel. The other is for the data channel. Control packets except $ACKs$ are sent without power control, and data packets are sent with power control. So, nodes C and D each overhear part of the handshake of node pair A and B.

Now, if node C intends to initiate some communication, it may be allowed to use the data channel that A and B are using if its transmission power is properly controlled. If C's intended receiver is D, D will reject C's request to use the same channel used by A and B because it is in the transmission range of node B. If C's intended receiver is E, C will be allowed to use the same channel that A and B are using because it is close. However, if C's intended receiver is farther away, say F, C will try to find a channel other than that used by A and B.

In the DCA-PC protocol, the transmitter obtains the proper transmission power level to use to send a data packet through the control packet exchange with the intended receiver. The following equations are used to obtain the proper transmission power in this protocol:

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^n g_t g_r. \tag{2}$$

When node X sends a packet with power P_t, it is heard by Y with power P_r. In Equation (2), λ is the carrier wavelength, d is the distance between the sender X and the receiver Y, n is the path loss coefficient and g_t and g_r are the antenna gains at the sender and the receiver, respectively. Note that λ, g_t and g_r are constants in normal situations. The value of n is typically 2, but may vary between 2 and 6 depending on the physical environment.

Now suppose that node Y wants to reply with a packet to X such that X receives the packet with a designated power P_X. Then Y's transmission power must satisfy Equation (3):

$$P_X = P_Y \left(\frac{\lambda}{4\pi d}\right)^n g_t g_r. \tag{3}$$

Dividing Equation (3) by Equation (2) gives:

$$\frac{P_X}{P_r} = \frac{P_Y}{P_t}. \tag{4}$$

Then Y can determine its transmission power P_Y if the other powers are known.

Some similar protocols to the DCA-PC are proposed in [27, 57]. In [57], Pursley et al. proposed a transmitter uses a desired transmission power level in the CTS to send a data packet. The receiver helps transmitters to choose the appropriate transmission power level, so as to maintain a desired signal to noise ratio. Suppose in Figure 14, nodes B and C use the minimum power required to reach each other for the data packet and ACK packet. Since node A cannot sense B's data transmission at the lower power level, a transmission at the maximum power from A can interfere with the reception of the ACK at B. Therefore, in the proposed protocol by Jung et al. [27], to avoid a potential collision with the ACK, the source node B transmits DATA at the maximum power level periodically, so that nodes in the carrier sensing zone can sense it. This prevents node A from initiating its transmission.

Lin et al. [37] propose a power controlled multiple channel MAC protocol which is an extended version of IEEE 802.11. In this protocol, they adopt ten

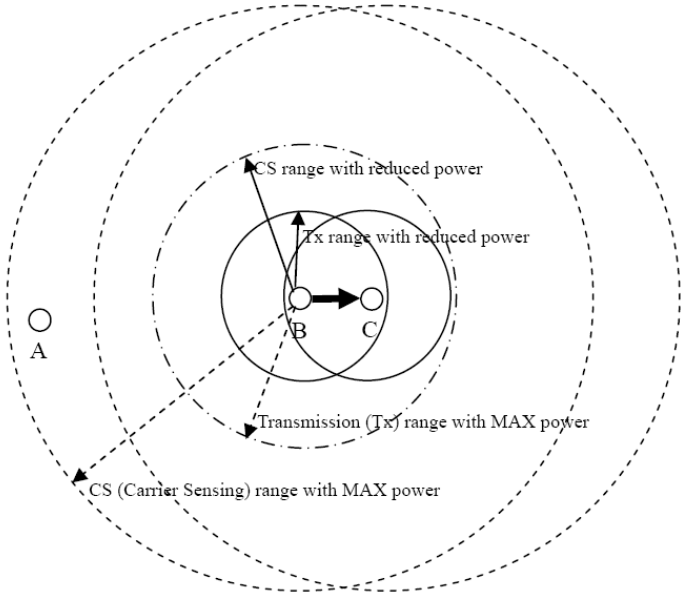


Fig. 14. Power control scheme [27].

classes of transmission levels between minimum and maximum transmission level. While nodes are exchanging control packets, they compute the transmission power to avoid packet collision. The transmitter uses a previous power level if it has a record of one, otherwise, it uses the maximum power level. If a transmitter does not receive any response, it increases the power level by one class until it reaches the maximum power level.

In [9] proposed by Chen et al., distance information to the receiver stored in the neighbouring node table is used to determine the proper transmission power level. The power level for transmitting data, P_{data}, from the transmitter to the mth neighbour is determined by

$$P_{data} = \overline{d} \times Rx_{thresh} \tag{5}$$

where Rx_{thresh} is the minimum necessary received signal strength. In this protocol, P_{data} from the transmitter to the mth neighbour is determined depending on the average estimated distance $\overline{d}$ instead of d_m which is a distance between the transmitter and the mth node. For the case $d_m > \overline{d}$, the transmitter may have to cancel the transmission to the mth node directly due to insufficient transmission power levels and the data packet has to be transmitted via one of its neighbours. The reason for using the average estimated distance $\overline{d}$ is to obtain a similar power level for the data packet transmission and better spatial reuse ratio.

2.6 Spread Spectrum

The performance of a MAC protocol has a lot to do with the access scheme of the physical layer as mentioned in Chapter 1. In this section, we introduce two well-known access schemes and review how they are used in protocols for wireless ad hoc networks. *Code division multiple access* (CDMA) and *orthogonal frequency division multiple access* (OFDMA) techniques are two well-known access schemes using spread spectrum methods. While OFDMA is used to separate the nodes in frequencies, CDMA accommodates more than one node communication on a frequency band.

2.6.1 Code Division Multiple Access (CDMA)

In CDMA, several transmitters can send information simultaneously over a single communication channel with very little interference. CDMA employs spread-spectrum technology and a special coding scheme (where each transmitter is assigned an orthogonal code) to allow multiple users to be multiplexed over the same physical channel [60]. The receiver can recover the transmission of an individual transmitter from multiple transmissions by an assigned orthogonal code. Figure 15 shows the difference between *frequency division multiple access* (FDMA) and CDMA in frequency domain.

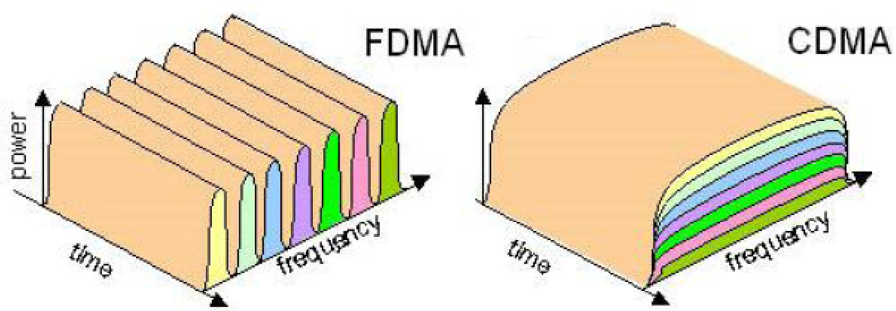


Fig. 15. Comparison of access schemes (FDMA vs. CDMA).

While CDMA is widely used in cellular systems there are challenges using it in wireless ad hoc networks. One big challenge is the near-far problem. The near-far problem occurs when a signal from a closer sender is much stronger than from a sender farther away.

Consider Figure 16, with two node pairs. The node pair A and B, and the node pair D and C cannot communicate at the same time even if CDMA

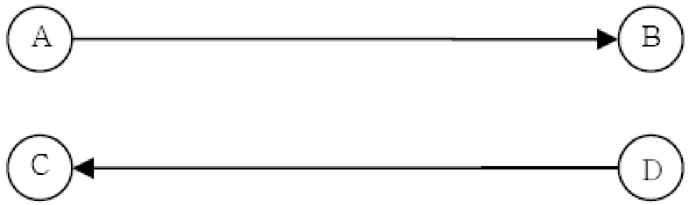


Fig. 16. Near-far problem.

is used. In CDMA, if the orthogonality of each transmission signal is not maintained, the near-far problem occurs. In this figure, since the distance between the receiver B and the transmitter A is far, the signal from node A is attenuated. On the other hand, since node D is located a short distance from B, the signal from node D is strong at node B. Similarly, since transmitter D is far from node C and node A is close to node C, the same problem happens. As a result, nodes B and C cannot receive the transmissions from nodes A and D correctly even though CDMA technology is used. In cellular networks, the power is equalized by the base station. Ad hoc networks have no centralized control. Therefore, decentralized power control mechanisms have to be considered when CDMA is adopted in wireless ad hoc networks.

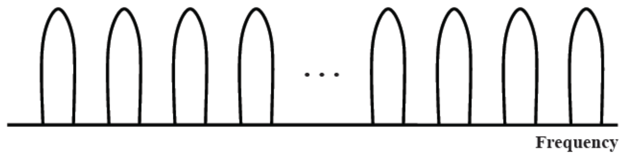
2.6.2 Orthogonal Frequency Division Multiple Access (OFDMA)

Orthogonal frequency division multiple access (OFDMA) is a multi-user version of the *orthogonal frequency-division multiplexing* (OFDM) scheme. In OFDM, the usable bandwidth is divided into a large number of smaller bandwidth channels, called sub-carriers, that are orthogonal to each other. In a *frequency-*

division multiplexing (FDM) system, signals from multiple transmitters are transmitted simultaneously over multiple frequencies. A spacing (guard band) is needed between sub-carriers to avoid signal overlap. Like FDM, OFDM also uses multiple sub-carriers but the sub-carriers are closely spaced to each other such that spacing between adjacent sub-carriers do not cause interference. One transmitter uses all sub-carriers to transmit a signal. The data are divided into several parallel data channels, one for each sub-carrier. If information about the channel quality is given, based on this information, adaptive modulation and a power allocation may be applied across all sub-carriers, or individually to each sub-carrier. In the latter case, if a particular range of frequencies suffers from interference or attenuation, the carriers within that range can be disabled or made to run slower by applying more robust modulation or error coding to those sub-carriers. OFDM in its primary form is considered a digital modulation technique, and not a multi-user channel access technique [64].

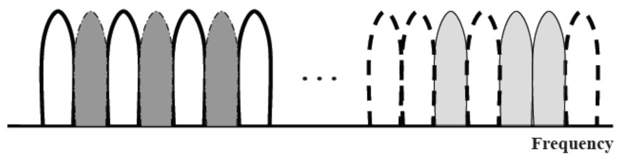
OFDMA also employs multiple closely spaced sub-carriers, but the sub-carriers are divided into groups of sub-carriers. Each group is named a sub-channel. OFDMA supports differentiated quality-of-service by assigning a different number of sub-carriers to different users [19]. Figure 17 shows the differences among the FDM, OFDM, and OFDMA schemes.

To use OFDMA in wireless ad hoc networks we must consider the channel synchronization problem. When the sub-channels are not synchronized



(a) FDM

(b) OFDM



(c) OFDMA

Fig. 17. Difference among the three access schemes FDM, OFDM, and OFDMA.

between a transmitter and receiver, the receiver cannot decode a data signal because it cannot detect the signal. Instead, the receiver recognizes the signal as noise. In cellular systems, the base station assigns the sub-channels according to the request of each node based on the channel quality information. However, in wireless ad hoc networks, the channel assignment must be done in a decentralized manner. Without knowledge about the channel conditions between the transmitter and receiver it is impossible to derive the optimal efficiency from OFDMA.

2.6.3 Protocols using CDMA or OFDMA

Garcia-Luna-Aceves et al. [15] propose an algorithm for distributed, dynamic channel assignment in multi-hop wireless radio networks. It uses the information about the transmission codes used by nodes one hop and two hops away. Joa-Ng [25], proposes two protocols using a *common-transmitter* (C-T) based code and a *receiver-transmitter* (R-T) based code. In the protocol using a C-T based code, while a common code is used to exchange an RTS and a CTS packet, a transmitter based code is used to transmit a data packet.

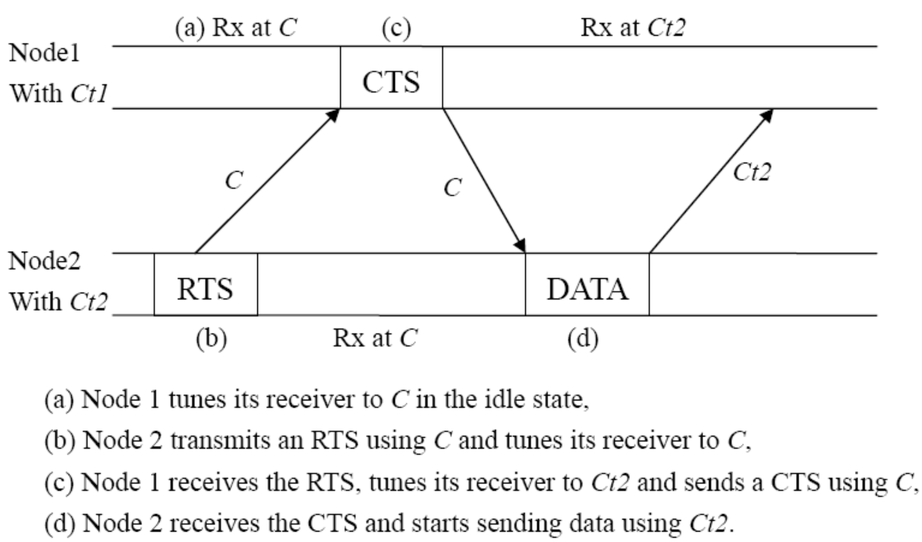


Fig. 18. Processing of data transmission using a common-transmitter protocol.

Figure 18 shows the processing of data transmission of C-T based code protocol. In the idle stage, all nodes tune their receivers to common code C. When node 2 wants to send data to node 1, node 2 sends an RTS to node 1 using code C and tunes its receiver to code C for a CTS. The source *id* and the destination id of this RTS are node 2 and node 1, respectively. Upon receiving the RTS, node 1 sends a CTS using code C and tunes its receiver to $Ct2$ (the transmitter code of node 2) for a returning data packet. Finally, node 2 receives the CTS and sends the data packet to node 1 using code $Ct2$. Moreover, multiple transmitters can send data packets successfully to different receivers because data packets are sent using transmitter-based codes.

On the other hand, as shown in Figure 19, in the protocol with an R-T based code, both transmitter and receiver codes are assigned to each node. Each node uses these codes to transmit and to receive packets except for sending an RTS packet. Since all the nodes tune their receivers to their own receiver code at the idle mode, each node has to use receiver's receiver code to transmit an RTS packet.

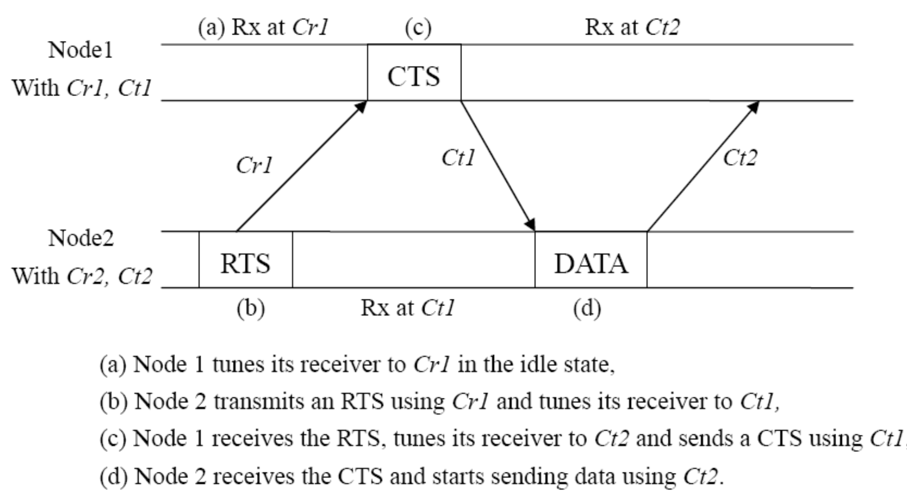


Fig. 19. Processing of data transmission using a receiver-transmitter protocol.

The processing of a data transmission is similar to the C-T based code protocol. In the idle stage, all nodes tune their receivers to their own receiver codes. When node 2 wants to send data to node 1, node 2 sends an RTS to node 1 using code $Cr1$, tunes its receiver to $Ct1$ and waits for a CTS. Upon receiving the RTS, node 1 tunes its receiver to $Ct2$ for a data packet and sends a CTS using code $Ct1$. Finally, node 2 receives the CTS and sends the data packet to node 1 using code $Ct2$. Since the RTS, the CTS and the data packets are sent using different codes, they only increase the interference level at the neighbouring nodes and may not cause any collision.

The spreading code protocols proposed by Sousa et al. [67] uses a similar method to that used in [25]. However, the spreading code protocols use either a common code or receiver's code for just the header part instead of using control packets and a transmitter's code for the rest of the packet.

Muqattash et al. [47] propose the *controlled-access* CDMA-based (CA-CDMA) MAC protocol for MANETs. In this protocol, a power control mechanism is used to address the near-far problem as well as to improve throughput.

The CA-CDMA protocol as shown in Figure 20 uses two frequency channels, one for control and one for data. A common code is used by all nodes over the control channel, while several different codes can be used over the data channel. Each user is allowed to overhear all the control packets exchanged on the control channel by using a common code. Moreover, the use of

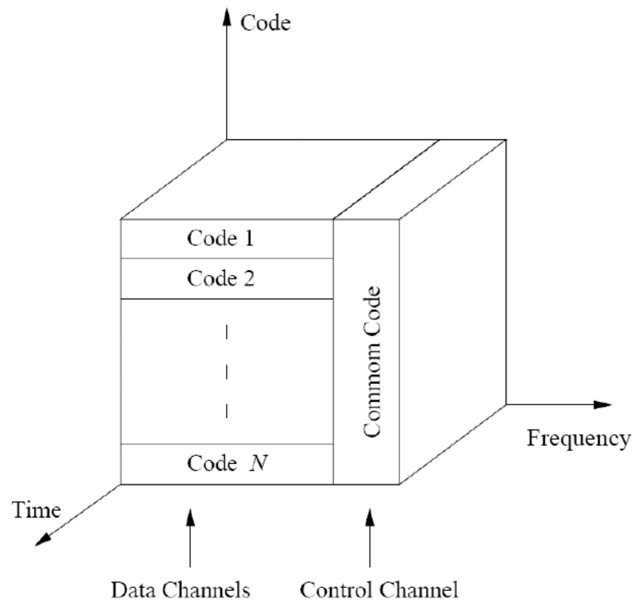


Fig. 20. Data and control codes.

a different code at each node allows more than one user to access the channel concurrently. The CA-CDMA protocol uses a modified RTS-CTS reservation mechanism. RTS and CTS packets are transmitted over the control channel at a fixed maximum transmission power. The transmission power for a data or an ACK packet is controlled for better performance. In the CA-CDMA protocol, nodes exploit knowledge of the power levels of the overheard RTS and CTS packets to determine the transmission power that they can use without disturbing the ongoing receptions. To obtain information about the strength of transmission power of neighbouring nodes, each node is equipped with two transceivers, one for the control channel and the other for the data channel.

Kim et al. [29] propose OFDMA-based reliable multicast MAC protocol (OMMP) for wireless ad hoc networks. By adapting OFDMA characteristics in CTS and ACK packets this protocol tries to achieve reliability over wireless multicast with minimum overhead. In the OMNP protocol, each node has a unique pre-assigned sub-carrier. Therefore, when all the nodes respond with a CTS for an RTS received, they put a binary phase-shift keying (BPSK) symbol which indicates their reception in the pre-assigned sub-carrier.

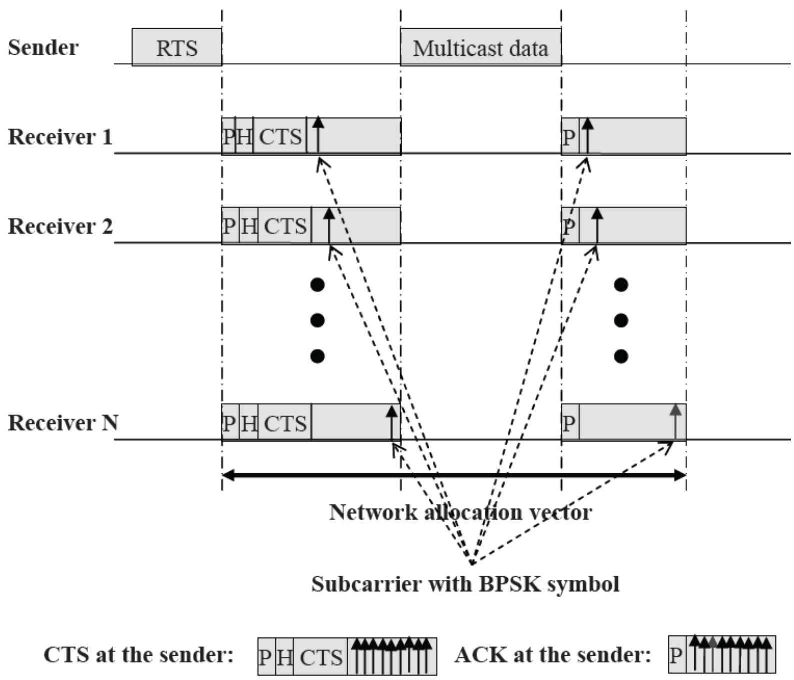


Fig. 21. Example of a data transmission cycle.

