Distributed Power Control and Medium Access Control Protocol Design for Multi-Channel Ad Hoc Wireless Networks

by

Khaled Hatem Almotairi

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Khaled H. Almotairi

Abstract

In the past decade, the development of wireless communication technologies has made the use of the Internet ubiquitous. With the increasing number of new inventions and applications using wireless communication, more interference is introduced among wireless devices that results in limiting the capacity of wireless networks. Many approaches have been proposed to improve the capacity. One approach is to exploit multiple channels by allowing concurrent transmissions, and therefore it can provide high capacity. Many available, license-exempt, and non-overlapping channels are the main advantages of using this approach. Another approach that increases the network capacity is to adjust the transmission power; hence, it reduces interference among devices and increases the spatial reuse.

Integrating both approaches provides further capacity. However, without careful transmission power control (TPC) design, the network performance is limited. The first part of this thesis tackles the integration to efficiently use multiple channels with an effective TPC design in a distributed manner. We examine the deficiency of uncontrolled asymmetrical transmission power in multi-channel ad hoc wireless networks. To overcome this deficiency, we propose a novel distributed transmission power control protocol called the distributed power level (DPL) protocol for multi-channel ad hoc wireless networks. DPL allocates different maximum allowable power values to different channels so that the nodes that require higher transmission power are separated from interfering with the nodes that require lower transmission power. As a result, nodes select their channels based on their minimum required transmission power to reduce interference over the channels. We also introduce two TPC modes for the DPL protocol: symmetrical and asymmetrical. For the symmetrical mode, nodes transmit at the power that has been assigned to the selected channel, thereby creating symmetrical links over any channel. The asymmetrical mode, on the other hand, allows nodes to transmit at a power that can be lower than or equal to the power assigned to the selected channel.

In the second part of this thesis, we propose the multi-channel MAC protocol with hopping reservation (MMAC-HR) for multi-hop ad hoc networks to overcome the multi-channel exposed terminal problem, which leads to poor channel utilization over multiple channels. The proposed protocol is distributed, does not require clock synchronization, and fully supports broadcasting information. In addition, MMAC-HR does not require nodes to monitor the control channel in order to determine whether or not data channels are idle; instead, MMAC-HR employs carrier sensing and independent slow channel hopping without exchanging information to reduce the overhead.

In the last part of this thesis, a novel multi-channel MAC protocol is developed without requiring any change to the IEEE 802.11 standard known as the dynamic switching protocol (DSP) based on the parallel rendezvous approach. DSP utilizes the available channels by allowing multiple transmissions at the same time and avoids congestion because it does not need a dedicated control channel and enables nodes dynamically switch among channels. Specifically, DSP employs two half-duplex interfaces: One interface follows fast hopping and the other one follows slow hopping. The fast hopping interface is used primarily for transmission and the slow hopping interface is used generally for reception. Moreover, the slow hopping interface never deviates from its default hopping sequence to avoid the busy receiver problem. Under single-hop ad hoc environments, an analytical model is developed and validated. The maximum saturation throughput and theoretical throughput upper limit of the proposed protocol are also obtained.

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To my wife Ebtisam and my daughter Rima ...

To my brothers and sisters ...

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List of Abbreviations

WLAN	Wireless local area networks
LAN	Local area network
BS	Base station
AP	Access point
MAN	Metropolitan area network
CDMA	Code division multiple access
TDMA	Time division multiple access
WiMAX	Worldwide interoperability for microwave access
LTE	Long term evolution
OFDM	Orthogonal frequency division multiplex
WAN	Wide area network
IEEE	Institute of electrical and electronics engineers
FHSS	Frequency hopping spread spectrum
DSSS	Direct sequence spread spectrum
ISM	Industrial, scientific and medical (unlicensed bands)
QoS	Quality of service
MAC	Medium access control
MIMO	Multiple input multiple output
WSN	Wireless sensor network
VANET	Vehicular ad hoc network

V2V	Vehicle-to-vehicle
V2I	Vehicle-to-infrastructure
WMN	Wireless mesh network
PAN	Personal area network
ACK	Acknowledge
NIC	Network interface card
TPC	Transmission power control
FDMA	Frequency division multiple access
DCF	Distributed coordination function
GPS	Global position system
CS	Carrier sense
CSMA	Carrier sense multiple access
CSMA/CD	Carrier sense multiple access with collision detection
CSMA/CA	Carrier sense multiple access with collision avoidance
PCF	Point coordination function
TBS	Time-bounded services
TR	Transmission range
CSR	Carrier sensing zone
PCS	Physical carrier sense
VCS	Virtual carrier sense
CCA	Clear channel assessment
RTS	Request-to-send
CTS	Clear-to-send
RES	Reservation
NAV	Network allocation vector
EIFS	Extended interframe space
DIFS	Distributed interframe space

BEB	Binary exponential backoff
SIFS	Short interframe space
ATIM	Ad hoc (or announcement) traffic indication messages
U-NII	Unlicensed national information infrastructure band
FCC	Federal communications commission

Chapter 1

Introduction

1.1 Wireless Networks

The development of wireless communication technologies and the convergence of wireless networks and the Internet have made the Internet services ubiquitous in addition to the relatively low cost of laptops, tablets, and smart phones. Different wireless networks employ different communication technologies, and the two most popular wireless networks are cellular networks and wireless local area networks (WLANs). Based on network coordination, wireless networks are classified into two main categories: centralized and distributed. Centralized wireless networks contain a network controller (e.g., a base station (BS) or an access point (AP)) and a set of mobile nodes. The network controller coordinates transmissions among mobile nodes and is connected to wired networks. For example, cellular networks provide wide coverage and seamless roaming and, therefore, they are identified as Metropolitan Area Networks (MANs). In contrast to centralized wireless networks, wireless nodes can communicate with each other without a pre-existing infrastructure in a distributed fashion, known as ad hoc networks, and consequently, they are also referred to as infrastructureless networks. An example of a distributed wireless network is one used for space communication known as Wide Area Networks (WANs).

To date, four generations of cellular networks have been developed. The first generation was based on analog communications that underutilize its bandwidth. To accommodate more users and enhance the network performance, the second generation (2G) cellular networks were developed and based on Code Division Multiple Access (CDMA) or Time Division Multiple Access (TDMA). The 2G networks support only circuit-switching voice transmission. The Internet services (packet-switching data transmission) were integrated into the third generation (3G) cellular networks, which support a data rate of between 144 *kbps* and 2 *Mbps*. Currently, the fourth generation (4G) is being developed and deployed to support a high data transmission rate, i.e., a rate expected to be more than 100 Mbps [8]. Two candidate systems have been proposed for the 4G wireless networks: Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE). Both technologies are based on the Orthogonal Frequency Division Multiplexing (OFDM) technology.

The fast *de facto* standards for WLANs are those established by the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard series [1, 9]. Comparing with the cellular networks, WLANs are inexpensive, easy to deploy, and provide a high data rate within small areas, about 100 meters. The first generation of the IEEE 802.11 standards provides up to 2 Mbps and uses either the Frequency Hopping Spread Spectrum (FHSS) or the Direct Sequence Spread Spectrum (DSSS) technology [1]. In addition, the IEEE 802.11b standard provides a maximum of 11 Mbps and uses the DSSS technology. To support a high data rate, the IEEE 802.11g standard is proposed and supports up to 54 Mbps based on the OFDM technology. The hardware of IEEE 802.11g is fully backwards compatible with 802.11b hardware. The IEEE 802.11b/g standards operate in the 2.4 GHz band, which is known as the unlicensed Industrial, Scientific and Medical (ISM) band; however, they suffer from interference not only from their neighboring WLANs, but also from other products operating over the same band. Another standard that uses the OFDM technology and can support up to 54 Mbps is IEEE 802.11a [10], but it operates over the 5 GHz band, which is less crowded. IEEE 802.11e improves the Quality of Service (QoS) over the Medium Access Control (MAC) layer [11] to support real-time applications, e.g., voice and video streaming. To meet user demands for higher data rates, the IEEE 802.11n standard can support up to 300 Mbps and uses a Multiple Input Multiple Output (MIMO) technology.

Two network modes are designed for WLANs in the context of the IEEE 802.11 standards. Similar to a cellular network, one network mode is an infrastructure network, which consists of an AP, which is analogous to a BS in the cellular network, and a set of wireless devices. The AP is connected to wired networks (e.g., the Internet), and any connection between two wireless nodes goes through the AP as shown in Figure 1.1. In contrast to the infrastructure network, an ad hoc network (a distributed network) can be established to allow wireless nodes to communicate directly with each other without the need of any AP. However, the ad hoc network can properly operate only if all nodes are within the communication range of each other, which is known as single-hop ad hoc networks. To increase coverage areas, multi-hop ad hoc networks are required, yet they are not supported by the IEEE 802.11 standards. Although the IEEE standard defines three orthogonal channels in the 2.4-GHz band and 12 channels in the 5-GHz band [1, 10], only one common channel is assigned for ad hoc networks, and this assignment does not utilize the other available channels.

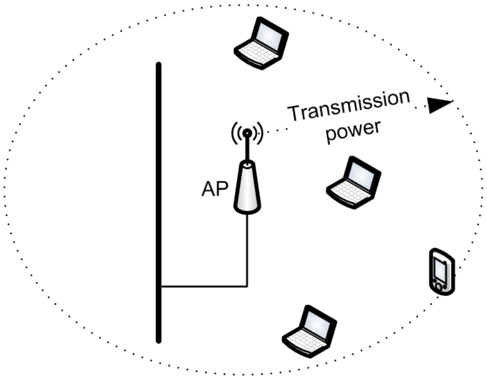

Figure 1.1: A centralized wireless network

1.2 Wireless Ad Hoc Networks

A wireless ad hoc network is a collection of wireless nodes (devices), which can be mobile. These nodes are able to communicate without the aid of a planned infrastructure or any central administration as shown in Figure 1.2. Each node is responsible for self-organization and self-configuration, and can be a source (transmitter), a destination (receiver), or a relay node.

Ad hoc networks can be single-hop or multi-hop networks. In single-hop ad hoc networks, a receiver is within the communication range of its transmitter. However, in multi-hop ad hoc networks, a transmitter is able to communicate with a receiver though intermediate nodes. In other words, multi-hop communications are efficiently supported by intermediate nodes.

Wireless ad hoc networks are highly appealing compared to their networking counterparts (wired and centralized networks) for many reasons. Ad hoc networks are cost-effective and easy to deploy. In addition, due to the distributed nature of ad hoc networks and relaying ability of traffic, they are highly robust. These properties are important especially for military applications, which are the first application for ad hoc networks. Another significant application of ad hoc networks occurs

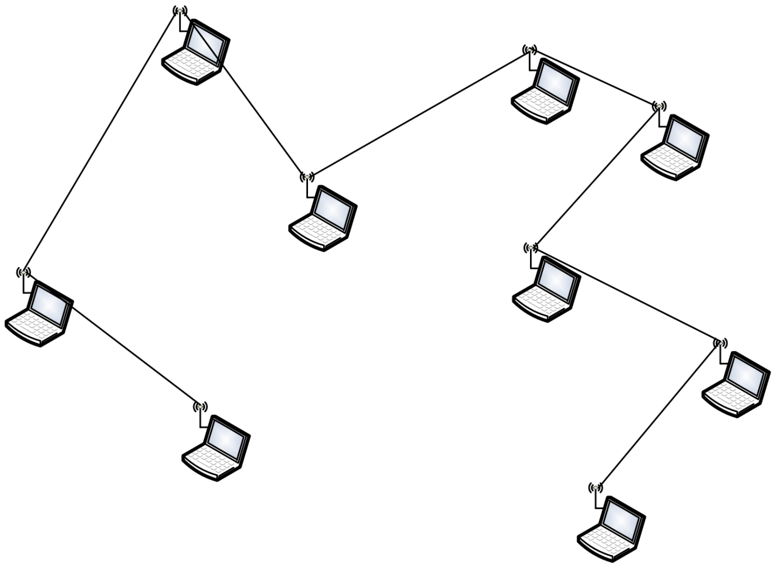

Figure 1.2: A wireless ad hoc network

in emergency operations. When earthquakes happen and destroy infrastructures, communication through ad hoc networks are a quick and viable solution. Space missions and undersea operations are other applications of ad hoc networks [12, 13, 14].

The concept behind wireless ad hoc networks results in multiple applications. Wireless sensor networks (WSNs) are a highly important class of ad hoc networks. The WSNs consist of a collection of many distributed sensor nodes that collect valuable information. Such information may be the movement of an enemy, fire in a forest, or an oil spill in the sea. There are several differences between typical ad hoc networks and sensor networks. Two main differences are the power and processing constraints in sensor nodes [12, 15]. Another new class of wireless ad hoc networks is vehicular ad hoc networks (VANETs), which have received noticeable attention not only from the research community, but also from car manufacturers. The main goal is to allow vehicles to communicate with each other, via either a vehicle-to-vehicle (V2V) or a vehicle-to-infrastructure (V2I) communication system, to provide safety and/or non-safety services. The main challenge with VANETs is the high mobility of vehicles [16].

One of the most interesting and commonly deployed classes of multi-hop ad hoc networks is wireless mesh networks (WMNs) [17]. The basic idea of WMNs is to provide an inexpensive and easy-to-deploy alternate infrastructure network. A common WMN architecture, for example, consists of fixed routers and a collection of nodes with a few routers connected to the Internet. In this way, the nodes communicate with each other as well as access Internet services [12, 18].

There are a number of operating WMNs in some countries worldwide, for example, the FunFeuer Net in Austria [19], VMesh in Greece [20], and ReMesh in Brazil [21]. In the United State of America (USA), some examples of deployed WMNs are MIT's RoofNet in Cambridge [22], UCSB's MeshNet in UC Santa Barbara [23], CUWin in Urbana, and Meraki Public Network in San Francisco [24]. In Canada, the City of Moncton, for instance, has offered free wireless Internet access since 2007 in certain downtown areas using multi-hop networks [25].

1.3 Research Challenges and Motivations

Although wireless ad hoc networks are appealing, they have many open issues to be addressed. For example, the performance of wireless ad hoc networks is congested because only one common channel is assigned for ad hoc networks despite the fact that the IEEE standard defines three orthogonal channels[1] in the 2.4-GHz band and 12 channels in the 5-GHz band [1]. Fortunately, many existing technologies can be used to resolve the congestion and improve the network performance, such as exploiting multiple orthogonal channels [26] and controlling transmission power. Using multiple channels with power control offers further increasing network capacity [27].

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[1] Orthogonal channels are a set of non-overlapping bandwidths in the spectrum domain.

Much research is currently being conducted to maximize the utilization of the available channels to meet the user demands because of the following reasons. First, in the single-hop case, WLANs can achieve a maximum of 11 or 54 Mbps and one transmission is allowed; however, in the multi-hop case, the network throughput is much lower than in the single-hop case due to the limitations discussed in Chapter 2. Second, using multiple channels will enhance the network performance (e.g., higher throughput and lower delay and collision probability) because multiple transmissions can take place over different channels. Under ideal conditions, using k channels should increase the throughput by k times the throughput over that used by a single channel. Third, many unlicensed and non-overlapping channels are available, e.g., three orthogonal channels defined in the 2.4-Ghz band and 12 orthogonal channels defined in the 5-GHz band. Under personal area networks (PANs), e.g., ZigBee, more than 12 unlicensed non-overlapping channels are available. Thus, using multiple channels provides a higher capacity over using a single channel.

With power control, more capacity can be extracted from multi-channel wireless networks. Two benefits are gained using power control in addition to power saving. First, adjusting the nodes' transmission power can increase the spatial reuse (i.e., to concurrently allow multiple transmissions), and therefore, the congestion is reduced [28]. The second benefit is that interference can be reduced when nodes decrease their transmission power [29]. Although much research work regarding transmission power control (TPC) has been proposed in centralized networks using multiple channels [30, 31], the focus of the thesis is on ad hoc networks.

Designing simple yet robust distributed multi-channel MAC protocols is preferred because of the lack of infrastructure support for ad hoc networks. There are several design challenges for multi-channel MAC protocols. First, a multi-channel MAC protocol should support broadcast because some applications use broadcast information such as routing. In single-channel ad hoc networks, all nodes communicate with each other over the same channel (if omni-antennas are employed), thereby supporting broadcast information. In multi-channel ad hoc networks, nodes might exist over different channels; as a result, some nodes might not receive broadcast information [32, 33, 5].

Another challenge in multi-channel environments is known as *channel synchronization* [34, 35]. In single-channel networks, senders know that receivers exist over the same shared channel. By contrast, in multi-channel networks, senders might not know which channel receivers are on.

The busy receiver problem is a new issue that occurs only in multi-channel networks [36]. When nodes are synchronized and each other's assigned channels are known (i.e., perfect channel synchronization), a transmitter cannot attain its receiver on a channel where the receiver is expected to be because the receiver is busy on another channel (either transmitting or receiving). Thus, the busy receiver problem increases the dropping rate of packets and wastes the channel bandwidth.

Moreover, the control channel saturation problem has been identified as a new problem and occurs only in multi-channel networks by having one dedicated control channel (e.g., DCA [37]) or one dedicated control time duration (e.g., MMAC [34]) to reserve data channels for transmissions [34, 38]. The problem occurs when the number of nodes and the network load increase preventing the data channels from being utilized efficiently; in other words, the control channel becomes the bottleneck.

The single-channel hidden terminal problem is a well-known problem that causes collisions. To eliminate this problem, request-to-send (RTS) and clear-to-send (CTS) handshaking is used [39]; however, this approach does not completely eliminate the problem. In multi-channel environments, the multi-channel hidden terminal problem is similar to the single-channel hidden terminal problem [34]. When a transmitter has a packet for a receiver that is on another channel, the transmitter switches to the receiver's channel. Before sending a packet, the transmitter must detect the channel. The transmitter assumes the channel is idle because it is within the transmission range of the receiver, but not within the carrier sensing range of the node currently transmitting to the receiver. Then, the transmitter sends its packet to the receiver, and therefore, a collision occurs at the receiver and thereby degrading the network performance.

Finally, in single-channel networks, the single-channel exposed terminal problem is a traditional issue, and there is yet no existing solution. This problem is not as serious as the hidden terminal problem because it does not cause collisions; however, the single-channel exposed terminal problem leads to poor channel utilization. In multi-channel networks, there is a new type of the exposed terminal problem known as the multi-channel exposed terminal problem due to poor channel assignment, which has not been well studied.

1.4 Main Research Contributions

The main contributions of this thesis are as follows:

- Proposal of a distributed transmission power protocol known as the distributed power level (DPL) protocol to resolve the deficiency of uncontrolled asymmetrical transmission power for multi-channel multi-hop networks without requiring clock synchronization and with broadcasting support. The main idea is to enhance the network performance by using multiple channels efficiently with TPC in a distributed manner. Specifically, DPL allocates different maximum allowable power values to different channels so that the nodes that require higher transmission power are separated from interfering with the nodes that require lower transmission power. As a result, nodes select their channel based on their minimum required transmission power, so interference is reduced over channels. Two TPC modes are introduced for DPL: symmetrical and asymmetrical. For the symmetrical DPL mode, nodes transmit at the power that has been assigned to the selected channel, thereby creating symmetrical links over any channel. The asymmetrical DPL mode, on the other hand, allows nodes to transmit at a power that can be lower than or equal to the power assigned to the selected channel. The asymmetrical DPL mode often works similarly to the symmetrical DPL mode because nodes could transmit over their preferred channels.

- Development of a multi-channel MAC protocol with hopping reservation (MMAC-HR) for ad hoc networks to resolve the multi-channel exposed terminal problem. MMAC-HR does not require nodes to monitor the control channel in order to determine whether or not data channels are idle; instead, MMAC-HR employs independent and slow channel hopping without exchanging information to reduce the overhead. In addition, the proposed protocol uses the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme over all channels to determine the channels' condition and avoid collisions. Furthermore, MMAC-HR is distributed, does not require clock synchronization, and supports broadcast information.

- Proposal of a novel multi-channel MAC protocol called the dynamic switching protocol (DSP) based on the parallel rendezvous approach (i.e., independent frequency hopping). There are several advantages of the proposed DSP: 1) utilization of multiple channels by allowing multiple transmissions at the same time; 2) the ability to avoid congestion because the proposed protocol does not need a dedicated control channel and enables wireless nodes dynamically switch among channels; 3) the contention level on any channel is reduced; and 4) avoiding the busy receiver problem because one interface in the DSP never deviates from its hopping sequence. Moreover, the proposed protocol does not change the IEEE 802.11 legacy and employs two half-duplex interfaces. One interface follows fast hopping and the other interface follows slow hopping. In general, the fast hopping interface is for transmission and the slow hopping interface is for reception; therefore, a node can work as a full-duplex system on different channels. Moreover, the slow hopping interface never deviates from its hopping sequence, while the fast hopping interface can deviate from its hopping sequence to communicate with other wireless nodes.

- Development and Modeling of the DSP to illustrate the network improvement within a single-hop network. Analysis and simulation results show the improvement of the network throughput and resolve the congestion. In order to compute the maximum throughput of each channel, the optimal transmission probability must consider the number of channels as well as the number of nodes and system parameters. In addition, the upper throughput limit is computed when the number of channels approaches to infinity.

1.5 Organization of the Thesis

The remainder of the thesis is organized as follows. Background and literature review are presented in Chapter 2. In Chapter 3, the asymmetric transmission power problem in multi-channel networks is discussed, and a novel distributed power protocol is proposed for multi-channel ad hoc networks with two TPC modes. In Chapter 4, the multi-channel exposed terminal problem is presented, and a new multi-channel MAC protocol is proposed to resolve the new exposed terminal problem. A novel distributed multi-channel MAC protocol is proposed and analyzed in Chapter 5. Finally, Chapter 6, concluding remarks of this thesis and possible future research directions are provided.

Chapter 2

Background and Literature Review

Wireless Medium Access Control (MAC) defines a set of rules for wireless nodes to effectively and fairly access the shared radio spectrum and resolve the contention among the nodes. Wireless MAC protocols can be classified into two categories: centralized and distributed. Centralized MAC protocols are suitable for infrastructure networks, e.g., Frequency Division Multiple Access (FDMA), CDMA, TDMA, or various hybrids. Distributed MAC protocols are designed for ad hoc networks because there are no centralized controllers. In this chapter, single-channel MAC protocols and their limitations are discussed. The IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol [1] defined as the mandatory protocol in WLAN environments is reviewed. In addition, an overview of multi-channel MAC protocols are provided as well as related works and their challenges.

2.1 Single-channel MAC protocols

Many MAC protocols have been proposed for wireless ad hoc networks. Every MAC protocol has been designed to achieve one or more objectives such as throughput, fairness, and/or QoS support. Throughput was the first and main objective in designing MAC protocols. Pure ALOHA [40], the first random access protocol, had poor throughput. To improve the throughput, slotted ALOHA [41] was invented and it had improved throughput compared to pure ALOHA. With the development of digital circuits and digital processing, carrier sensing (CS) became a reality. Shortly thereafter, carrier sense multiple access (CSMA) protocols were used widely because they outperform ALOHA systems [42, 43, 44].

Because the characteristics of a wireless medium are completely different than the characteristics of a wired medium, the CSMA with Collision Detection (CSMA/CD) cannot be used in wireless networks. Thus, CSMA/CA protocols are used in wireless networks. In CSMA/CA, a transmitting node first senses the medium. If the medium is idle, the node can begin to transmit its data. If the medium is busy, the node backs off its own transmission to prevent a collision. Different backoff algorithms have been proposed to efficiently utilize the shared channel (e.g., uniform backoff, geometric backoff, and binary exponential backoff), but the most well-know backoff algorithm is the binary exponential backoff scheme which has been adopted by the IEEE 802.11 standard.

Researchers have proposed single-channel MAC protocols to improve the performance of ad hoc wireless networks using different technologies and techniques [13, 12, 45, 46, 47]. One of many technologies that enhance the shared channel is smart antennas. Directional antennas (beamforming), a type of smart antennas, are able to focus the transmission power in one direction to a desired node. As a result, the shared channel is used more wisely than using omnidirectional antennas by reducing channel interference and increasing frequency reuse [48]. MIMO systems by employing multiple antennas per node improve system performance in terms of transmission rate and link reliability via multiplexing and diversity gains, respectively. The MIMO systems are also known as smart antennas in the sense that they do not require any additional bandwidth or power. Subsequently, smart antennas provide higher network capacity for ad hoc networks.

Some researchers use the clustering approach and apply it to ad hoc networks to divide mobile nodes into different virtual groups according to certain rules. The nodes belong to one of these sets: clusterhead, clustergateway, or clustermember. The clusterhead plays the same role in the cluster as the central controller in the centralized networks. A clustergateway is a non-clusterhead node and can forward information between clusters, and a clustermember is not a clusterhead without any inter-cluster links. The clustering approach can achieve Time-Bounded Services (TBS) within a cluster. The ADHOC-MAC protocol is proposed in [49] and is based on TDMA and clustering.