Figure 21 shows an example scenario of this method. A sender multicasts an RTS packet to all the nodes from receiver 1 to receiver N. Each receiver responds with an OFDM symbol for its pre-assigned sub-carrier, and these symbols are merged at the sender as a CTS packet. Note that the OFDM symbol in the CTS packet is indicated by frequency domain, and the overall transmission sequence is indicated by the time scale in the figure. If receiver i, $1 \leq i \leq N$, does not receive the RTS packet, it does not send an OFDM symbol to the sender. After receiving the CTS packet, the sender checks the sub-carriers assigned to nodes. If any one of the node sub-carriers is not allocated any symbol or is allocated the BPSK symbol -1, the sender prepares to retransmit the RTS packet. When a CTS packet is received correctly, the sender transmits a multicast data packet to the nodes. When the nodes receive the multicast data packet from the sender, they allocate a symbol on the pre-assigned sub-carrier as an acknowledgement for the packet. The generation of an ACK packet is the same as that of a CTS packet.

Veyseh et al. [72] propose a parallel interaction medium access protocol called PIMA. This work shows that even if the nodes in wireless ad hoc networks are equipped with a single half duplex transceiver, they still can either transmit multiple packets to multiple destinations in parallel or receive multiple packets from multiple transmitters in parallel using OFDMA technology. In the the PIMA protocol, two basic factors are required to make sure that the channel assignment procedure is carried out successfully: (a) No other transmitter in the one-hop vicinity of the receiver should send messages on the channels that the receiver is going to assign to its neighbour, and (b) the channel that the receiver is going to assign to node A should not be used by node A's neighbours for data reception. Regarding these two factors, each node creates a list of channels that are clear to receive and informs the neighbours of the list of prohibited channels for each one-hop neighbour prior to channel selection. The *prohibited for transmission list* (PTL) is the list of the channels currently being used by the two-hop neighbours for transmitting data packets. This list is created by each node and is updated when a new *ready to receive* (RTR) is received on the control channel. Every time a node broadcasts a hello message to its one-hop neighbours, it appends its updated PTL to the message. A dedicated channel is used for transmission of hello messages. It is periodically used by nodes to broadcast their neighbour discovery messages.

Figure 22 illustrates the operation of PIMA. Node A sends an RTR on the control channel at time t_1. Note that channel 2 is being used by node F to transmit data to node E. Since node A had received the PTL of node B through the transmission of *hello* messages, it knows that channel 2 is prohibited for node B. So, node A selects channel 1 for node B. After the successful reception of RTR by nodes B, C, and D, they immediately start sending messages on the assigned channels. At time t_2 both nodes G and I attempt to access the control channel by sending RTR, however a collision occurs and no transmission takes place. At time t_3, only node G sends an

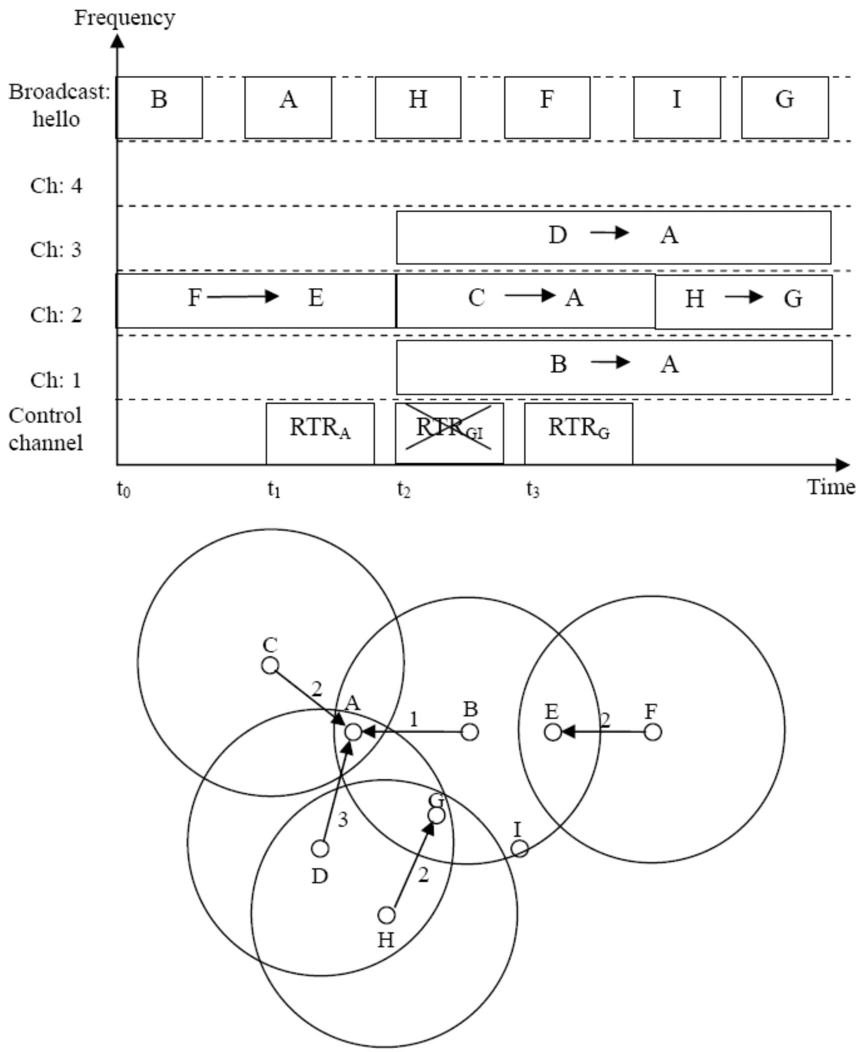


Fig. 22. Operation of PIMA.

RTR and assigns channel 2 to node H. This is due to the fact that channel 1 and 3 are occupied by the one-hop neighbours of G.

In the PIMA protocol, each potential receiver uses an RTR control packet to assign a non-overlapping sub-channel to potential transmitters on a dedicated control channel.

2.7 Summary

In this chapter, we reviewed the related work on MANETs, multi-channel systems and protocols, node cooperation, transmission power control, and spread spectrum techniques. In the next chapter, we introduce a cooperative CDMA-based multi-channel MAC protocol for MANETs.

A COOPERATIVE CDMA-BASED MULTI-CHANNEL MAC PROTOCOL

In this chapter, we introduce the Cooperative CDMA-based Multi-channel MAC (CCM-MAC) protocol for wireless ad hoc networks. We provide an analysis of the maximum throughput of CCM-MAC and validate it through simulation.

3.1 The CCM-MAC Protocol

The CCM-MAC protocol is designed for nodes with a single half-duplex transceiver. It uses multiple channels for data transmission and *code division multiple access* (CDMA) technology [60] on each channel to increase channel efficiency. It also leverages cooperation among nodes for interference awareness as well as channel selection.

We assume that 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 and decode the channel negotiation. When a node transmits a data packet on a data channel it uses its unique pseudo-random code. Such a code assignment may be provided by the method described by Garcia-Luna-Aceves et al. [15]. for a possible approach to this problem.

In order to effectively utilize the multiple channels with CDMA, and address the near-far problem, we use information gathered from cooperating nodes. For simplicity, we ignore the influence of various phenomena such as multi-path fading or narrowband interference.

3.1.1 Channel Negotiation in CCM-MAC

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

Figure 23 show an example of channel negotiation in the simple case where there is no collision among ITI packets. In the figure, suppose that node B has a packet to transmit to node C. As in IEEE 802.11, if the control channel is clear for a time interval equal to a DCF interframe space (DIFS), node B transmits an RTS to node C. If this is received by node C, it responds with a CTS containing a list of channels it believes are free. Suppose that node A overhears only the RTS from node B and that node D overhears only the CTS from node C. Since each node maintains a channel status table (see Section 3.1.1.1 for details on this table), nodes A and D each send an ITI to node B and C, respectively, with information about the channel state around its intended receiver.

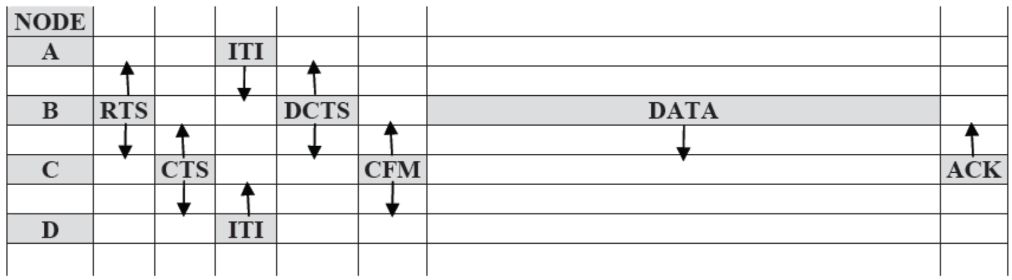


Fig. 23. Example of channel negotiation with no collision among ITI control packets.

Using the information contained in the CTS and ITI from node A, node B selects a channel and sends its choice in a DCTS to node C. When node A overhears the channel selection it stores this information together with the packet duration in its channel status table. On receiving the DCTS, if the selected channel is available at the receiver side, node C returns a CFM to node B to confirm the choice. This ensures that neighbours of the receiver also overhear and store the channel selection and duration. If the cooperating nodes A and D do not hear DCTS or CFM, respectively, they clear the channel information in their status table. Finally, on receipt of the CFM, node B transmits the data packet to node C. If the data transmission is completed successfully, node C transmits an ACK to node B *on the data channel* to avoid a potential collision with another handshake on the control channel.

Now consider a case such as shown in Figure 24 where there are competing cooperating nodes. In this example, we consider an ongoing communication between nodes A and B whose negotiation has been overheard by cooperating nodes $CN_1, \ldots, CN_5$. Suppose that node C has a packet queued for transmission to node D. As before, if the control channel is clear for DIFS time, node C transmits an RTS to node D. Following the CTS from D, all cooperating neighbours CN_1 through CN_5 of node C transmit an ITI to node C concurrently.

Generally, whenever more than one packet is transmitted at the same time, all the packets involved in the collision are destroyed. This is reasonable when the packets are received with nearly equal power. However, this is unlikely in a MANET. When packets from different nodes collide, it may be possible to successfully decode the packet with the strongest received signal strength using the *capture effect* of CDMA [61]. In this example, node C captures the ITI from its closest cooperating node CN_2. Indeed, since CN_2's transmission range overlaps that of C the most, it can overhear most of the packets transmitted around C and therefore provide more valuable information to C.

If there is a collision of RTS control packets, each node follows the binary exponential backoff algorithm for collision resolution; this algorithm is in common use, e.g., in IEEE 802.11 DCF [21].

3.1.1.1 Contents of Channel Status Table

Figure 25 shows the format of an entry in the channel status table stored at each node. Entries are inserted into the table when a node is acting as a cooperating node and are deleted when they expire or are incomplete.

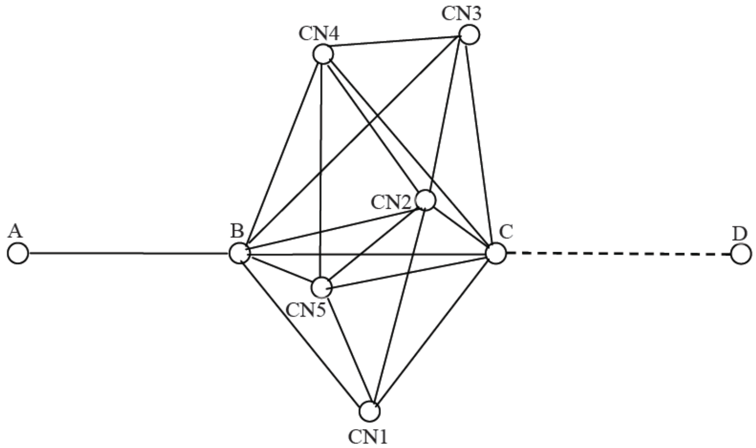


Fig. 24. Example of channel negotiation with collision among ITI packets.

An entry has six fields: N_{id} is a node identifier, S_{id} is the communication status of node N_{id}, $D_{id-coop}$ is the estimated distance between N_{id} and the cooperating node, $D_{tx/rx}$ is the estimated distance between node N_{id} and its partner in communication, Dur is the duration in time of the data transmission, and C is the channel number negotiated for the communication.

N_{id}	S_{id}	$D_{id\text{-}coop}$	$D_{tx/rx}$	Dur	C

Fig. 25. An entry in the channel status table for the CCM-MAC.

Specifically, if a cooperating node overhears an RTS from node i it creates a new entry in the channel status table and sets $N_{id} \leftarrow i$, $S_{id} \leftarrow$ `transmit` representing the fact that i is a transmitter, copies the Dur field from the RTS, and estimates $D_{id-coop}$ (see Section 3.1.2 for an explanation of how distances are estimated). If the cooperating node subsequently overhears a DCTS the channel number is copied. Similarly, if a CFM is overhead, then both the channel number and the $D_{tx/rx}$ distance are copied from it into the entry. If after overhearing an RTS, a DCTS or CFM is not overheard, then the entry is incomplete and deleted.

If a CTS is overheard from node i, the only difference in how it is handled is that the communication status S_{id} is set to `receive` representing that i is a receiver.

The *Dur* field of each entry behaves as a count-down timer; when the timer reaches zero the entry expires and is deleted.

3.1.1.2 Packet Formats in CCM-MAC

Figure 56 shows the format for each CCM-MAC control packet and the field width in bits. In each, *frame control* (FC) contains information about the packet, such as the version of the protocol, the packet type (data or control) and subtype (RTS, CTS, etc.). In all cases, RA denotes the receiver address, TA denotes the transmitter address, CRC is a checksum, and *Dur* is the duration in time required to complete the data transmission.

The format of an RTS control packet is the same as in IEEE 802.11. A CTS control packet includes a list of free channels at the receiver. We use $N = 3$ as the number of data channels in our evaluation of CCM-MAC in Section 5.2 hence three bits suffice for the free channel list (F).

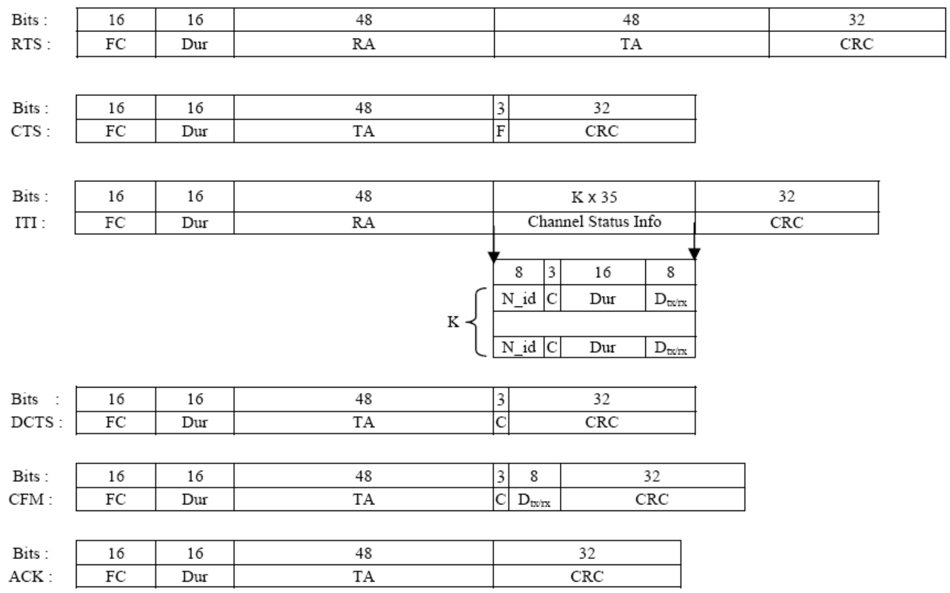


Fig. 26. Packet format for each CCM-MAC control packet.

An ITI is a variable length packet whose content is constructed from entries in the channel status table. If the cooperating node overheard an RTS then it scans its channel status table for entries with transmitter communication status, i.e., $S_{id} = \texttt{transmit}$. For each entry found, the fields N_{id}, C, Dur, and $D_{tx/rx}$ are copied into the channel status information field of the ITI. The number of such entries, k, is set in the frame control field of the ITI. If the cooperating node overheard a CTS then it behaves similarly, except that the channel status table is scanned for receivers instead of transmitters.

Both a DCTS and a CFM control packet contain the channel number selected in the negotiation. The CFM also contains an estimate of the distance separating the transmitter and receiver, $D_{tx/rx}$. The format of an ACK control packet is the same as in IEEE 802.11.

Finally, the format of a data packet in CCM-MAC is the same as the data packet format in IEEE 802.11 [21].

3.1.2 Mitigating the Multi-channel Hidden and Exposed Terminal Problems

We use Figure 27 to provide an example of how the CCM-MAC protocol mitigates the multi-channel hidden and exposed terminal problems. Suppose that node A is transmitting to node B. Node C is hidden to node A and could therefore cause a collision at node B if it were to transmit. This hidden terminal problem is addressed by the CCM-MAC handshake. Through the ITI and CFM packets, node C obtains the distance between nodes A and B and the channel in use. Together with information from its channel status table C can make an informed decision about channel selection, avoiding the hidden terminal problem.

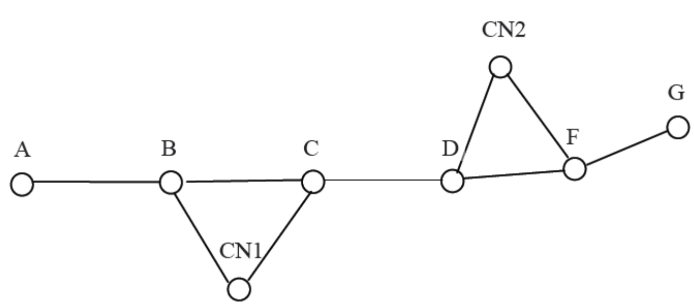


Fig. 27. Example for mitigation of the hidden and exposed terminal problems.

There may be some situations in which there is not enough information available to make a channel selection. Consider Figure 27 again, and assume that nodes C and D complete a transmission. Even though node B is in the transmission range of C, and F is in the transmission range of D, nodes C and D may not know which channels are in use or the communication status of B and F, respectively. In CCM-MAC, cooperating neighbours are again the key to addressing the problem.

Assume that node C has another packet for node D. When node D (and any other neighbour of node C) receives the RTS, it estimates its distance d to node C from the expression for the ratio of signal power

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2}\frac{(4\pi f d)^2}{c^2} \tag{6}$$

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, and f is the frequency. Alternatively, if GPS is available it could be used for distance estimation. As well, various localization algorithms could be used (see, e.g., [53]).

As well, node D determines the free channel list and includes it in the CTS back to node C. The cooperating neighbours CN_1 and CN_2 each transmit an ITI to nodes C and D, respectively. In this example, suppose that the distance between nodes B and C and nodes D and F is less than the distance between nodes A and B and nodes F and G. Therefore, to avoid the hidden-terminal problem, C should not select the same channel as nodes A and B or nodes F and G.

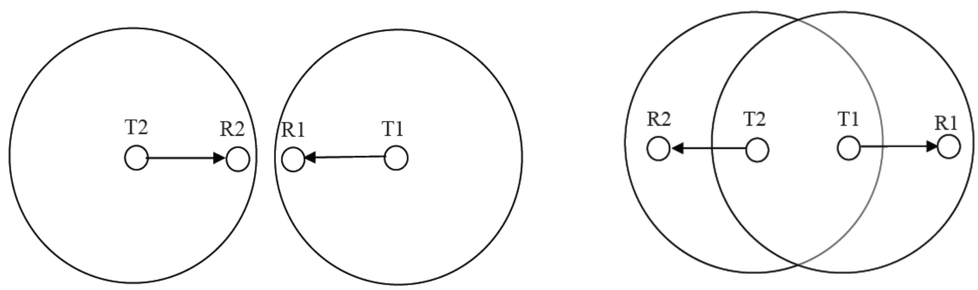
The argument for the exposed terminal problem is very similar. For example, in Figure 27, suppose that node B has a packet to transmit to node A while node C has a packet for D. In IEEE 802.11 nodes B and C are exposed terminals. If IEEE 802.11 were used, one of node B or node C defers its communication. However, in the CCM-MAC protocol, the second transmission is not deferred. Through the ITI from node CN_1, node C obtains the communication status of the adjacent node. As explained next, if the communication status is the same, then both transmissions can proceed concurrently.

3.1.3 Mitigating the Near-Far Problem of CDMA

For the CCM-MAC protocol 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 an existing communication. There are two factors to consider for the near-far problem in MANETs: the distance between nodes, and the communication status of the node.

We use Figure 28 to explain that the near-far problem is unlikely to occur between two nodes having the same communication status. Consider two transmitters T_1 and T_2 and their corresponding receivers R_1 and R_2. In Figure 28(a), while the receivers R_1 and R_2 are close to each other, the signal from T_2

and T_1 does not affect reception at R_1 and R_2, respectively. In Figure 28(b), nodes T_1 and T_2 transmit packets concurrently with their respective receivers which are each far enough away from the other transmitter. Therefore, while nodes R_1 and R_2 are receiving, the signal from the other transmitter does not affect reception.



(a) Receivers do not suffer (b) Transmitters do not suffer

Fig. 28. Nodes having the same communication mode do not suffer interference.

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

Using this information, a transmission may be added to a channel with an ongoing transmission if it does not cause interference. Otherwise, another channel is selected. However, if there is no available channel, the node must wait until another node finishes its transmission in accordance with the duration information.

In this way, the CCM-MAC protocol makes effective use of multiple channels, and supports a high spatial reuse ratio in the system as more nodes may transmit data concurrently.

3.2 Maximum Throughput Analysis of the CCM-MAC Protocol

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 multiple users on a channel because it has 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.

Recall from Section 3.1 that we assume there is one dedicated control channel and N data channels in the CCM-MAC protocol. CDMA is used on each channel. A common code is used when transmitting on the control channel, while each node uses its unique pseudo-random code when transmitting on a data channel.