Power control is another effective technique to enhance the network bandwidth in ad hoc networks by adjusting the transmission power of wireless nodes to gain desired achievements [50, 51, 52]. In Chapter 3, the power control approach is discussed as well as the design criteria of TPC for multi-channel ad hoc networks.

2.1.1 IEEE 802.11 Distributed Coordination Function

This section describes the IEEE 802.11 standard, which is designed to operate in a single channel only; thus, it does not exploit the other available channels. The 802.11 MAC layer protocol has two mechanisms to access the shared channel medium: DCF and Point Coordination Function (PCF). DCF is a mandatory MAC protocol, and PCF is optional. In addition, DCF is based on random access and

CSMA/CA strategies, and it is a distributed MAC protocol. PCF, alternatively, is based on polling, and it is a centralized MAC protocol that provides collision free and time-bounded services [1].

Three important terms are used throughout the thesis [53, 54]:

1. **Transmission range (TR).** If a node is within the transmission range, it can receive packets successfully. For example, in Figure 2.1, nodes B and D are within the transmission range of node C.

2. **Carrier sensing range (CSR).** When a node is within the carrier sensing range, it can sense a transmission of a transmitter. The carrier sensing range is approximately double the transmission range (e.g., the transmission range is 250 meters and the carrier sensing range is 550 meters). The carrier sensing range depends on the transmission power of a transmitter. Figure 2.1 is an example where nodes A, B, and D are within the carrier sense range of node C.

3. **Interference range (IR) or carrier sensing zone.** The area of the carrier sensing range that extends beyond the area of the transmission range is known as the interference range or carrier sensing zone [53]. When a node is within the interference range, it can sense transmissions on the medium, but it cannot correctly decode the transmissions. In Figure 2.1, node A is within the CS zone of node C, so node A can only detect the transmission packet from node C without successfully decoding this packet. Moreover, if node A receives a data packet, and, at the same time, node C transmits a packet to node D, node C interferes with the ongoing transmission of node A because node A is within the interference range of node C.

DCF is based on the unslotted CSMA/CA scheme and uses a discrete-time backoff scale. The time immediately following an idle slot for an interval of time

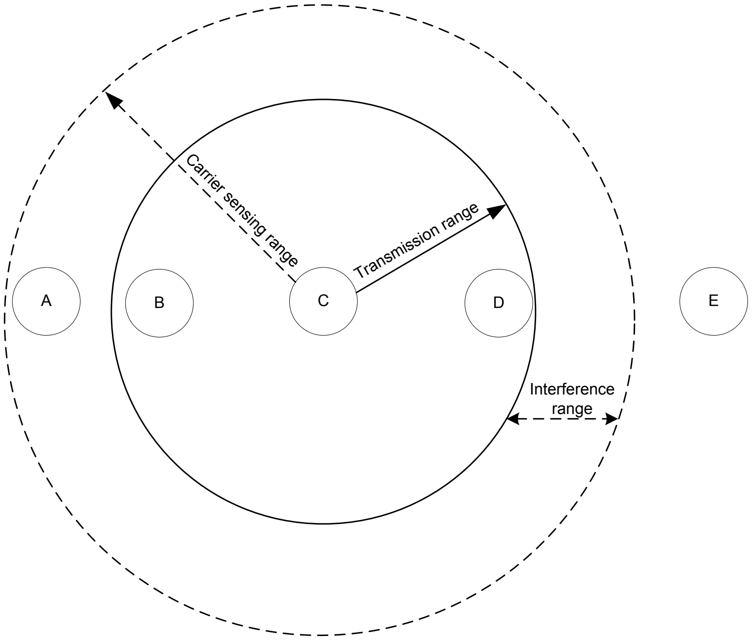

Figure 2.1: Transmission carrier range

equal to a distributed interframe space (DIFS) is slotted, and a node is allowed to transmit only at the beginning of a slot. The slot size allows nodes to detect transmissions on the channel and takes into account the propagation delay, the clear channel assessment (CCA) time, and an RX_TX_turnaround time, which is the time required to switch from the receiving state to the transmitting state. The slot size depends on the physical layer.

The DCF protocol has two methods for channel access: basic access and RTS/CTS access methods. For each (re)transmission, the basic access transmits data and acknowledge (ACK) packets while the RTS/CTS access transmits RTS, CTS, data, ACK packets. DCF has also two types of carrier sensing: physical carrier sensing (PCS) and virtual carrier sensing (VCS). PCS discovers whether the channel is busy or not through the CCA function, while VCS updates a network allocation vector (NAV) field by receiving any RTS and CTS packet. VCS is limited to the transmission range while PCS is extended to the CSR.

Figure 2.2 illustrates the RTS/CTS access mechanism. When a source node has a data packet to transmit, it must monitor the channel before attempting to transmit. If the channel is sensed as being busy, the node must defer until the channel is sensed as being idle for the DIFS. Then, the node generates a random backoff interval for an additional time to the DIFS interval, which minimizes collisions. The node transmits an RTS packet when the backoff timer reaches zero. Upon receiving the RTS packet successfully, the destination node transmits a CTS packet after waiting for an interval known as a short interframe space (SIFS). Other stations receiving the RTS or CTS packets update their NAVs with the duration of the packet transmission. Consequently, hidden nodes that hear either the RTS or CTS packets defer their transmissions, and thus collisions are avoided. However, other stations within the CS zone of the transmitting station defer their transmissions for at least the extended interframe space (EIFS)[1]. The source node sends the data packet once it has received the CTS packet correctly. If the data packet is received without errors, the destination node sends an ACK packet after waiting for SIFS. Once the source node receives the ACK packet successfully, the source node ensures the transmission has been completed. Otherwise, the source node waits until the ACK timeout is reached. Then, the source node assumes the packet is lost and increases the number of retrials. If the number of retrials reaches the maximum number of retrials, the packet is dropped. Otherwise, the packet is rescheduled for retransmission according to the backoff rule.

The standard adapts the binary exponential backoff (BEB) scheme. The backoff time is chosen uniformly for any packet (re)transmission from the interval $(0, CW-1)$, where CW is termed the contention window. At the first transmission, CW is set to CW_{min}, where CW_{min} is identified as the minimum contention window size. For each unsuccessful transmission, the value of CW is doubled until it reaches

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[1] $EIFS = SIFS + DIFS + [(8 * ACK) + PHY_{hdr}]/R_c$, where PHY_{hdr} is the PHY header and R_c is the basic data rate for the control packets.

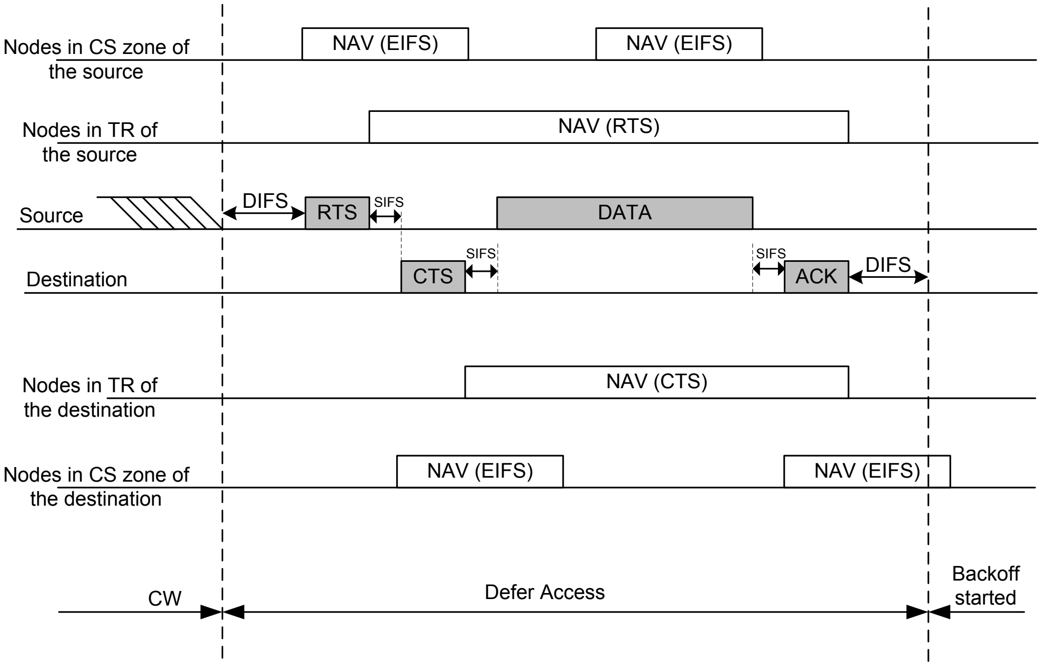


Figure 2.2: IEEE 802.11 DCF mode using RTS/CTS access

the maximum value CW_{max}, which is equal to $2^m CW_{min}$, where m is the maximum backoff stage. Then, the CW value is reset to CW_{min} when the packet is transmitted successfully or it is dropped. The values of CW_{min} and CW_{max} can be distinct for different PHY technologies. During the random backoff interval, the node monitors the channel status. If the channel is sensed as being idle, the node decreases the backoff timer by one every idle slot. Otherwise, the backoff timer is suspended. It resumes again after the medium is sensed as being idle for a DIFS interval. The node can transmit when the backoff timer reaches zero.

2.1.2 Limitations of Single-channel Ad Hoc Wireless Networks

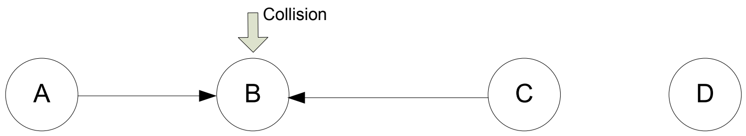
In ad hoc wireless networks, wireless nodes share a common radio channel. The shared medium should be used fairly and efficiently by the nodes. In single-hop ad hoc networks, one transmission is allowed and can achieve up to 11 or 54 Mbps. However, the performance of multi-hop ad hoc networks is even lower due to several problems. In the following, we briefly present certain major problems in the multi-hop ad hoc networks, and these problems are associated not only with IEEE 802.11 networks, but also for networks based on CSMA/CA.

Hidden Terminal Problem

This problem causes packet collisions at receiving nodes because of simultaneous transmissions from the nodes that are not within the TR of each other but that are within the CSR of the receiving nodes. An illustration of this problem is provided in Figure 2.3a. While node A transmits to node B, node C wants to transmit a packet to node B. Node C senses the channel and it discovers that the channel is idle because node C is not in the CSR of node A, so node C starts transmitting. Thus, a collision occurs at node B due to simultaneous transmissions from nodes A and C. Thus, node C is a hidden node to node A and vice versa [12, 55].

Exposed Terminal Problem

This problem is not as serious as the hidden terminal problem because it does not cause collisions, but it defers any transmission of other nodes. The nodes, whose transmissions have been deferred, are in the carrier sensing range of the sending nodes, but they are not in the CSR of the receiving nodes. This problem leads to



(a) Hidden terminal problems

(b) Exposed terminal problems

Figure 2.3: Scenarios of hidden and exposed terminal problems

poor channel utilization. As shown in Figure 2.3b, while node B transmits to node A, node C has a packet to transmit to node D. Node C senses the channel and finds that the channel is busy. Hence, node C has to defer its transmission to node D, even though node C does not cause any interference with node A. Therefore, node C is called an exposed terminal.

Capture Problem

The capture problem is illustrated in Figure 2.4. If nodes A and C transmit simultaneously to node B, and the signal strength received by node B from node A is much higher than the signal strength received from node C. Then, node B is able to decode the packet information received from node A correctly. This problem is less serious than the hidden terminal problem because the capture problem does not cause any collision and it improves the channel utilization. This problem, however, causes unfairness among nodes [55].

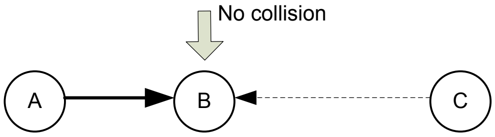


Figure 2.4: The capture problem in which the signal strength is much higher from node A than from node C.

Deafness Problem

This problem does not cause collisions, but it increases the packet loss and thereby increases the delay and wastes the channel bandwidth. A simple example is illustrated in Figure 2.5. During the transmission between nodes B and A, node D has a packet for node C. Node D senses the channel and discovers that the channel is idle because node D is not within the CSR of node B. Next, node D transmits an RTS packet to node C, but node C cannot reply to node D since node C is in the CSR of node B. Thus, node D assumes that a collision occurs and backs off for a period of time. Then, node D attempts several times to transmit to node C, but node D will eventually drop the packet if these attempts are unsuccessful. Hence, node D is known as a deaf terminal.

2.2 Multi-channel MAC protocols

In this section, multi-channel medium access control (MCMAC) protocols are classified and related work is presented. Then, certain issues in designing MCMAC protocols are discussed.

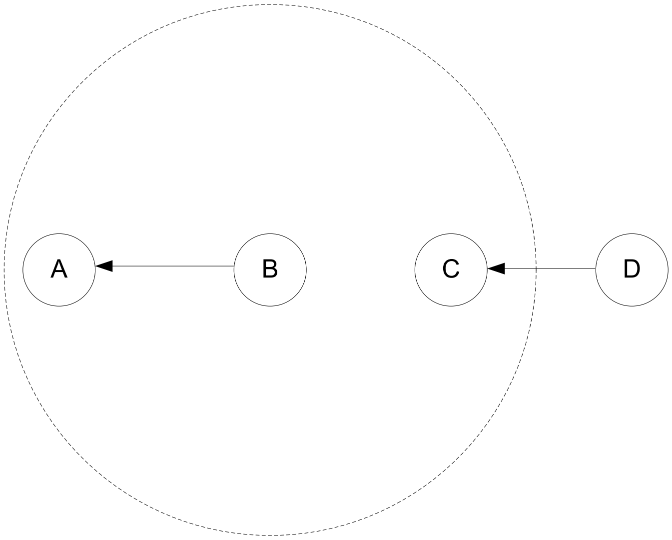


Figure 2.5: The deafness problem in which node D is unaware of the current transmission between nodes A and B.

2.2.1 Classification

Researchers have proposed MCMAC protocols using different approaches to exploit multiple channels and thereby increase the network capacity by allowing concurrent transmissions and reducing the congestion and interference levels on each channel [34, 56, 32, 57, 58, 59, 60, 61, 62, 63, 64, 65].

One way of categorizing MCMAC protocols is based on the number of radios (transceivers) installed in each node: single and multiple. Alternatively, MCMAC protocols can be classified generally into two categories based on their operations [36, 66], i.e., single rendezvous (SR) and multiple rendezvous (MR) protocols. In SR-MCMAC protocols, one agreement made between a transmitter and a receiver occurs over only one channel at any time, whereas, in MR-MCMAC protocols, multiple agreements made between different transmitter-receiver pairs occur over multiple channels at the same time. Thus, MR-MCMAC protocols generally outperform SR-MCMAC protocols [36, 67].

Single-interface MCMAC protocols can be further classified into four categories [60, 36, 32]:

1. **Common hopping**. All nodes follow the same hopping sequence and hop between channels, e.g., the Channel-Hopping Multiple Access (CHMA) protocol [68] and the Hop-Reservation Multiple Access (HRMA) protocol [69]. Although nodes need only one interface, frequent switching between channels (i.e., the dwell time is equal to the RTS transmission) and tight global clock synchronization are required in these protocols [36]. Another issue that should be addressed in these protocols is the busy receiver problem [36], which is also termed the missing receiver problem [70].

2. **Independent hopping**. Unlike common hopping, nodes independently hop from channel to channel according to their hopping sequence and make multiple agreements at the same time to resolve the congestion on the common channel. Independent hopping MCMAC protocols require pairwise clock synchronization, but suffer from the busy receiver problem. Examples include the Slotted Seeded Channel Hopping (SSCH) protocol [58] and the Multi-channel MAC (McMAC) [71] protocol. Bluetooth also employs independent hopping [72].

3. **Split phase**. Time is divided into two phases. The first phase is the control phase in which the nodes meet on a predefined control channel to make agreements. In the second phase (the data phase), successful pairs tune to their agreed upon channels and exchange data. The Multi-channel MAC (MMAC) protocol [34], which uses the Ad hoc (or Announcement) Traffic Indication Messages (ATIM) window defined in the IEEE 802.11 standard for the power saving mechanism (power management), belongs to this set.

4. **Dedicated control channel**. One channel is dedicated for control and broadcasting packets and the remaining channels are data channels for data transmissions. This approach does not require clock synchronization and does not fully support broadcasting because stations have a single interface and some stations could not be over the control channel. In addition, nodes are required to monitor the control channel and create a channel list, but this mechanism leads to poor channel utilization due to the multi-channel exposed terminal problem [3]. The congestion on the control channel should be addressed, for example, the Asynchronous Multichannel Coordination Protocol (AMCP) [70] and the Asynchronous Multi-Channel MAC (AMCMAC) protocol [73].

Single-interface MAC protocols are considered SR-MCMAC protocols except independent hopping MCMAC protocols, which are considered as MR-MCMAC protocols and suffer from the busy receiver problem described in Section 2.2.3.

However, when nodes have multiple radio interfaces, different techniques have been adapted. The main difference between those techniques is the duration time when an interface is required to switch from channel to channel. Those techniques are summarized as follows:

1. **Static assignment**. All interfaces are fixed during the network operating after channel assignment algorithms are executed [74, 75]. The interfaces are not able to switch. The simple protocol is identified as the common channel set (CCS) where, in each node, interface 1 is assigned to channel 1, interface 2 is assigned to channel 2, etc. CCS is adopted in [64].

2. **Dynamic assignment**. All interfaces switch between channels, and the switching time is at a fast time scale (e.g., less than a minute). To the best of our knowledge, we are not aware of any protocol that requires all interfaces to

switch. We are the first researchers to investigate this approach as proposed in Chapter 5.

3. **Semi-dynamic assignment**. The switching time occurs at a slow time scale (e.g., minutes or hours) or depends on channel assignment algorithms as in [57]. The authors propose a multi-channel WMN architecture (Hyacinth) that uses a heuristic distributed load-aware algorithm which depends on the aggregate traffic load and topology information [57]. In [76], a centralized interference-aware channel assignment algorithm (BSF-CA) based on a multi-radio conflict graph is proposed. When the topology, for example, changes, both protocols are required to reassign channels.

4. **Hybrid assignment**. Combining the static and dynamic assignments, some interfaces are fixed on specific channels and the other group is dynamically tuned between channels. In [37], the protocol has two interfaces: the first interface is fixed on a predefined dedicated control channel and the second interface switches between channels.

Multi-interface MAC protocols are considered MR-MCMAC protocols except for some hybrid assignment protocols, which are the SR-MCMAC protocols because they require a dedicated control channel. The dedicated control channel approach is widely used because it does not require clock synchronization and is able to fully support broadcasting information because all nodes are over a dedicated control channel all the time. Figures 2.6 and 2.7 show the classifications of single-interface and multi-interface MCMAC protocols, respectively.

Various MCMAC protocols split the shared bandwidth into one dedicated control channel and multiple data channels. In [77], the Split-channel Reservation Multiple Access (SRMA) is proposed and divides the whole channel into two channels: the control and data channels. The control channel is also divided into two sub-channels: the request and the answer-to-request sub-channels. Nodes compete over the request channel and receivers reply over the answer-to-request channel. Then, data packets are transmitted over the data channel. The idea of splitting the shared channel into one dedicated control channel and data channel(s) has been analyzed in [78, 79, 80], and the findings from the analysis are that having one whole shared channel performs better than splitting the shared channel due to the congestion on the control channel.

2.2.2 Related Work

Previously, the purpose of using multiple channels was to eliminate the hidden terminal problem, e.g., the Busy Tone Multiple Access (BTMA) [81] and Receiver-Initiated Busy-Tone Multiple Access (RI-BTMA) [82] protocols. In BTMA, the shared channel is divided into two sub-channels; one channel is used as an indicator channel and the other channel is used for data transmissions. The bandwidth for the indicator channel is much shorter than the bandwidth for the data channel. If a node needs to transmit a packet, the node checks the indictor channel to detect whether or not the data channel is idle. If the indicator channel is idle, the node transmits a busy tone signal over the indicator channel and the data packet over the data channel. BTMA uses only one data channel and does not exploit multiple channels.

Single Interface Approaches

Installing a single transceiver on node is cost-effective, but most protocols require clock synchronization. Based on the split phase approach, the MMAC protocol is proposed by So and Vaidya [34] to utilize all available channels. They solve the multi-channel hidden terminal problem by synchronization. The time is divided into

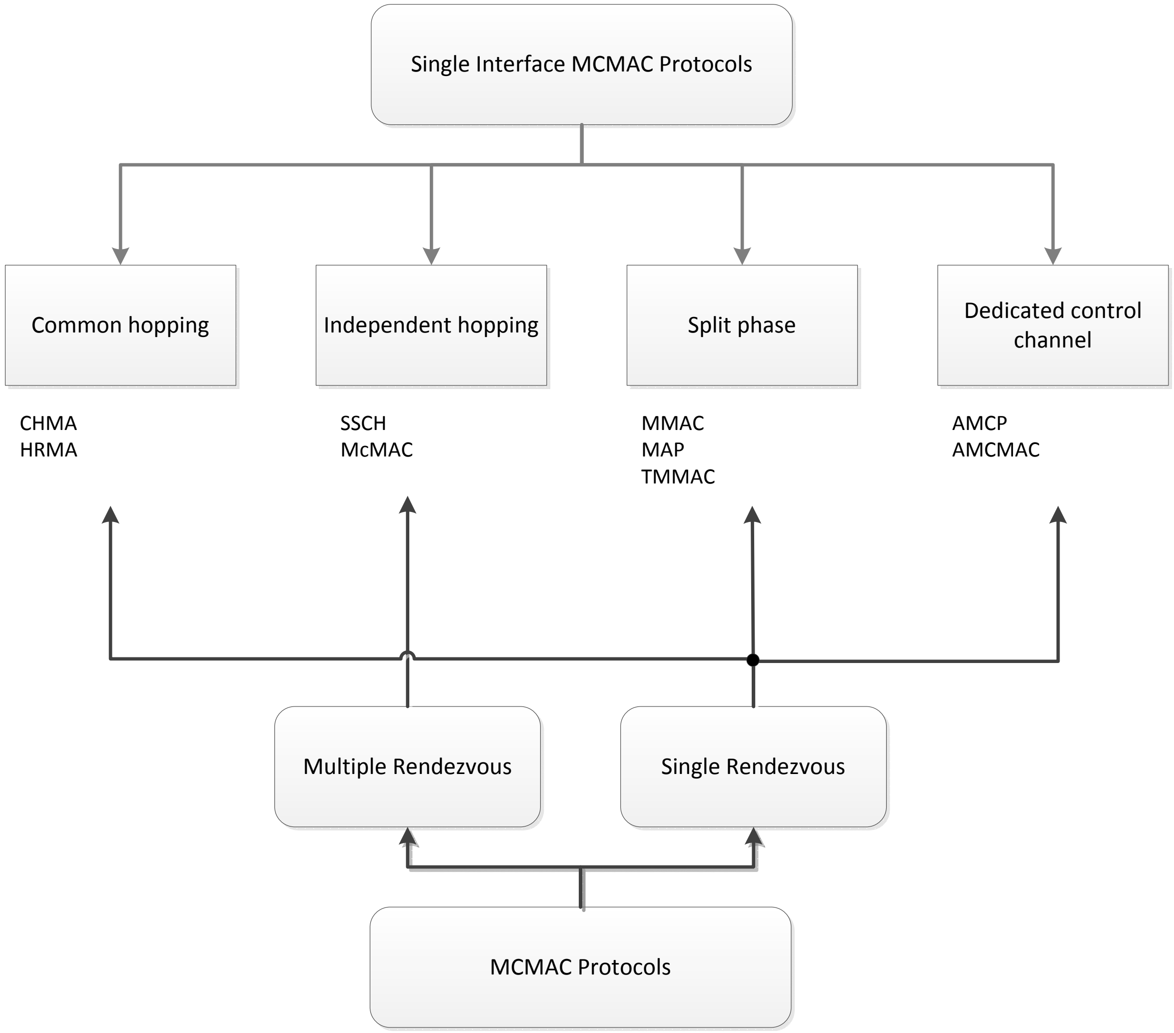


Figure 2.6: Classification of single-interface MCMAC protocols

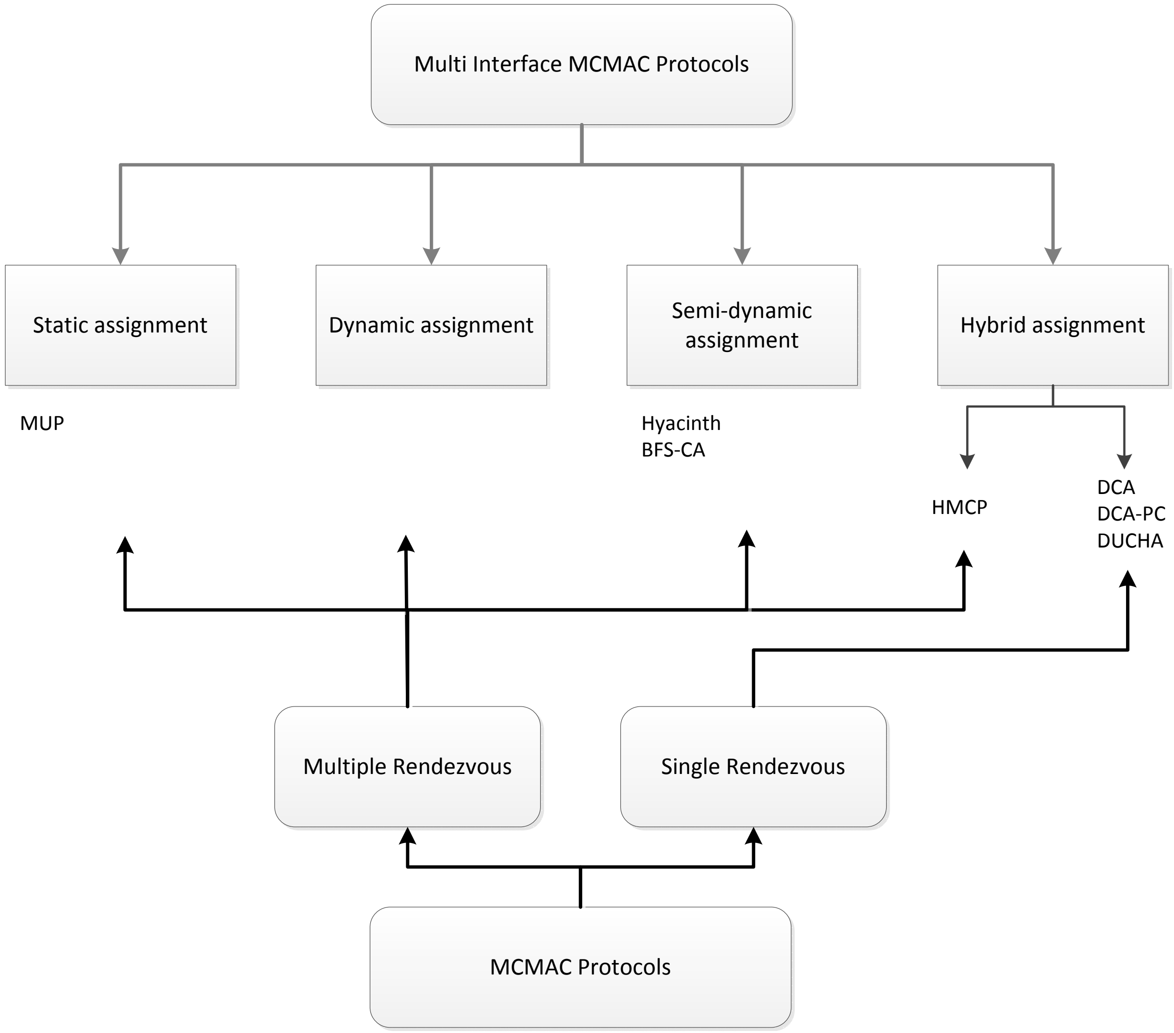


Figure 2.7: Classification of multi-interface MCMAC protocols

beacons. The beacons consist of two windows: ATIM and data. At the beginning of the ATIM window, nodes tune their transceivers into the default channel. A pair of nodes reserves a channel by exchanging ATIM, ATIM-ACK, and ATIM-RES (REServation) packets during the ATIM window. After the ATIM window, the successful pairs tune their transceivers to their agreed channels (including the default channel). Then, the nodes start transmitting following the IEEE 802.11 MAC standard. Each node has a single half-duplex transceiver, which is able to switch between channels. In [83], the TDMA-based Multi-channel MAC protocol (TMMAC) is proposed and extended with the same idea as MMAC to enable the nodes that have not exchanged ATIM, ATIM-ACK, and ATIM-RES packets during the ATIM window to sleep after the ATIM window. MMAC and TMMAC require tight global clock synchronization, which is difficult to achieve in multi-hop networks [84, 85]. In [86], the Cluster-Based Multi-Channel Management Protocol (CMMP) is proposed, and each cluster has a subset of channels. Within a cluster, nodes use the same idea as MMAC for data transmissions. Gateway nodes switch between clusters at the beginning of a beacon for intercluster transmissions. Clock synchronization is still an issue in CMMP.

Chen *et al.* [87] propose a new multi-channel access protocol for IEEE 802.11 ad hoc WLANs to be known as the Multichannel Access Protocol (MAP). Using a single radio, MAP supports parallel transmissions. Moreover, MAP is based on CSMA/CA. The channel access is divided into two alternative and non-overlapping time intervals: the Contention-Reservation Interval (CRI) and the Contention-Free Interval (CFI). The CRI is fixed and all nodes turn their transceivers into a common channel, and, during the CRI, nodes contend on the channel and exchange RTS and CTS packets. Every successful sender and receiver pair must stay on the common channel until the end of the CRI, and, after that, every pair switches to one of the available channels or remains on the common channel for data transmissions according to the proposed Channel Scheduling Algorithm (CSA). The interval of the CFI depends on CSA. This protocol is a type of splitting phase that depends on clock synchronization. However, providing synchronization in ad hoc networks is a challenging problem due to the distributive nature of the nodes.

Li *et al.* [88] modify the IEEE 802.11 MAC standard to propose a new multi-channel MAC protocol and utilize multiple channels. This idea is based on a dedicated control channel and multiple data channels in which nodes has a single half-duplex radio. This protocol does not address the multi-channel hidden terminal problem and the busy receiver problem.

The CHMA protocol is proposed to exploit the available channels [68]. This protocol is based on common hopping, meaning that all nodes must follow a common hopping sequence. The dwell time is the time needed for a handshake (e.g., RTS), and, during the dwell time, no carrier sensing or code assignment is needed. CHMA requires too many switchings between frequencies. The HRMA protocol is proposed in [69], which is similar to CHMA. Both protocols require tight clock synchronization. Another issue that occurs in these protocols is the busy receiver problem [36].

The SSCH protocol [58] and the McMAC protocol [71] are based on the independent hopping (parallel rendezvous) approach and require only one radio interface per node. Both protocols allow nodes to independently hop between channels according to their channel hopping sequences. Specifically, SSCH and McMAC construct their channel hopping sequences based on the prime module and linear congruential generators, respectively. As a result, SSCH follows a deterministic hopping sequence and McMAC follows a pseudorandom hopping sequence. In SSCH, nodes may synchronize using the same hopping sequence due to its deterministic channel hopping construction so that the SSCH protocol forces the nodes to desynchronize to avoid congestion if the number of nodes is more than twice the previous occurrence. SSCH employs an optimistic synchronization technique, while McMAC is based on a pairwise synchronization. A sender needs to synchronize with a receiver to transmit a packet so that the sender might deviate from its default hopping sequence; as a result, The SSCH protocol and the McMAC protocol suffer from the busy receiver problem (the missing receiver problem) [36, 70].

The Efficient Multichannel MAC (EM-MAC) protocol is proposed in [89]. EM-MAC is duty-cycling MAC protocol and follows the parallel rendezvous approach, similar to McMAC. However, EM-MAC also suffers from the busy receiver problem [60, 5].

Multiple Interface Approaches

In general, equipping multiple transceivers per node reduces the complexity (e.g., synchronization) but increases the cost. The Dynamic Channel Assignment (DCA) protocol is proposed for multi-hop networks and does not need clock synchronization [37]. Two interfaces are installed on each node. One interface is fixed on the control channel and the other interface switches between data channels. The control packets are RTS, CTS, and reservation (RES) packets that are transmitted over the control channel; data and ACK packets are transmitted over data channels. All nodes maintain a channel usage list (CUL) to determine the data channels' activities by overhearing the control channel, thereby channel assignment is accomplished. However, this channel list causes the multi-channel exposed terminal problem described in Chapter 4.

Using multiple channels with TPC can further increase the network capacity [6, 90]. In [90], an extension of the DCA with the power control (DCA-PC) protocol is introduced. Nodes transmit at the maximum power over the control channel and determine the minimum power for each transmission on data channels. DCA-PC suffers from the deficiency of uncontrolled asymmetrical transmission power. This deficiency is discussed in more detail in Chapter 3 and a new power control protocol for multi-channel ad hoc networks is introduced.

Other protocols require nodes to be equipped with multiple wireless interfaces which are equal to the number of the channels such as [63, 91, 64, 92]. In [63], the protocol divides the channel bandwidth into N non-overlapping channels, similar to the FDMA scheme. The nodes are able to sense all channels at the same time and transmit over one idle channel randomly. In [64], the Multi-radio Unification Protocol (MUP) is proposed for IEEE 802.11 networks. MUP is a link layer protocol that coordinates the installed multiple radios and does not modify the IEEE 802.11 legacy. Consequently, each node has multiple transceivers, which are equal to the number of channels, and each node uses only one transceiver at a time. MUP selects a channel by estimating the channel load using a Smooth Round-Trip Time (SRTT). The main issue with this protocol is that it requires each node to have the same number of transceivers as the number of channels.

Nasipuri *et al.* divide the entire bandwidth into M non-overlapping channels [92]. A node in the network can transmit or receive over all channels, but it is allowed to transmit or receive over only one channel at a time. All nodes have the capability of listening to all channels and select their channels that have the minimum interference; this feature implies the nodes have the same number of interfaces as the channels. However, it is unpractical to have as many wireless interfaces as channels in each node (e.g., IEEE 802.11a has 12 channels).

Zhai *et al.* [93] propose a dual-channel MAC protocol named dual-channel MAC protocol with an out-of-band busy tone (DUCHA). Every node is equipped with two transceivers where one is dedicated for control packets and the other is for data packets. Moreover, DUCHA employs busy tone to mitigate the hidden terminal problem. Similar to DCA [37], it does not require any form of synchronization.

The control packets are RTS, CTS, and Negative CTS (NCTS), which are used to solve the receiver blocking (deafness) problem. On the data channel, data packets and negative ACK (NACK) are transmitted. A NACK packet is used by a sender when it does not receive the data packet or the data packet has errors.

In [94], it is required one interface to be fixed and the second interface to be switchable known as the Hybrid Multi-Channel Protocol (HMCP). This protocol resolves the congestion on the control channel, and the fixed interface randomly selects its channel. Generally, the performance of this protocol relies on the channel assignment of the fixed interfaces. When a sender needs to transmit a packet to the receiver, the sender determines which channel the receiver is on. If both fixed interfaces of the sender and the receiver are with the same channel, the sender transmits the packet through its fixed interface. Otherwise, the sender tunes its switchable interface to the channel over which the fixed interface of the receiver is and then starts to transmit the packet. Moreover, a routing metric is developed in [94] to engage the switching delay. Although existing wireless interfaces can switch between channels with delays of 130 μs [95], in the near future, it is expected that the channel switching delay of wireless interfaces will be reduced to 40-80 μs [58].

Li *et al.* propose Medium Access Control with a Separate Control Channel (MAC-SCC) for multi-hop wireless networks [96]. The channel bandwidth is divided into two orthogonal channels: a data channel and a signaling channel. The data channel bandwidth is much greater than the signaling channel bandwidth, and they assume each node is equipped with two transceivers, one for each channel. Two NAVs are also introduced, one for each channel. When the data channel is busy, the signaling channel is used to determine the next data frame to be transmitted through the data channel.

Pathmasuntharam *et al.* [97] propose a Primary Channel Assignment based MAC (PCAM) protocol. The PCAM protocol requires each node to be equipped with three transceivers. The primary transceiver is randomly assigned to a channel known as the primary channel, and this primary channel serves as a means to be contacted by others. The secondary transceiver is used mainly for transmitting data and is switchable. If a transmitter-destination pair is not with the same primary channel, the transmitter switches its secondary transceiver to the primary channel of the destination so that the transmitter can send its packet to the destination. The third transceiver is fixed to a dedicated broadcast channel to transmit and receive broadcast packets.

2.2.3 Issues in Multi-channel MAC Protocols

In the following, the major issues to design MCMAC protocols are discussed.

Channel Synchronization

In single-channel environments, when a transmitter successfully captures the shared channel, the transmitter knows that its receiver is on the same channel. However, in multi-channel networks, a transmitter might be able to determine which channel its receiver is on. If node A, for example, has a packet for node B and each node has a single interface, node A must use Channel 1, which is the common control channel, to reserve a data channel by exchanging RTS/CTS packets illustrated in Figure 2.8. Upon agreeing on a data channel (e.g., Channel 3) nodes A and B change their interfaces to the agreed channel. After that, node A transmits its packet to node B on Channel 3. During that time, node C wants to transmit a packet to node B, but node C is on Channel 2. Thus, node C must return to Channel 1 and transmit an RTS packet to node B. However, node B is not on Channel 1. Another factor that can contribute to the channel synchronization problem is the hardware clock of a node is imperfect.

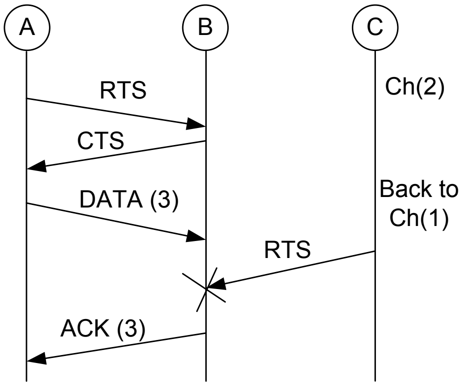


Figure 2.8: A scenario of the channel synchronization problem occurs in which node C does not know which channel node B is on.

Multi-channel Hidden Terminal Problem

For the purpose of illustration, a simple MCMAC protocol that requires a single transceiver per node, and one control channel (e.g., Channel 1) and multiple data channels are assume to exist. The problem is similar to the channel synchronization problem. However, node C that is on Channel 2 knows that node B is on Channel 3. Thus, node C changes to Channel 3 and transmits an RTS packet to node B because node C has missed the CTS from node B and is not within the CSR of node A, thereby causing a collision at node B (Figure 2.9).

Another example illustrating the multi-channel hidden terminal problem is provided in Figure 2.10. If node A has a packet for node B, nodes A and B exchange RTS and CTS packets over the control channel (e.g., Channel 1) to reserve a data channel. Upon agreeing on a data channel (e.g., Channel 3) nodes A and B change their transceivers to the agreed channel. After that, node A transmits the packet to node B on Channel 3. Meanwhile, node C wants to transmit a packet to node D, but node C is on Channel 2. Therefore, node C must return to Channel 1 and exchange RTS and CTS packets with node D. Both nodes C and D agree on Channel 3 because node C is unaware of the previous negotiation between node A and node B. As a result, a collision occurs at node B on Channel 3.

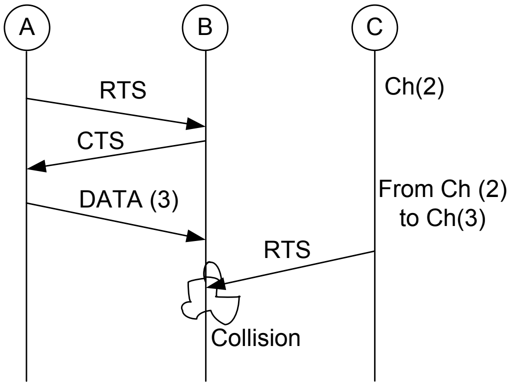


Figure 2.9: An illustration of the multi-channel hidden terminal problem. If node C knows that node B is on Channel 3, node C switches to Channel 3 and starts transmitting because node C is not within the CSR of node A and misses the CTS packet from node B. Thus, node C causes a collision at node B.

Busy Receiver Problem

This busy receiver problem occurs only in multi-channel wireless networks. Assume that nodes are equipped with one radio interface, and the nodes hop between channels similar to SSCH [58] or McMAC [71]. A channel is divided into slots, and nodes may switch at the beginning of a slot or stay at the same channel. A single-hop scenario is considered. If node A has a packet for node B, node A has two choices. The first choice is that node A deviates from its default hopping sequence to follow the hopping sequence of node B as illustrated in Figure 2.11. Node A starts transmitting to node B, and the transmission time may take more than one slot. While node A is transmitting to node B, node C has a packet for node A. Consequently, node C follows node A's hopping sequence and starts transmitting. However, node C does not receive any reply from node A because node A is not on its hopping slots where it should be. Therefore, this busy receiver problem wastes

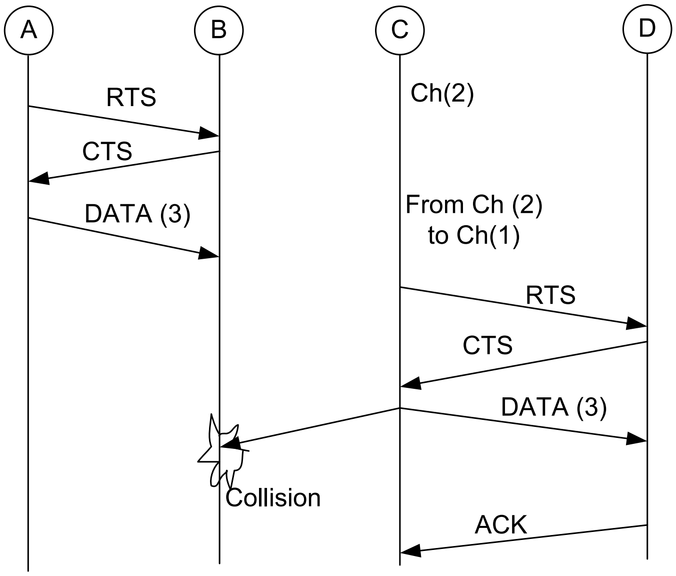


Figure 2.10: Another example of the multi-channel hidden terminal problem.

the channel bandwidth and increases the packet dropping rate. The second choice for node A is to wait until nodes A and B meet on the same slot. However, this choice is not preferred because it will increase the packet delay.

Consider now that node A wants to transmit to node B, node B has a packet for node C, node C needs to relay a packet to node D, and node D wants to transmit to node A. If most nodes decide to deviate from their hopping sequences, the problem severely affects the network performance. Note that all nodes are within the communication range of each other.

Broadcast Support

Wireless medium is considered as an unguided medium if omni-antennas are employed. In single-channel networks, all nodes listen to their shared channel, so if any node transmits its broadcasting packets successfully, its neighboring nodes receive the packets. In multi-channel environments, nodes may be on different channels, and some nodes may not receive broadcasting packets. MCMAC protocols should

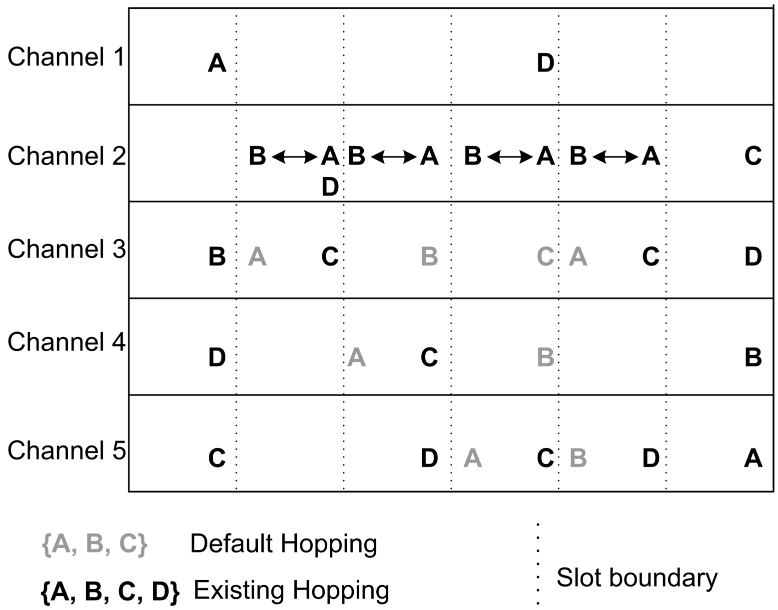


Figure 2.11: A simple example of the busy receiver problem in which node A deviates from its hopping sequence to transmit to node B and node C cannot negotiate with node A because node A have already deviated from its default hopping sequence.

support broadcasting packets or. One basic solution is to have one interface fixed on a dedicated control channel, so all nodes sense the dedicated channel.

Chapter 3

Distributed Power Control over Multiple Channels for Ad Hoc Wireless Networks

Due to the transmission power constraint, multi-hop ad hoc networks have recently gained significant attention because of their low cost deployment, infrastructureless, and coverage extension. However, the performance of wireless ad hoc networks is limited due to interference when nodes transmit at the maximum power. Unwanted transmission power added to useful power over a channel becomes interference that not only degrades the network performance, but also wastes nodes' energy, a crucial resource. Thus, transmission power is a major factor that can affect the network performance, and transmission power control (TPC) is one solution that can not only improve the spatial reuse but also reduce the interference.

This chapter examines the deficiency of uncontrolled asymmetrical transmission power in multi-channel ad hoc wireless networks. We propose a novel distributed transmission power control protocol called the distributed power level (DPL) protocol for multi-channel ad hoc wireless networks in order to resolve the uncontrolled asymmetrical transmission power problem. The main idea is to enhance the network throughput by efficiently using multiple channels with TPC in a distributed manner. DPL allocates different maximum allowable power values to different channels so that the nodes that require higher transmission power are separated from interfering with the nodes that require lower transmission power. As a result, nodes select their channel based on their minimum required transmission power, so interference is reduced over channels. We also introduce two TPC modes for the DPL protocol: symmetrical and asymmetrical. For the symmetrical DPL protocol[1], nodes transmit at the power that has been assigned to the selected channel, thereby creating symmetrical links over any channel. The asymmetrical DPL protocol, on the other hand, allows nodes to transmit at a power that can be lower than or equal to the power assigned to the selected channel. In addition, simulation results using ns-2 show that the symmetrical and asymmetrical DPL protocols achieve significant improvement.

The remainder of the chapter is organized as follows. Section 3.1 reviews the related work, and Section 3.2 presents the deficiency of uncontrolled asymmetric transmission power in multi-channel networks. In Section 3.3, we propose the novel distributed power control protocol for multi-channel ad hoc networks. We then evaluate the symmetrical and asymmetrical DPL protocols in Section 3.4. Section 3.5 briefly presents some discussions about our proposed protocols and some practical aspects related to power assignments for different frequency ranges. Finally, we summarize this chapter in Section 3.6.

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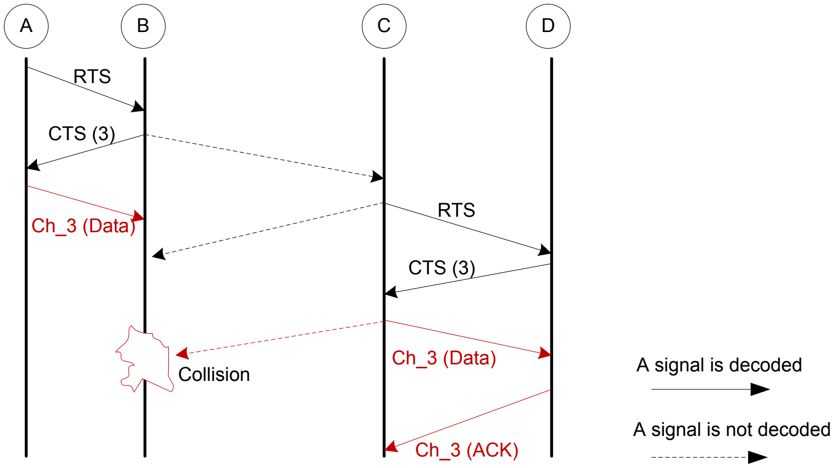
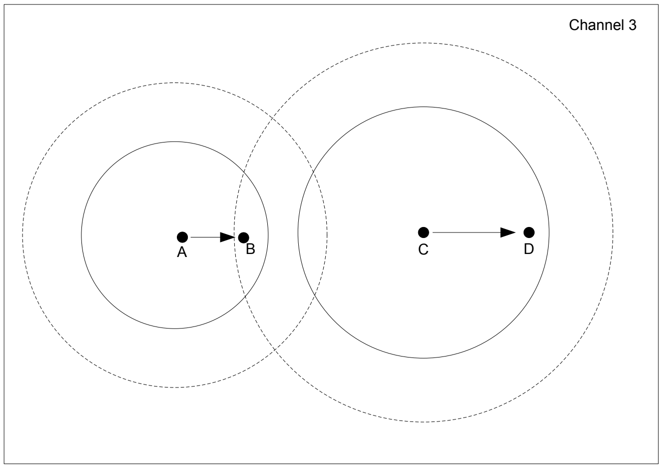
[1] In this chapter, we use the term the symmetrical (asymmetrical) mode and the symmetrical (asymmetrical) DPL protocol interchangeably.