To compute the maximum throughput of the CCM-MAC protocol we use the notion of a *transmission frame time*. A transmission frame time includes the time required to complete the CCM-MAC handshake, the time to transmit the data packet, and the time to respond with 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 number of transmissions that may proceed concurrently is dependent on the number N of data channels, as well as the maximum number H_{max} of node pairs completing the handshake successfully in a transmission frame time. For CDMA-based protocols, we expect $H_{max} > N$. Without considering noise, H_{max} is given by:

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

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

$$Throughput(\text{CCM-MAC}) = \frac{H_{max} \times L}{\frac{L}{B} + T_{ACK}}. \quad (7)$$

However, if H_{max} is more than the number of transmissions that 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 and Ferreira [70], and Turin [68], the received signal Y_{pi} of the ith user in the pth symbol period is given as:

$$\begin{aligned} Y_{pi} &= \sqrt{E_s}(x_{pi} + \eta_i) + \eta_{pi} \\ &= \underbrace{\sqrt{E_s}x_{pi}}_{signal} + \underbrace{(\sqrt{E_s}\eta_i + \eta_{pi})}_{noise}. \end{aligned} \tag{8}$$

Here, E_s is the energy per symbol, x_{pi} is the data bit 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 Equation (8) as

$$\begin{aligned} \alpha_{pi} &= \frac{E[\sqrt{E_s}x_{pi}]^2}{E[(\eta_i + \eta_{pi})^2]} \\ &= \frac{E_s}{E[\eta_i^2] + 2E[\eta_i, \eta_{pi}] + E[\eta_{pi}^2]} \end{aligned} \tag{9}$$

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 [70].

Following Pursley [56], $E[\eta_i^2] \approx \frac{K-1}{3N_c}$, 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 (9) yields an approximate expression for the SNR:

$$\begin{aligned}\alpha_{pi} &= \frac{E_s}{\frac{K-1}{3N_c} + \frac{N_0}{2E_s}} \\ &\approx \left(\frac{K-1}{3N_c} + \frac{N_0}{2E_s}\right)^{-1} \qquad (10)\end{aligned}$$

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 (10) to obtain an expression for K, the maximum number of users considering noise, gives:

$$K = 3N_c\left(\frac{1}{\alpha_{pi}} - \frac{N_0}{2E_s}\right) + 1. \qquad (11)$$

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 and Ferreira [70], is

$$\alpha_0 = \frac{3N_cP}{\frac{N_0}{T_c} + \sum_{j=1}^{K}\left(\frac{d_{is}}{d_{ij}}\right)^{\beta} P} \qquad (12)$$

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 interference 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 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 four). The inter-node powers are scaled by the distance d_{ij}. Using Equations (10) and (12) a value for K, the maximum number of users with noise, is derived.

Finally, by Equations (7), (8), and (10), the throughput of CCM-MAC in the best case is

$$Throughput(\text{CCM-MAC}) = \frac{M \times L}{\frac{L}{B} + T_{ACK}} \tag{13}$$

where

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

This analysis only considers a single-hop scenario because that is what is considered in the evaluation in simulation.

3.3 Performance Evaluation of the CCM-MAC Protocol

We use Matlab to simulate our CCM-MAC protocol, the IEEE 802.11 DCF [21], and the MMAC-CC multi-channel MAC protocol [50]. For the CA-CDMA protocol [47] we present analytical results. The assumptions underlying the analysis of CA-CDMA are consistent with the assumptions made in the analysis of CCM-MAC. See Chapter 2 for more details about each of these protocols.

The MMAC-CC protocol extends IEEE 802.11 DCF to multiple channels [50]. The best channel is defined as the one with the minimum amount of interference among the data channels. The protocol uses a free channel list embedded in each control packet to exchange interference information about the channels. In addition, while a node is receiving a data packet, it sends busy-tones on the data channel in use to help the transmitter estimate the distance to the receiver. With this additional mechanism, the transmitter can select the best channel more effectively.

Muqattash and Krunz [47] propose the *controlled-access CDMA* (CA-CDMA) MAC protocol for MANETs. They address the near-far problem by using power control. To obtain information about the strength of transmission power of neighbouring nodes, each node is equipped with two transceivers, one for the control channel and the other for the data channel. Each node listens to the control channel in order to determine the average number of active nodes in its neighbourhood. The number of nodes that can transmit concurrently is estimated by considering the multiple access interference calculated from transmission power of each node.

A summary of the high-level features of the protocols is given in Table 1. We attempt to take into account these features in interpreting the results.

3.3.1 Parameters of the Simulation

We assume that the channel bandwidth for each protocol is the same: $2\,Mbps$. Since IEEE 802.11 runs on a single channel it uses the full bandwidth for each transmission. CCM-MAC has one control channel and three data channels

TABLE 1. A summary of the features of the protocols evaluated

Protocol	**IEEE 802.11**	**MMAC-CC**	**CCM-MAC**	**CA-CDMA**
Evaluation	Matlab	Matlab	Matlab	Analysis
Number and type of channels	1 channel	1 control and 3 data	1 control and 3 data	1 control and 1 data
Number of transceivers	1	1	1	2
Uses CDMA?	No	No	Yes	Yes
Uses transmission power control?	No	No	No	Yes

with the bandwidth split equally among all channels.[1] In MMAC-CC, the bandwidth is split into a 200 $Kbps$ control channel and three 600 $Kbps$ data channels. In CA-CDMA the control channel rate is 400 $Kbps$ while the data channel rate is 1.6 $Mbps$.

A total of 30 nodes is placed in a square area of $1000\,m \times 1000\,m$ distributed uniformly at random. For mobile scenarios, the move sequences are generated according to the stationary random waypoint mobility model [52] with a node speed that is uniformly between zero and $2\,m/s$.

Since our interest is an evaluation of throughput at the MAC layer, we select destinations from the one-hop neighbourhood of the source nodes. Half of the nodes are sources. For each packet generated, a destination is randomly selected from one of the source's one-hop neighbours. Each node generates

[1] For simplicity, we do not model the guard bands between sub-channels.

TABLE 2. Simulation parameters for the CCM-MAC protocol

Frequency	$2.4\,GHz$
IEEE 802.11 channel rate	$2\,Mbps$
CCM-MAC data channel rate (total) CCM-MAC control channel rate	$500\,Kbps$ ($\times 3 = 1.5\,Mbps$) $500\,Kbps$
MMAC-CC channel rate (total) MMAC-CC control channel rate	$600\,Kbps$ ($\times 3 = 1.8\,Mbps$) $200\,Kbps$
CA-CDMA data channel rate CA-CDMA control channel rate	$1.6\,Mbps$ $400\,Kbps$
Transmission power Processing gain SNR threshold Reception threshold Carrier-sense threshold Interference threshold	$20\,dBm$ $11\,chips$ $15\,dB$ -68 dBm -74 dBm 2.78

packets according to a Poisson process with rate λ, $0 \leq \lambda \leq 60\,pkt/s$, with the same rate used by each node.

Table 2 shows other parameters of the simulation; the parameters for transmission power, processing gain, and the various thresholds correspond to realistic hardware settings of the Aironet 350 series [10].[2] Each simulation runs for $300\,s$ of simulated time. The results plotted are averaged over 30 replicates resulting in a very small 95% confidence interval.

3.3.2 Simulation Results

We begin by comparing the throughput approximation from our analysis (Equation (13)) to the throughput measured in the Matlab simulation of

[2]The interference threshold for the Aironet 350 series is not provided in [10]. Hence, we used a specification in [70] compatible with the Aironet series.

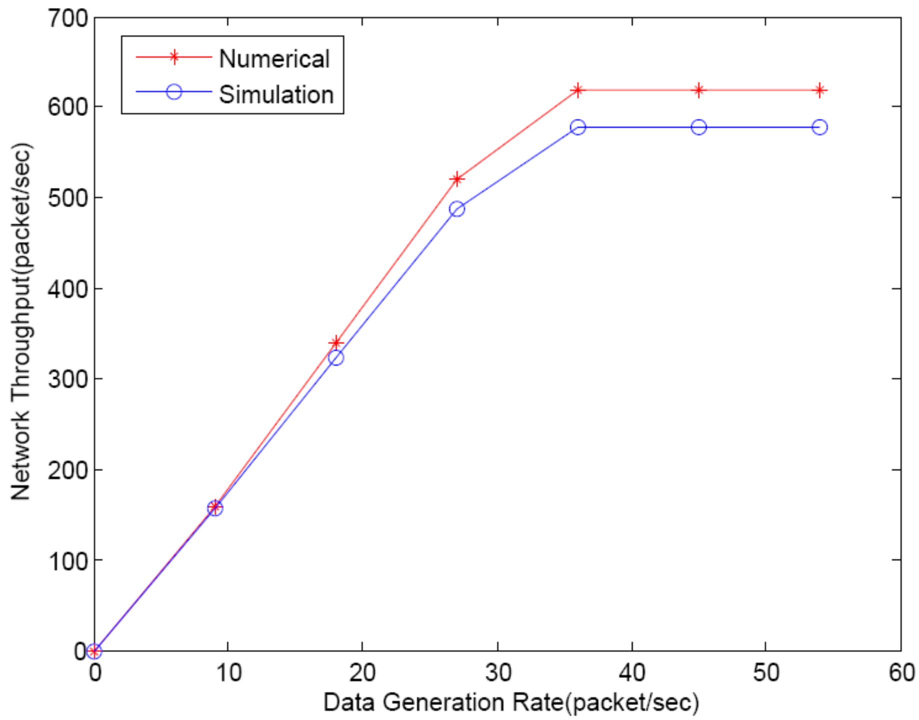


Fig. 29. Numerical analysis v. MATLAB simulation of CCM-MAC throughput.

the CCM-MAC protocol. Figure 29 shows this comparison for a mobile network when the data packet size is 1 *Kbyte*. At low data generation rates, the approximation error is less than 2%. As the data generation rate increases the error increases to a maximum of about 6.5%. Henceforth, we only plot the results from the MATLAB simulation.

Next, we investigate the throughput obtained in static scenarios compared to that obtained in mobile scenarios. Again, a data packet size of 1 *Kbyte* is used. Figure 30 plots these results showing that there is about a 2.5% difference between these types of scenarios. This is because our emphasis is on MAC layer

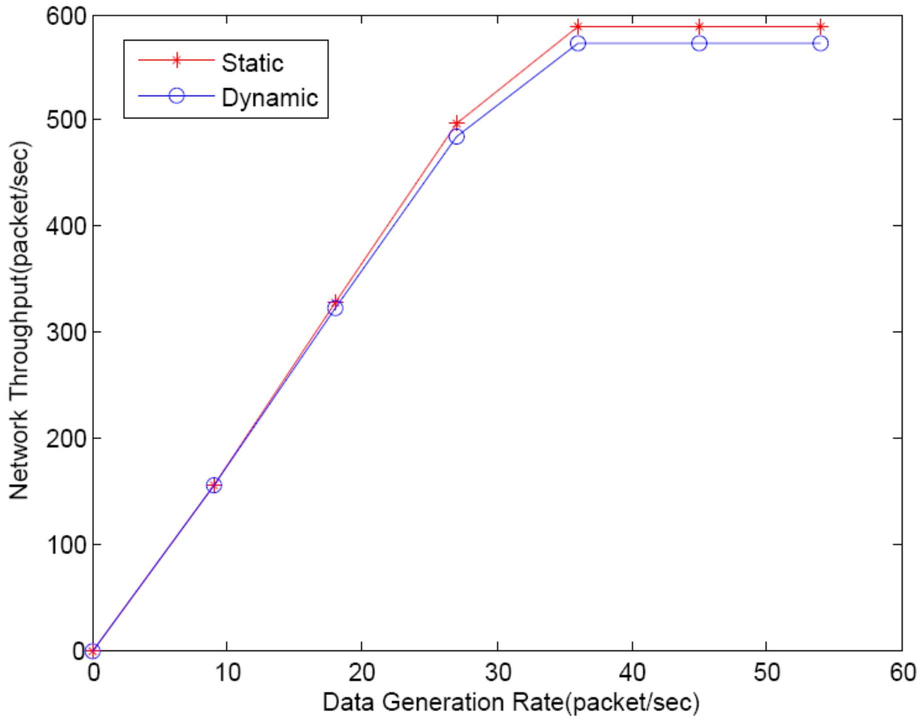


Fig. 30. CCM-MAC throughput in static v. mobile topologies.

throughput with destinations in the single-hop neighbourhood only. In mobile scenarios, it is possible that a destination moves out of the transmission range of its source, or that a source moves into the range of another destination causing interference; both these would account for a decrease in throughput. As a result, we restrict our presentation to mobile scenarios only.

Figures 31–33 show throughput as a function of the network load for increasing data packet size. In general, the throughput of the MMAC-CC protocol is always higher than IEEE 802.11, and the throughput of the CCM-MAC protocol is always higher than MMAC-CC. This can be interpreted first, as

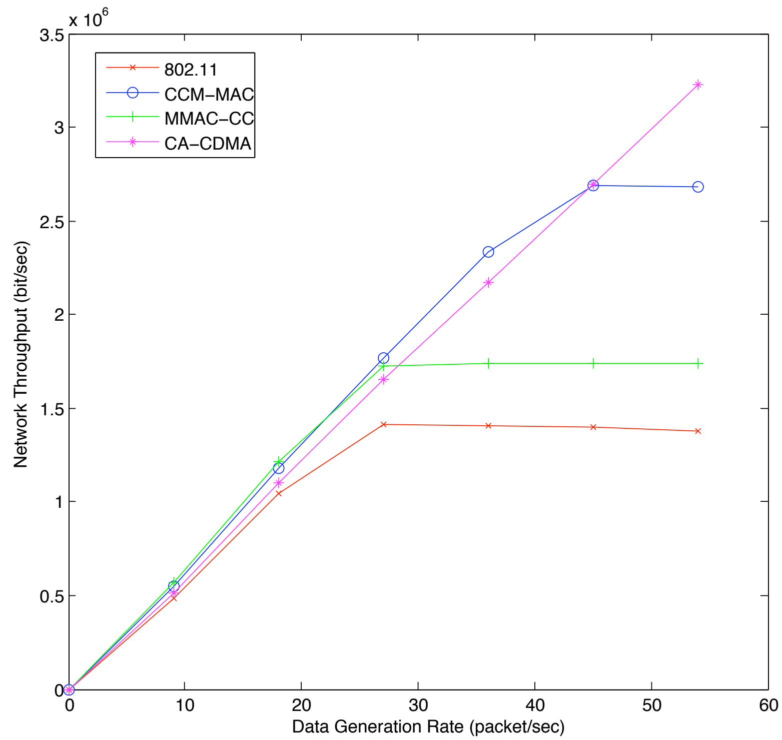


Fig. 31. Throughput as a function of network load for 500 *byte* data packets.

the advantage that using a multi-channel protocol brings over a single channel, and second, the advantage that CDMA brings over and above using multiple channels. In MMAC-CC, at most N nodes may transmit data packets on N data channels but CDMA allows more than one node on each channel until the channel is saturated. IEEE 802.11 works with a single channel and is easily saturated as the number of nodes increases.

As the packet size increases, the gap in throughput between CCM-MAC and IEEE 802.11, and between CCM-MAC and MMAC-CC, increasingly widens. In CCM-MAC the number of nodes that may transmit a data packet

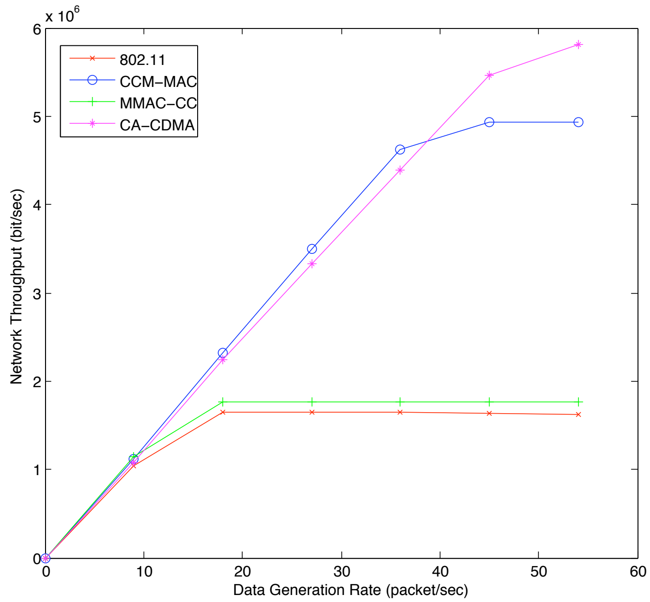


Fig. 32. Throughput as a function of network load for 1 $Kbyte$ data packets.

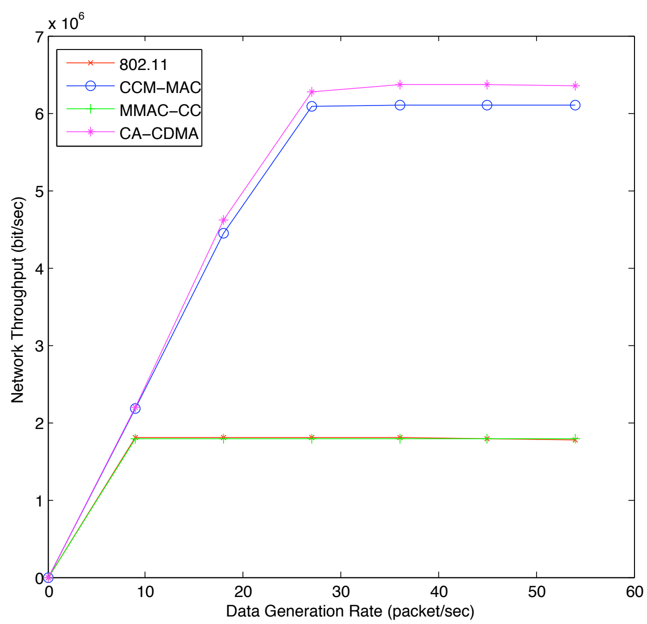


Fig. 33. Throughput as a function of network load for 2 $Kbyte$ data packets.

concurrently equals the number of nodes that complete a handshake in the transmission frame time (taking into account noise). If the packet size increases then the data transmission time increases hence the longer the transmission frame time, with more chances for other node pairs to complete their handshake.

CA-CDMA eventually always outperforms CCM-MAC, with the crossover point at lower packet arrival rates as the packet size increases. Recall that the CA-CDMA protocol assumes that each node has two transceivers. As well, it makes use of transmission power control, giving it distinct advantages over CCM-MAC.

Specifically, in Figure 31 the throughput of CA-CDMA is at best 1.2 times higher than CCM-MAC, CCM-MAC is at best 1.5 times higher than MMAC-CC, and the throughput of MMAC-CC is at best 1.2 times higher than IEEE 802.11. For $1\,Kbyte$ packets, the throughput CA-CDMA is still at best 1.2 times higher than CCM-MAC. CCM-MAC is now 2.7 times higher than MMAC-CC at best, while the throughput of MMAC-CC is now only 1.1 times higher than IEEE 802.11 at best. For $2\,Kbyte$ packets, the throughput of CA-CDMA saturates and is 1.05 times higher than CCM-MAC at best. CCM-MAC is at best 3.2 times higher than the throughput of the other two protocols.

We measured the average packet delay in CCM-MAC, CA-CDMA, 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 [30], the average delay is given by

$$\begin{aligned} D &= \left(\frac{G}{S} - 1\right) \times R + N + a, \text{ where} \qquad (14) \\ R &= N + 2a + \alpha + \delta \end{aligned}$$

and where G is the offered traffic load, S is throughput, and N is the number of channels. R is the sum of the packet transmission time, the round trip propagation delay ($2a$), the transmission time for the acknowledgment (α), and the average retransmission delay (δ). We assume that the ACK transmission and propagation delay time is so small that we can ignore their contribution to delay. We also assume that each protocol has the same value of δ. In this way, we can get a fair average delay for all of the protocols.

Figure 34 shows that the average delay for CCM-MAC remains stable at the higher traffic loads. The average delay of CA-CDMA is also stable and about half that of CCM-MAC. At low traffic loads, IEEE 802.11 and MMAC-CC have a slightly better delay than CCM-MAC but this advantage is quickly lost.

We show the control overhead of CCM-MAC and IEEE 802.11 in Figure 35 assuming a 1 $Kbyte$ data packet size. The figure shows that the control overhead to obtain the throughput for a given packet arrival rate is about

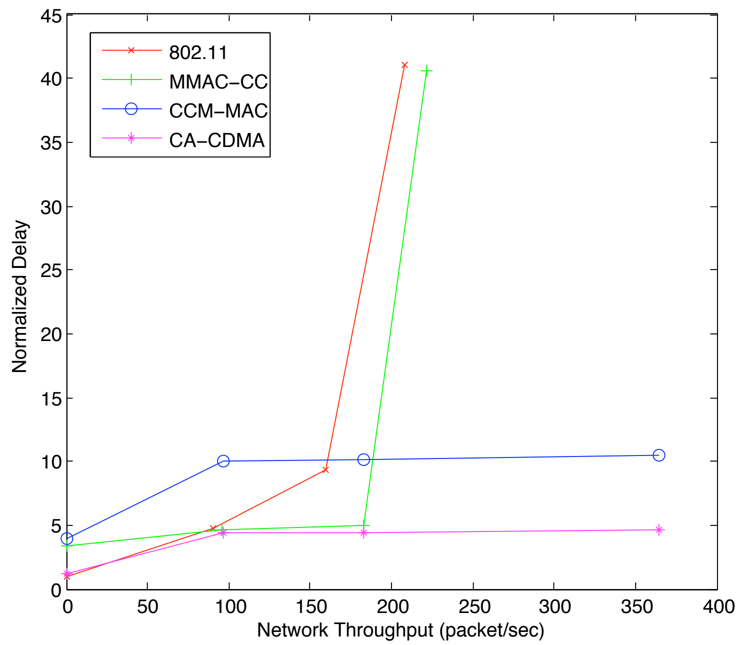


Fig. 34. Average delay v. throughput.