(a) Channel negations where node C is transmitting to node D and node A is transmitting to B



(b) Different ranges when different transmission powers of transmitters are used, leading to unfairness and collisions

Figure 3.1: The illustration of the uncontrolled asymmetrical transmission power problem in multi-channel environments.

3.1 Related Work

Designing multi-channel MAC protocols and TPC protocols for wireless networks has been studied [57, 98, 71, 99, 58, 59, 62, 37, 3, 90, 100, 101, 102, 103, 104].

For single-channel networks, the TPC protocols that are similar to BASIC are proposed in [105, 106]. Nodes transmit RTS and CTS packets at the highest power and then determine the minimum required transmission power to transmit data and ACK packets. In [105], the power-aware routing optimization (PARO) protocol is proposed. PARO is a routing protocol where the routing metric is the summation of transmission power values so that nodes select the minimum transmission power values to save energy. As mentioned before, The BASIC scheme has been proven to increase collisions and consume more energy [103, 53, 107].

A new TPC protocol is proposed at the MAC layer called Power Control MAC (PCM) [53] to resolve the asymmetrical links associated with BASIC. Unlike BASIC, PCM determines the minimum transmission power, but, during data packet transmissions, nodes periodically increases and decreases the transmission power between the maximum power and minimum power. The main focus of this protocol is to save energy. Power-stepped protocol (PSP) is proposed in [108], and it allows each nodes to operate at one of transmission power levels. The selected power level of any node must be within one level higher or lower than that of any of its neighbors.

In [102], a new TPC protocol, called POWMAC, has been proposed to create asymmetrical links in the network. The idea is similar to the BASIC scheme, but more complex. In [109], a new adaptive transmission power controlled MAC protocol, called ATPMAC, is proposed to enhance the network throughput using a single channel and a single transceiver. ATPMAC adjusts not only the transmission power, but also the carrier sensing threshold.

Other approach that incorporates power control is called *topology control*, which determines a common minimum transmission power for such networks to be used by all nodes so that the networks are connected [101, 110, 111].

Slotted symmetric power (SSP) in [104] divides the time into large slots, and each large slot contains small slots. In each small slot, nodes turn their maximum power values to a fixed value (e.g., meaning that the transmission power is P_1 and P_2 in small slot i and small slot $i + 1$, and so on). After each large slot, nodes begin to use the same sequence of power values again. A global position system (GPS) is employed in each node to synchronize the network, and SSP does not utilize multiple channels.

A recent study shows the capacity of multi-channel multi-radio wireless networks can be increased by exploiting power control [27]. For multi-channel networks, much research work of TPC has been done for centralized networks [30, 31, 112]. A centralized polynomial-time Linear Programming with Sequential Fixing (LPSF) is proposed in [113] to solve the joint power/rate control and channel assignment problem. Our focus is on distributed multi-hop ad hoc networks. In [114], the authors propose a distributed power allocation utilizing game theory in cognitive radio networks. Extra monitoring stations are required, and time synchronization is assumed for both user nodes and the extra monitoring stations for their distributed algorithm. The authors in [115] use game theory similar to [114] to propose a distributed algorithm to achieve distributed power control in cognitive radio networks. Similar to [114], the proposed distributed power control in [115] assumes that monitoring sensors are placed on the edge of the primary network cell by the secondary network, and secondary users are synchronized. A distributed power control for cognitive networks is proposed in [116], and secondary users adjust their transmission power according to the primary link control feedback. In addition, the secondary users operate on only one licensed channel.

Wu *et al.* propose the dynamic channel assignment with power control (DCA-PC) protocol [90], which is an extension of the dynamic channel assignment (DCA) protocol [37] that sets the power levels of all channels to the maximum level. They show that DCA-PC performs better than DCA because of power control. DCA-PC resolves three problems: channel assignment, medium access, and power control. DCA-PC does not require any kind of synchronization among nodes, so does our proposed protocol. Whenever a node has a packet to transmit, it must compete over the control channel to reserve a data channel. The channel assignment occurs on an *on-demand* basis. For example, sender S negotiates with receiver R over the control channel using RTS, CTS, and RES packets with the highest power to select a data channel and determine the necessary power for the data transmission. Thus, DCA-PC creates asymmetric links over any data channel, or, specifically, tends to be similar to BASIC over each data channel. Comparing our proposed DPL protocol with the DCA-PC protocol, there are two major differences. First, DPL forces a node in the network to select an idle channel based on the received power and its corresponding required transmission power (i.e., composing between channel assignment and power control) while DCA-PC allows the node to select an idle channel regardless of the received power (i.e., decomposing between channel assignment and power control). Second, DPL allocates different maximum allowable power values to different channels, and nodes only transmit at a power that is less than or equal to the allocated power of a selected channel. However, DCA-PC does not have this constraint.

In [117], a multi-channel power-controlled directional MAC (MPCD-MAC) protocol is proposed, and the protocol has two radio interfaces. One interface is an omnidirectional antenna and fixed on the control channel while the other one is a directional antenna and switchable between data channels. Nodes exchange RTS and CTS packets at the maximum power over the control channel to determine the minimum required power, a selected data channel, and the direction. The proposed MPCD-MAC protocol selects an idle data channel without power constraint, but because it uses a directional antenna on data channels, the uncontrolled asymmetrical transmission power problem does not occur even though the problem has not been mentioned.

An intelligent MAC with busy tones and power control protocol is introduced in [118]. Specifically, it uses a dual busy tone multiple access protocol [119] with power control. The common bandwidth is divided into four sub-channels: a data channel, a control channel, a narrow-band transmit tone (BT_t), and a narrow-band receive tone (BT_r). The BT_t and BT_r tones indicate whether there is a transmission or reception, respectively. If there is no signal over BT_r, a sender transmits an RTS packet at the maximum power. However, if the sender senses BT_r to be busy, the sender transmits at the minimum power computed by the received power signal from BT_r. If the receiver senses BT_t to be idle, the receiver transmits a CTS packet and turns its busy receive tone BT_r on. Otherwise, the receiver ignores the RTS packet. An enhancement of the above protocol is presented in [120]. There is only one data channel, which does not exploit multiple channels.

3.2 Deficiency of Uncontrolled Asymmetrical Transmission Power in Multi-channel Multi-hop Networks

This section details the deficiency of uncontrolled asymmetrical transmission power, another form of the hidden terminal problem that wastes the channel bandwidth, in multi-channel networks [107, 53, 34, 121].

Figure 3.1a illustrates this problem. Suppose each node has two transceivers: one is fixed on the control channel to reserve a data channel, and the other is switchable between data channels. RTS and CTS packets are transmitted over the control channel, and data and ACK packets are transmitted over any reserved data channel. In addition, physical carrier sensing is used before transmitting. TPC is also used and determined via RTS/CTS handshaking. The maximum power is emitted over the control channel, and minimum required powers are applied over any selected data channels. The illustrated protocol is similar to the DCA-PC protocol [90].

Without loss of generality, suppose that node A has a packet for node B. To obtain a data channel, node A transmits an RTS packet, which attaches its free channel list available at A, at the maximum transmission power. If node B successfully receives the RTS packet, node B selects a data channel, determines the minimum transmission power, and transmits a CTS packet, which includes the selected channel and the minimum power, over the control channel. For example, as shown in Figure 1(a), if node B chooses Channel 3, then nodes A and B turn their transceivers to Channel 3. Before transmitting, node A must sense the channel for a certain amount of time to avoid collisions (e.g., the distributed interframe space (DIFS) period). If no transmission exists within the carrier sensing range (CSR) of node A, node A starts the transmission using the determined minimum power. As shown in Figure 3.1a, node C cannot decode the CTS packet correctly since node C is not within the transmission range (TR) of node B.

If node C has a packet for node D, node C follows the same procedure as node A to select a data channel; thus, nodes C and D may choose Channel 3 for the data transmission. Node C must sense Channel 3 before transmitting the packet to node D. Because node A is transmitting at a low power, node C assumes that the channel is idle and starts transmitting. Meanwhile, node D determines the transmission power emitted from node C. Three cases are possible: 1) node C transmits at the same power as node A, such case has been studied in [54]; 2) node C transmits at a low power than node A, in which case node C might not interfere with the ongoing transmission between nodes A and B; and 3) node C is required to transmit at a higher power than node A, leading to a possible collision over Channel 3 at node B. In our example, node C transmits at a higher power than node A, so node C might interfere with the transmission between nodes A and B. Figure 3.1b shows different transmission ranges, which is the top view of Figure 3.1a.

Figure 3.2 shows how the asymmetrical transmission power problem occurs *without having control* over any data channel. Nodes transmit RTS and CTS packets at the maximum power over the control channel (e.g., Channel 1), and data and ACK packets at any minimum power over any data channel. In the figure, node A cannot sense the hidden power from node H over Channel 2; assuming node H starts the transmission before node A. Thus, node H is interfered by node A. At the same time, because node E cannot sense the ongoing transmission between nodes C and D over Channel 3, it interferes with the ongoing transmission. This problem depends on the node distribution, node density, and traffic load, and it is likely that the problem can occur when there are few channels in the network.

In single-channel networks, Xu *et al.* study the effectiveness of the RTS/CTS packets where all nodes transmit all packets at the highest power [54]. In [121], the authors study the POwer control INduced hidden Terminal problem (POINT) problem, which the interferer always transmits at the maximum power because RTS and CTS packets are transmitted at the maximum power. In multi-channel networks, RTS and CTS packets are transmitted at the maximum power over the control channel while data and ACK packets are transmitted at a power, which is equal to or less than the maximum power, on any data channel. In the following discussion, we analyze the effect of asymmetrical transmission power over a single channel, and the analysis can be applied to multiple channels. This problem has not been well studied.

A packet is received correctly if $SINR \geq T_{SINR}$, where $SINR$ is the signal-to-interference-plus-noise ratio, and T_{SINR} is the threshold to accept the packet. With the two-ray path loss model, the received power at the receiver calculated as

$$P_r = P_t^t \frac{G_t G_r h_t^2 h_r^2}{d^k}, \tag{3.1}$$

where P_t^t is the transmission power from a transmitter (P_t^t can be less than, or equal to, P_{max}), and G_t and G_r are the antenna gains of the transmitter and the receiver, respectively. The antenna heights of the transmitter and the receiver are h_t and h_r, respectively. The distance between the transmitter and the receiver is d, and k is the path loss exponent, which is equal to 4. In this chapter, we focus on the homogeneous wireless network, meaning that all nodes share the same parameters[2] similar to [54]. Consider one interfering node is presented, which has a distance r from the receiver, so the receiver measures $SINR$ as follows:

$$SINR = P_r/P_i = \frac{P_t^t \frac{G_t G_r h_t^2 h_r^2}{d^k}}{P_t^i \frac{G_t G_r h_t^2 h_r^2}{r^k}} = (\frac{P_t^t}{P_t^i})(\frac{r}{d})^k, \tag{3.2}$$

where P_i is the interference received power at the receiver, and P_t^i is the transmission power from the interferer (P_t^i is less than, or equal to, P_{max}) [123]. In (3.2), we neglect the thermal noise because the interference received power is much higher than the thermal noise. If P_t^t is equal to P_t^i, then $SINR$ depends only on the ratio distance between the interferer and transmitter distances as follows:

---

[2] G_t is equal to G_r which is 1, and h_t is equal to h_r which is 1.5 meters. T_{SINR} is equal to 10. These values are the default values in the ns-2 simulator [122].

$$SINR = P_r/P_i = (\frac{r}{d})^k \geq T_{SINR}. \tag{3.3}$$

However, when the transmission power is different from node to node, $SINR$ is different:

$$SINR = P_r/P_i = (\frac{P_t^t}{P_t^i})(\frac{r}{d})^k \geq T_{SINR}. \tag{3.4}$$

If $(\frac{P_t^t}{P_t^i})$ is much less than 1, with high probability, $SINR$ is less than T_{SINR}. In this case, a transmission might fail (i.e., a collision might occur); therefore, it results in unfairness[3] because the nodes that transmit at higher transmission power values send their packets correctly. Figures 3.3 and 3.4 illustrate (3.4) where P_t^t and P_t^i vary from one of the following power values: $281.1, 56.4,$ and 18.8 mW; their corresponding transmission ranges are $250, 167,$ and 127 meters, respectively. In Figures 3.4 and 3.4, the shadowed areas are the vulnerable areas in which $SINR$ is less than 10 at the receiver; in other words, a collision occurs at the receiver. Note that when the transmitter sends its packet at a lower power than the interferer, the shadowed areas increase. However, when the transmitter sends its packet at a higher power than the interferer, the shadowed areas decrease.

In summary, to design a TPC protocol, the transmission power transmitted over a channel should be the same (e.g., $\frac{P_t^t}{P_t^i} = 1$) or be approximately the same (e.g., $\frac{P_t^t}{P_t^i} \approx 1$). This design yields to a fair share of a channel among nodes. The higher value of the transmission power is, the greater interference exists [124].

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[3] The capture effect problem may occur and result in unfairness.

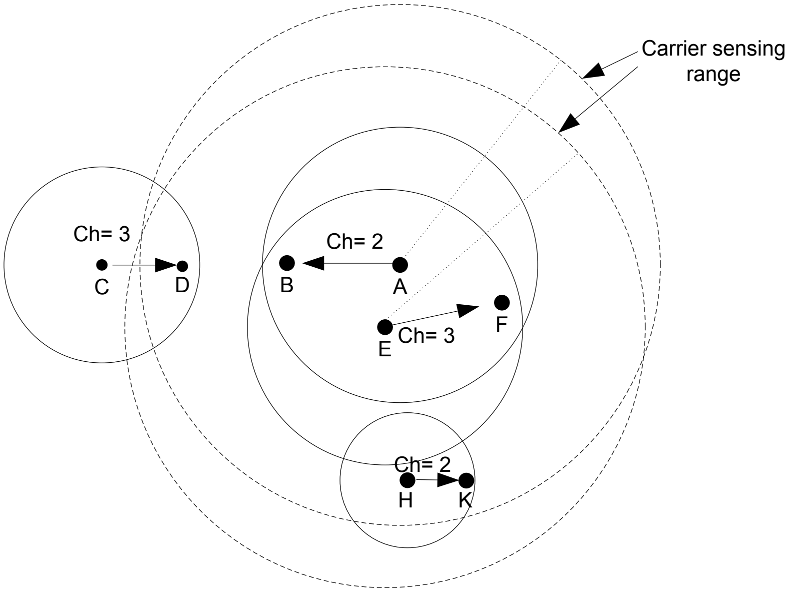


Figure 3.2: The asymmetrical transmission power can occur without control over multiple channels.

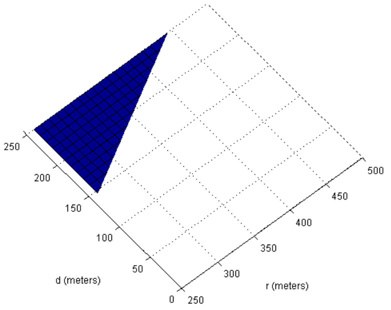
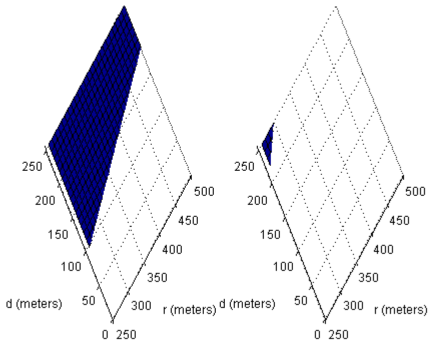


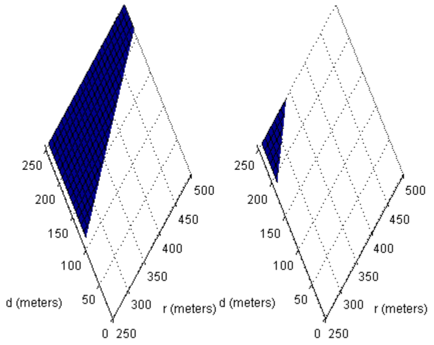
Figure 3.3: The transmission power of all nodes are the same $P_t^t = P_t^i$.

3.3 Distributed Power level (DPL) for Multi-channel Ad Hoc Networks

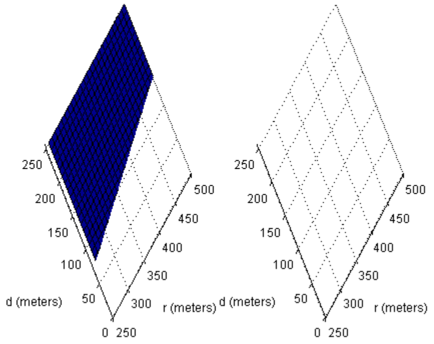
This section presents our novel distributed DPL protocol for multi-channel ad hoc networks. The key idea behind our proposed protocol is to differentiate allowable transmission power levels among channels. In other words, different transmission



(a) The left-hand side ($P_t^t = 0.0564$; $P_t^i = 0.2818$), while the right-hand side ($P_t^t = 0.2818$; $P_t^i = 0.0564$)



(b) The left-hand side ($P_t^t = 0.0188$; $P_t^i = 0.0564$), while the right-hand side ($P_t^t = 0.0564$; $P_t^i = 0.0188$)



(c) The left-hand side ($P_t^t = 0.0188$; $P_t^i = 0.2818$), while the right-hand side ($P_t^t = 0.2818$; $P_t^i = 0.0188$)

Figure 3.4: The effect of using different transmission power over a channel. The shadowed areas are the vulnerable areas where collisions occur.

power levels are assigned to different channels. Thus, nodes select an idle data channel in which the received power is less than or equal to the select data channel. In the following, we first summarize our assumptions, and then explain the channel selection of our protocols. In Section 3.3.3, we present the symmetrical and asymmetrical DPL modes followed by the list structures. Finally, we present the implementation of DPL.

3.3.1 Assumptions

- There are M channels that have equal bandwidths, where all channels are able to carry information. One channel is known as the control channel, and the remaining $M-1$ channels are data channels. We treat channels as a set of bandwidths in the spectrum domain. All broadcast and control packets are transmitted over the control channel.

- Each node is equipped with two interfaces. The two interfaces are installed separately from each other (approximately half of the waveform) without interfering with each other. Therefore, the two interfaces can operate simultaneously. Each interface is a half-duplex transceiver, meaning that it cannot transmit and receive at the same time. One interface is fixed on the control channel, and the second interface is able to switch between data channels.

- Nodes transmit over the control channel at the maximum power P_{max}. However, each data channel is associated with a maximum allowable transmission power as shown in Figure 3.5. For example, the maximum allowable power of the data channel i is set to be P_i^{max}, where $P_{max} = P_1^{max} \geq P_2^{max} \geq P_3^{max} \geq \cdots \geq P_M^{max}$. The power assignment is known prior to the nodes in the network (i.e., the power assignment is configured before the nodes join the network); therefore, the stability and convergence issues do not exist in

Table 3.1: List of Symbols

R_d	The rate of the data channel
R_c	The rate of the control channel
τ	Maximum propagation delay
L_d	Payload length of a data frame
L_{ACK}	Payload length of an ACK frame
T_{DIFS}	Time duration of the distributed interframe space
T_{SIFS}	Time duration of the short interframe space
T_{RTS}	Time to transmit an RTS frame
T_{CTS}	Time to transmit a CTS frame
T_{RES}	Time to transmit an RES frame
NOW	The local current time in each node
T_{data}	Time duration of a complete data transmission $T_{data} = L_d/R_d + T_{SIFS} + L_{ACK}/R_c + 2\tau$
P_{max}	The maximum transmission power
P_i^{max}	The maximum transmission power for Channel i
P_{min}	The minimum required power for a data transmission
P_r	The received power
T_{SINR}	The threshold power to accept a packet

our proposed protocol. Note that the notion of the transmission power of a node is not the same as the maximum allowable power of a data channel (e.g., the transmission power of node A is P_t^A and the maximum allowable power of the data channel i is P_i^{max}), and the node is able to change its transmission power, but not the power assignment $(P_1^{max}, P_2^{max}, \cdots, P_M^{max})$. In this chapter, we choose the power assignment *arbitrarily* (i.e., no optimization is considered), we study the impact of different power assignments on the network throughput in section 5.4.

3.3.2 Channel Selection

The MAC protocol uses a dedicated control channel and multiple data channels as illustrated in Figure 3.6, followed the RTS/CTS/RES handshaking, similar to that of the DCA protocol [37]. We follow this mechanism because clock synchronization is not necessary. However, our proposed TPC protocols can be implemented using other mechanisms, such as parallel rendezvous protocols [71].

In DCA-PC, receivers select any idle data channel without any restriction. However, in DPL, receivers select a data channel based on the received power so that the maximum allowable power of the data channel is larger than or equal to the received power. If the data channel of the least maximum power is busy, nodes are able to select the next data channel, etc. For example, when node A needs to transmit a data packet to node B, node A first transmits to node B an RTS packet, which includes the free channel list that node A is able to use. When node B receives the RTS packet, it measures the received power. Next, node B searches for a free channel based on the received power, so the maximum allowable power of the channel must be larger than or equal to the received power; at the same time, both nodes A and B are able to use the channel. If node B is able to use Channel 3, but Channel 3 is busy, then node B can select Channel 2 (because of $P_2^{max} \geq P_3^{max}$). If Channel 2 is free, node B transmits a CTS packet over the control channel using P_{max}. Upon receiving the CTS packet, node A transmits its packet to node B over Channel 2. After the short interframe space (SIFS) period, node A transmits an RES packet over the control channel. If node B successfully receives the data packet, node B responds to node A with an ACK packet over Channel 2. However, if node B does not find any idle channel, it transmits a CTS packet to node A. The CTS packet does not indicate any selected channel and includes the minimum time for node A to start over again (i.e., node A restarts the negotiation process). Section 3.3.5 presets the details of the proposed protocol.

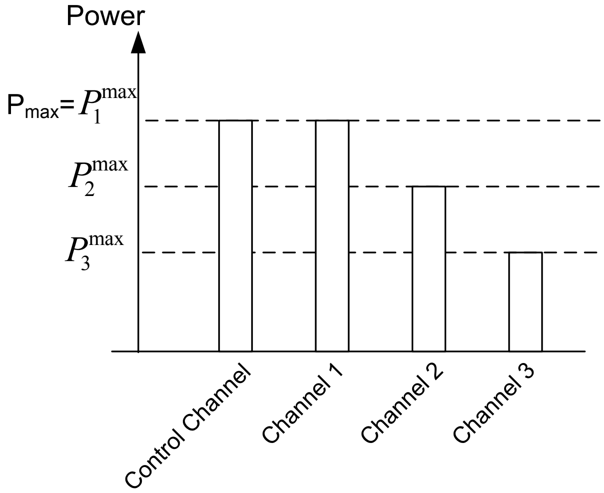


Figure 3.5: Different allowable powers over different channels.

3.3.3 Power Control

DPL sets different emission powers over different data channels. Nodes compute the minimum required power, and then select a data channel whose power is equal to or greater than the minimum power. In other words, we separate the nodes that need higher transmission powers from the nodes that require lower transmission powers over different channels.

Two power control modes are introduced for DPL. First, the symmetrical DPL protocol maintains symmetrical links over all channels (e.g., over Channel i, all nodes are required to transmit at P_i^{max}). For example, if node A prefers Channel 3 to transmit a packet to node B and Channel 3 is busy, then node A can use Channel 2, but transmits the packet at $P_t^A = P_2^{max}$ (not P_3^{max}). Second, the asymmetrical DPL protocol adjusts the transmission power over a channel so that nodes are allowed to transmit at the minimum power if necessary. As a result, the asymmetrical DPL protocol decreases interference over any data channel, and is beneficial especially when nodes take a longer time to transmit a packet. Note that, by using the asymmetrical DPL protocol, nodes do not always create asymmetrical links over data channels, but nodes decrease their powers if the preferred channels are busy. For example, if node A can reach node B using Channel 3 and Channel 3 is busy, then node A is able to transmit a packet to node B using Channel 2 at $P_t^A = P_3^{max}$ (not P_2^{max}).

3.3.4 List Structures

Each node maintains two local list structures: a node allocation list (NAL) and a channel allocation list (CAL). NAL maintains nodes' activities, and CAL monitors the information of data channels. These lists are maintained by listening to the control channel. A node updates its NAL and CAL whenever it receives any of RTS, CTS, or RES packets. NAL contains the following three fields: $nodeID$ (identification of a node), *duration* (duration how long node $nodeID$ has been busy), and $preChannel$ (preferred channel to reach node $nodeID$). The received power of node $nodeID$ is equal to or less than the maximum power of Channel $preChannel$ ($P_{preChannel}^{max}$), and the $preChannel$ field is continuously updated.

CAL has the following three fields: $chID$ (identification of a channel), *duration* (time duration indicates how long Channel $chID$ has been busy), and P_{chID}^{max} (the maximum allowable power assigned to Channel $chID$). The *duration* field is important to avoid the multi-channel hidden problem [34], and the P_{chID}^{max} field of channel $chID$ is fixed and does not changed.

One more list that is generated from CAL is called an available channel indicator (ACI) list, which indicates whether Channel i is free ($ACI(i) = 1$) or not ($ACI(i) = 0$). Before a node transmits an RTS packet, the node must generate a new ACI list and include the new ACI list in the RTS packet. Therefore, a receiving node can look for an idle data channel. The use of the above lists are shown in the next section.

3.3.5 Operations

To explain how the proposed protocol operates, we use an example shown in Figure 3.6. Suppose node A has a packet for node B, node C is within the transmission range of node A, and node D is within the transmission range of node B. Table 3.1 presents the lists of the symbols, and Figure 3.6 shows how the MAC protocol works. The details of DPL are presented in the following steps.

Step 1. In order for node A to transmit an RTS packet, three conditions must be satisfied:

1. Node B is not busy, which is

$$\begin{aligned} NAL[B].duration \; &\leq \; NOW + T_{DIFS} + T_{RTS} + \\ &\quad T_{SIFS} + T_{CTS} + 2\tau, \end{aligned} \tag{3.5}$$

   where NOW is the current time of node A, T_{DIFS} is the time length of DIFS, T_{RTS} is the time duration to transmit an RTS packet, T_{SIFS} is the time length of SIFS, T_{CTS} is the duration to transmit a CTS packet, and τ is the maximum propagation delay.

2. There is at least one available data channel that must be available, and there are two cases. The first case is node A does not know the preferred channel of node B, node A searches for all the available data channels, such that

$$\begin{aligned} CAL[i].duration \; &\leq \; NOW + T_{DIFS} + T_{RTS} + \\ &\quad T_{SIFS} + T_{CTS} + 2\tau, \end{aligned} \tag{3.6}$$

   for all i. The second case is when node A knows the preferred channel of node B, node A searches for the data channels whose maximum allowable powers are greater than or equal to the power of the preferred channel of node B using (3.6) for all $i \leq NAL[B].preChannel$, where $preChannel$ is the preferred channel to reach node B.

3. The control channel is idle for DIFS, following the IEEE 802.11 MAC standard.

If all the above conditions are satisfied, node A transmits the RTS packet which includes the packet size (L_d) and the ACI that node A is able to use. Otherwise, node A defers its transmission; i.e., node A performs a standard backoff procedure. If the control channel is idle, node A rechecks conditions 1 and 2. If conditions 1 and 2 are not satisfied, node A regenerates another random backoff interval and repeats Step 1.

Step 2. When node B receives the RTS (ACI, L_d) packet successfully, node B has to determine the desired minimum power[4] P_{min}. Since we consider the two-ray path loss model in our model, it can be computed (which is similar to [90, 53]) as follows:

$$P_{min} = \frac{P_{max} T_{SINR}}{P_r}, \tag{3.7}$$

where T_{SINR} is the threshold power and P_r is the received power. Then, node B compares P_{min} with transmission powers that are associated with each data channel. Finally, node B selects a data channel that satisfies the two following conditions:

1. The power level of the data channel is equal to or greater than P_{min}, i.e., $P_i^{max} \geq P_{min}$, $i \in M-1$.

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[4] In reality, the desired required power takes into account both the large-scale effect and small-scale effect.

2. The data channel i is idle

$$\begin{aligned} CAL[i].duration &\leq (NOW + T_{SIFS} + T_{CTS} + \\ &\quad \tau) \wedge (ACI[i] = 1). \end{aligned} \tag{3.8}$$

When the channel with the least power is busy (e.g., Channel 3 is the preferred channel to reach node A), node B checks the channel to see if the power level is greater than the least power level. If node B finds a free channel, e.g., Channel 2, node B replies to node A with a CTS packet that includes the selected data channel and the transmission duration time, CTS (Ch_i, T_{data}), where $T_{data} = L_d/R_d + T_{SIFS} + L_{ACK}/R_c + 2\tau$, where R_c and R_d are the transmission rates for both control and data channels, respectively. L_d and L_{ACK} are the packet lengths of payload and ACK frames, respectively. Meanwhile, node B switches its switchable interface to the selected channel and updates its lists as follows:

$$\begin{aligned} NAL[A].duration &= T_{data} + T_{CTS} + T_{SIFS} + \tau, \\ NAL[A].preChannel &= Ch_3, \\ CAL[2].duration &= NAL[A].duration. \end{aligned} \tag{3.9}$$

However, if all channels that satisfy the least power are busy, node B sends a CTS (T_{min}) packet including the minimum waiting time (T_{min}) (i.e., $T_{min} = min\{CAL[i].duration\}$, for all $i \leq NAL[A].preChannel$) after SIFS. Moreover, node B updates only the preferred channel to reach to node A, i.e., $NAL[A].preChannel = Ch_3$.

Step 3. If node A receives the CTS (Ch_i, T_{data}) packet that has a selected channel, Ch_i, e.g., Channel 2, then node A measures the received power of the

CTS packet and determines the preferred channel to reach node B. Moreover, node A switches its second interface to the selected data channel and starts transmitting the data packet. Node A transmits its packet over Ch_i at a power according to the power controls described in Section 3.3.3. After the SIFS duration, node A transmits an RES packet (a special packet) that contains the selected channel and the remaining transmission duration over the control channel, RES (Ch_i, T_{rem}), where $T_{rem} = T_{data} - T_{RES} - T_{SIFS} - \tau$. At the same time, node A updates its lists as follows:

$$\begin{aligned} NAL[B].duration &= T_{data}, \\ NAL[B].preChannel &= Ch_3, \\ CAL[2].duration &= T_{data}. \end{aligned} \tag{3.10}$$

However, if node A receives the CTS (T_{min}) packet, indicating that there is no available channel, node A defers its transmission for at least T_{min}, specified by node B. After that, node A returns to Step 1.

Step 4. If node A does not receive the CTS packet within the $T_{SIFS} + T_{CTS} + 2\tau$ interval, then node A assumes that the RTS packet is collided, doubles the contention window, counts the number of retries, and goes to Step 10.

Step 5. Whenever node C receives the RTS packet from node A, it measures the received power, determines the preferred channel, e.g., Channel 4, that reaches node A, and refreshes its NAL (i.e., $NAL[A].preChannel = Ch_4$). Moreover, node C updates its network allocation vector (NAV) field (i.e., $NAV = T_{CTS} + T_{RES} + 2T_{SIFS} + 2\tau$) so that node C does not interrupt the channel negation between nodes A and B.

Step 6. If node D receives the CTS (Ch_i, T_{data}) packet, which $Ch_i = 2$, from node B, node D measures the received power of the CTS packet, determines the reachable channel for node B, and updates its lists as follows:

$$\begin{aligned} NAL[B].duration &= T_{data} + \tau, \\ NAL[B].preChannel &= Ch_2, \\ CAL[2].duration &= T_{data} + \tau. \end{aligned} \tag{3.11}$$

In addition, node D updates its NAV field (i.e., $T_{SIFS} + T_{RES} + \tau$) so that node D does not interfere with node A. However, when the CTS packet does not have a selected data channel, node D measures the received power of the CTS packet, determines the reachable channel for node B, and updates its NAL list.

Step 7. When node C hears the RES (Ch_i, T_{rem}) packet from node A, node C first measures the received power of the RES packet, then evaluates the preferred channel, e.g., Channel 4, for node A, and finally updates its lists as follows:

$$\begin{aligned} NAL[A].duration &= T_{rem}, \\ NAL[A].preChannel &= Ch_4, \\ CAL[2].duration &= T_{rem}. \end{aligned} \tag{3.12}$$

Step 8. When node B receives the data packet with no errors over Ch_i, it waits for SIFS and replies to node A with an ACK packet over the same channel. If the packet has errors, node B just ignores it.

Step 9. If node A does not receive any ACK packet within the $T_{ACK} + T_{SIFS} + \tau$ interval after transmitting its data packet, then node A doubles the contention

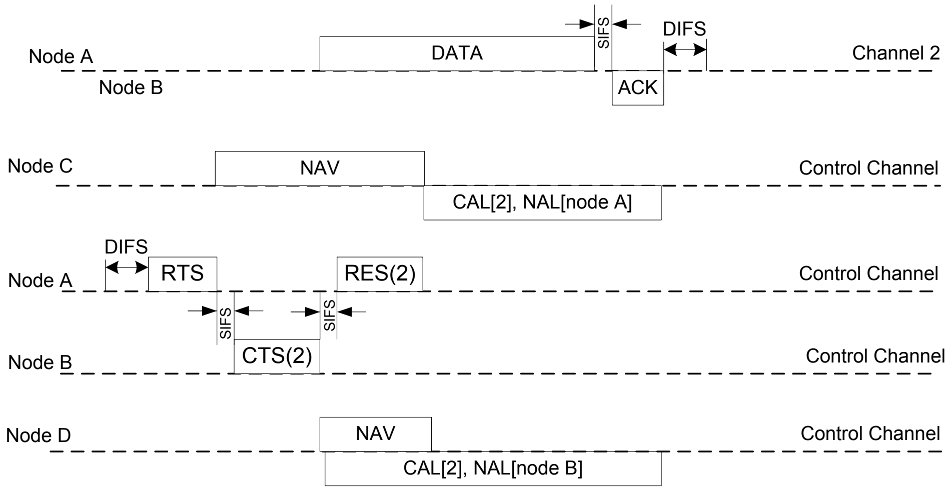


Figure 3.6: The MAC protocol using a dedicated control channel and multiple data channels.

window, counts the number of retries, and goes to Step 10. The data transmission is completed if node A receives the ACK packet, and, therefore, node A resets the number of retries and the contention window, schedules the next packet, and goes to Step 1.

Step 10. If the number of retries reaches the maximum number of retries, then the packet is dropped, and the contention window is reset. Node A schedules the next packet and goes to Step 1. If the number of retries has not reached the maximum number of retries, node A goes to Step 1.

3.4 Performance Evaluation

This section presents the performance evaluation of the symmetrical and asymmetrical DPL modes, and our performance metric is the aggregate throughput of all flows in the network. We compare our proposed protocols with DCA-PC [90] and 802.11 MAC. Although DPL and DCA-PC protocols use a dedicated control channel for exchanging the control packets and the remaining channels for data transmissions; however, the main differences are the design of TPC and the channel assignment strategy.

3.4.1 Simulation Model

We have implemented our proposed protocols and DCA-PC [90] on ns-2 (version 2.30) [122], and the simulation parameters are provided in Table 3.2. The radio interface parameters follow the Lucent's WaveLAN parameters. The carrier sensing range is approximately twice the communication range, and the radio propagation model is the two-ray path loss model. Using the maximum power, the communication range is 250 meters, and the carrier sensing range is about 550 meters. In addition, the channel bit rate for the control channel is 1 Mbps and 2 Mbps for data channels.

Four channels are available in the network unless otherwise mentioned. The transmission powers assigned to each channel are: $281.1, 281.1, 56.4$, and 18.8 mW, respectively; their corresponding transmission distances are $250, 250, 167$, and 127 meters, respectively. The first channel is the dedicated control channel, and the remaining channels are data channels.

In the simulations, no mobility and the constant bit rate (CBR) traffic model are assumed. Each point in the simulation results is the average over 30 different scenarios, and each simulation lasts 100 seconds. We consider two different types of topologies for simulations:

We consider two different types of topologies for simulations:

- **Chain topology** consists of 30 nodes. As shown in Figure 3.7, node 1 sends to node 2, node 2 sends to node 3, and so on. As a result, there are 29 flows.

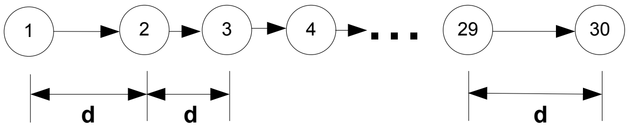


Figure 3.7: A chain topology consists of 30 nodes and 29 flows, and the distance **d** between two nodes is a uniform random variable between 20 and 230 meters.

The packet size is 512 bytes, and the distance between two adjacent nodes is uniformly distributed between 20 and 230 meters.

- **Random topology** includes 50 wireless nodes deployed randomly in a 1000m x 1000m square area. Each node randomly chooses its destination located within its communication range. As a result, there are 50 flows, and a node could be involved in multiple communications.

3.4.2 Simulation results

This section presents and discusses the simulation results under different topologies. We first show the aggregate throughput of the chain topology with different network loads. We then show the aggregate throughput of the random topology in terms of various network loads, packet sizes, sensitivity of power assignments, and number of channels.

Figure 3.8 shows the simulation results of 30 nodes arranged in the chain topology. In the figure, we simulate the network with different loads. As the data rate per flow increases, the throughput of all protocols increases. However, as the network load increases, the proposed protocols outperform the DCA-PC protocol

Table 3.2: System Parameters Used in Simulations [1, 2]

Parameters	Values
Carrier sense threshold	$1.56 * 10^{-8}$ mW
Receiver sensitivity	$3.65 * 10^{-7}$ mW
T_{SINR}	10
Maximum transmission power P_{max}	281.8 mW
Transmission rate for data channels	2 Mbps
Transmission rate for the control channel	1 Mbps
Retry limit	7
DIFS	50 μs
SIFS	10 μs
Slot time	20 μs
CW_{min}	32
CW_{max}	1024
Maximum propagation delay (τ)	1 μs
RTS (bits)	208 + PHY_{hdr}
CTS (bits)	256 + PHY_{hdr}
RES (bits)	208 + PHY_{hdr}
ACK (bits)	112 + PHY_{hdr}
MAC_{hdr} (bits)	272
PHY_{hdr} (bits)	192

because it suffers from the uncontrolled asymmetrical transmission power problem. Note that the throughputs of the asymmetrical and symmetrical DPL protocols are identical due to low node density and short data transmission time.

Figure 3.9 shows the aggregate throughput of the random topology when the packet size is 1000 bytes and the number of channels is four. It can be seen that as the flow data rate increases, the network throughput can be improved for all protocols. When the network load is low, DCA-PC achieves better performance than the proposed protocols because the uncontrolled asymmetrical transmission power problem does not occur. However, the symmetrical and asymmetrical DPL protocols achieve the best performance for high data rate. In addition, the asymmetrical DPL protocol achieves a slightly higher throughput than the symmetrical DPL protocol because it may adjust the transmission power over any channel and

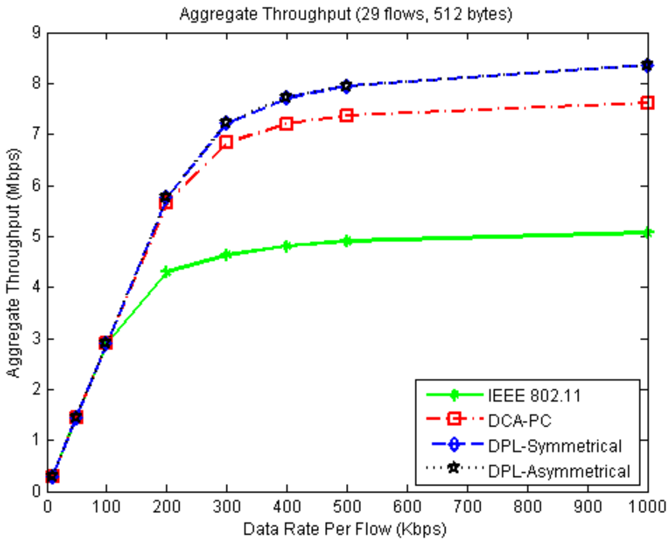


Figure 3.8: Aggregate throughput in the chain topology with different network loads.

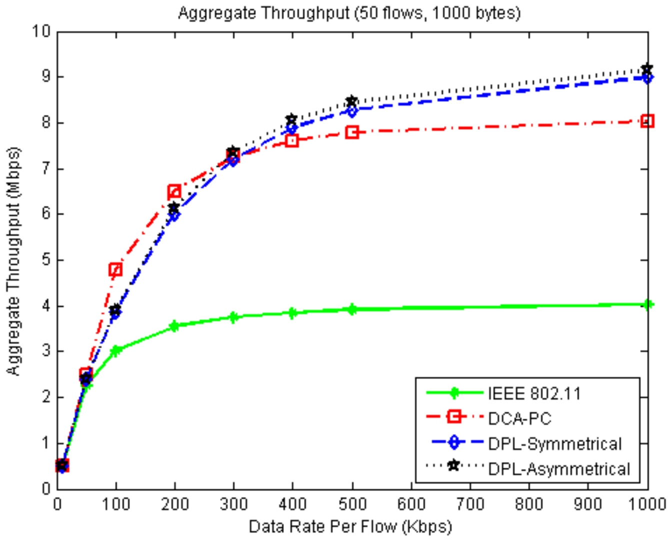


Figure 3.9: Aggregate throughput in the random topology with different network loads.

thereby reducing interference as mentioned in Section 3.3.3.

Figure 3.10 shows the network throughput of the random topology for different packet sizes. We assume that the rate of each flow is 1 Mbps, and the number of channels is four. As the packet size increases, the aggregate throughput of

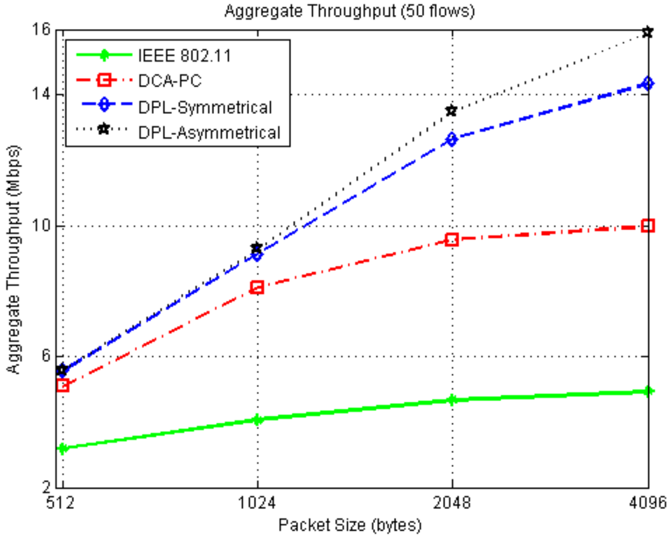
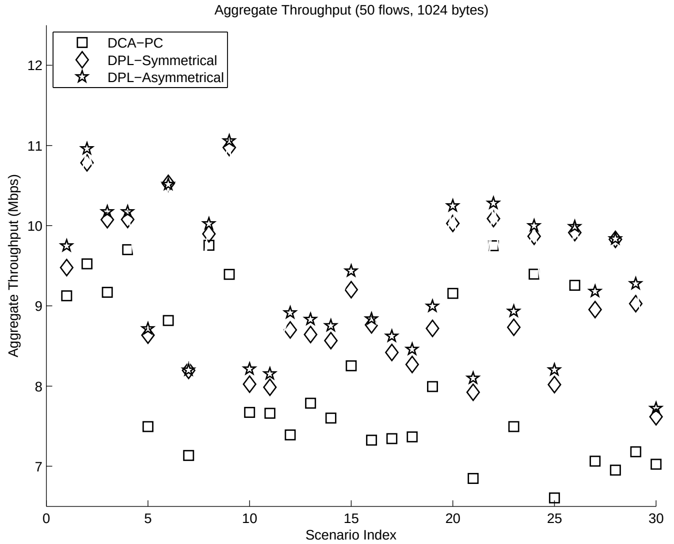


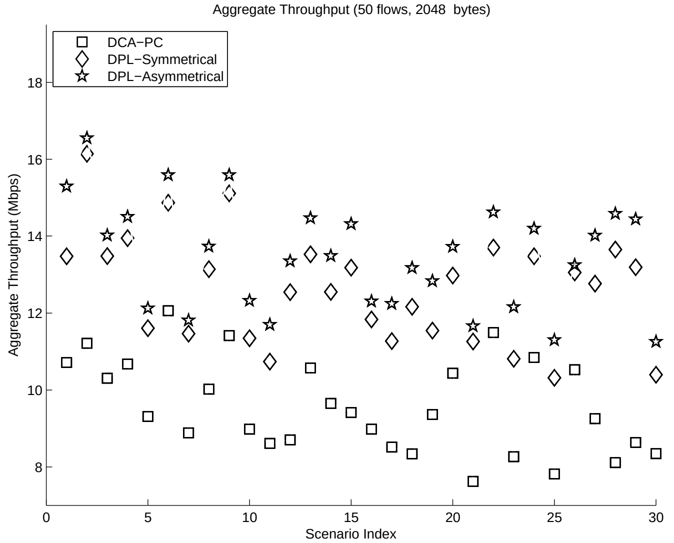
Figure 3.10: Aggregate throughput vs. packet size in the random topology

all protocols increase. Both the asymmetrical and symmetrical DPL protocols outperform the other protocols. However, the asymmetrical protocol achieves the highest throughput due to lower interference. Figure 3.11 shows the aggregate throughput of 30 different scenarios when the rate of each flow is 1 Mbps for two different packet sizes (1024 bytes as shown in Figure 3.11a, and 2048 bytes as shown in Figure 3.11b). Each point shown in the figures represents one scenario averaged over time. When the packet size is 2048 bytes, the performance difference between the asymmetrical DPL protocol and the symmetrical DPL protocol is more obvious.

Next, we examine the sensitivity of the aggregate throughput on power assignments. There are many factors affecting the best power assignment. Such factors are node density, network topology, traffic flow, mobility, and number of channels. Table 3.3 presents the throughput of different power assignments when the number of channels is three. Note that the first channel is the dedicated control channel, and the allowable transmission power is set to the maximum transmission power. To maintain the network connectivity, the second channel is also set to the maximum transmission power. The third channel is the only channel that we can



(a) The packet size is 1024 bytes



(b) The packet size is 2048 bytes

Figure 3.11: Aggregate throughput of 30 different scenarios in the random topology.

change its maximum allowable power. In Table 3.3, the throughput changes when the power assignment changes. Using Power Assignment 1 (PA-1), both the asymmetrical and symmetrical DPL protocols achieve better performance than that of PA-4 because the transmission range of Channel 3 using PA-4 is 200 meters, which is near the transmission range of the maximum transmission power P_{max} and that is 250 meters. Since the network topology is random, the ideal transmission range

Table 3.3: Sensitivity of Throughput based on Power Assignments in the random topology

Power Assignment $(P_1^{max}, P_2^{max}, P_3^{max})$ mW (d_1, d_2, d_3) meters	Throughput (Mbps)	
	DPL-Symmetrical	DPL-Asymmetrical
PA-1 $= (281.8, 281.8, 9.36)$ $(250, 250, 100)$	6.949792	7.193493
PA-2 $= (281.8, 281.8, 17.61)$ $(250, 250, 125)$	7.275610	7.565689
PA-3 $= (281.8, 281.8, 28.18)$ $(250, 250, 140)$	7.215666	7.587570
PA-4 $= (281.8, 281.8, 115.42)$ $(250, 250, 200)$	6.145187	6.539171

for Channel 3 is approximated the half of the maximum transmission range (≈ 125 meters). The asymmetrical DPL protocol does not agree with the symmetrical DPL protocol on choosing the same power assignment. From Table 3.3, the asymmetrical DPL protocol achieves its highest throughput using PA-3, whereas the symmetrical DPL protocol achieves its highest throughput using PA-2. This difference occurs because the symmetrical DPL protocol uses the same transmission power that is assigned to a channel, but the asymmetrical DPL protocol could adjust the transmission power over any channel as presented in Section 3.3.3.