1.4% of the CCM-MAC throughput while it is about 0.7% of the throughput in IEEE 802.11. This is consistent with the additional control packets in the CCM-MAC handshake. This overhead does not take into account processing the ITI packets for channel selection, or creating and maintaining the channel status table in CCM-MAC.

Finally, Figure 36 shows the probability of successful packet transmission in CCM-MAC for one and three data channels for increasing node density. It is expected that the probability of successful transmission increases as the number of available channels increases.

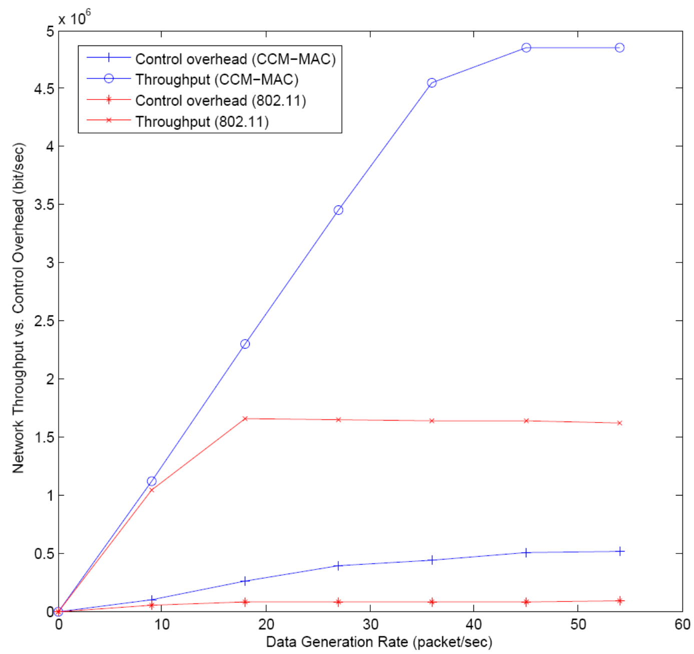


Fig. 35. Control packet overhead of CCM-MAC and IEEE 802.11.

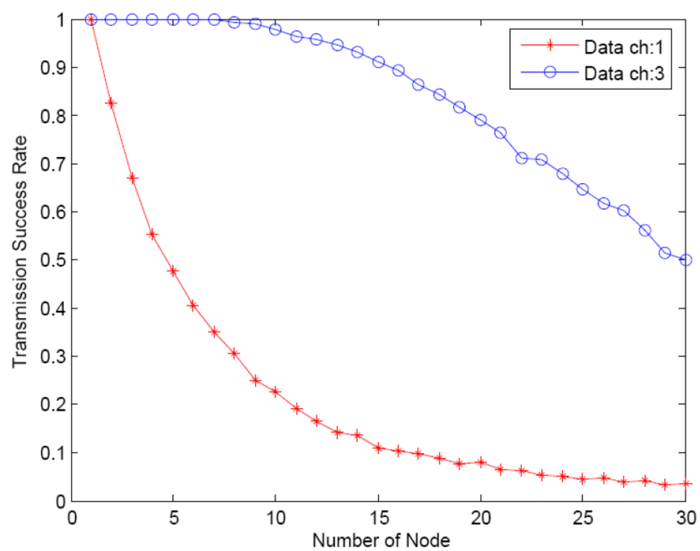


Fig. 36. Probability of successful packet transmission as a function of number of nodes.

In conclusion, the proposed CCM-MAC protocol performs better than IEEE 802.11 and also MMAC-CC, another multi-channel protocol. It is even competitive with another CDMA-based protocol that has more hardware available at each node. Thus, the CCM-MAC appears to successfully mitigate the multi-channel hidden and exposed terminal problems, and also the near-far problem of CDMA through effective use of cooperating nodes.

3.4 Summary

In this chapter, we proposed CCM-MAC, a cooperative CDMA-based multi-channel MAC protocol for wireless ad hoc networks in which each node has one half-duplex transceiver. In order to improve performance, we used multiple channels and spread spectrum methods in this protocol. Also, it addresses the near-far problem and mitigates the hidden- and exposed-terminal problems in multi-channel systems, through information obtained from cooperating nodes. The simulation results show that at high loads, and in denser networks, CCM-MAC shows a significant improvement in throughput as well as lower delay than IEEE 802.11 and MMAC-CC, another multi-channel MAC protocol. It also has competitive throughput with another CDMA-based protocol (CA-CDMA) with twice as much hardware at each node.

In the next chapter, we describe a new CDMA-based MAC protocol incorporating transmission power control mechanism and using different spreading factors.

A POWER CONTROLLED CDMA-BASED MULTI-CHANNEL MAC PROTOCOL

In this chapter we describe PCC-MAC, a power controlled CDMA-based multi-channel *medium access control* (MAC) protocol for wireless ad hoc networks. Through this protocol, we show how transmission power control and the use of different sizes of spreading factor help mitigate *multiple access interference* (MAI) and to increase the channel reuse ratio. We provide a simulation based performance evaluation of PCC-MAC protocol.

4.1 The PCC-MAC Protocol

In the PCC-MAC protocol, we assume that there are two different channels, one for the control packets and another for data packets, and that the signal on one channel does not interfere with the other, and that each node is equipped with a single half-duplex transceiver which can not send and receive simultaneously. We also assume that nodes always use *maximum transmission power* (P_{max}) to send control packets on the control channel, while they use adjusted transmission power to send data packets on the data channel. All of the control packets except the ACK packet use a common *orthogonal variable spreading factor* (OVSF) code with a low *spreading factor* or a narrow band signal on the control channel. For an ACK packet, one of the OVSF codes with a high spreading factor, which is orthogonal to the common OVSF code, is used. The size of the spreading factor for an ACK packet is fixed. For a data packet, each node uses its unique pseudo-random code over the data channel. Such a code assignment is out of the scope of this paper; see [15] for a potential solution to this problem.

PCC-MAC uses a modified CSMA/CA style handshake to reserve the authority to access the data channel. Each node collects and stores the information required to adjust the level of transmission power for data transmission when they overhear control packets, and to mitigate collisions that may occur on the control channel in the exchange of a handshake.

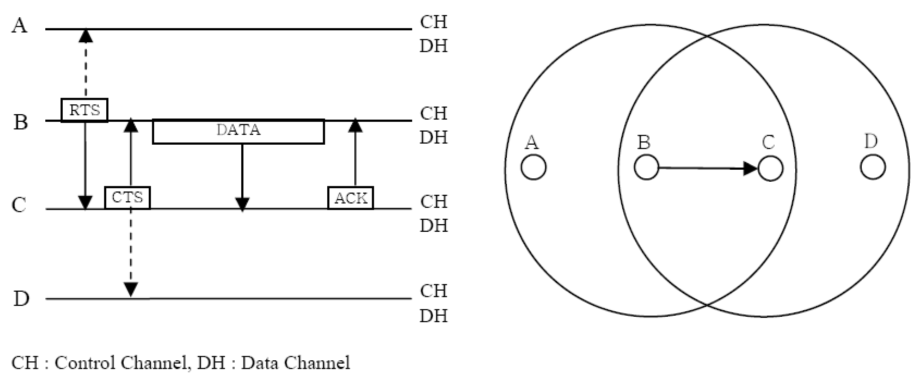


Fig. 37. Processing of handshake.

Figure 37 shows the processing of a handshake for a data transmission. In this figure, suppose that node B has a packet to transmit to node C. As in IEEE 802.11, if the control channel is clear for a time interval equal to a DCF interframe space (DIFS), node B transmits an RTS to node C, which contains a random number used to select an OVSF code to use to spread an ACK packet and a *maximum allowable power* (MAP). If this is received by node C, it responds with a CTS containing a *maximum allowable interference power* (MAIP) and a selected power level.

Suppose that node A overhears only the RTS from node B and that node D overhears only the CTS from node C. When nodes A and D overhear the RTS and the CTS, respectively, they store all information that they obtain in a node status table (see Section 4.1.1.2 for details on this table). Finally, on receipt of the CTS, node B transmits the data packet to node C with the selected power level. If the data transmission is completed successfully, node C transmits an ACK to node B on the control channel. If there is any collision of control packets, each node follows the binary exponential backoff algorithm to resolve the collision; this algorithm is in common use, e.g., in IEEE 802.11 DCF [21].

4.1.1 Channel Negotiation in PCC-MAC

4.1.1.1 Control Packet Formats in PCC-MAC

Figure 56 shows the packet frame format for PCC-MAC control packets. The control packet frame format is similar to that of control packets in IEEE 802.11 except some fields are added for power control.

An RTS control packet sent by a transmitter contains the MAP which is maximum power a transmitter can use to not interrupt any ongoing communication around the transmitter. It also contains a random number (RN) between 1 and 96 used to choose one of the ninety six OVSF codes with a spreading factor of 128, which are all orthogonal to each other and the common code. The CTS control packet also contains additional power information fields. The $MAIP$ is the *maximum allowable interference power* (P_{maip}) that a receiver can tolerate from unintended transmitters. Each transmitter uses the $MAIP$ to calculate the MAP. The selected power level (SPL) is the transmission power level for data transmission calculated by the receiver. The format of an ACK control packet is the same as in IEEE 802.11 [21].

Bits :	16	16	48	48	7	8	32
RTS :	FC	Dur	RA	TA	RN	MAP	CRC

Bits :	16	16	48	8	8	32
CTS :	FC	Dur	RA	MAIP	SPL	CRC

Bits :	16	16	48	32
ACK :	FC	Dur	RA	CRC

Fig. 38. Control packet formats in PCC-MAC.

4.1.1.2 Contents of the PCC-MAC Node Status Table

The nodes in the vicinity of the transmitter or the receiver that overhear some or all of the handshake store information in the node status table. Each node has a node status table storing 9-tuples as seen in Figure 39. Here, N_{id} is a node identifier, S is the communication status of N_{id}, P_{ipl} is the incoming power level from node N_{id}, P_{map} is the maximum allowable power level at the transmitter side, C_{rn} is the random number used to select an OVSF code for

N_{id}	S	P_{ipl}	P_{map}	C_{rn}	P_{id}	P_{spl}	P_{maip}	Dur

Fig. 39. Node status table for the PCC-MAC.

ACK transmission, P_{id} is the partner node identifier of node N_{id}, and P_{spl} is the selected power level for data transmission. Finally, P_{maip} and Dur are the maximum allowable interference power at the receiver side and the duration in time of the data transmission, respectively.

When a neighbour node overhears an RTS from node i, it creates a new entry in the node status table and sets $N_{id} \leftarrow i$, $S \leftarrow$ `transmit` representing the fact that i is a transmitter, and estimates P_{ipl} to calculate interference from i. C_{rn}, P_{map}, P_{id}, and Dur are copied from the RN, the MAP, the RA, and the Dur fields of the RTS, respectively. However, if their is an entry in the node status table for N_{id}, then the information is simply updated. Similarly, if a CTS is overheard, then both P_{spl} and P_{maip} are copied from the SPL and $MAIP$ fields, respectively, into the status table for node N_{id}. Entries are inserted into the table when a node is in idle mode, i.e., it is a cooperating node, and deleted when their duration expires or they are incomplete. Updating of the information stored in the node status table is important because P_{map} is decided based on the information of the node status table. However, sometimes, nodes cannot update the information since they cannot overhear the control packets of other pairs while they are engaged in communication. In this case, latest information stored in the table is used.

4.1.2 Power Controlled Channel Access Scheme

In PCC-MAC, when a node sends a data packet to its intended receiver, the transmission power level is controlled by the information collected while exchanging the control packets. If the transmission power from a transmitter increases, the bit error rate of the signal received at the intended receiver is reduced. However, since a strong signal increases the *multiple access interference* (MAI), it could weaken the performance of the protocol. On the contrary, if the transmission power decreases, the bit error rate increases. However, since a weak signal does not influence the MAI, more nodes are accommodated on a single channel. Therefore, the choice of the transmission power level influences the system throughput.

The processing of a data transmission uses the following sequence: When a node has a packet to send, it first listens on control channel for a *DCF interframe space* (DIFS) time. If there is no activity detected during this time, it checks the maximum allowable power (P_{map}) based on the information in its node status table ($P_{map} = P_{max} - P_{maip}$), generates a random number to be used for selecting a code for an ACK and sends an RTS, containing these values, to the receiver at a fixed maximum transmission power over the control channel. If there is no active node around the transmitter, $P_{map} = P_{max}$. When the receiver receives the RTS, it checks the signal strength to obtain the channel gain and MAI to calculate the minimum power (P_{min}) which enables the nodes to communicate, and calculates the maximum allowable interference power (P_{maip}) for unintended transmitters by following equations (16) and (17), respectively.

Since the received power for each receiver is different, the SNR in this case, following Van Rooyen and Ferreira [70] (see also Chapter 3, page 66), is

$$\theta = \frac{3N_c P}{\frac{N_0}{T_c} + \sum_{j=1}^{K} \left(\frac{d_{is}}{d_{ij}}\right)^{\beta} P} \tag{15}$$

where the $3N_cP$ of the numerator is the received power multiplied by the processing gain.

$$P_{min} = \frac{\theta(P_{thermal} + P_{mai})}{G}. \tag{16}$$

Here, $P_{thermal}$ is the thermal noise power which is $P_{thermal} = \frac{N_0}{3N_cT_c}$ of (15), P_{mai} is the multiple access interference power which is $P_{mai} = \frac{\sum_{j=1}^{K} \left(\frac{d_{is}}{d_{ij}}\right)^{\beta} P}{3N_c}$ of (15), and G is the channel gain ($\frac{P_r}{P_t}$).

$$P_{maip} = \frac{\xi_{max}\theta P_{thermal}}{G} - P_{min} \tag{17}$$

where ξ_{max} is the interference margin [54]. If $P_{map} < P_{min}$, communication is impossible. If $P_{map} \geq P_{min}$, then the PCC-MAC protocol uses following simple equation (18) to obtain the power level for data transmission.

$$P_{spl} = \frac{P_{map} + P_{min}}{2}. \tag{18}$$

These P_{maip} and P_{spl} values are included in a CTS packet and the CTS is sent to the transmitter. On receipt of the CTS, the transmitter checks to see if the P_{spl} is greater than P_{map}. If so, the transmitter follows a backoff policy. If not, the transmitter sends a data packet coded by its own unique pseudo random code with the chosen P_{spl}. If the data transmission is completed successfully, the receiver transmits an ACK encoded with a high spreading factor to the transmitter in order to avoid potential collision with another handshake on the control channel at the fixed maximum transmission power.

Figure 40 shows the effect of using transmission power control. In Figure 40(a), each node uses a fixed maximum transmission power to send packets. In this case, node C uses the maximum transmission power to transmit a packet even though node D is close to node C. This interferes with the reception at node B, that is, this is an occurrence of the near-far problem. However, in Figure 40(b), since node C sends the packet with a reduced transmission power, the signal will not interfere with the reception at node B. Therefore, the near-far problem is solved by controlling the transmission power.

4.1.3 Use of Spreading Factors on the Control Channel

One processing method that distinguishes PCC-MAC from other multi-channel MAC protocols, is that all the nodes exchange their control packets only through a dedicated control channel. Many multi-channel MAC protocols proposed use the data channel to transmit an ACK packet to reduce the NAV

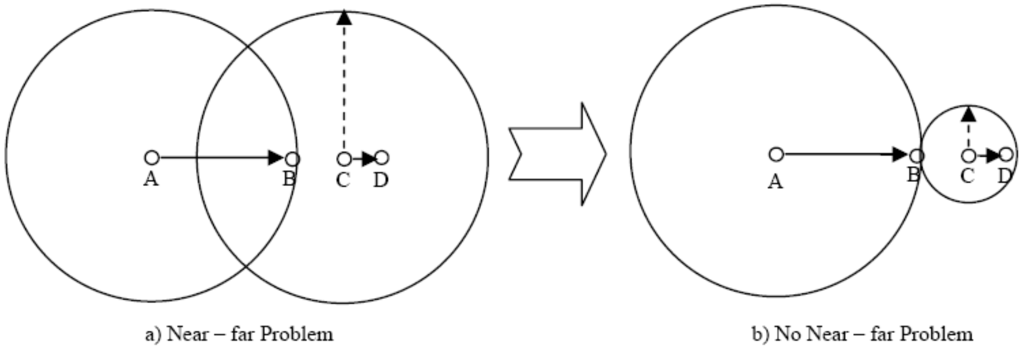


Fig. 40. Effect of controlling transmission power level.

time and to avoid the collision with another handshake on the control channel. However, there is a disadvantage in using the data channel for an ACK packet. In Figure 41, suppose that the nodes A, C, and E have ongoing transmissions with their corresponding receivers B, D, and F, respectively, using CDMA. Suppose also that RTS and CTS packets are sent through the control channel, and that the data and ACK packets are sent through the data channel. If they are synchronized exactly in time, the three pairs of nodes can communicate simultaneously. However, the probability of achieving perfect synchronization is not likely in MANETs. In this example, it presents no issues between the pairs A and B, and C and D, and between the pairs C and D, and E and F, assuming they are far enough apart to avoid the near-far problem. However, the near-far problem may happen between the pairs A and B, and E and F even though the transmitters of each communication pair are far enough apart not to interfere with the reception of another receiver. If either B or F, which finishes its receiving first responds with an ACK to its transmitter, the near-far problem may occur between the nodes B and F because nodes B and F are very close. Therefore, one of communication pairs may be deferred to avoid the near-far problem. This decreases the channel reuse ratio, undermining the advantage of using CDMA. For this case, if each node sends an ACK packet through the control channel, the channel reuse ratio for a data transmission at each node increases. As a result, the system throughput increases as well.

However, since all control packets are sent by a maximum transmission power, the near-far problem should be taken into account. Consider Figure 42, which shows the interference range of the node T. Here, d is the distance between T and R, and the small dashed circle which has a radius of $\frac{1}{2.78}d$ is the interference range of T. If there is no node in interference range as shown in Figure 42 and the code for the ACK packet is orthogonal to the common code for the RTS and CTS, PCC-MAC is able to achieve a reliable ACK packet transmission [45, 70]. However, if there are any transmitters transmitting in the interference range of node T, they will interfere with the reception of node T while it is receiving. Similarly, if there are any receivers receiving in the interference range of node T, they will suffer interference while node T is transmitting. In other words, if there are any other nodes communicating in the interference range of a node, the near-far problem occurs.

In PCC-MAC, since each node sends an ACK packet with a maximum transmission power on the control channel, a collision with another handshake

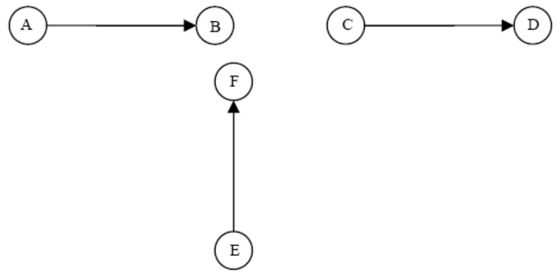


Fig. 41. Near-far problem at receiver side.

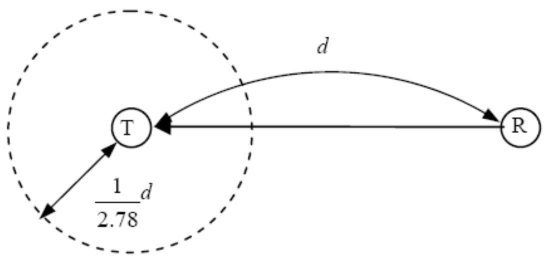


Fig. 42. Interference range.

on the control channel inevitably happens if nodes are in interference range of each other. Figure 43 shows an example of a collision between an ACK packet and another handshake on the control channel. Suppose that the nodes A, D, and E, and the nodes B, C, and F are transmitters and receivers, respectively. Suppose also that node A has ongoing data transmission with node B, node C has finished receiving a data packet from node D, and that node E has a packet to send to the node F. If node E sends an RTS to node F and at the same time, node C sends an ACK to node D, a collision occurs on the control channel. Similarly, the ACK packet from a receiver can collide with a CTS from another node in the vicinity of the intended transmitter.

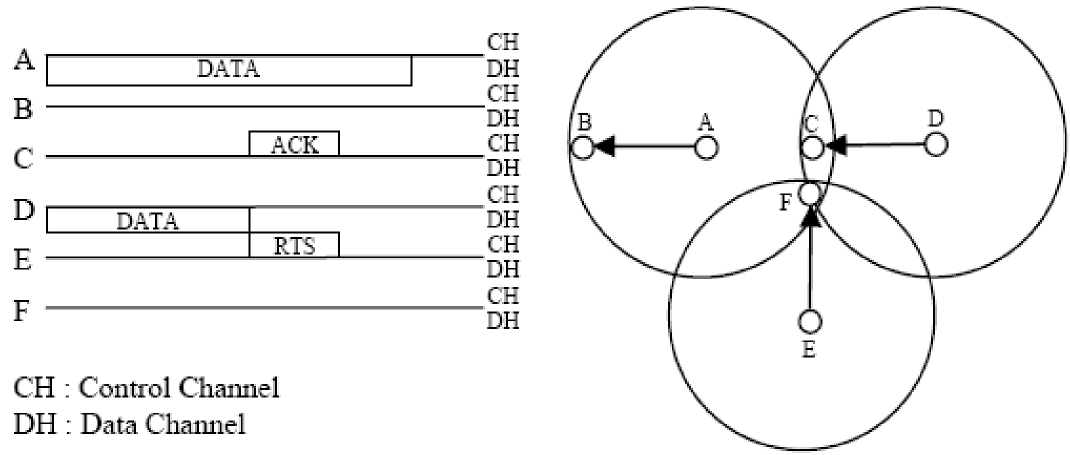


Fig. 43. Collision on the control channel.

To address this problem, the PCC-MAC protocol adopts different sizes of spreading factors (SFs) to produce different spreading degrees of the signals for control packets on the control channel. As a result, it reduces the incidence of the near-far problem than when the same spreading factor is used, and enhances the advantage of using CDMA.