Finally, we examine the impact of the number of channels on the network throughput. We assign different maximum transmission powers to different numbers of channels as shown in Table 3.4. Note that we do not optimize the power assignments; our power assignments are chosen arbitrarily. However, from the previous discussions, choosing power assignments does affect the network performance. Figure 3.12 shows the throughput of the random topology when the number of channel increases from three to eight for two different packet sizes. Note that the IEEE 802.11 MAC protocol has the same performance because it uses a single channel. However, the throughput of DPL and DCA-PC protocols increases when the number of channels increases. From the figure, the proposed protocols

Table 3.4: Maximum Transmission Power Values and their Corresponding Transmission Distances for Different Numbers of Channels

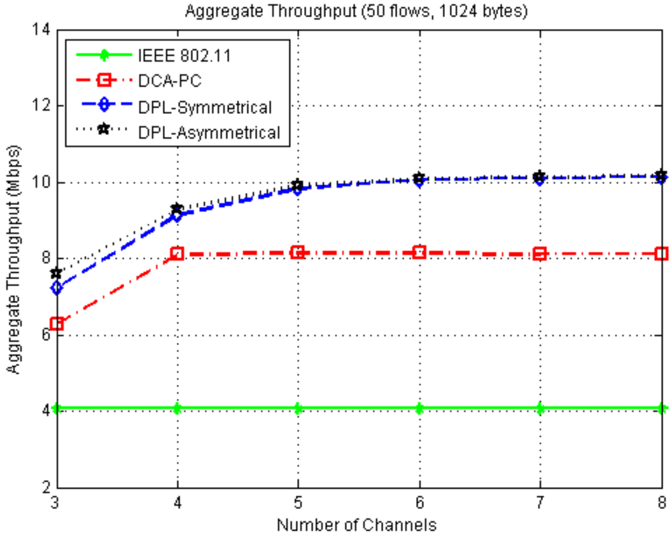
Numbers of Channels (M)	$(P_1^{max}, P_2^{max}, \ldots, P_M^{max})$ mW $(d_1, d_2, \ldots, d_M)$ meters
3	$(281.8, 281.8, 28.18)$ $(250, 250, 140)$
4	$(281.8, 281.8, 56.4, 18.8)$ $(250, 250, 167, 127)$
5	$(281.8, 281.8, 93.93, 40.26, 18.8)$ $(250, 250, 190, 153, 127)$
6	$(281.8, 281.8, 93.93, 56.36, 28.18, 18.8)$ $(250, 250, 189, 167, 140, 127)$
7	$(281.8, 281.8, 140.9, 70.45, 35.225, 18.8, 14.09)$ $(250, 250, 210, 176, 148, 127, 118)$
8	$(281.8, 281.8, 140.9, 70.45, 35.225, 18.8, 14.09, 9.36)$ $(250, 250, 210, 176, 148, 127, 118, 100)$

achieve significant throughput improvement than DCA-PC and IEEE 802.11 protocols. Moreover, DCA-PC saturates sooner than the proposed protocols because of the uncontrolled asymmetrical transmission power problem described in Section 3.2. When the packet size is smaller, and the number of channels is larger, the asymmetrical DPL protocol behaves similar to the symmetrical DPL protocol since nodes often transmit over their preferred channels.

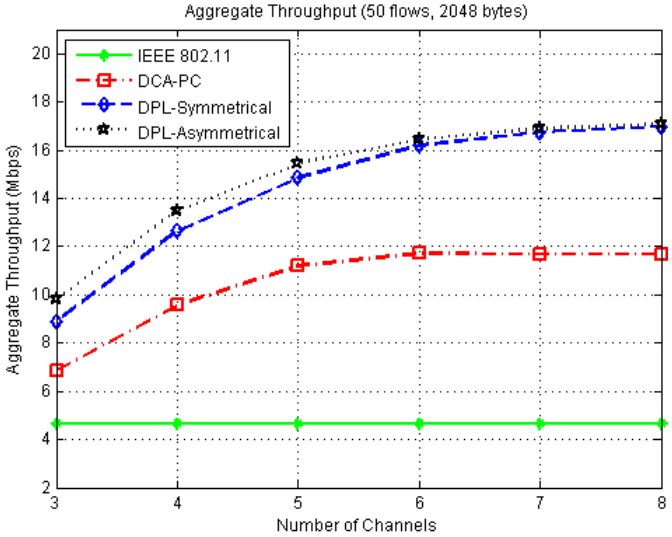
3.5 Discussions

One of the techniques that can be used to improve the network performance of both the DPL and DCA-PC protocols is to use a dedicated control channel for data transmissions, thereby enhancing the network throughput, especially in a network with few channels [38].

DPL is implemented over the DCA protocol [37], which requires two interfaces per node (i.e., increasing the cost). The main advantage of using DCA is that it does not require any kind of synchronization. However, the asymmetrical and



(a) The packet size is 1024 bytes



(b) The packet size is 2048 bytes

Figure 3.12: Aggregate throughput vs. number of channels in the random topology.

symmetrical DPL protocols can be implemented using other multi-channel MAC protocols, such as McMAC [71] or MMAC [34]. In MMAC, while the common channel must be set to the maximum power, other channels can be different. MMAC requires one transceiver per node, but requires clock synchronization.

The IEEE 802.11a operates in the 5 Ghz band, which is known as the unlicensed national information infrastructure (U-NII) band. The bandwidth is divided into

Table 3.5: Power Allocation for the 5 Ghz Band

Frequency Band (GHz)	Maximum Allowable Power (mW)
5.15 – 5.25	40
5.25 – 5.35	200
5.725 – 5.825	800

non-overlapping channels. Different allowable powers are set to different channels, and the power values vary from one country to another. The maximum transmission power for the U-NII band according to the Federal Communications Commission (FCC) is provided in Table 3.5 [10]. To the best of our knowledge, limited research work actually considers the allowable power over different channels so that the DPL protocols are realistic. Most existing multi-channel MAC protocols for multi-hop ad hoc networks assume that transmission power over different channels is the same.

The proposed DPL protocols assign different power levels to different channels (e.g., the maximum power level of data channel 1 is set to be P_1^{max}, the maximum power level of data channel 2 is set to be P_2^{max}, and so on), and different power assignments lead to different throughputs. Therefore, choosing a proper power assignment is very critical. One particular power assignment is to set the same power level for all channels to be equal to the highest maximum transmission power (P^{max}) so that the symmetrical DPL protocol behaves similarly to the DCA protocol [37], while the asymmetrical DPL protocol behaves similarly to the DCA-PC protocol [90].

3.6 Summary

In this chapter, we have proposed a novel transmission power control protocol called the distributed power level (DPL) protocol to overcome the uncontrolled asymmetrical transmission power problem in multi-channel ad hoc networks. The proposed protocol allocates different allowable power levels to different channels so that nodes can determine the minimum required transmission power and then select appropriate data channels for their data transmissions. In addition, two TPC modes are introduced for DPL: symmetrical and asymmetrical. For the symmetrical DPL protocol (mode), nodes transmit at the power allocated to the selected data channel. Alternatively, for the asymmetrical DPL protocol, nodes transmit at a lower or equal power level as that assigned to the selected channel. We compare our proposed protocols with existing uncontrolled asymmetrical transmission power protocol, i.e., DCA-PC, and the simulation results using ns-2 demonstrate that the proposed protocols can effectively prevent the uncontrolled asymmetrical transmission power problem in multi-channel wireless networks, thereby achieving higher throughput.

Chapter 4

Multi-channel Medium Access Control with Hopping Reservation for Ad Hoc Wireless Networks

In this chapter, we focus on the multi-channel exposed terminal problem that leads to poor channel utilization over multiple channels, and this problem has not been well studied. We propose the multi-channel MAC protocol with hopping reservation (MMAC-HR) for ad hoc networks to resolve the multi-channel exposed terminal problem. MMAC-HR does not require nodes to monitor the control channel in order to determine whether or not data channels are idle; instead, MMAC-HR employs independent, slow channel hopping without exchanging information to reduce the overhead. In addition, the proposed protocol uses the CSMA/CA scheme over all channels to determine the channel condition and avoid collisions. Furthermore, MMAC-HR is distributed, does not require clock synchronization, and supports broadcast information.

The remainder of the chapter is organized as follows. Section 4.1 reviews some related work. In Section 4.2, the multi-channel exposed terminal problem is discussed. To resolve the problem, we propose a novel multi-channel MAC protocol in Section 4.3, and the performance evaluation of the proposed multi-channel MAC protocol is presented in Section 4.4. Finally, the discussion and summary are given in 4.5 and Section 4.6, respectively.

4.1 Related Work

Some protocols require that nodes have to be equipped with multiple wireless interfaces which are equal to the number of the channels such as [63, 64]. In [63], the protocol divides the channel bandwidth into N non-overlapping channels, similar to the frequency division multiple access (FDMA) scheme. The nodes are able to sense all channels at the same time and transmit over one idle channel randomly. Therefore, it is costly. In this chapter, we only require nodes to have two interfaces.

The Dynamic Channel Assignment (DCA) protocol is proposed for multi-hop networks [37]. Two interfaces are installed on each node. One interface is fixed on the control channel, and the other interface switches between data channels. The control packets are RTS, CTS, and reservation (RES) that are transmitted over the control channel; data and acknowledgment (ACK) packets are transmitted over data channels. All nodes maintain a channel usage list (CUL) to determine the data channels' activities by overhearing the control channel, thereby channel assignment is accomplished. However, this channel list causes the multi-channel exposed terminal problem as described in Section 4.2. DCA does not need clock synchronization, so does our protocol. Although our proposed protocol is similar to DCA, there are several key differences between the two protocols. Our protocol: 1) uses CSMA/CA over all channels; 2) does not require nodes to monitor the control channel in order to determine whether data channels are idle or not; 3) resolves the multi-channel exposed terminal problem because MMAC-HR does not use any channel list which causes poor channel utilization; and 4) utilizes data channels by independent hopping. Using multiple channels with transmission power control (TPC) will increase the network capacity [6, 90], and this approach has been discussed in Chapter 3.

Channel-Hopping Multiple Access (CHMA) is proposed to exploit the available channels [68]. This protocol is based on common hopping, meaning that all nodes must follow a common hopping sequence. The dwell time is the time needed for a handshake (e.g., RTS), and, during the dwell time, no carrier sensing or code assignment is needed. CHMA requires too many switchings between frequencies. Hop-Reservation Multiple Access (HRMA) for ad hoc networks [69] is similar to CHMA. Both protocols require tight clock synchronization. Our proposed protocol does not need any synchronization. Another issue occurs in these protocols is the busy receiver problem [36]. For example, while node A is transmitting to node B on a specific channel, node C transmits to node D on another channel. Nodes A and B are unaware of the negotiation between nodes C and D. Therefore, if node A has a packet for node C, the busy receiver problem occurs because node A does not know over which channel node C exists.

The Multi-channel MAC (MMAC) protocol is proposed in [34], which is based on splitting phases (similar to the TDMA scheme). The time is divided into beacons. The beacons consist of two windows: Ad Hoc Traffic Messages (ATIM) and data. At the beginning of the ATIM window, wireless nodes tune their radios into the known channel. A pair of nodes selects a channel by exchanging ATIM, ATIM-ACK, and ATIM-RES packets during the ATIM window. After the ATIM window, the successful pairs switch their radios to their agreed channels. Then, source nodes start competing using the IEEE 802.11 MAC standard. MMAC solves multi-channel hidden terminal problems by synchronization, which is difficult to achieve in multi-hop networks.

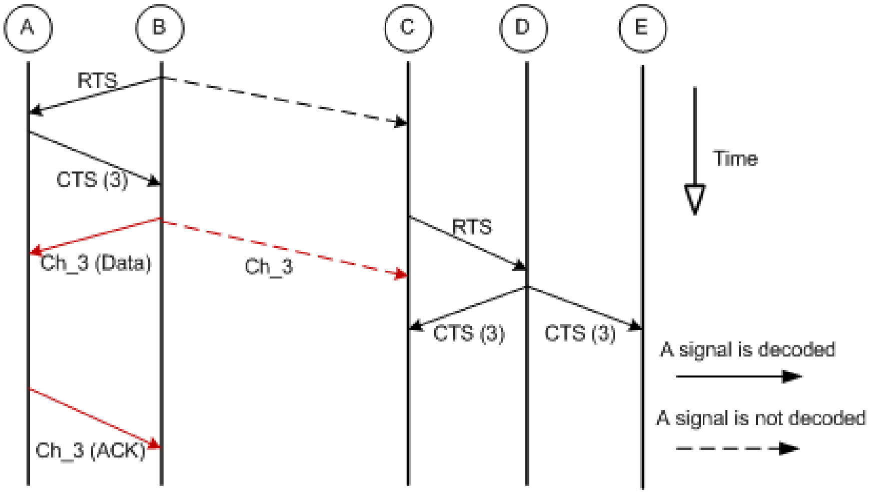
A new technique to improve the network performance is to use parallel rendezvous such as the Slotted Seeded Channel Hopping (SSCH) [58] and Multichannel MAC (McMAC) [71] protocols, which require only one radio interface. SSCH and McMAC are based on the prime module and linear congruential generator, respectively. A sender needs to synchronize with a receiver to transmit a packet so that the sender might deviate from its default hopping sequence; as a result, the busy receiver problem occurs [36]. In addition, they also require clock synchronization.

4.2 Multi-channel Exposed Terminal Problem

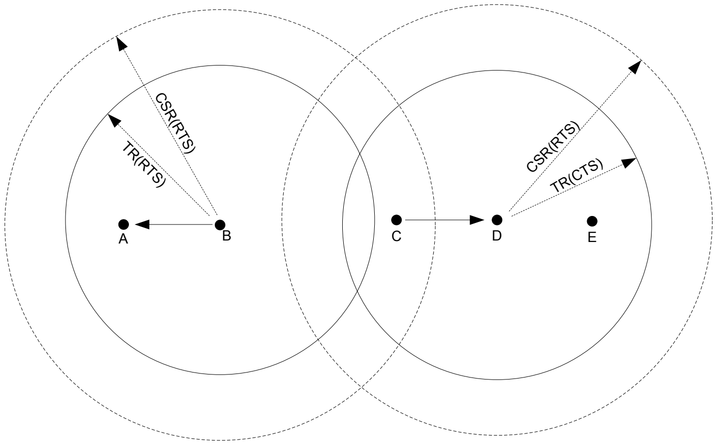
In this section, we study the multi-channel exposed terminal problem. We first describe the single-channel exposed terminal problem, and this problem leads to poor channel utilization because it defers transmissions of other nodes which are within the carrier sensing range of the sending nodes, but they are not within the carrier sensing range of the receiving nodes.

As shown in Figures 4.1a and 4.1b, while node B is transmitting to node A, node C wants to transmit a packet to node D. Node C senses the channel and it finds that the channel is busy and thus must defer its transmission. Therefore, node C is called an exposed terminal because node C is not within the range of node A but within the carrier sensing range of node B [125]. However, node E is clearly able to either transmit or receive because node E is not within the carrier sensing range of node B.

To describe the multi-channel exposed terminal problem, we introduce a simple multi-channel MAC protocol, which is similar to the DCA protocol [37] where the multi-channel exposed terminal problem has not been addressed. [126, 70, 127] are other examples. Each node has two interfaces; one interface is fixed over the



(a) Packets exchange



(b) The top view of Figure 4.1a showing different ranges of different nodes.

Figure 4.1: An illustration of the exposed terminal problem in multi-channel networks.

control channel and the second interface is switchable between data channels. In addition, each node maintains a local *channel list* updated by overhearing control packets over the dedicated control channel. The channel list indicates whether a data channel is busy or not, and thus the nodes select an idle data channel from the channel list for their transmissions. In other words, channel assignment is accomplished through the channel list. Another list also used and known as a free channel list is generated from the channel list and attached into RTS packets by transmitters. The free channel list determines which channels are idle, and therefore the transmitters are able to use it for transmission.

Nodes use RTS and CTS packets for channel negotiations over the control channel and use CSMA/CA over all channels before transmitting data packets to avoid collisions. Notice that the DCA protocol does not use carrier sensing over data channels; as a result, collisions occurs.

Figures 4.1a and 4.1b illustrate the multi-channel exposed terminal problem. There are five nodes: A, B, C, D, and E. Node C is not within the transmission range of node B (i.e., node C cannot decode any packet that is transmitted by node B), and node E is within the transmission range of node D. Moreover, node B has a packet for node A, and node C has a packet for node D. Therefore, nodes B and C must compete over the control channel. If node B transmits to node A an RTS packet that includes node B's free channel list, node C must defer its transmission. Node C is not able to decode the RTS packet. Therefore, node C is unaware of the channel negation between nodes B and A because node C is not within the transmission range of node B. After node A receives the RTS packet correctly, node A selects a data channel that must be idle not only for node A but also for node B. Then, node A replies to node B with a CTS packet, which includes a selected data channel (e.g., Channel 3) and switches its transceiver to Channel 3. Upon receiving the CTS packet correctly, node B turns its switchable transceiver to the selected data channel. Node B must sense Channel 3 for a certain amount of time (e.g., the distributed interframe space (DIFS) period) to avoid collisions. If Channel 3 is idle, node B starts transmitting its data packet to node A over Channel 3. After the short interframe space (SIFS) period, node B transmits an ACK packet to node A over the same channel if the packet is received correctly.

As soon as the control channel becomes idle for a period of time (e.g., the DIFS period), node C transmits an RTS packet that includes node C's free channel list and indicates Channel 3 as being free, to node D. When node D receives the CTS packet successfully, node D selects an idle data channel and replies to node C with a CTS packet, which includes a selected channel (e.g., Channel 3). Both nodes C and E receive the CTS packet because they are within the transmission range of node D. Node E updates its channel list indicating that Channel 3 is busy. Node C switches to Channel 3, and then node C must sense Channel 3 before transmitting to avoid collisions. However, Channel 3 is sensed as being busy, and thus node C cannot transmit because node C is within the carrier sensing range of node B. Therefore, node C is an exposed terminal. Recall that node E has already updated its channel list indicating that Channel 3 is being used. Inadvertently, node E is also an exposed terminal because node E cannot use Channel 3 for any transmission resulting in poor network performance. Nonetheless, node E can use Channel 3 without causing collisions with nodes A and B.

In summary, node C is an exposed terminal in both single- and multi-channel networks. However, node E is an exposed terminal only in multi-channel networks because it uses a channel list to indicate whether a channel is busy or not. Node E is known as *a multi-channel exposed terminal* because it occurs only in multi-channel networks. Note that node E cannot cause any collision with nodes B and A. Thus, the multi-channel exposed terminal problem is more severe than the single-channel exposed terminal problem because the multi-channel exposed terminal problem leads to poor channel utilization (due to poor channel assignment) more than the single-channel exposed terminal problem. In this chapter, we propose a new protocol to resolve the multi-channel exposed terminal problem.

4.3 MMAC-HR: Multi-channel Medium Access Control with Hopping Reservation

In this section, we propose the multi-channel MAC protocol with hopping reservation (MMAC-HR) to eliminate the multi-channel exposed terminal problem. Our approach uses a dedicated control channel without any channel assignment; however, channel hopping is employed to maximize the utilization of multiple channels. In MMAC-HR, since nodes do not know which data channel is idle, they must sense data channels (using carrier sensing) to determine the channels' conditions and avoid collisions. Our system model is as follows:

- The network has M channels. One channel is known as a dedicated control channel, and the rest $M-1$ channels are data channels. All channels have equal bandwidths and are able to transport information.
- Each node has two interfaces. One interface is fixed on the dedicated control channel, and the other interface is switchable between data channels. The two interfaces do not interfere with each other, and each interface is a half-duplex transceiver.
- Nodes transmit at the maximum power, P_{max}, over all channels.
- Broadcast and control packets are transmitted over the control channel.

The switchable interface hops between channels and hopping is accomplished randomly between data channels without exchanging information. The dwell time

Algorithm 1 Source Node

```
1: $nrsv$ : the number of reservation nodes
2: if The control channel is idle $\wedge$ $nrsv = 0$ then
3:     backoff
4: else
5:     Transmit an RTS packet on the control channel following the 802.11 DCF MAC protocol
6:     if A CTS ($Ch_i$,$Wt$,$Rt$) packet receives then
7:         $CW^f \leftarrow CW_{min}$
8:         $WR \leftarrow Wt - T_{CTS} - St - \tau$
9:         $timer \leftarrow Rt$
10:        Start decrementing $timer$
11:        if the switching interface is not on $Ch_i$ then
12:            Switch to $Ch_i$
13:            if $WR > 0$ then
14:                Listen to $Ch_i$ for $WR$ before attempting
15:            end if
16:        end if
17:        Transmit the packet over $Ch_i$ following the 802.11 DCF MAC protocol without
           RTS/CTS packets
18:        if An ACK packet receives then
19:            $CW^s \leftarrow CW_{min}$
20:            Reset the number of retrials
21:        else
22:            Double the contention window $CW^s$
23:            Increase the number of retrials
24:            if the number of retrials = the maximum of trials then
25:                $CW^s \leftarrow CW_{min}$
26:                Drop the packet
27:                Reset the number of retrials
28:            else
29:                Go back to Line 17
30:            end if
31:        end if
32:        if $timer = 0$ then
33:            $CW^s \leftarrow CW_{min}$
34:            Increase the number of retrials
35:            if the number of retrials = the maximum of trials then
36:                $CW^s \leftarrow CW_{min}$
37:                Drop the packet
38:                Reset the number of retrials
39:            else
40:                Go back to Line 2
41:            end if
42:        end if
43:    else
44:        Double the contention window $CW^f$
45:        Increase the number of retrials
46:        if the number of retrials = the maximum of trials then
47:            $CW^f \leftarrow CW_{min}$
48:            Drop the packet
49:        else
50:            Go back to Line 2
51:        end if
52:    end if
53: end if
54: Continue hopping
```

should be large enough to allow multiple data transmissions. When the dwell time expires and a node is idle, the node selects the next data channel randomly. Then, the node tunes its switchable interface to the next selected channel. Moreover, we maintain two separated contention window (CW) sizes, one for each interface (e.g., CW^s is designated for the switchable interface, and CW^f is designated for the fixed interface). Each node retains a new integer variable, $nrsv$, to track the number of reservation nodes. If $nrsv$ is equal to zero, then a node is idle and able to transmit a packet. Algorithms 1 and 2 present the pseudo codes of the source and destination nodes.

The control packets used in our proposed protocol are RTS and CTS packets. The RTS packets in our proposed protocol are similar to the RTS packets in the IEEE 802.11 DCF MAC protocol, but the CTS packets have three additional fields: Ch_i (the current channel i of a receiver), Wt (the waiting time, which is the time to hold for a transmitter before attempting), and Rt (the reservation time before releasing the switchable interface). The Wt field is the amount of time indicating the channel condition of the current data channel, Ch_i, which is idle or busy. This field is computed just before transmitting the CTS packet and is used to eliminate the multi-channel hidden terminal problem. The Rt field is a committed time from the receiver to be on the current channel, Ch_i, and can be adaptive.

In order to better understand how our protocol resolves the multi-channel exposed terminal problem, we use Figure 4.1a for illustration. Whenever node C has a packet for node D, two conditions must be satisfied: 1) node C is not busy, which means node C does not commit to receive, and 2) the control channel is idle for DIFS, following the IEEE 802.11 MAC standard. If the two conditions are satisfied, node C transmits an RTS packet to node D over the control channel as shown in Figure 4.2. If the RTS packet collides, node C doubles the contention window size of the fixed interface, CW^f, and increases the number of retrials. If the number of retrials reaches the retry limit, node C drops the packet and resets the contention window size, CW^f. If the RTS packet is received correctly by node D, node D replies with a CTS (Ch_i,Wt,Rt) packet to node C. If the current channel, Ch_i, of node D is busy, Wt is set to be the maximum packet duration (T_{max}) in the network. However, if the current channel is idle, Wt is set to be zero. To avoid the multi-channel exposed terminal problem, node E can decode the CTS packet, but node E will simply ignore the CTS packet. If node C receives the CTS packet successfully, node C checks whether its switchable interface is over Ch_i or not. If yes, node C then starts competing the data channel, similar to the IEEE 802.11 MAC standard, because node C knows the channel condition of the current channel. If no, node C switches to the channel Ch_i. Node C first computes WR if Wt is not equal to zero:

$$WR = Wt - T_{CTS} - St - \tau,$$

where St is the switching delay, τ is the maximum propagation delay, and T_{CTS} is the transmission time of the CTS packet. Then, node C listens to Ch_i for Wt. After WR expires, node C starts competing the data channel, Ch_i, following the IEEE 802.11 MAC standard. If the data packet is received correctly by node D, node D replies with an ACK packet over the same channel after SIFS. If a collision occurs, node C doubles the contention window size of the switchable interface (CW^s) and increases the number of retrials. Node C retransmits the data packet over Ch_i. If Rt expires, node C resets CW^s, starts the procedure again, and increases the number of retrials. If the number of retrials reaches the maximum number of retrials, node C drops the packet. If Rt expires, node D first checks whether the current channel is idle or busy, If the channel is busy, node D waits until the current channel becomes idle, and then check whether the current transmission is for node D itself or not. If it is idle, node D continues hopping.

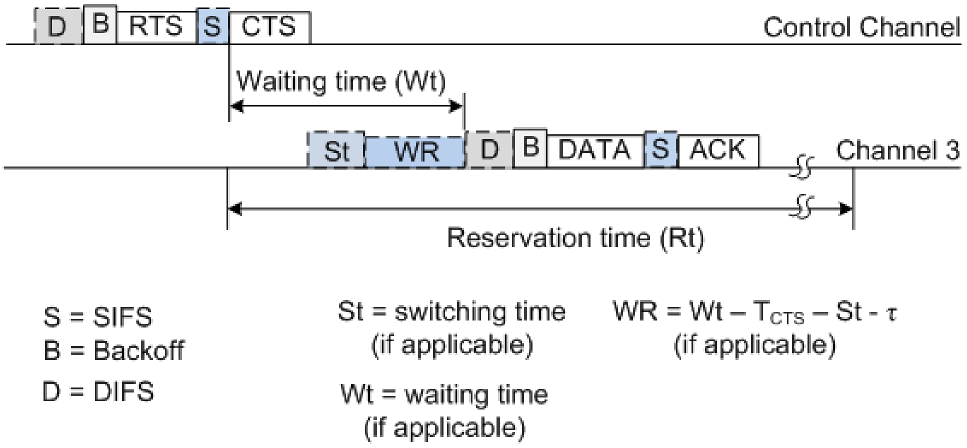


Figure 4.2: A successful transmission of MMAC-HR

Algorithm 2 Destination Node

```
 1: $T_{max}$ : the maximum packet duration in the network
 2: $Ch_i$ : the current channel of the switchable interface
 3: if An RTS packet receives correctly over the control channel then
 4:     if $Ch_i$ is not idle then
 5:         $Wt \leftarrow T_{max}$
 6:     else
 7:         $Wt \leftarrow 0$
 8:     end if
 9:     Attach $Ch_i$, $Wt$, and $Rt$ to a CTS packet
10:     $timer \leftarrow Rt$
11:     Start decrementing $timer$
12:     Transmit the CTS ($Ch_i$, $Wt$, $Rt$) packet over the control channel after the SIFS
        period
13:     $nrsv \leftarrow nrsv + 1$
14: end if
15: Wait for the packet
16: if the packet receives correctly then
17:     Transmit an ACK packet to the source node over $Ch_i$
18:     $nrsv \leftarrow nrsv - 1$
19: end if
20: if $timer = 0 \wedge$ Channel $Ch_i$ is idle then
21:     $nrsv \leftarrow 0$
22: else
23:     Go to Line 15
24: end if
25: Continue hopping
```

Table 4.1: Parameters Used in the Simulations [1, 2]

Parameters	Values
Carrier sense threshold	$1.56 * 10^{-8}$ mW
Receiver sensitivity	$3.65 * 10^{-7}$ mW
Maximum transmission power (P_{max})	281.8 mW
Transmission rate for data channels	2 Mbps
Transmission rate for the control channel	1 Mbps
CW_{min}	32
CW_{max}	1024
Retry limit	7
DIFS	50 μs
SIFS	10 μs
Slot time	20 μs
Dwell time	100 ms
Maximum propagation delay (τ)	1 μs
Switching delay time (St)	100 μs
Reservation time (Rt)	10 ms

4.4 Performance Evaluation

In this section, we evaluate our proposed protocol and compare it with the DCA and IEEE 802.11 DCF MAC protocols. Recall that MMAC-HR and DCA use a dedicated control channel, but MMAC-HR employs channel hopping and DCA uses channel assignment through a channel list. Two performance metrics are considered as follows:

1. *Average aggregate throughput.* Ideally, when the number of channels is M, the throughput should be M-folder over a single channel. The M-folder throughput can be achieved if each node has M interfaces, which is unpractical. Our protocol has only two interfaces per node, and the objective is to maximize the utilization of all channels.

2. *Average packet delay.* The packet delay is the duration of time for a packet to be received correctly by its destination. The delay occurs because of queueing,

backoff, propagation, access, switching, and transmission times. The MAC queueing size of each node is 50 packets. We do not take into account the dropped packets. This metric is important for real time applications.

4.4.1 Simulation Model

For simulations, we have used the ns-2 simulator (ns-2.30) [122] to evaluate the proposed protocol with the simulation parameters in Table 4.1. The two-ray path loss model is adopted in the simulations. Transmitting at the maximum power, the transmission range is 250 meters, and the carrier sensing range is 550 meters. The constant bit rate (CBR) traffic model is used for all flows.

We assume the switching delay time is 100 μs, and the switching delay can be decreased to 40-80 μs for IEEE 802.11a cards [58]. The simulation results are the average of 50 different scenarios, and each simulation scenario lasts 100 seconds.

4.4.2 Simulation Topology

We consider three different network topologies: single-hop network, small-scale multi-hop network, and large-scale multi-hop network. For the single-hop and small-scale multi-hop networks, we use the network throughput as the network metric. For the large-scale network, we consider both the average aggregate throughput and packet delay to be the performance metrics.

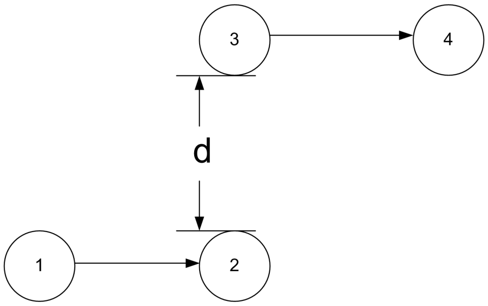
Single-hop network In this network, all nodes are within the transmission ranges of each other. Hence, the single-hop network is limited to a single collision domain, and thus the multi-channel hidden and exposed terminal problems do not occur. The rationale behind simulating this network is to investigate the control saturation problem [34, 127]. The number of nodes is 50, 100, and

200 nodes, and the number of flows is 25, 50, and 100, respectively, because the flows are disjointed. In other words, half the nodes are transmitters and the others are receivers. Joint flows are not studied in the single-hop ad hoc network, but are studied in the multi-hop network. The payload size is 1024 bytes and the number of channels is three, six, and nine.

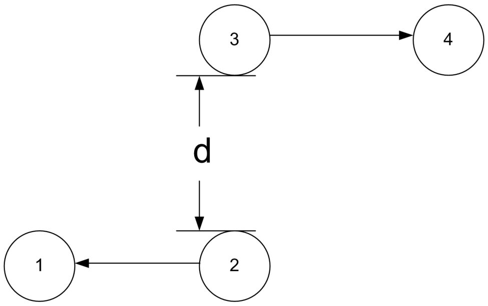
Small-scale multi-hop network We have four nodes and only two flows. In addition, the data rate of the flows is 1 Mbps, and the packet size is 1024 bytes. Two scenarios are selected to demonstrate the network throughput. As shown in Figure 4.3a, the first scenario is that node 1 has packets for node 2 and node 3 has packets for node 4. The second scenario is the same as the first except that node 2 is transmitting to node 1, as shown in Figure 4.3b. The distance between nodes 1 and 2 is the same as the distance between nodes 3 and 4, which is 200 meters.

We compare DCA and MMAC-HR with the IEEE 802.11 DCF MAC protocol. The DCA and MMAC-HR protocols have two channels, which one channel is a dedicated control channel and the second channel is a data channel, and the IEEE 802.11 DCF protocol has only a single channel. The throughput of the 802.11 DCF MAC and MMAC-HR protocols is expected to be the same as the throughput of the DCA protocol.

Large-scale multi-hop network We have 100 nodes placed randomly in a 500x500 m^2 flat area, and there are 45 flows in the network. A source node randomly chooses its destination node, and a node may be a destination for multiple source nodes. The packet size is 1024 bytes unless otherwise mentioned.



(a) Scenario 1: node 1 transmits to node 2 and node 3 transmits to node 4



(b) Scenario 2: node 2 transmits to node 1 and node 3 transmits to node 4.

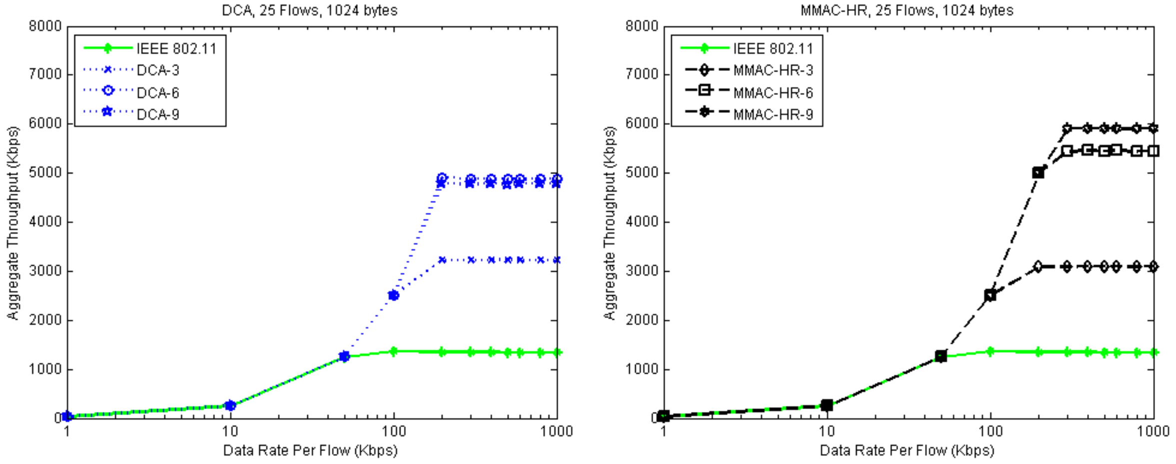
Figure 4.3: Selected topology scenarios for the small-scale multi-hop network

4.4.3 Simulation Results

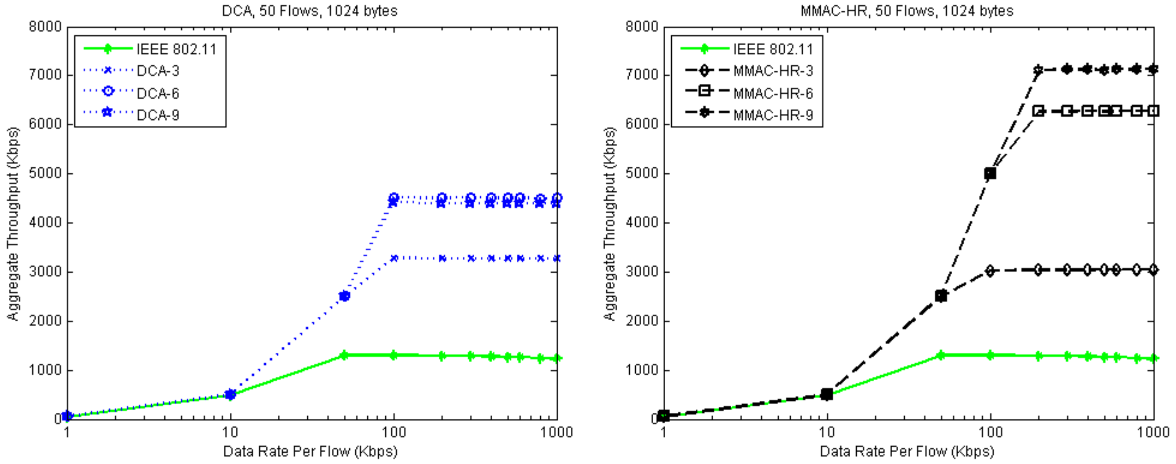
This subsection presents and discuss the simulation results. We show the results of the single-hop networks and the multi-hop networks.

Single-hop network

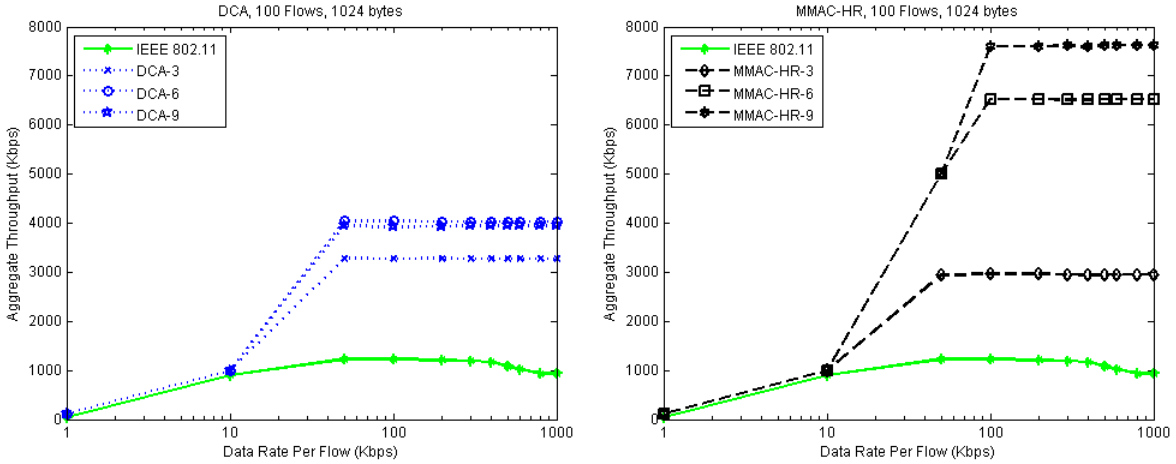
Figure 4.4 shows the aggregate throughput of the single-hop networks. "MMAC-HR-3" indicates that three channels are available for the MMAC-HR protocol, and "DCA-6" indicates that six channels are available for the DCA protocol. The throughput of the IEEE 802.11 MAC protocol using only a single channel is also shown in the figures for comparison. Figure 4.4a and Figure 4.4b present the throughput for the DCA and MMAC-HR protocols, respectively, with 50 nodes. When the data rate increases, the throughput of all protocols increases. However,



(a) 50 nodes (DCA) (b) 50 nodes(MMAC-HR)



(c) 100 nodes (DCA) (d) 100 nodes (MMAC-HR)



(e) 200 nodes (DCA) (f) 200 nodes (MMAC-HR)

Figure 4.4: The aggregate throughput of the single-hop networks for various numbers of nodes and network loads. The graphs on the left side are the throughput of DCA, and the graphs on the right side are the throughput of MMAC-HR.

when the number of channels increases, the throughput of DCA decreases. This behavior is also observed in [34]. The reason the throughput of DCA decreases when the number of channels increases is that all idle transmitters, which have ready packets to send, must wait on the control channel when all data channels are busy. As soon as any data channel becomes idle, all the idle transmitters compete over the control channel. Thus, the collision probability increases over the control channel, and, consequently, the data channels are not unitized efficiently.

Unlike DCA, the throughput of MMAC-HR increases when the number of channels increases. In MMAC-HR, whenever a transmitter has a packet, the transmitter sends its RTS packet over the control channel to a receiver regardless of all data channels being busy. Upon receiving the RTS packet, the receiver responds with a CTS packet to the transmitter. Then, the transmitter waits for the receiver's data channel; thus, the congestion of the control channel is avoided.

When the number of nodes increases, the aggregate throughput of DCA decreases (as shown in Figure 4.4c when the number of nodes is 100 and in Figure 4.4e when the number of nodes is 200). However, in MMAC-HR, the throughput increases as the number of nodes increases (as illustrated in Figure 4.4d when the number of nodes is 100 and in Figure 4.4f when the number of nodes is 200).

Multi-hop network: small-scale

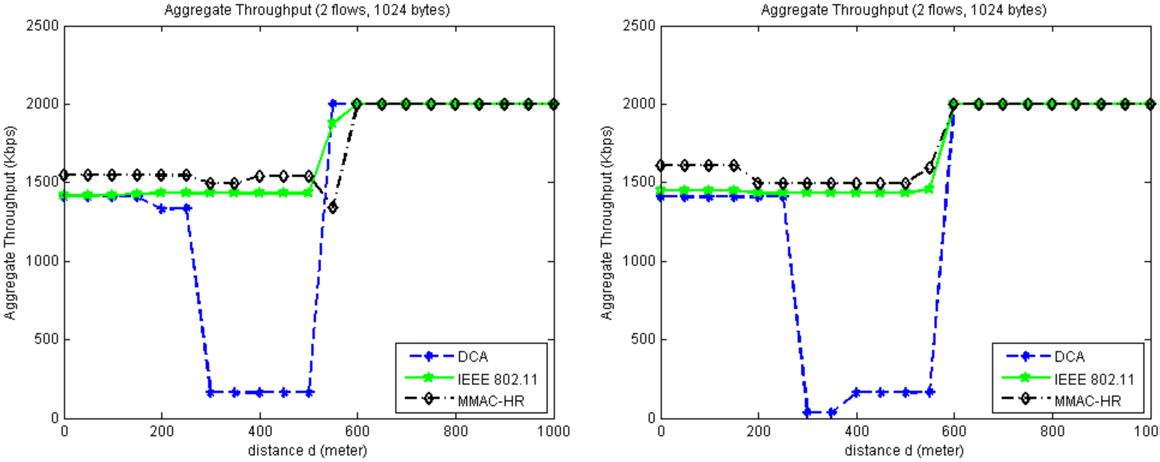
Figure 4.5a illustrates the network throughput of the first scenario with respect to the distance denoted as **d** between node 2 and node 3. As shown in the figure, the throughput of the MMAC-HR and IEEE 802.11 DCF MAC protocols is the same.

However, for DCA, when the distance between nodes 2 and 3 is between 5 and 250 meters, nodes 2 and 3 update their channel lists because they are within the transmission range of each other. Consequently, the throughput of DCA is comparable with the throughput of MMAC-HR and DCF. However, as the distance **d** is more than 250 meters up to a limited range (interference range), nodes 2 and 3 are unaware of the channel negotiations of each other; as a result, collisions occur over only the data channel within the interference range because DCA does not employ carrier sensing over data channels. Consequently, the throughput of DCA drops significantly compared with MMAC-HR and IEEE 802.11 DCF MAC. More than the interference range, the nodes do not interfere with each other, and thus the throughput of DCA is the same as MMAC-HR and IEEE 802.11 DCF MAC and reaches to the maximum (the sum of the two flows). Figure 4.5b shows the throughput of the second scenario, and the observations from the second scenario are the same as in the first scenario.

Therefore, a channel list does not have complete information about the data channels. Moreover, if DCA employs carrier sensing, then the multi-channel exposed terminal problem will occur in multi-channel wireless network as described in Section 4.2. Hence, our proposed protocol does not use a channel list to determine if a data channel is idle; instead, MMAC-HR employs both channel hopping and carrier sensing to utilize the available channels.

Multi-hop network: large-scale

Figure 4.6 shows the throughput of the multi-hop network with four channels. Admitting higher data-rate flows will result in increasing the throughput of the protocols. However, MMAC-HR outperforms the other protocols (the packet size is 512 bytes in Figure 4.6a and 1024 bytes in Figure 4.6b). The throughput degradation of DCA is the result of the multi-channel exposed terminal problem leading to poor channel assignment presented in Section 4.2. The MMAC-HR protocol does not depend on channel assignment, but depends on channel hopping done randomly and independently.



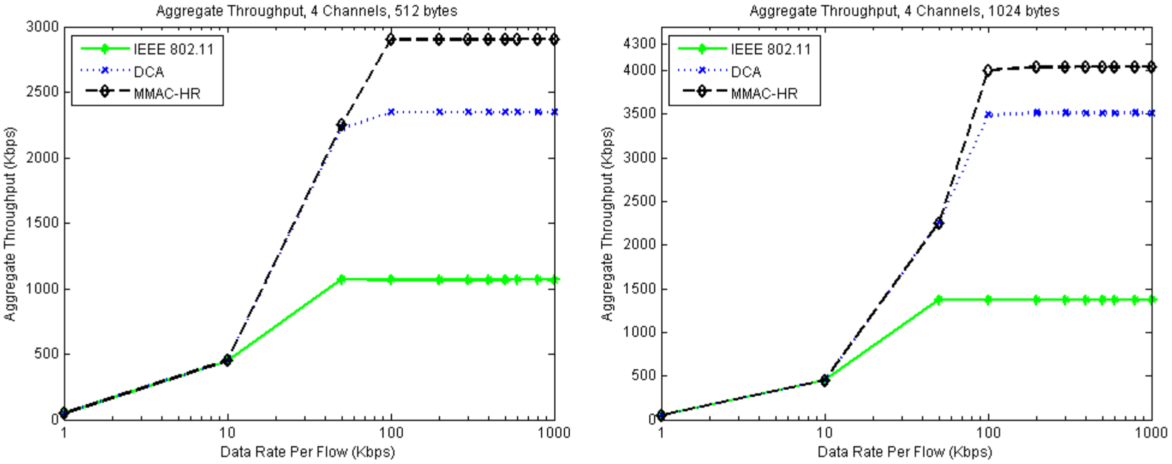
(a) Aggregate throughput of Scenario 1 (b) Aggregate throughput of Scenario 2

Figure 4.5: Aggregate throughput vs. the distance **d** between node 2 and node 3 as shown in Figure 4.3.

Figure 4.7 shows the average packet delay of all flows in the network when the number of channels is four. MMAC-HR achieves less delay than the other protocols as shown in Figure 4.7a and in Figure 4.7b.

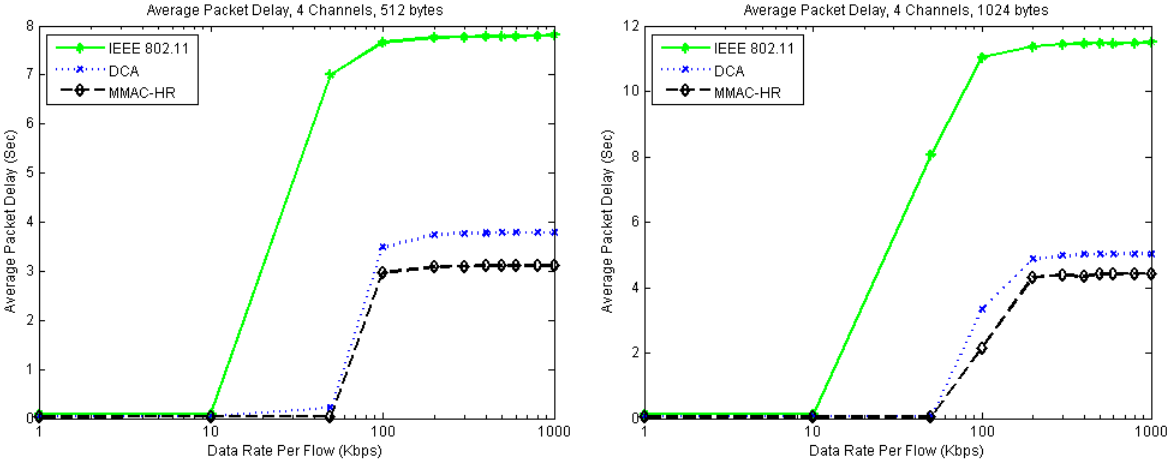
Figure 4.8 shows the network throughput for different numbers of channels with 1 Mbps data rate for each flow. When the number of channel increases, the network throughput increases for MMAC-HR and DCA. However, MMAC-HR has higher throughput than DCA because as the number of channels increases, the number of nodes that compete a data channel decreases. Moreover, the DCA protocol reaches its saturation point when the number of channel is five. The data channels are spatially reused through channel assignment. As mentioned in Section 4.2, nodes using DCA select data channels through their channel lists resulting in poor channel selection. We can see the effect of the multi-channel exposed terminal problem on DCA when the number of channel is more than five.

In Figure 4.9, we examine the average packet delay of all flows. As the number of channels increases, the average delay decreases for MMAC-HR and DCA. The



(a) 512 bytes (b) 1024 bytes

Figure 4.6: Aggregate throughput vs. different network loads when the number of channels is 4 in the multi-hop network.



(a) 512 bytes (b) 1024 bytes

Figure 4.7: Average packet delay vs. different network loads when the number of channels is 4 in the multi-hop network.

DCA protocol encounters higher delay than MMAC-HR because DCA does not utilize data channels efficiently.

So far, the value of the reservation time (Rt) has been 10 ms, and this value has been used in both the single-hop and multi-hop networks. Figure 4.10 shows the aggregate throughput of the multi-hop network, and how different Rt values can affect the MMAC-HR protocol. From the figure, "MMAC-HR-256," "MMAC-HR-512," and "MMAC-HR-1024" indicate the packet sizes are 256, 512, and 1024 bytes, respectively. As the *Rt* value increases, the throughput of MMAC-HR increases and then the throughput of MMAC-HR decreases, particularly when the packet size is large. This pattern occurs because of two reasons. First, a receiver may have a packet to transmit, but the receiver cannot switch from its current channels because the flows in the network are jointed. Second, if a data channel is busy, a transmitter holds its attempt for Wt, which is set to the maximum packet transmission time in the network; consequently, the Wt value wastes most of the reservation time. In general, the best *Rt* value depends on the network density and traffic, but can adapt to obtain the achievable throughput because receivers always send CTS packets including the *Rt* value.