Figure 44 shows the OVSF code tree to depth 3 which is a complete binary tree that reflects the construction from Hadamard matrices. The codes at each level are mutually orthogonal to each other. In PCC-MAC, each spectrum for control packets is spread differently according to the code used, which is derived from an OVSF code tree. For a narrow band signal, a spreading factor 1 can be used. Therefore, if the narrow band signal, spread by $SF = 1$ which is very low is used for an RTS and a CTS, and the ACK packet is spread by high SF value, the near-far problem can be mitigated. In other words, the higher the

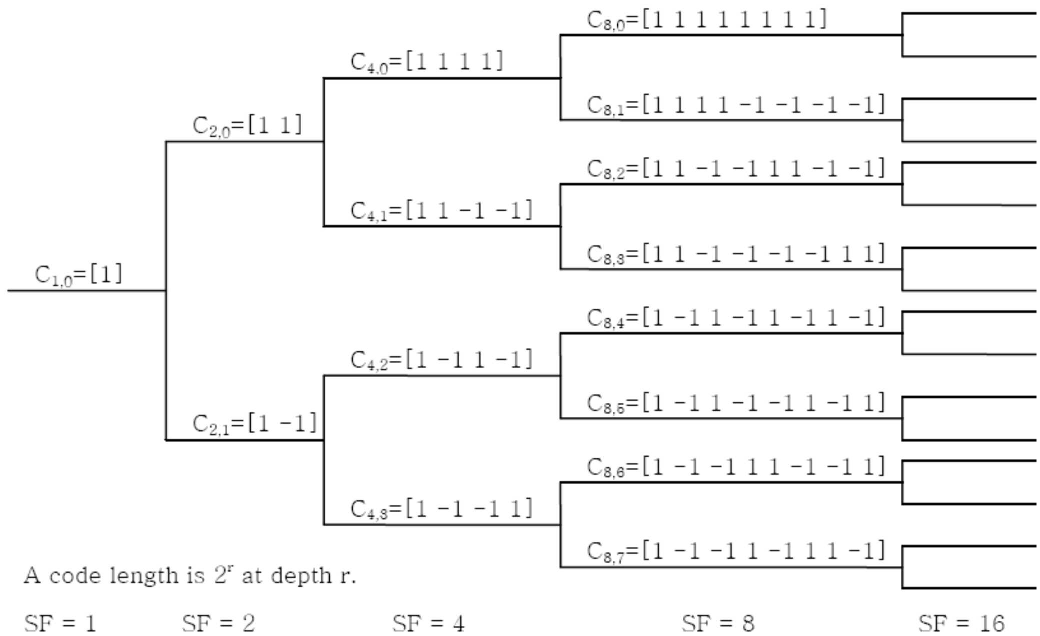


Fig. 44. OVSF Code Tree to depth 3.

difference between two spreading factors, the higher processing gain between two signals. The increase of processing gain aids in mitigating the near-far problem. Of course, if the transmission power of the interfering signal is too strong, the spreading factor alone is not enough to solve the near-far problem. This is an active research problem and many solutions have been proposed to detect multiple users such as *minimum mean square error* (MMSE) or *parallel interference cancelation* (PIC) [3, 28, 55].

In the PCC-MAC protocol, the spreading codes used for both RTS and CTS packet, and the ACK packet, all are orthogonal to each other when using OVSF codes. PCC-MAC spreads the signal using a low spreading factor for the RTS and CTS, and using a high spreading factor for an ACK packet. When

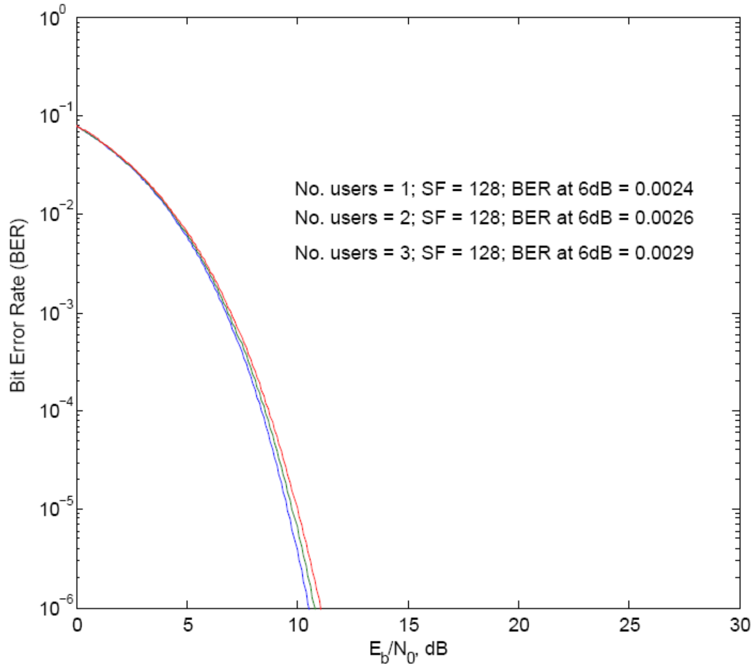


Fig. 45. Bit Error Rate for CDMA using DSSS.

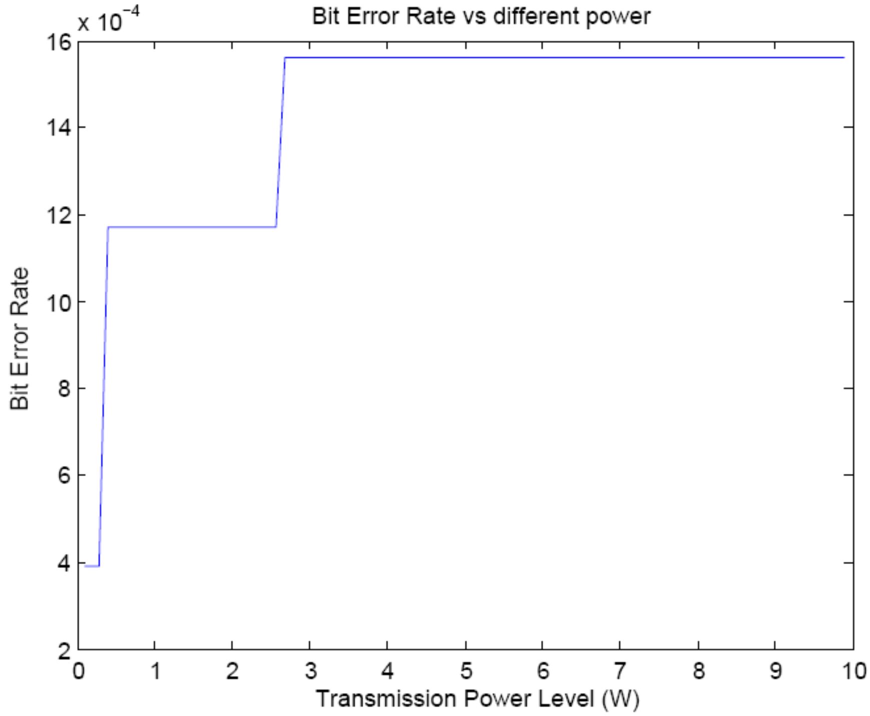
the receiver receives the signal, through the despreading process it recovers the signal of packet correctly.

Figure 45 shows the standard *bit error rate* (BER) versus $\frac{E_b}{N_0}$ for CDMA using *direct-sequence spread spectrum* (DSSS). In this figure, $6dB$ is the interference margin [54]. In Figure 45, the standard bit error rate with one, two, and three users is 2.4×10^{-3}, 2.6×10^{-3}, and 2.9×10^{-3}, respectively. Therefore, if the bit error rate of the packet received is less than the standard bit error rate at $6dB$, the packet can be decoded correctly. In other words, if the bit error rate of a packet is lower than that of the interference margin, the packet is still decodable.

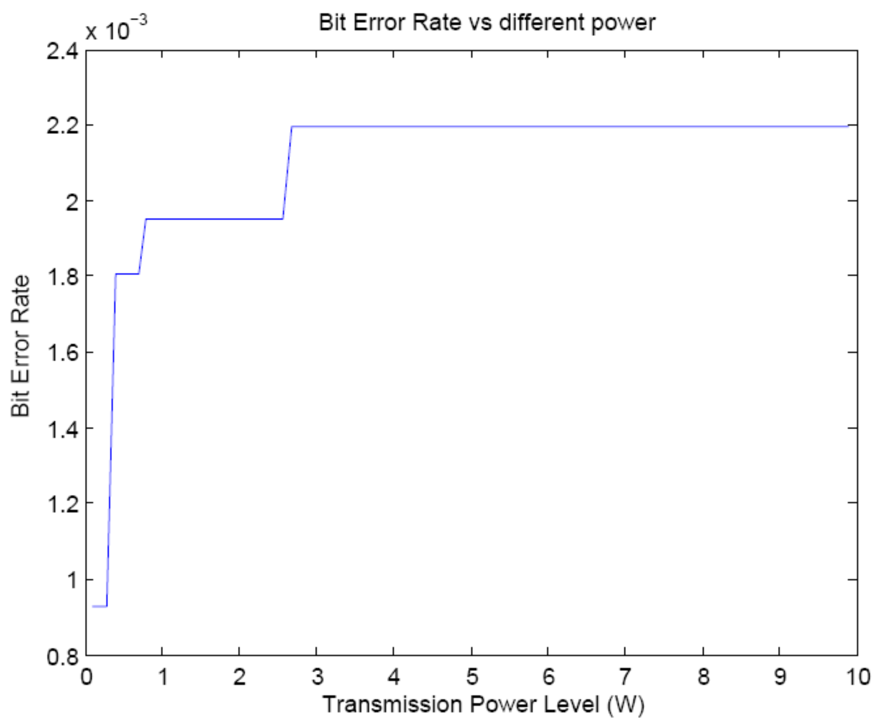
Consider Figure 46, which shows the simulation results of the bit error rate with one interfering node, and two interfering nodes, within the interference range, respectively. In this simulation, we assume that a collision by an ACK may occur with a maximum of two other handshaking pairs. This is a reasonable assumption because the channel access scheme for the control channel is contention based and the probability that several nodes within interference range transmit a packet at exactly the same time is very low. We use $SF = 4$ for an RTS and a CTS, and a $SF = 128$ for an ACK packet. As seen Figure 46, the bit error rate with one and two interfering node is less than or equal to 1.58×10^{-3} and 2.2×10^{-3}, respectively. The results are slightly lower than that of interference margin, which means that the PCC-MAC protocol mitigates collisions of the ACK with one or two other sources on the control channel.

4.2 Performance Evaluation of the PCC-MAC Protocol

In this section, the performance of the PCC-MAC protocol is compared with the IEEE 802.11 DCF [21], another CDMA based MAC protocol named CA-CDMA [47] both described in Chapter 2, and also, with a cooperative CDMA based MAC protocol (CCM-MAC) [45], which is described in Chapter 3. We use MATLAB to simulate the PCC-MAC protocol, CCM-MAC and IEEE 802.11 DCF [21]. For the CA-CDMA protocol [47], we present analytical results derived in [47].



(a) Bit Error Rate with one interfering node



(b) Bit Error Rate with two interfering nodes

Fig. 46. Bit Error Rate.

4.2.1 Parameters of the Simulation

We assume that the channel bandwidth for each protocol is the same: $2\,Mbps$. For the PCC-MAC protocol and CA-CDMA, we set $400\,Kbps$ for the control channel rate while the data channel rate is $1.6\,Mbps$. The CCM-MAC has one control channel and three data channels with the bandwidth is split equally among all channels. Since IEEE 802.11 works on a single channel, it uses the whole bandwidth for each transmission.

In our simulations, we placed a total of 34 nodes in $1000 \times 1000 m^2$ area distributed uniformly at random. For mobile scenarios, we used the stationary random way-point mobility model with a node speed that is uniformly between zero and $2\,m/s$. In addition, we assume that the transmission range at maximum transmission power is the same for IEEE 802.11, CCM-MAC, CA-CDMA, and the PCC-MAC protocol.

In this experiment, we select destinations from the one-hop neighbours of source nodes to evaluate the throughput at the MAC layer. Half of the nodes are sources. Each node generates packets according to a Poisson process with rate λ, $0 \leq \lambda \leq 60\,pkt/s$, with the same rate for all nodes. Each simulation runs for $300\,s$ of simulated time. The results plotted are averaged over 50 replicates resulting in a very small 95% confidence interval. More parameters used in the simulation are provided in Table 3.

TABLE 3. Simulation parameters for the PCC-MAC protocol

Frequency	2.4 GHz
Data packet size	1 $Kbyte$
IEEE 802.11 channel rate	2 $Mbps$
CCM-MAC data channel rate (total)	500 $Kbps$ ($\times 3 = 1.5\,Mbps$)
CCM-MAC control channel rate	500 $Kbps$
CA-CDMA & PCC-MAC data channel rate	1.6 $Mbps$
CA-CDMA & PCC-MAC control channel rate	400 $Kbps$
Transmission power	20 dBm
SNR threshold	15 dB
Interference margin	6 dB
Reception threshold	-68 dBm
Carrier-sense threshold	-74 dBm
Interference threshold	2.78

4.2.2 Simulation results

We begin by comparing the throughput obtained in static scenarios compared to that obtained in mobile scenarios. For this comparison, a data packet size of 1 $Kbyte$ is used. Figure 47 shows that there is about a 2.4% difference between these types of scenarios, which means that mobility has a little effect to the throughput. The reason for this is because our protocol focuses on one hop transmissions only. Besides, since the duration of transmission of the handshake followed by a data packet is in the tens of milliseconds, there is no big changes in topology for that duration. However, it is still possible that a destination moves out of the transmission range of its source, or that a source moves into the range of another destination causing the near-far problem in

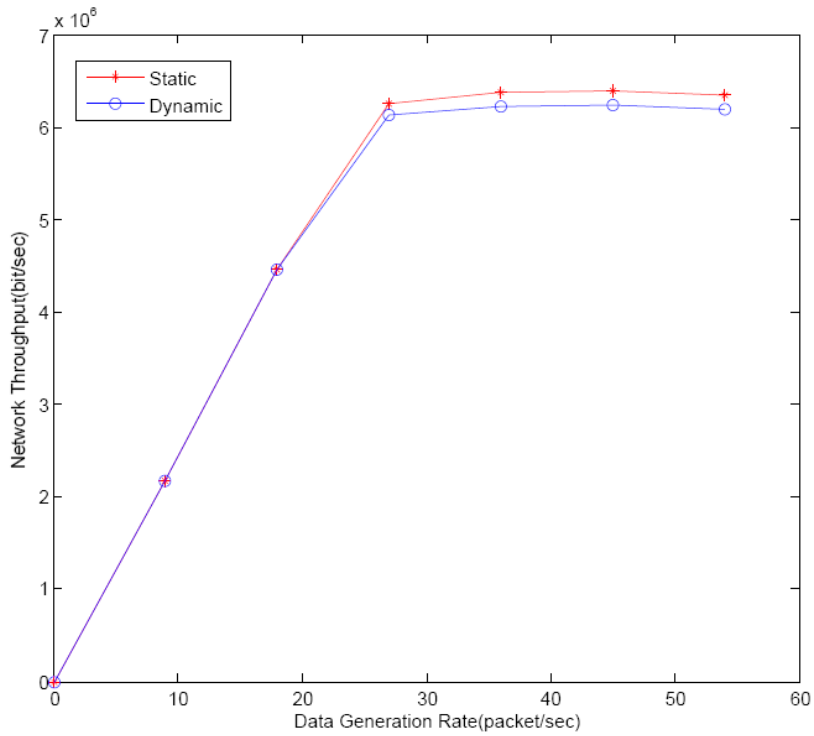


Fig. 47. PCC-MAC throughput in static vs. mobile topologies.

mobile scenarios. Both of these would account for the decrease in throughput. As a result, we restrict our presentation to mobile scenarios only.

Next, we compare the PCC-MAC protocol with IEEE 802.11, CA-CDMA, and also, with CCM-MAC. Figure 48 shows throughput as a function of data generation rate. In general, the throughputs of PCC-MAC, CCM-MAC and CA-CDMA protocol are always higher than IEEE 802.11. This can be interpreted as the advantage that CDMA brings. Since CDMA allows more than one node on the same channel, the number of simultaneous transmissions increases. However, IEEE 802.11 works on a single channel and cannot support

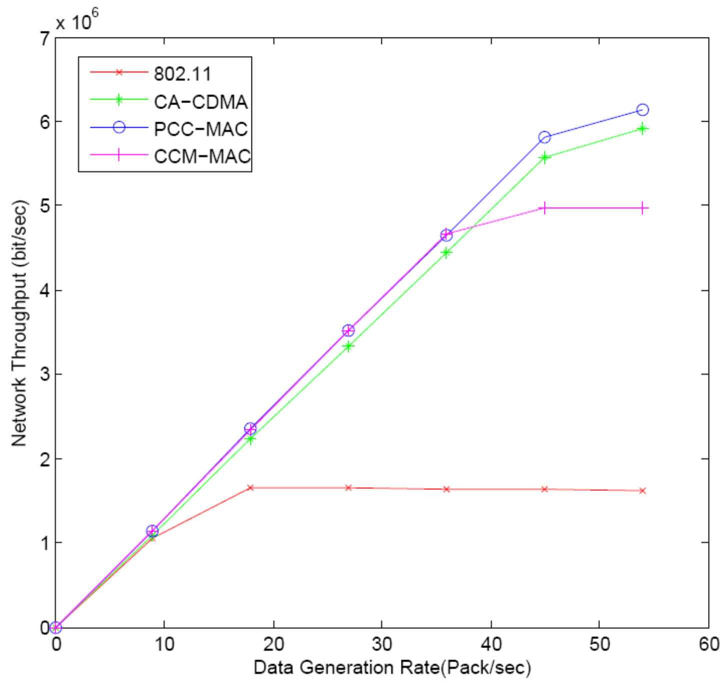


Fig. 48. Throughput as a function of network load for 1 $Kbyte$ data packets.

concurrent transmissions. Besides, as the network load increases the channel is easily saturated. The throughput of PCC-MAC protocol is slightly better than CA-CDMA, while the throughput of CA-CDMA is better than CCM-MAC. As shown in this result, CCM-MAC does not beat the performance in throughput of CA-CDMA, which has the advantage of the use of multiple transceivers and power control, while PCC-MAC shows better performance than CA-CDMA, even with a single transceiver. This is because PCC-MAC achieves a better channel reuse ratio for data transmission on the data channel by controlling transmission power as well as by sending the ACK packet through the control channel.

Specifically, in Figure 48, the throughput of PCC-MAC is at best 3.55 times higher than IEEE 802.11 and 1.06 times higher than CA-CDMA at best, while the throughput of CA-CDMA is at best 1.17 times higher than CCM-MAC.

We also investigated the throughput as a function of increasing the number of nodes n, $0 \leq n \leq 64$, for increasing packet size with data generation of $30\,packets/s$. As shown in Figure 49, the throughput of PCC-MAC protocol is still higher than IEEE 802.11, CCM-MAC, and CA-CDMA. This is also interpreted as an advantage of the use of CDMA, power control, and different spreading factors for the control packets on the control channel. In Figure 49, the throughput of PCC-MAC is at best 3.52 and 1.05 times higher than IEEE 802.11 and CA-CDMA respectively, while the throughput of CA-CDMA is 1.06 times higher than CCM-MAC at best.

We also measured the average packet delay in PCC-MAC, CA-CDMA, and IEEE 802.11 by using the method proposed by Kleinrock and Tobagi [30] (see also Chapter 3, page 76). The average packet delay is the time elapsed in transmitting one data packet using the entire system bandwidth. We keep the assumptions made in CCM-MAC protocol [45] and Chapter 3 to measure the average packet delay.

Figure 50 shows the average delay in PCC-MAC, CA-CDMA, and IEEE 802.11. In this figure, the average delay for both PCC-MAC and CA-CDMA

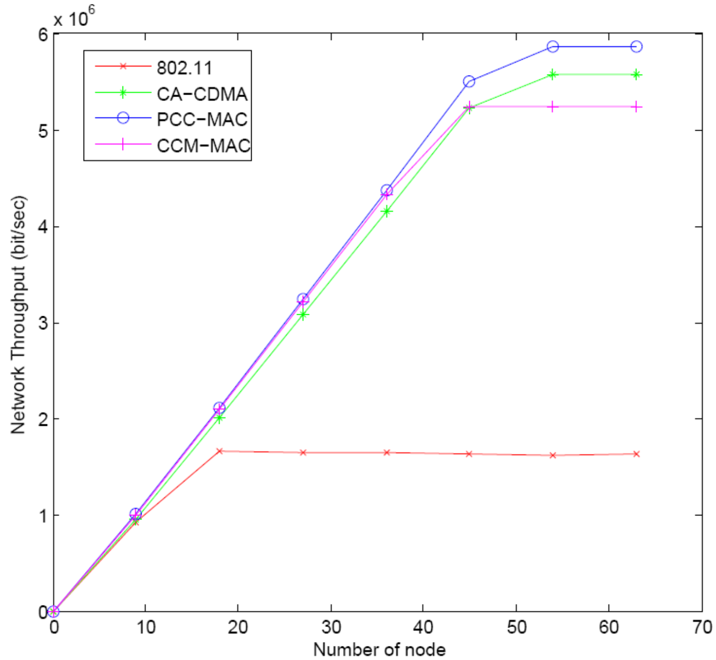


Fig. 49. Throughput as a function of the number of node for 1 $Kbyte$ data packets.

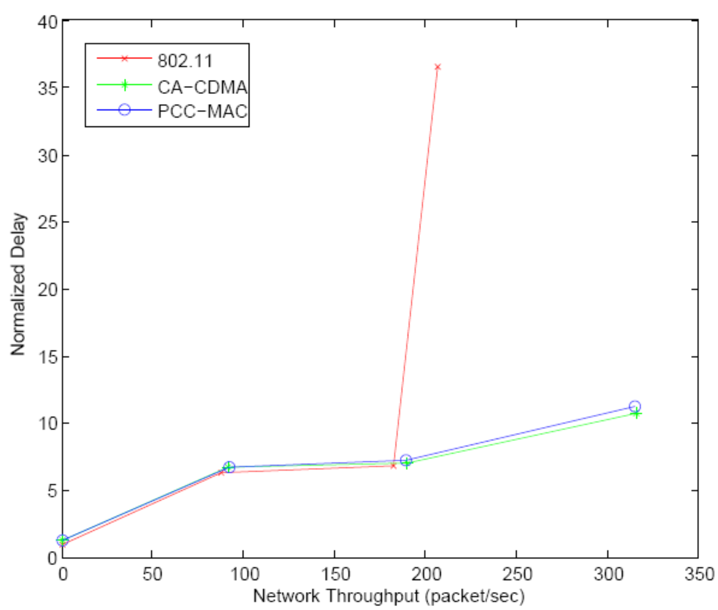


Fig. 50. Average delay v. throughput.

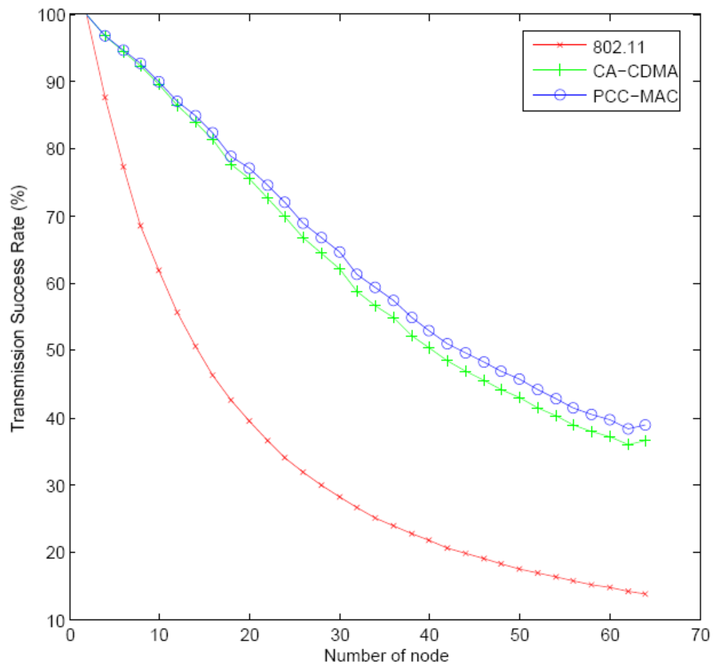


Fig. 51. Probability of successful packet transmission.

remains stable at higher traffic loads. Indeed, the average delay for CA-CDMA protocol is a slightly better than the delay of PCC-MAC, about 1.04 times at best. This is because in the CA-CDMA protocol, the ACK packet is sent through the data channel which has the wider bandwidth than the control channel. IEEE 802.11 has a slightly better delay than both PCC-MAC and CA-CDMA at low traffic loads but, it gets worse quickly. This is interpreted as IEEE 802.11 taking advantage of using the whole bandwidth at low traffic loads.

Finally, we show the results of transmission success rate as a function of number of nodes in the IEEE 802.11, CA-CDMA, and PCC-MAC protocols.

In Figure 51, while the transmission success rate of both CA-CDMA and PCC MAC protocol drops steadily, the transmission success rate of IEEE 802.11 drops more sharply. Specifically, the transmission success rate of PCC-MAC is about 2.8% higher than CA-CDMA at best, and is 37.8% higher than IEEE 802.11. This is interpreted as the PCC-MAC has better channel and spatial reuse ratio than CA-CDMA by sending an ACK packet through the control channel, and the advantage of using CDMA technology.

4.3 Summary

In this chapter, we presented PCC-MAC, a power controlled CDMA-based multi-channel MAC protocol for wireless ad hoc networks with one half-duplex transceiver at each node. This protocol obtains a better channel reuse ratio by using a dedicated control channel for all control packets exchanged. In addition, it mitigates the incidence of collisions of control packets on the control channel by using different sizes of spreading factors to have different processing gains for the control signal. Also, PCC-MAC addresses the near-far problem of CDMA occurring on the data channel by accounting for the *multiple access interference* (MAI) through controlling transmission power at each node. The results show that PCC-MAC maximizes the advantage of using CDMA by achieving a better channel reuse ratio on both the control and data channel and achieves a significant improvement in throughput as well as delay over IEEE 802.11. Moreover, it shows a slightly better throughput and competitive delay than CA-CDMA [47] which use multiple transceivers equipped at each node even though each node in PCC-MAC is equipped with a single transceiver. In the next chapter, we introduce a new MAC protocol that combines *orthogonal frequency division multiple access* (OFDMA) and *code division multiple access* (CDMA).

A COOPERATIVE DUAL ACCESS MULTI-CHANNEL MAC PROTOCOL

In this chapter, we propose, a cooperative dual access multi-channel MAC protocol for ad hoc networks, combining the use of *orthogonal frequency division multiple access* (OFDMA) and *code division multiple access* (CDMA) to mitigate the multi-channel hidden- and exposed-terminal problems as well as to increase channel reuse ratio, respectively. Also, we introduce node cooperation and a resolvable *balanced incomplete block design* (BIBD) to mitigate the near-far problem and to minimize interference, respectively. We provide a performance evaluation of the CDM-MAC protocol in simulation.

5.1 The CDM-MAC protocol

The CDM-MAC protocol is designed for nodes which are equipped with one half-duplex transceiver. It combines the use of OFDMA and CDMA access technologies. To ease OFDMA channel management the network is clustered. Through OFDMA, each node in the network has an advantage of using various number of channels simultaneously. In addition, channel groups are defined by a resolvable BIBD to minimize interference of the channel group. Unique CDMA codes assigned to each cluster increases the channel reuse ratio. Clusterheads manage and assign channel groups through an extended handshake. Idle nodes that overhear the handshake cooperate to reduce the incidence of the multi-channel hidden- and exposed-terminal problems and also the near-far problem of CDMA.

We assume there are N sub-carriers of which a certain fraction form a control channel group and the remaining form several channel groups for data transmission. All sub-channels are orthogonal with respect to each other. The network is clustered by one of the clustering algorithms (see [36,48] for details on clustering algorithms) for the purpose of channel management, i.e., each node is affiliated with one cluster and is in direct transmission range of its clusterhead. Clusterheads are not, in general, connected. Each clusterhead is responsible for managing the allocation of the OFDMA channel groups to transmissions; this includes maintaining the duration of each allocation. Furthermore, a unique CDMA code is assigned to each cluster (see [15] for a potential solution to code assignment). Transmission on an OFDMA channel group uses the CDMA code of the transmitter's cluster, while transmission on the control channel group uses a common code permitting all overhearing nodes to decode the transmission.

5.1.1 Channel Group Negotiation and Assignment in CDM-MAC

5.1.1.1 Transmitter-Receiver affiliated with the Same Cluster

In our protocol, the cluster head performs a function similar to the base station in a cellular system maintaining information regarding channel assignment in its cluster. With two exceptions, the handshake takes place on the control channel group and is used to obtain a channel group for data transmission.

A transmitter initiates the handshake with a *channel request message* (CRM) to request a channel group from its clusterhead. If there is one available, the clusterhead responds with a *channel assignment message* (CAM) to assign channel group $\mathcal{G}$. If the receiver is affiliated with the same cluster as the transmitter, it overhears the CAM and sends a *confirm message* (CFM) to confirm the channel group selected. If a cooperating neighbour overhears the CAM and is aware of channels in $\mathcal{G}$ that may experience interference, it transmits a *channel information message* (CIM) to the transmitter containing a list $\mathcal{L}$ of such channels on the data channel group $\mathcal{G}$.

Importantly, OFDMA enables the transmitter to decode the simultaneous transmission of the CFM and CIM; these two control packets do not collide. If multiple cooperating neighbours transmit a CIM, we take advantage of the capture effect of CDMA to decode the strongest signal of simultaneously transmitted CIMs [60]. Therefore, the transmitter decodes the CIM from its closest cooperating node. The transmitter removes sub-carriers experiencing interference from the group, i.e., it computes $\mathcal{G} = \mathcal{G} \setminus \mathcal{L}$, and if the resulting set is non-empty, it transmits a *channel duration message* (CDM) to inform both the clusterhead and its receiver of $\mathcal{G}$ and the duration of the data transmission; the receiver tunes its receiving channels to those in $\mathcal{G}$. After the data is transmitted on $\mathcal{G}$, if the data transmission is successful, the receiver transmits an *acknowledgement* (ACK) on the same channel group $\mathcal{G}$ to avoid possible interference with another handshake.

Figure 52 and 53 show an example network topology and the handshake processing when transmitter A and its receiver B are affiliated with the same cluster; here D is a cooperating node. Suppose that node A has a packet to transmit to node B. If the control channel is clear, node A transmits a CRM, containing the intended receiver address to the *clusterhead* (CH). When the CH receives the CRM correctly, it checks if the receiver is affiliated with the same cluster as the transmitter. If so, and if there is one available channel group and node B is available, the CH sends a CAM, containing a channel group $\mathcal{G}$ and an indicator which shows that the transmitter and receiver are affiliated with the same cluster. When A receives the CAM, it checks the indicator. If the receiver is in the same cluster, node A waits for a CFM or a CIM. Suppose that node D is the only neighbour node that overhears the CRM. When node D overhears the CAM, it checks the indicator. If both transmitter A and receiver B are affiliated with the same cluster and node D aware of channels in $\mathcal{G}$ that may suffer from interference, it transmits a CIM through the available data channels in $\mathcal{G}$ to node A, containing a list of unavailable channels in $\mathcal{G}$.

In the meantime, node B receiving the CAM compares the channels of $\mathcal{G}$ with the channels in use at the receiver side. If there are available channels in $\mathcal{G}$,

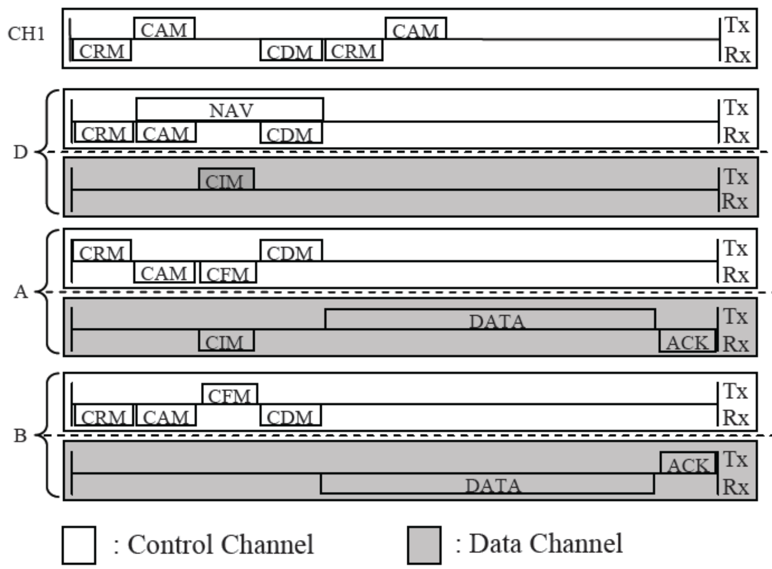


Fig. 52. Channel assignment using control packets for transmitter and receiver affiliated with the same cluster.

B sends a CFM to node A, containing a list of the selected channels in $\mathcal{G}$. Based on the information obtained from CFM and CIM, node A selects channels in $\mathcal{G}$ for data transmission and transmits a CDM to inform both CH and B of the selected channels and the duration of the data transmission. On reception of the CDM, nodes B and D tunes its receiving channels to the selected channels and updates the channel usage and duration of the transmission of node A, respectively.

Finally, node A transmits the data packet to node B through the selected channels. If the data transmission is successful, B responds with an ACK. If there is no channel group available at the clusterhead, or the channel group $\mathcal{G}$ is reduced to the empty set, the transmitter backs off using the *binary exponential backoff algorithm* (BEBA) [21].

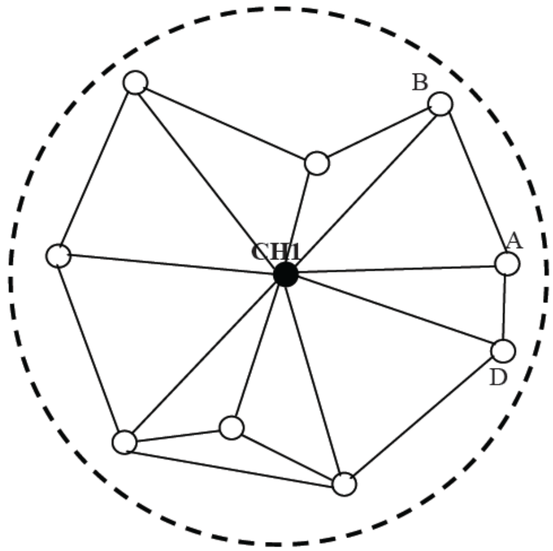


Fig. 53. Node topology for the communication between transmitter and receiver affiliated with the same cluster.

5.1.1.2 Transmitter-Receiver affiliated with the Different Clusters

Since the receiver is out of range of the transmitter's clusterhead if the transmitter and receiver are affiliated with different clusters, it is not able to receive the CAM, containing an assigned channel group for data transmission. Therefore, the handshake is extended with additional control packets.

Two more control packets are used: A *request to send* (RTS) is used to inform the assigned channel group. A *clear to send* (CTS) is used for the same function as a CFM.

Figure 54 and 55 shows an example of the handshake processing when transmitter A and receiver E are affiliated with different clusters and node topology.

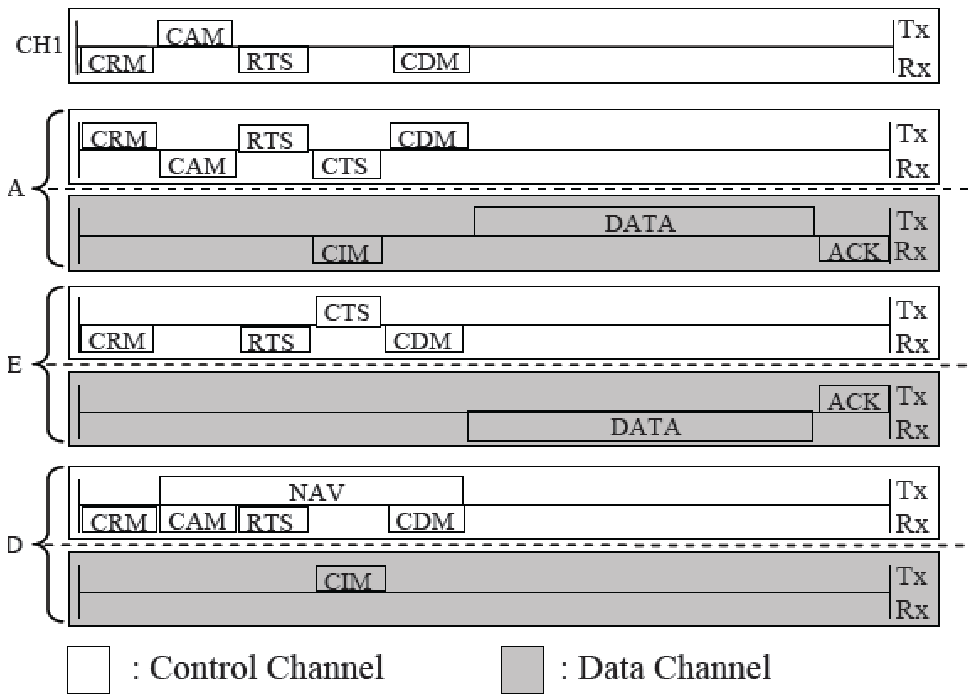


Fig. 54. Channel assignment using control packets for transmitter and receiver affiliated with the different clusters.

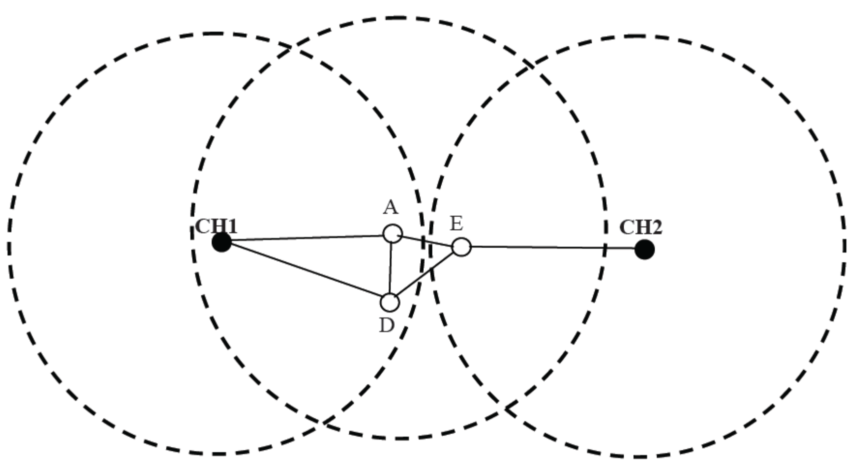


Fig. 55. Node topology for the communication between transmitter and receiver affiliated with the different clusters.

Suppose that node A has a data packet to transmit to node E, and that there is a cooperating neighbour node D. As before, node A starts with a CRM to its clusterhead CH_1. When CH_1 receives the CRM, it checks if the receiver is in the same cluster as the transmitter and there is an available channel group. If there is one available channel group but the receiver is not in the same cluster as the transmitter, CH_1 responds with a CAM containing an available channel group $\mathcal{G}$ and an indicator which shows that the transmitter and receiver are affiliated with the different clusters. From the indicator, a bit in the packet header, node A deduces node E is affiliated with different cluster and cannot receive the CAM. So node A transmits an RTS to node E effectively forwarding $\mathcal{G}$. Node E synchronizes to node A's code (found in the packet header), and responds with a CTS. In this case, a cooperating node defers the transmission of a CIM to be concurrent with the CTS instead of the CFM. The rest of the handshake is unchanged.

5.1.1.3 Control Packet Format in CDM-MAC

Figure 56 shows the format for each control packet and the field width in bits. In each, *frame control* contains various information, such as the version of the protocol, the packet type (data or control), and subtype (CRM, CAM etc.). In all cases, RA and TA denote the receiver address and the transmitter address respectively, CRC is a checksum, and Dur is the duration in time required to complete the data transmission.

The CRM includes a CHA (*address of the clusterhead*) and the unique orthogonal code (O) of the cluster. The CAM includes SA (*address of the source node*), the indicator (I) showing if the transmitter and receiver are affiliated with the same cluster, and an assigned channel group. The RTS contains information of an assigned channel group and the orthogonal code of the transmitter's cluster. The orthogonal code is used to decode the data packet received at the receiver. The CFM and CTS include a list (L) of available channels from the assigned channel group at the receiver and the orthogonal code to inform the neighbours of the receiver. The CIM contains a list of available channels from the assigned channel group, which do not overlap with other nodes around the transmitter. The CDM contains duration of the data transmission and channel list to be used.

Bits :	16	16	48	48	48	3	32
CRM :	FC	Dur	RA	TA	CHA	O	CRC

Bits :	16	16	48	48	48	3	1	32
CAM :	FC	Dur	RA	SA	Channel Group	O	I	CRC

Bits :	16	16	48	48	6	3	32
CFM :	FC	Dur	RA	TA	L	O	CRC

Bits :	16	48	6	32
CIM :	FC	RA	L	CRC

Bits :	16	16	48	6	32
CDM :	FC	Dur	RA	L	CRC

Bits :	16	16	48	48	48	3	32
RTS :	FC	Dur	RA	TA	Channel Group	O	CRC

Bits :	16	16	48	48	6	3	32
CTS :	FC	Dur	RA	TA	L	O	CRC

Bits :	16	16	48	32
ACK :	FC	Dur	RA	CRC

Fig. 56. Packet formats for each control packet in CDM-MAC.

5.1.1.4 Contents of the CDM-MAC Node Status Table

Figure 57 shows the format of an entry in the node status table stored at each node. Entries are inserted into the table when a node is acting as a cooperating node and are deleted when they expire or are incomplete. An entry has nine fields: N_{id} is the node identifier, S is the communication status (Transmitter or Receiver) of node N_{id}. P_{id} is the partner node identifier of node N_{id}, C is the channel number negotiated for the communication, $Code$ is the orthogonal code which is used by the N_{id}, $D_{coop-Nid}$, and $D_{coop-Pid}$ are the estimated distance between the cooperating node and N_{id}, and the cooperating node and P_{id}, respectively. IP_{id} is the node identifier of the nodes which are in the interfering position of the N_{id}, and Dur is the duration in time of the data transmission.

Specifically, if a cooperating node overhears a CRM from node i it creates a new entry in the node status table and sets $N_{id} \leftarrow i$, $Code \leftarrow 0010$ representing an orthogonal code used for data transmission, $S \leftarrow transmit$ representing the fact that i is a transmitter, $P_{id} \leftarrow j$ obtained from the RA field and $D_{coop-Nid}$ (see Section 3.1.2 in Chapter 3 for an explanation of how distances are estimated). If the cooperating node subsequently overhears a CAM it checks the orthogonal code, an assigned channel group, and the indicator in the CAM. If the orthogonal code is same as the orthogonal code of the cluster to which it belongs to, the channel field is set, $C \leftarrow 0010001...$ representing the assigned channel group expressed by 48 bits, and NAV time is determined by the information of the indicator which shows if the transmitter and receiver are affiliated with the same cluster. If an RTS is overheard, the cooperating node checks the orthogonal code and if the code is different from that of the cluster to which it belongs, it copies the orthogonal code from the RTS. When a CTS or a CFM is overheard, a cooperative node looks up the node identifier of the CTS or CFM sender in the node status table. If there is no information then N_{id} is set to that of the CTS or CFM sender k, $N_{id} \leftarrow k$, and S is set to receive. It also sets $P_{id} \leftarrow RA$, and copies the available channel list for C field and orthogonal code for $Code$ field from the CTS or CFM. $D_{coop-Nid}$ or $D_{coop-Pid}$ is estimated. If the cooperating node overhears a CDM it updates the C field and copies the Dur field. When the cooperating node overhears CTS or CFM from a receiver j affiliated with a different cluster, if some channels used by a communication pair T in the same cluster to which it belongs have been removed from the available channel list of j, it sets N_{id} of the transmitter of T into IP_{id} field of j and j into IP_{id} field of the transmitter of T.

N_{id}	S	P_{id}	C	Code	$D_{coop-Nid}$	$D_{coop-Pid}$	IP_{id}	Dur

Fig. 57. Node status table entry for the CDM-MAC.

5.1.2 Mitigating the Multi-Channel Hidden Terminal Problem

Since a clusterhead assigns a channel group to the transmitters in its transmission range without overlap of other channel groups, it may solve the multi-channel hidden- and exposed-terminal problem in a cluster. In addition, the feature of CDMA may aid to lower the incidence of hidden- and exposed-terminal problem in the network.

However, the multi-channel hidden-terminal problem arising from the near-far problem occurring between nodes which are affiliated with different clusters is still a concern. It is because of the collapse of the orthogonality of the CDMA signal of the communication pairs affiliated with other clusters. In [60], CDMA technology can accommodate more than one user on one channel without data packet collision if it can still tolerate interference from other nodes. However, if any transmitter exists in 1/2.78 times closer to the receiver than its partner transmitter and they use the same channel for communication, the near-far problem occurs [70]. The near-far problem may happen among the adjacent nodes which are affiliated with different clusters because there is no direct or indirect connection among the clusterheads to inform each other of the channel group assigned. In this section, channel group design and node cooperation mechanisms are presented to mitigate the near-far problem.

5.1.2.1 Channel Group Design

Since all the channels are reused in each cluster, if a node in one cluster is very close to another receiver affiliated with an adjacent cluster and they use same channel then the receiver may not receive a data packet correctly because of interference. In this case, a channel group design may be key to mitigate the interference problem occurring by channel overlap. As we will see, a transmitter contacts its clusterhead to obtain a channel group for communication. To ensure that sub-carriers do not overlap when multiple transmitter/receiver pairs affiliated with the same cluster communicate concurrently, a resolvable *balanced incomplete block design* (BIBD) is used to define the channel groups.

A BIBD is a pair $(V, \mathcal{B})$ where V is a v-set and $\mathcal{B}$ is a collection of b k-subsets of V (blocks) such that each element of V is contained in exactly r blocks and any 2-subset of V is contained in exactly λ blocks [11]. A BIBD is *resolvable* if there exists a partition of its set of blocks $\mathcal{B}$ into parallel classes, each of which in turn partitions the set V. In the following example, each column is a parallel class in a resolvable BIBD with$v = 9$, $k = 3$, and $\lambda = 1$:

$$\begin{array}{cccc} \{\ 1, 2, 3\ \} & \{\ 1, 4, 7\ \} & \{\ 1, 5, 9\ \} & \{\ 1, 6, 8\ \} \\ \{\ 4, 5, 6\ \} & \{\ 2, 5, 8\ \} & \{\ 2, 6, 7\ \} & \{\ 2, 4, 9\ \} \\ \{\ 7, 8, 9\ \} & \{\ 3, 6, 9\ \} & \{\ 3, 4, 8\ \} & \{\ 3, 5, 7\ \} \end{array}$$

In our application, v corresponds to the number of sub-carriers, k to channel group size, and r to the number of clusters. Each parallel class corresponds to the channel groups available for allocation in a cluster.

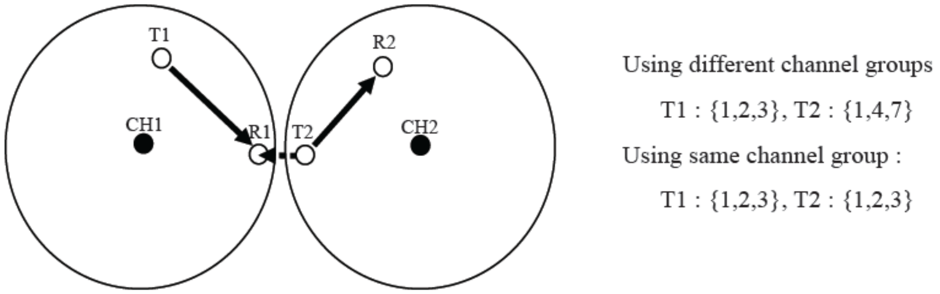


Fig. 58. Example of the advantage of using different channel groups when hidden terminal problem occurs.

Using a *resolvable BIBD* (R-BIBD) minimizes the size of the intersection of the channel groups when a transmitter and receiver are affiliated with different clusters. In this example, because $\lambda = 1$, the size of the intersection of two blocks from different classes is at most one; this limits interference.

Figure 58, shows an example of the advantage of using different channel groups when two nodes which are affiliated with the different clusters are located in interference range of each other. Suppose that nodes T_1 and R_1 have an ongoing data transmission. When nodes T_2 and R_2 complete their communication, neither node T_2 nor R_2 has overheard the control packet for channel selection between nodes T_1 and R_1. Suppose that node T_2 has a data packet to transmit to R_2, and there are no cooperating neighbours around transmitter T_2. In this case, node T_2 chooses channels from its assigned channel group without updated information of channel usage. Since the distance between nodes R_1 and T_2 is very close, the near-far problem occurs between nodes R_1 and T_2 if the same channel or channel group is used for transmission.

However, since our proposed protocol uses an R-BIBD for channel group assignment, the near-far problem only happens on at most one narrow channel out of the assigned channel group. In Figure 58, when nodes T_1 and T_2 use different channel groups, the near-far problem only happens on channel 1. The R-BIBD minimizes the size of the intersection of the channel group in different clusters. For example,

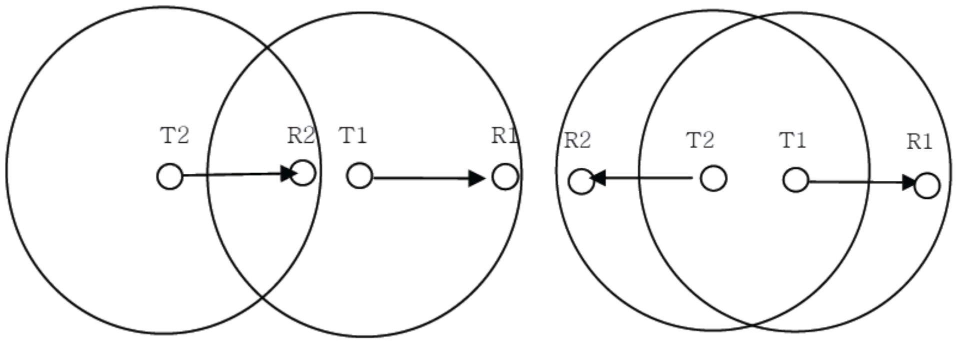
$$CH_1 = \{1, 2, 3\},\ CH_2 = \{1, 4, 7\},$$

$$CH_1 \bigcap CH_2 = \{1\}, \qquad |CH_1 \bigcap CH_2| = 1.$$

5.1.2.2 Node Cooperation Mechanism

The use of the unique code assigned to each cluster helps to mitigate the near-far problem if the communication pairs affiliated with each cluster are far from each other. Also, the use of the channel groups designed by R-BIBD mitigates the rate of channel collision. However, when nodes through the use of these techniques cannot avoid the near-far problem, node cooperation mechanism can help to address this problem.

Cooperation is used in two important ways in our protocol: (1) to help negotiate the OFDMA channel group, and (2) to help mitigate the near-far problem of CDMA. To enable cooperation, each node maintains a *channel status table* containing information extracted from packet headers, such as node identifiers, CDMA code, channel group, duration etc.



(a) Adjacent nodes R2 and T1 have different communication mode (b) Adjacent nodes T1 and T2 have same communication mode

Fig. 59. Example of the limitation of signal sensing.

Consider Figure 59, which shows an example of the problem that may happen when nodes only depend on signal sensing to select a channel. All nodes in our protocol monitor all the channels in $\mathcal{G}$ before it selects the channels for the data packet transmission. However, monitoring all the channels cannot give sufficient information to select trouble-free channels. Moreover, since channel groups are assigned by the clusters which are not connected each other, it is more difficult to obtain channel usage information by signal sensing only.

As seen in Figure 59, there are two transmitters T_1 and T_2 and their partner receivers R_1 and R_2. We assume that node T_1 did not overhear the control packet exchange between nodes T_2 and R_2. In Figure 59(a), if node T_1 tries to communicate with node R_1 without any knowledge of channel usage of R_2, T_1 may select the channel being used by the T_2 and R_2 pair. Since node T_1 is out of the transmission range of node T_2, it will sense the channel as usable. However, if T_1 selects same channel as T_2, node R_2 cannot receive data packets correctly from node T_2 because of the interference from T_1. In Figure 59(b), T_1 may suffer from delaying of the transmission. Since node T_1 is close to another transmitter node T_2, when node T_1 senses one or more strong signals on the assigned channels, node T_1 may set those as unusable channels even though it is not necessary. If there are any channels available, it uses another. But if not, it postpones its data packet transmission. Therefore, obtaining the information of channel usage aids to avoid the packet collision on the same channel or a waste of the bandwidth.

In the CDM-MAC protocol, when a transmitter/receiver pair is negotiating a channel group $\mathcal{G}$, a cooperating node checks its channel status table to see if another pair has negotiated a channel group $\mathcal{G}'$ involving a sub-carrier in $\mathcal{G}$. Any such sub-carrier must necessarily be from overhearing a channel group assignment in another cluster because the blocks in the BIBD used within a cluster are disjoint. Since we use BIBDs with parameter $\lambda = 1$ the interference is limited to one sub-carrier (see §5.1.2.1). The cooperating node sends the sub-carrier experiencing interference $\mathcal{G} \cap \mathcal{G}'$ in a CIM. Since OFDMA supports flexible channel group sizes, this sub-carrier is removed from $\mathcal{G}$.

Mitigating the near-far problem of CDMA is more challenging. The near-far problem occurs if a transmitter/receiver pair T/R is separated by distance d, and another transmitter is within distance $\frac{d}{2.78}$ of the receiver R, then communication between the pair is impossible [70].

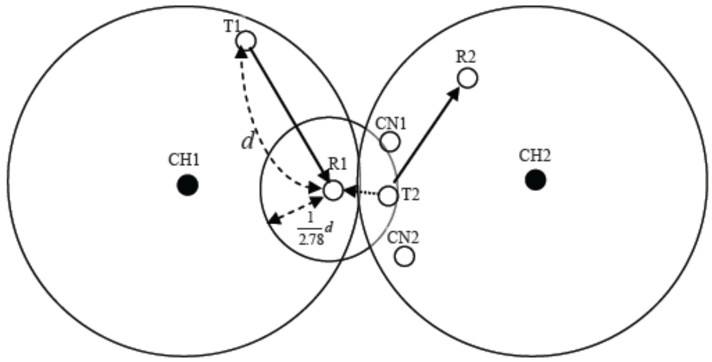


Fig. 60. Example of the node in interfering position.

Consider Figure 60, in which the small circle centered about R_1 shows interference area of R_1. If any transmitter is located in the interference area of R_1, the near-far problem occurs [70]. For this problem, we use a solution that relies on the capability of cooperating nodes to estimate distance based on signal strength [45]. In Figure 60, suppose that the nodes CN_1 and CN_2 are idle nodes that act as cooperative nodes, and that the nodes T_1 and T_2 are transmitters with corresponding receiver nodes R_1 and R_2. Each communication pair is affiliated with a different cluster. Assume that node T_1 has an ongoing transmission with R_1, that nodes CN_1 and CN_2 have overheard the control packet exchange between nodes T_1 and R_1, and that T_2 is in the interference range of node R_1. When node T_2 has a data packet to send, it transmits a CRM to clusterhead CH_2. On receipt of the CRM, CH_2 sends a CAM to nodes T_2 and R_2 containing an assigned channel group. Nodes T_2 and R_2 start to monitor the assigned channel group. Node R_2 sends a CFM with the available channel list to node T_2. If the cooperating neighbours CN_1 and

CN_2 are aware of channels in the assigned channel group $\mathcal{G}$ that may interfere with reception at R_1, they transmit concurrently with the CFM a CIM with the channel usage at R_1 through the available channels in $\mathcal{G}$. T_2 takes the strongest one of those CIMs from neighbouring nodes.

5.2 Performance Evaluation of the CDM-MAC Protocol

We use the ns-2 simulator version 2.29 with extensions to support ad hoc networks to evaluate the CDM-MAC protocol, using a total channel bandwidth of $2\,Mbps$. We compare our protocol with the default characteristics of the *distributed coordination function* (DCF) of IEEE 802.11. Also, we use MATLAB for additional experiments to compare the throughput the CDM-MAC protocol achieves to the 802.11, MMAC-CC, and the CA-CDMA which is a CDMA based multi-channel MAC protocol.

5.2.1 Parameters of Simulation

For the CDM-MAC protocol, we assume that bandwidth is divided into 64 sub-channels. Of those 64 sub-channels, one quarter (16) are dedicated to the transmission of control packets, while the remaining (48) are used for the transmission of data.

The necessary conditions for the existence of a (v, k, λ) resolvable BIBD are that $\lambda(v-1) \equiv 0 \bmod (k-1)$ and $v \equiv 0 \bmod k$ [11]. The smallest R-BIBD with $v \geq 48$ has parameters $(49, 7, 1)$. As a result, some channel groups have

6 sub-carriers, while others have 7, i.e., sub-carrier 48 is deleted from channel groups in which it occurs.

In the ns-2 simulation, our experiments use *constant bit rate* (CBR) traffic sources sending $512\,byte$ data packets at a rate of $4\,pkts/s$ over the *user datagram protocol* (UDP). Each flow is a single hop communication. Each transmitter selects one of its neighbours as its receiver uniformly at random. Table 4 summarizes these and other simulation parameters for ns-2.

For the MATLAB simulation, we set same size of bandwidth of $2\,Mbps$ and same number of sub-channels as in ns-2. In this experiment, we select destinations from the one-hop neighbourhood of the source nodes to evaluate the throughput at the MAC layer. Half of the nodes are sources. For each packet generated, a destination is randomly selected from one of the source's one-hop neighbours. Each node generates packets according to a Poisson process with rate λ, $0 \leq \lambda \leq 60\,pkt/s$, with the same rate used by each node. The random way-point mobility model for this simulation is used with a node speed that is uniformly between zero and $5\,m/s$.

Each simulation runs for $300s$ of simulated time. The results plotted are averaged over 20 replicates resulting in a very small 95% confidence interval. More parameters used in the simulation are provided in Table 5.

We begin with 25 nodes placed in a $500 \times 500\,m^2$ area, with all nodes affiliated with the same cluster. Further experiments increase the number of

TABLE 4. Simulation parameters for ns-2 for the CDM-MAC protocol

Parameter	Value
Simulation area	$500 \times 500\, m^2$
Number of nodes	$\{25, 65\}$
Transmission range	$250\, m$
Traffic type	CBR with rate $4\, pkt/s$
Data packet size	$512\, bytes$
Transport and routing protocol	UDP and AODV
Radio propagation model	Two ray ground
Mobility model	Random way-point 0-5 m/s, no pause
Total channel bandwidth	$2\, Mbps$
Number of sub-carriers	64, each $31.25\, Kbps$ wide
Sub-carriers for control, data	$\frac{64}{4} = 16$, $\frac{3\times 64}{4} = 48$
Parameters of R-BIBD	$(v = 49, k = 7, \lambda = 1)$ R-BIBD

nodes, flows, and clusters. Here, our primary interest is to investigate how the node density and number of flows affect performance, comparing to IEEE 802.11, MMAC-CC and CA-CDMA, using a $2\, Mbps$ channel.

5.2.2 A Single Cluster Scenario

For the single cluster scenario, we place 25 nodes in a 5×5 grid topology, with nodes separated by $85\, m$ both horizontally and vertically. The center node serves as the clusterhead and all other nodes are affiliated with it.

Figure 61 shows average delivery ratio as a function of the number of flows. Here, the IEEE 802.11 DCF protocol shows better performance than the CDM-MAC protocol until the number of flows increases to ten. Since in the CDM-MAC protocol, as all channels are managed and assigned by the clusterhead, the performance of the CDM-MAC protocol is limited by the number of sub-

TABLE 5. Simulation parameters for MATLAB for the CDM-MAC protocol

Parameter	**Value**
Frequency	$2.4\,GHz$
IEEE 802.11 channel rate	$2\,Mbps$
MMAC-CC data channel rate	$1.8\,Mbps$
MMAC-CC control channel rate	$200\,Kbps$
CA-CDMA data channel rate	$1.6\,Mbps$
CA-CDMA control channel rate	$400\,Kbps$
Our protocol data channel rate	$31.25\,Kbps$ ($\times$ 48 = $1.5\,Mbps$)
Our protocol control channel rate	$31.25\,Kbps$ ($\times$ 16 = $0.5\,Mbps$)
Data packet size	$512\,bytes$
Transmission power	$20\,dBm$
SNR threshold	$15\,dB$
Reception threshold	$-68\,dBm$
Carrier-sense threshold	$-74\,dBm$
Interference threshold	2.78

channel groups assigned by the clusterhead. With a small number of flows, IEEE 802.11 DCF seems to take advantage of channel reuse because each node with IEEE 802.11 DCF still can communicate if there is no active node in its transmission range. However, as the number of flows increases, the CDM-MAC protocol achieves up to a maximum of 15% better average delivery ratio than IEEE 802.11 DCF.

Figure 62 shows the result of the average delay as a function of the number of flows. In this figure, the IEEE 802.11 DCF protocol shows better average delay than our protocol until we increase the number of flows to six as this protocol uses the entire bandwidth for packet transmission. However, as the number of flows increases, the average delay of our protocol remains stable

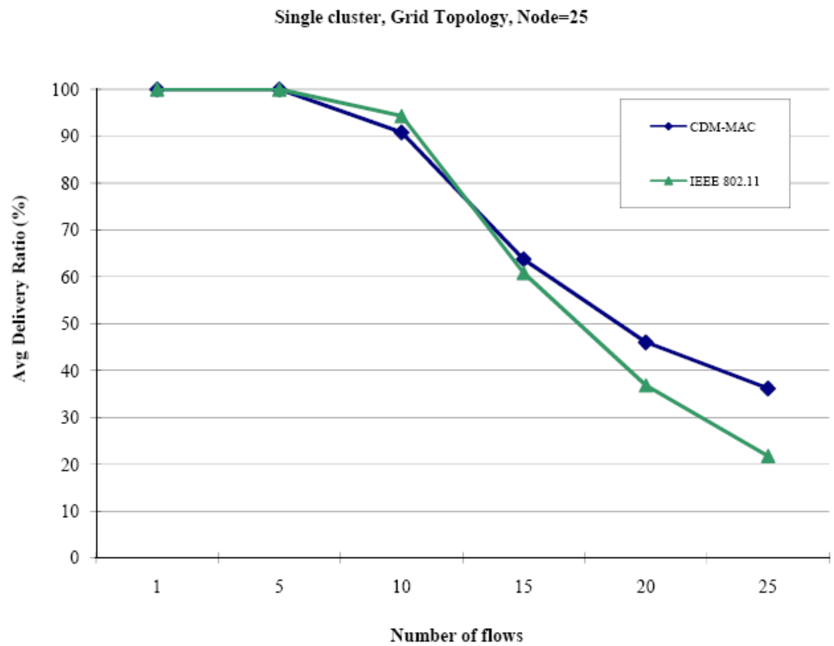


Fig. 61. Average delivery ratio as a function of number of flows with single cluster.

between 0.02s and 0.022s while the average delay of IEEE 802.11 DCF increases to approximately 9.4s. Since the CDM-MAC protocol takes advantage of using multiple channels, many communication pairs can communicate simultaneously. It decreases the average delay effectively. However, in IEEE 802.11 DCF using a single channel, as the number of flows increases, the average delay increases because each node contends to occupy the channel for transmission.

We also computed the throughput as a function of increasing node density (number of nodes n, $0 \leq n \leq 65$). A total of 65 nodes is placed in the $500 \times 500\,m^2$ area, arranged in one cluster. A data packet size of 512bytes is used. As shown in Figure 63, the throughputs of both CA-CDMA and

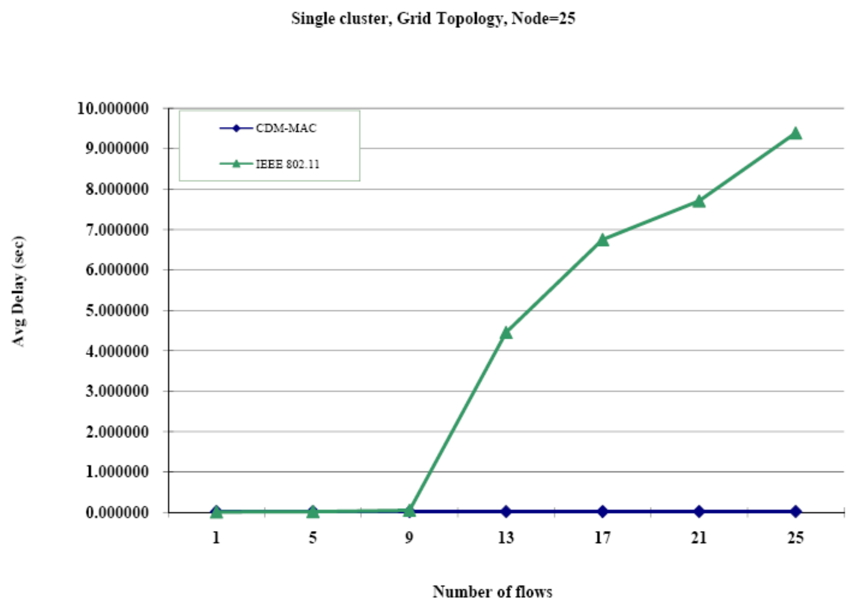


Fig. 62. Average delay as a function of number of flows with single cluster.

MMAC-CC are higher than the CDM-MAC protocol, while the throughput of the CDM-MAC protocol is slightly higher than IEEE 802.11 as in Figure 61. This is because CA-CDMA takes advantage of CDMA which allows more than one node on the same channel and MMAC-CC assigns more bandwidth for data transmission.

However, even though the CDM-MAC protocol has the advantage multi-channel protocols bring over a single channel, it does not take any advantage of CDMA in one cluster. Moreover, it assigns a wider bandwidth to the control channel to deal with control overhead than MMAC-CC. Therefore, it performs with reduced bandwidth for data transmission. IEEE 802.11 works with a single channel and is easily saturated as the number of nodes increases.

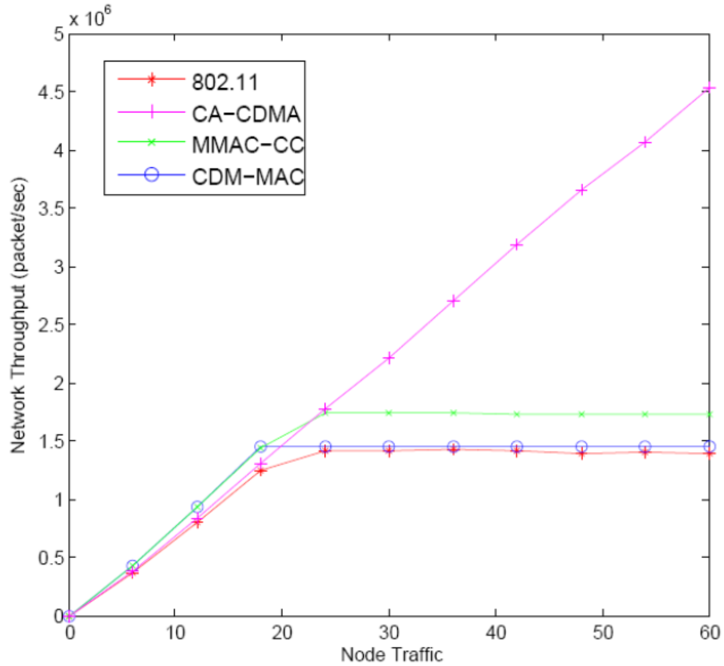


Fig. 63. Throughput as a function of node traffic with a single cluster.

Specifically, in Figure 63, the throughput of each CA-CDMA and MMAC-CC are at best 3.11 and 1.19 times higher than the CDM-MAC protocol, while the throughput of the CDM-MAC protocol is now only 1.05 times higher than IEEE 802.11 at best.

5.2.3 A Multi-Cluster Scenario with and without Mobility

Now, we place 65 nodes in the $500 \times 500\,m^2$ area, arranged in three non-overlapping clusters. Each node is affiliated with one of the three clusterheads.

Figure 64 shows the average delivery ratio in this static multi-cluster scenario. Now, the average delivery ratio of the CDM-MAC protocol is always higher than IEEE 802.11. Specifically, the delivery ratio of the CDM-MAC

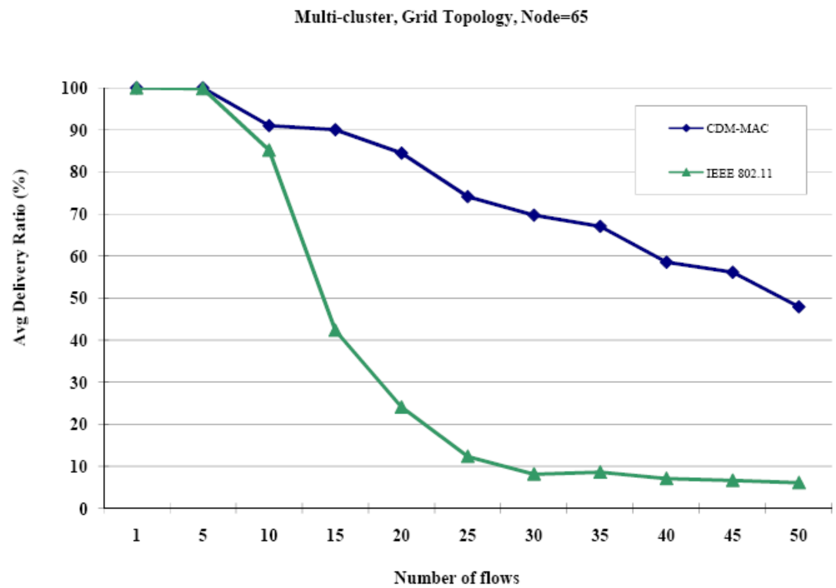


Fig. 64. Average delivery ratio as a function of number of flows with multiple clusters.

protocol ranges from 1.05 to 5.00 times better than IEEE 802.11. Some reasons for this include the fact that the CDM-MAC protocol takes advantage of using multiple channels assigned independently by each clusterhead, uses the R-BIBD combinatorial object to minimize the channel overlap (interference) of channel groups, and takes advantage of the use of orthogonal CDMA codes assigned to each cluster. These features in the CDM-MAC protocol improve the channel and spatial re-use ratio and thereby, in cases of high node density and node traffic, the CDM-MAC protocol performs more effectively than IEEE 802.11.

Figure 65 shows the delivery ratio when node mobility is introduced. For simplicity, in this model, we do not take the handoff of nodes between clusters

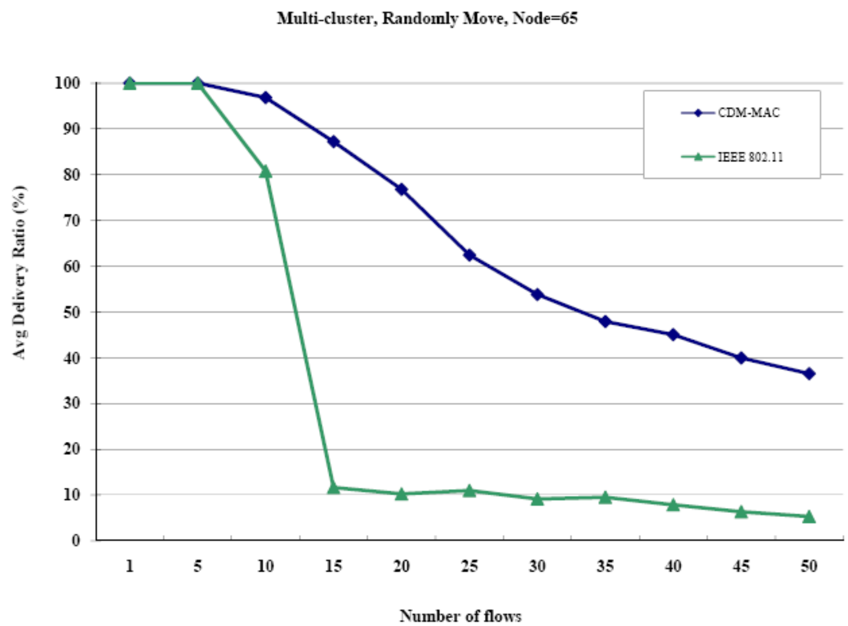


Fig. 65. Average delivery ratio as a function of flows with multiple clusters and random movement.

into account. The random way-point model is used for mobility, with user speed that is uniformly between zero and 5 m/s with constant movement (i.e., no pausing). In this case, while the average delivery ratio of the CDM-MAC protocol drops steadily, the average delivery ratio of IEEE 802.11 drops sharply starting at about 10 flows. Specifically, the average delivery ratio of the CDM-MAC protocol ranges from 1.0 to 8.5 times higher than IEEE 802.11. Thus the CDM-MAC protocol is less vulnerable to mobility than IEEE 802.11.

Figures 66 and 67 show the throughput as a function of increasing node density. In Figure 66, a total of 65 nodes is placed in the $500 \times 500\, m^2$ area, arranged in three non-overlapping clusters. In this figure, the throughput of the CDM-MAC protocol is always higher than MMAC-CC, and the throughput of MMAC-CC is always higher than IEEE 802.11. This can be interpreted first, as the advantage that using a multi-channel protocol brings over a single channel, and second, the advantage that using CDMA in each cluster brings. CA-CDMA eventually outperforms the CDM-MAC protocol, with the cross-over point at lower node traffic. This is because in CA-CDMA, each node takes advantage of CDMA as well as is equipped with two transceivers. Besides, in the CDM-MAC protocol, the increase in channel reuse ratio is restricted by the number of clusters.

Consider Figure 67. Here, we placed 140 nodes in the $1000 \times 1000\,m^2$ area, arranged in seven non-overlapping clusters. As shown in Figure 67, the throughput of the CDM-MAC protocol is always higher than CA-CDMA. This is because by increasing the number of non-overlapping clusters, the channel reuse ratio increases. As a result, the throughput of the CDM-MAC protocol is improved. Specifically, in Figure 66, the throughput of CA-CDMA is at best 1.12 times higher than the CDM-MAC protocol, while the throughput of the CDM-MAC protocol is at best 2.31 and 2.83 times higher than MMAC-CC and IEEE 802.11 respectively. In Figure 67, the throughput of the CDM-MAC protocol is 1.7 times higher than CA-CDMA at best, while the throughput of the CDM-MAC protocol is at best 5.12 and 6.22 times higher than MMAC-CC and IEEE 802.11, respectively.

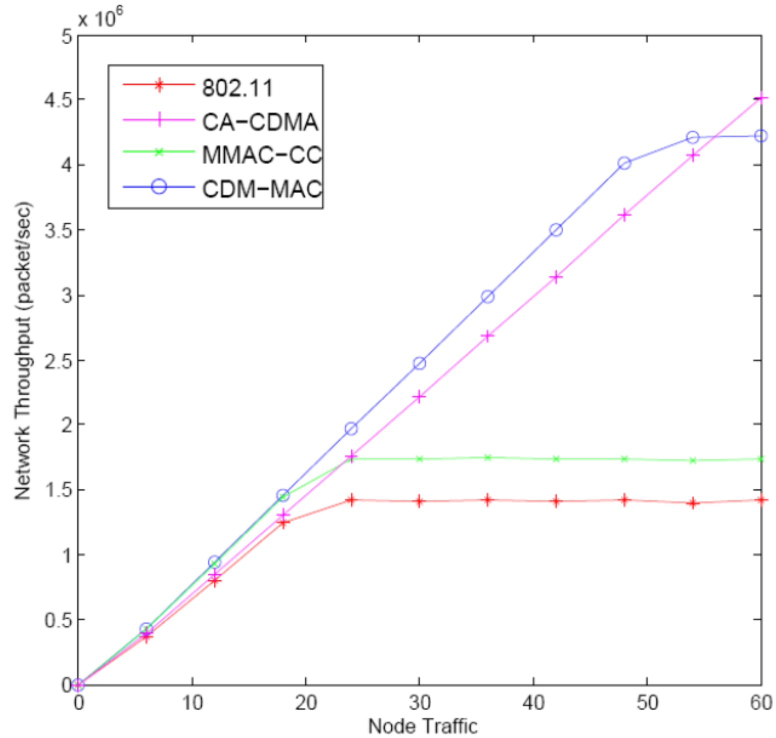


Fig. 66. Throughput as a function of node traffic with three clusters.

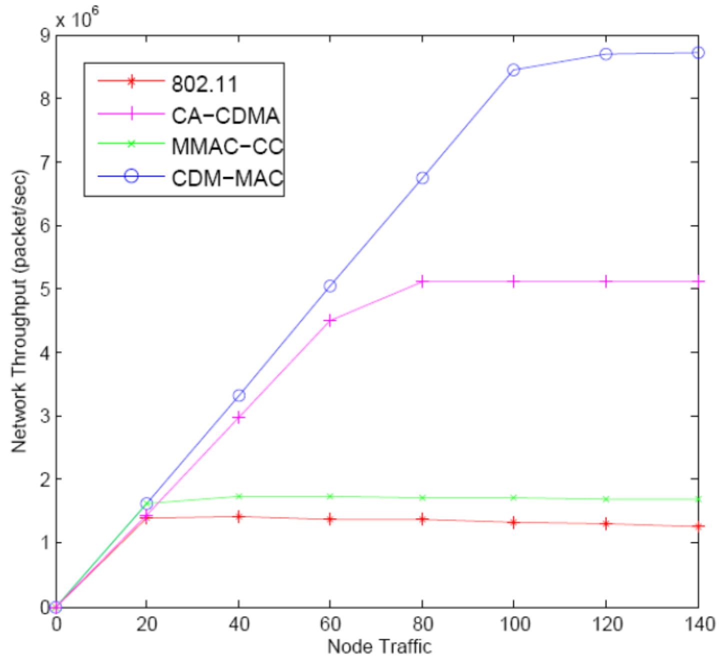


Fig. 67. Throughput as a function of node traffic with seven clusters.

We also measured the average packet delay in the CDM-MAC protocol, CA-CDMA, MMAC-CC and IEEE 802.11 by using the method proposed in Kleinrock and Tobagi [30] (see also Chapter 3, page 76). The average packet delay is the time elapsed in transmitting one data packet using the entire system bandwidth. We keep the assumptions made in CCM-MAC protocol [45] (see also Chapter 3) to measure the average packet delay.

Figure 68 shows that while the average delay for the CDM-MAC protocol remains stable at the higher traffic loads, the average delay of CA-CDMA increases little by little and is 2.29 times higher than CDM-MAC at best.

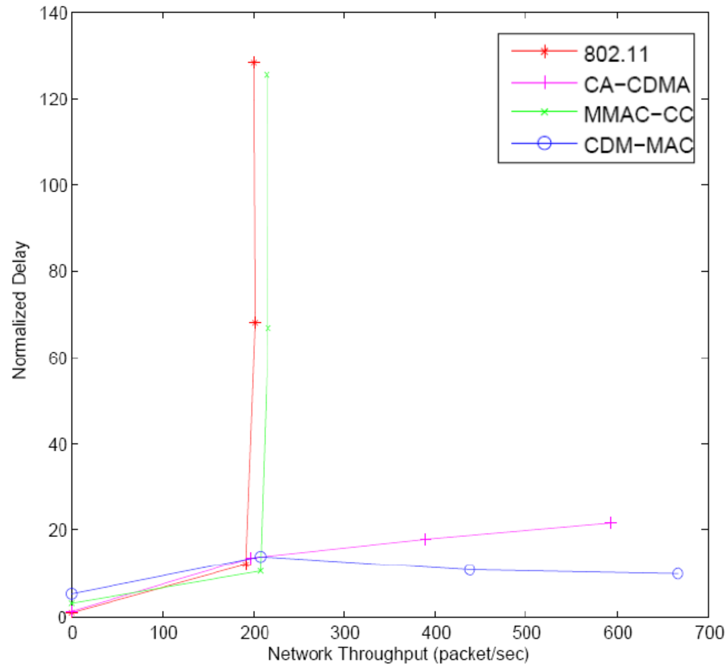


Fig. 68. Average delay vs. throughput.

IEEE 802.11 and MMAC-CC have a slightly better delay than the CDM-MAC protocol at low traffic loads. However, they lost this advantage quickly.

5.3 Summary

In this chapter, we proposed a new multi-channel MAC protocol named CDM-MAC for ad hoc networks, combining the use of OFDMA and CDMA. In this protocol, we make several contributions. First, we combined two access technologies: OFDMA enables either transmission or reception of multiple packets to/from multiple users in parallel, while CDMA increases spatial channel reuse. Second, the channel synchronization problem of OFDMA is addressed by clustering the network. Third, OFDMA supports a flexible channel group size;

cooperating nodes help negotiate the channel group. Fourth, the near-far problem of CDMA is mitigated with the help of cooperating nodes to facilitate communication set up. Finally, the multi-channel hidden- and exposed-terminal problems are solved when the communicating pair are affiliated with the same cluster, and mitigated otherwise. The results show that the CDM-MAC protocol achieves a better throughput performance as well as lower delay than IEEE 802.11, MMAC-CC and CA-CDMA, in particular when node density and traffic load are high.

CONCLUSIONS AND FUTURE WORK

In this dissertation, we proposed multi-channel MAC protocols for MANETs using more sophisticated physical layer technologies, including CDMA and OFDMA. We used *cooperating nodes* to provide vital information to facilitate communication set-up between source-destination node pairs and help overcome limitations of physical layer technologies in MANETs.

Specifically, we proposed three new multi-channel MAC protocols for MANETs for nodes equipped with a *single* half-duplex transceiver. All make use of a control channel for channel negotiation through an extended *carrier sense multiple access with collision avoidance* (CSMA/CA) style handshake. The Cooperative CDMA-based Multi-channel MAC (CCM-MAC) protocol uses CDMA to enable concurrent transmissions on each channel. In the Power-controlled CDMA-based Multi-channel MAC (PCC-MAC) protocol, transmission power control is used. It addresses the near-far problem of CDMA occurring on the data channel by accounting for the *multiple access interference* through controlling transmission power at each node. Also, PCC-MAC mitigates collisions of control packets on the control channel by using different sizes of the spreading factor to have different processing gains for the control signals. The Cooperative Dual-access Multi-channel MAC (CDM-MAC) protocol combines the use of OFDMA and CDMA. To ease OFDMA channel management and address the channel synchronization problem of OFDMA the network is clustered. In addition, channel groups are defined by a resolvable *balanced incomplete block design* (BIBD) to minimize interference. CDMA codes assigned to each cluster increases the channel reuse.

The node cooperative mechanism in this dissertation collects the information about channel usage and informs neighbouring nodes of the information collected. Transmitters can make a better decision about what channel to select based on the information obtained from cooperating nodes. In each protocol, cooperating nodes help reduce the incidence of the multi-channel hidden- and exposed-terminal problems by accounting for *multiple access interference*. In addition, the node cooperative mechanism enables a MAC protocol to use the physical access schemes such as CDMA and OFDMA without the aid of a central controller through the exchange of critical information between nodes.

Simulation results show that each of the proposed protocols achieve significantly better system performance when compared to IEEE 802.11 (a single-channel protocol), other multi-channel protocols, and a CDMA-based MAC protocol.

Several research directions arise from the research presented in this dissertation. However, there are still difficulties that remain to be carefully considered. A study to understand how node density and node cooperation relate is required. In a cooperative protocol, in order to make a correct decision, nodes need channel usage information of neighbour nodes. However, if every idle node which can cooperate responds, collisions are likely to happen. Therefore, in a dense network, even if CDMA is used, the number of cooperative nodes must be limited to alleviate interference among their responses. In contrast, when the network topology is too sparse, nodes may not obtain any cooperation and system performance may degenerate as a result.

A study to overcome the control channel bottleneck problem is necessary. Most existing multi-channel based MAC protocols using a single transceiver use a dedicated control channel. The control channel is used by nodes to compete for a data channel and to exchange control packets if necessary in order to select a free data channel for transmission. The use of node cooperation to help channel selection incurs more control packet exchange on the control channel, increasing control overhead. The control channel may become a performance bottleneck. In this case, it may possible that some free data channels are available but cannot be used immediately due to control channel congestion. As a result it lowers system performance.

Space diversity may be achieved by the use of a relay node between a source and destination. If the channel quality of the direct path between a transmitter and receiver is not good or the use of another path through a relay node achieves better performance than direct path between a transmitter and receiver, the transmitter may transmit a packet to its receiver through a relay node. However, when a relay node helps to forward the packet, the transmission from the relay node can interfere with another ongoing transmission which is out of transmission range of the source but, in transmission range of the relay node. This results in decreased spatial reuse ratio. In addition, if there are many candidate relay nodes, a collision may happen at a source due to multiple responses from the relay nodes. Without a proper design, these problems can cause deleterious effects on system performance.

Cooperative diversity achieves antenna diversity gain by using the cooperation of distributed antennas belonging to each node. It enables nodes to save their power consumption. By cooperative diversity, signals with $1/n$ power level from each node can reach the same distance where a signal with maximum power from a node can reach as well as a signal is sent farther than when a node sends alone. Here, n is the number of cooperative nodes. As a result in multi-hop network, cooperative diversity may reduce the number of hops between a source and destination. However, there are also some difficulties that must be studied. To simultaneously transmit signals from multiple nodes accurate time synchronization techniques should be studied. Also when a node sends a signal together with cooperative nodes, it must count accurately the number of cooperative nodes to estimate the transmission power level. However, obtaining this count it is not easy, especially in MANET. Moreover, an extended transmission range through a cooperative diversity may influence other communications out of the original transmission range.

In the PCC-MAC protocol proposed in this dissertation, to mitigate the collision of control packets on the control channel each spectrum for control packets is spread differently by the different sizes of spreading factor. In other words, the higher the difference between two spreading factors, the higher the processing gains between two signals. The increase of processing gain aids in mitigating the near-far problem. However, if the transmission power of the interfering signal is too strong, the spreading factor alone is not enough to solve the near-far problem. The resistance to the near-far problem is is an active research problem [3, 28, 55].

Also, an evaluation in simulation of the performance of the proposed protocols in conjunction with a multi-hop routing protocol, and the implementation of proposed protocols in a real physical wireless multi-channel system are left for future work.

The results of the research presented in this dissertation provide strong evidence that node cooperative mechanisms are effective in addressing problems that arise in using advanced PHY technologies in multi-channel MAC protocols in MANETs as well as improving system performance with a single transceiver. However, it also raises numerous further research questions for future work.

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