4.5 Discussions

MMAC-HR is simple, distributed, and fully supports broadcasting. In addition, the proposed protocol does not require any kind of synchronization. MMAC-HR allocates one channel for control and broadcast packets (i.e., this control channel is not used for data transmission) so it utilizes $k-1$ channels, where k is the number of channels. It also requires two radio interfaces per node; therefore, it increases the cost and consumes more energy.

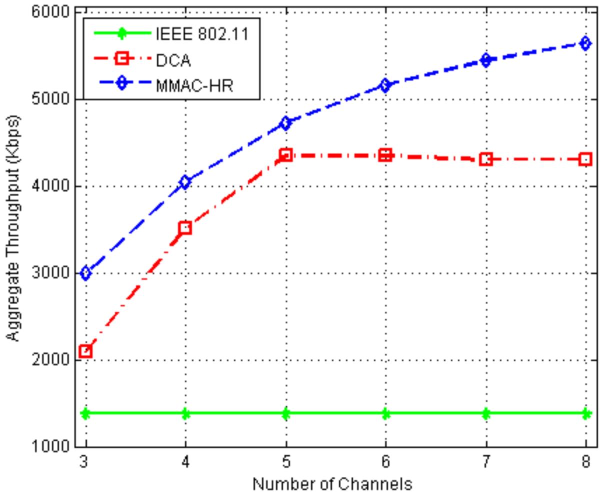


Figure 4.8: Aggregate throughput vs. different numbers of channels in the multi-hop network.

4.6 Summary

In this chapter, we have proposed the multi-channel medium access control protocol with hopping reservation (MMAC-HR) to resolve the multi-channel exposed terminal problem, which leads to poor channel utilization. MMAC-HR uses carrier sensing over all channels and does not use a channel list. Therefore, nodes do not need to sense the control channel to determine if any data channel is idle. In addition, the proposed protocol employs an independent and slow hopping strategy to utilize the multiple channels without exchanging information. Moreover, MMAC-HR is a distributed protocol and does not require synchronization. Using ns-2, the simulation results show that MMAC-HR achieves higher throughput and lower delay than DCA.

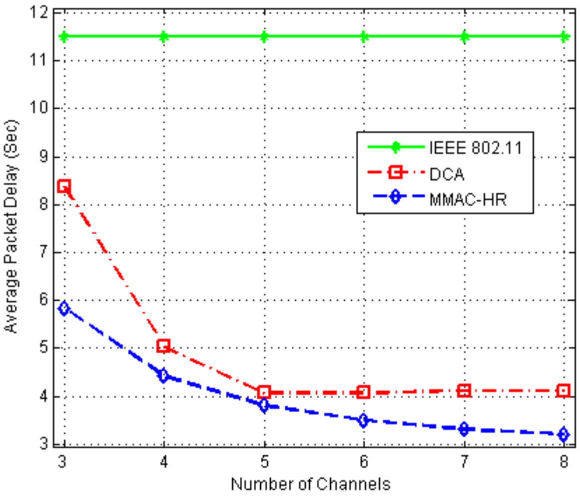


Figure 4.9: Average packet delay vs. different numbers of channels in the multi-hop network.

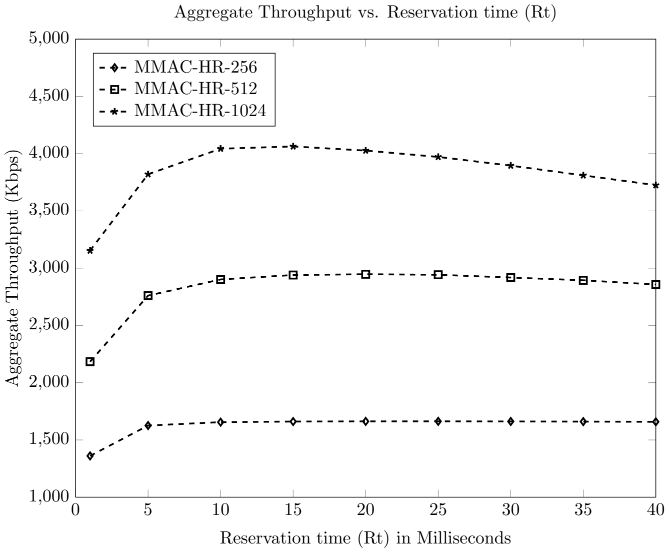


Figure 4.10: Average aggregate throughput vs. reservation time (Rt) when the number of channels is 4 in the multi-hop network.

Chapter 5

A Distributed Multi-channel MAC Protocol for Ad Hoc Networks

Multi-channel medium access control (MCMAC) protocols can be generally classified into two categories based on their operations [36], i.e., single rendezvous (SR) and multiple (parallel) rendezvous (MR) protocols. In SR-MCMAC protocols, one agreement made between a transmitter and a receiver occurs over only one channel at any time, whereas, in MR-MCMAC protocols, multiple agreements made between different transmitter-receiver pairs occur over multiple channels at the same time. The SR-MCMAC protocols suffer from the congestion on the common channel because a single agreement are made at any time [36]. On the other hand, multiple agreements are made at the same time in the context of the MR-MCMAC protocols to resolve the congestion on the common channel. Thus, the MR-MCMAC protocols outperform the SR-MCMAC protocols [36].

The Slotted Seeded Channel Hopping (SSCH) protocol [58] and the multichannel MAC (McMAC) [71] protocol belong to the MR-MCMAC protocols. Both protocols employ only one radio interface per node, which independently hops between channels. In order to send a packet to the receiver, the sender must synchronize with the receiver. SSCH employs an optimistic synchronization technique, and McMAC is based on a pairwise synchronization [128]. Therefore, the sender deviates from its default hopping sequence to meet the receiver. As a result, the busy receiver problem occurs (see Section 2.2.3).

Another protocol that follows the parallel rendezvous strategy is proposed in [94], and it is required one interface to be fixed and the second interface to be switchable. This protocol resolves the congestion on the control channel, and the fixed interface randomly selects its channel. Generally, the performance of this protocol relies on the channel assignment of the fixed interfaces. When a sender needs to transmit a packet to the receiver, the sender determines which channel the receiver is on. If both fixed interfaces of the sender and the receiver are with the same channel, the sender transmits the packet through its fixed interface. Otherwise, the sender tunes its switchable interface to the channel over which the fixed interface of the receiver is and then starts to transmit the packet.

In this chapter, we propose a novel multi-channel MAC protocol [5] based on the parallel rendezvous approach (i.e., independent frequency hopping). There are several advantages of the proposed protocol: 1) utilization of multiple channels by allowing multiple transmissions at the same time; 2) the ability to avoid congestion because the proposed protocol does not need a dedicated control channel and enables wireless nodes dynamically switch among channels; 3) the contention level on any channel is much less compared with SR-MCMAC protocols; 4) no changes is required to the IEEE 802.11 standard; and 5) avoiding the busy receiver problem, which has not been addressed in other multiple rendezvous protocols (e.g., the McMAC [71] and SSCH [58] protocols) because one interface in our protocol never deviates from its hopping sequence. Moreover, the proposed protocol employs two half-duplex interfaces per node. One interface follows fast hopping and the other interface follows slow hopping. In general, the fast hopping interface is for transmission and the slow hopping interface is for reception, so a node can work as a full-duplex system on different channels. Moreover, the slow hopping interface never deviates from its hopping sequence, while the fast hopping interface can deviate from its hopping sequence to communicate with other wireless nodes.

The remainder of this chapter is organized as follows. First, we describe the system model in Section 5.1. In Section 5.2, we present the proposed protocol. Section 5.3 presents the analytical model to evaluate the proposed protocol, followed by the validation of the analytical model in Section 5.4. The maximum saturation throughput and throughput limit are computed in Sections 5.5 and 5.6, respectively. In Section 5.7, simulation results in multi-hop networks are illustrated. Section 5.8 briefly presents some discussions about the proposed protocol. Finally, we summarize this chapter in Section 5.9.

5.1 System Model

Consider that k orthogonal channels are with an equal bandwidth. All nodes are equipped with two half-duplex interfaces, and both interfaces are able to switch between multiple channels. The two interfaces do not share the same channel at any time and do not interfere with each other so that they can work simultaneously. One interface follows a slow hopping sequence and the other one follows a fast hopping sequence. In addition, the slow hopping interface never deviates from its hopping sequence to avoid the busy receiver problem [36]. In general, the fast hopping interface is for transmission while the slow hopping interface is for reception. However, the fast hopping interface is able to receive any packet (e.g., a broadcast packet). For the slow hopping interface, it transmits HELLO and broadcast packets. In addition, a transmitter can communicate with its receiver if their slow hopping interfaces share the same channel.

Each node picks a seed to generate an independent pseudo-random hopping sequence for its slow hopping interface, which never deviates from the hopping sequence and follows slow hopping to reduce the channel switching and synchronization overhead. Each node should synchronize only with its neighboring slow hopping interfaces. Note that the proposed protocol does not require a global synchronization, but requires a pairwise synchronization[1] between neighbors, which is similar to the existing parallel rendezvous protocol [71]. In this chapter, we assume the clocks of the nodes are perfectly synchronized. To facilitate sequence synchronization and node discovery, each node periodically transmits a HELLO packet through its slow hopping interface when switching to a new channel. The HELLO packet can be received by one of the two interfaces of the neighboring nodes. As a result, each node creates or updates a record of its neighboring after receiving any HELLO packet.

The nodes within the communication range of each other are able to communicate over one hop transmission, so a transmitting node must meet (rendezvous) with a receiving node over a channel. If both the slow hopping interfaces of the transmitting and receiving nodes share the same channel, the transmitting node starts the data transmission using its slow hopping interface (e.g., nodes C and D during slot i shown in Figure 5.1 in which node C is the transmitter and node D is the receiver). Otherwise, the transmitter deviates its fast hopping interface to meet the slow hopping interface of the receiver (e.g., the fast hopping interface of node D switches to Channel 4 to meet the slow hopping interface of node A as shown in Figure 5.1). Consequently, multiple communications can take place at

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[1] Pairwise synchronization techniques are scalable with different network densities and achieve a better level of synchronization especially for operating MCMAC protocols [128] [129]. However, this chapter is not concerned about any implementation of pairwise synchronization protocols.

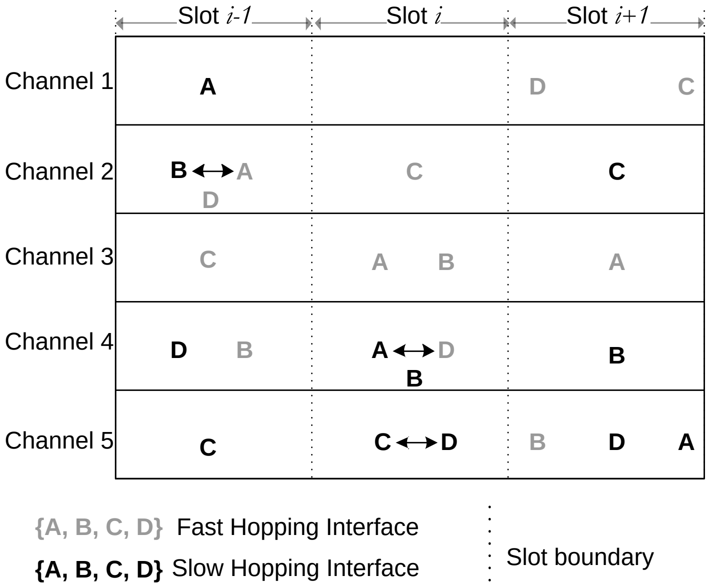

Figure 5.1: Instances of the channel activities using the proposed protocol.

the same time and a node is able to concurrently transmit and receive over different channels. Each transmission follows the IEEE 802.11 MAC scheme and the distributed coordination function (DCF) protocol [1], showing that we do not modify the IEEE 802.11 MAC strategies. In multi-hop networks, a routing protocol is required to determine the routing path. In Section 5.7, we evaluate the proposed protocol without modifying the DSR protocol.

5.2 Dynamic Switching Protocol (DSP) Using Frequency Hopping

In this section, we propose a novel MCMAC protocol called dynamic switching protocol (DSP). The proposed protocol is based on the parallel rendezvous approach (i.e., independent frequency hopping) and uses two interfaces that can switch dynamically. One interface follows fast hopping while the other one follows slow hopping. The proposed protocol is distributed and based on the IEEE 802.11 MAC strategies.

All nodes randomly generate hopping sequences for their slow hopping interfaces, and the slow hopping interfaces never deviate from their hopping sequences. Nodes should only synchronize with the slow hopping interfaces of each other. In this chapter, we assume that the network is synchronized. In single-hop wireless networks, all nodes can sense each other's transmissions. However, in multi-hop networks, to avoid the multi-channel hidden terminal problem [34], each interface after switching must sense a channel before attempting to transmit for a period of time.

There are four components that control the proposed protocol:

- Hopping Control: This control is used to generate hopping sequences for both the slow and fast hopping interfaces. Moreover, it guarantees that the two interfaces do not share the same channel at the same time. Nodes only need to know each other's hopping sequence of the slow hopping interface.

- Discovery: New and existing nodes should periodically transmit HELLO packets over channels. The HELLO packets include the following: 1) the hopping sequence of the slow hopping interface; 2) the current time of the node; and 3) the time to switch to the next channel.

- Rendezvous: When a node has a packet, the node determines which channel the slow hopping interface of a destination node is on. Then, the node sends the packet through one of its two interfaces. Note that the fast hopping interface is allowed to deviate from current hopping sequence.

- Broadcast support: Broadcast packets are essential in wireless networks. For example, routing protocols maintain their routing tables or determine nodes through routing discovery based on broadcast packets. Whenever a broadcast packet needs to be transmitted, the proposed protocol transmits the broadcast packet over both interfaces. In other words, two copies of the broadcast packet are generated; one for each interface to be transmitted.

5.2.1 Hopping Control

The two interfaces are not allowed to share the same channel at any time, and the hopping control is used to generate hopping sequences for both interfaces. The hopping sequence of the slow interface of a node is based on a pseudo-random generator. We use a linear congruential generator (similar to [71]), which can be described by

$$X(t) = 16807 \cdot X(t-1)\, mod\, (2^{31}-1), \tag{5.1}$$

where $X(t)$ is the current channel number of the t^{th} sequence. $X(t)$ must be within the range of the number of channel, so $X(t)$ is modular to k, the number of channels. $X(0)$ is the seed of the hopping sequence and generated randomly.

For the fast hopping interface, the hopping control generates a deterministic hopping sequence:

$$f(t) = (f(t-1)+1)\; mod\; (k), \tag{5.2}$$

where $f(t)$ is the current channel of the t^{th} sequence. The hopping control does not allow both interfaces to be on the same channel. Consequently, if the sequence of the fast hopping interface is equal to the sequence of the slow hopping interface, then (5.2) is executed again. In other words, the fast hopping sequence jumps to another channel.

5.2.2 Discovery

New and existing nodes should periodically transmit HELLO packets over channels, and the nodes can receive the packets by one of the two interfaces; therefore, the nodes can discover each other. The HELLO packets are only transmitted through the slow hopping interfaces after they switch to new channels. Despite the fact that the HELLO packets are broadcasted, they are only transmitted through slow hopping interfaces to reduce the overhead in the network. When the nodes receive any HELLO packet through one of their interfaces, the nodes maintain records of their neighbors. These records are important for the nodes to determine their destinations.

A HELLO packet contain three fields. The first field is the seed of the slow hopping sequences of a node, and this field determines the current and future channels of the node using (5.1). The second field is the local clock time of the node to determine the slot hopping boundary of the node. Finally, the third field contains the remaining time to switch to the next channel. The reason for the existing of the third field is to align the slow hopping boundary because the HELLO packet may not be transmitted immediately after switching.

5.2.3 Rendezvous

A node transmits only one unicast packet at any given time and uses the IEEE 802.11 MAC strategies for any transmission because we do not change the legacy IEEE 802.11 MAC protocols. Similar to parallel rendezvous multi-channel protocols, the proposed protocol allows multiple concurrent transmissions. This approach solves the congestion problem in single rendezvous multi-channel protocols [36].

The fast hopping interfaces of nodes are used for transmission, and the slow hopping interfaces of nodes are generally for reception. Therefore, if a source node has a packet to transmit, the source first determines the current channel of the slow interface of the destination node. Next, the fast hopping interface of the source switches to the same channel which the slow hopping interface of the destination is on. Finally, the packet is transmitted over the fast hopping interface according to the IEEE 802.11 MAC strategies. If the slow hopping interface of the destination is on the same channel as that of the source, the packet is transmitted through the slow hopping interface of the source.

Figure 5.1 shows five channels and four nodes using the proposed protocol. During slot $i-1$, if node A has a packet for node B, but the slow hopping interface of node A is not with the same channel of the slow hopping interface of node B, node A switches its fast hopping interface to meet the slow hopping interface of node B. After that, node A uses the IEEE 802.11 MAC strategies to transmit its packet to node B through its fast hopping interface. Nodes C and D want to transmit packets to nodes D and A, respectively, during slot i. The slow hopping interfaces of nodes C and D are over Channel 5, so node C transmits its packet through its slow hopping interface. The slow hopping interface of node A, on the other hand, is on Channel 4. As a result, node D switches its fast hopping interface to Channel 4 and then transmits its packet. As a result, node D is able to transmit and receive concurrently during slot i.

5.2.4 Broadcast Support

Unlike the existing parallel rendezvous multi-channel protocols that have a single radio interface, the proposed protocol has two interfaces per node. When a broadcast packet needs to be transmitted, two copies of the broadcast packet are generated and passed to each interface. Then, the broadcast copies are transmitted through both interfaces, which are on two different channels. Recall that the two interfaces do not share the same channel at any time and hop according to the hopping control presented in Section 5.2.1. The proposed protocol schedules the next packet when both interfaces transmit their broadcast copies. Any node within the communication range of the transmitter has a high probability to receive the broadcast packet through one of the interfaces if no collisions occur.

5.3 System Analysis

In this section, we present the system analysis of the proposed protocol. We adapt Bianchi's model [130] to analyze the throughput of our protocol because we do not change the legacy IEEE 802.11 MAC protocols.

We track only the slow hopping interface of a receiver. At each time instance, the nodes randomly select the channels for next transmissions. Similarly, we have n balls (nodes) that are thrown into k bins (channels). Thus, the number of nodes[2] on a particular channel follows the binomial distribution. This model provides a probabilistic system, and similar derivation has been considered in [131, 36, 132].

Following Bianchi's approach [130], all nodes have packets at all times (saturation condition), meaning that each node has a packet to transmit after each successful transmission. From [130], the transmission probability, τ, that a node transmits a packets over a channel is given

$$\tau = \frac{2(1-2p_c)}{(1-2p_c)(CW_{min}+1)+p_c CW_{min}(1-(2p_c)^m)}, \tag{5.3}$$

where p_c is the conditional collision probability over one channel seen by one node transmitted its packet, CW_{min} is the minimum contention window size, and m is the

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[2] When we say nodes, we indicate the slow hopping interfaces of the nodes.

maximum backoff stage. The probability p_c is defined as one or more of remaining nodes transmit their packets given that one node has already transmitted its packet on the same channel so that a collision occurs over that particular channel. The probability p_c is assumed to be independent and constant and can be computed as follows:

$$\begin{aligned} p_c &= \sum_{i=1}^{n-1} \left(1-(1-\tau)^i\right) \left(\binom{n-1}{i} (\frac{1}{k})^i (1-\frac{1}{k})^{n-1-i} \right) \\ &= 1-(1-\frac{\tau}{k})^{n-1}. \end{aligned} \tag{5.4}$$

Note that the transmission probability τ defined in (5.3) is different from the transmission probability defined in Bianchi's paper because the conditional collision probability is different. τ depends on the unknown variable p_c, and Equations (5.3) and (5.4) can be solved numerically similar to [130].

P_i is defined as the probability that there is no transmission (idle) in any given time over a channel and given as follows:

$$\begin{aligned} P_i &= \sum_{j=0}^{n} \left((1-\tau)^j\right) \left(\binom{n}{j} (\frac{1}{k})^j (1-\frac{1}{k})^{n-j} \right) \\ &= (1-\frac{\tau}{k})^n. \end{aligned} \tag{5.5}$$

P_s denotes the probability that a successful transmission occurred over a particular channel given that at least one node transmits (i.e., exactly one station transmits over that channel). P_s is given

$$\begin{aligned} P_s &= \frac{\sum_{j=1}^{n} \left(\binom{j}{1}\tau(1-\tau)^{j-1}\right)\left(\binom{n}{j}(\frac{1}{k})^{j}(1-\frac{1}{k})^{n-j}\right)}{1-P_i} \\ &= \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{1-P_i}. \end{aligned} \tag{5.6}$$

The throughput ψ_l for channel l can be expressed as

$$\psi_l = \frac{P_s(1-P_i)E[P]}{P_i\sigma + P_s(1-P_i)T_s + (1-P_s)(1-P_i)T_c}, \tag{5.7}$$

where $E[P]$ is the average packet payload size, σ is the slot time, T_s is the average successful time because one node transmits over channel l successfully, and T_c is the average collision time that channel l is sensed as being busy because two or more nodes transmit their packets causing a collision. The total throughput for all channels is given

$$\Psi = \sum_{l=1}^{k} \psi_l. \tag{5.8}$$

Notice that (5.7) indicates the saturation throughput without specifying the access methods. In our protocol, we use only the RTS/CTS access mechanism, but it is very easy to apply the analytical model to the basic access method. Therefore, T_s and T_c are obtained as follows:

$$\begin{aligned} T_s &= RTS + T_{SIFS} + \delta + CTS + T_{SIFS} + \delta + H \qquad (5.9) \\ &\quad + E[P] + T_{SIFS} + \delta + ACK + T_{DIFS} + \delta, \\ T_c &= RTS + T_{DIFS} + \delta, \qquad (5.10) \end{aligned}$$

where $H = PHY_{hdr} + MAC_{hdr}$ is the packet header, and δ is the propagation delay.

5.4 Model Validation

In this section, we validate our analytical model presented in Section 5.3. The simulation platform used to validate our analysis is the ns-2 simulator (ns-2-30). We also present the performance of the IEEE 802.11 MAC protocols for comparison.

Table 5.1 provides the system parameters, and Figure 5.2 and Figure 5.3 show the saturation throughput of the proposed protocol and the IEEE 802.11 MAC protocol. The average packet payload, E[P], is 1000 bytes. The proposed protocol encounters certain overheads. Such overheads are Hello packets and switching delay for each radio interface. It can be seen that the analytical and simulation results are matched well.

As shown in Figure 5.2a, when the number of channels increases, more nodes are needed to match the analytical results[3]. Figure 5.3a demonstrates the throughput with different available channels and payloads, i.e., 256, 512, and 1024 bytes, when the number of nodes is 25.

To measure the improvement of the proposed protocol with respect to the IEEE 802.11 protocol, Figure 5.2b and Figure 5.3b show the normalized saturation throughput. We normalize the analytical throughput driven in Section 5.3 with the analytical throughput driven in [130] and the simulation throughput of the proposed protocol with the simulation throughput of the IEEE 802.11 MAC protocol both obtained from the ns-2 simulator [122]. As shown in Figure 5.2b, the proposed protocol approximately achieves as many times as the number of channels. If the payload length is changed, the proposed protocol still achieves about k times the throughput of the IEEE 802.11 MAC scheme as shown in Figure 5.3b.

Recall that the node distribution over channels follows the binomial distribution

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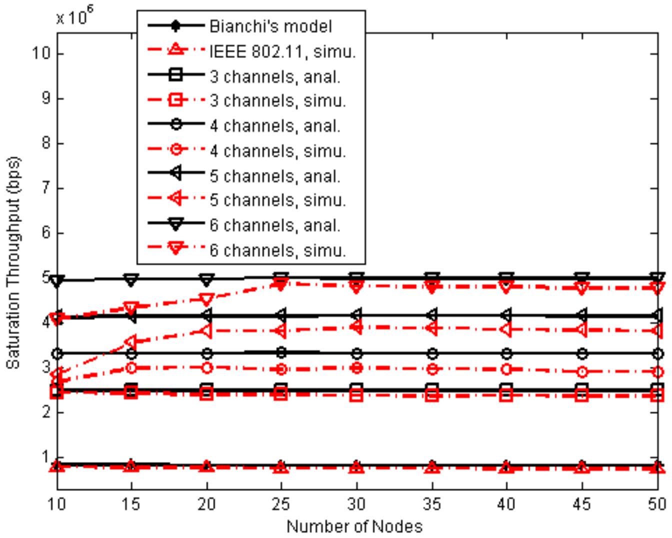
[3] Bianchi has stated that his model is accurate when the number of nodes is large [130]. This statement is also true in our model because our model is based on Bianchi's model.

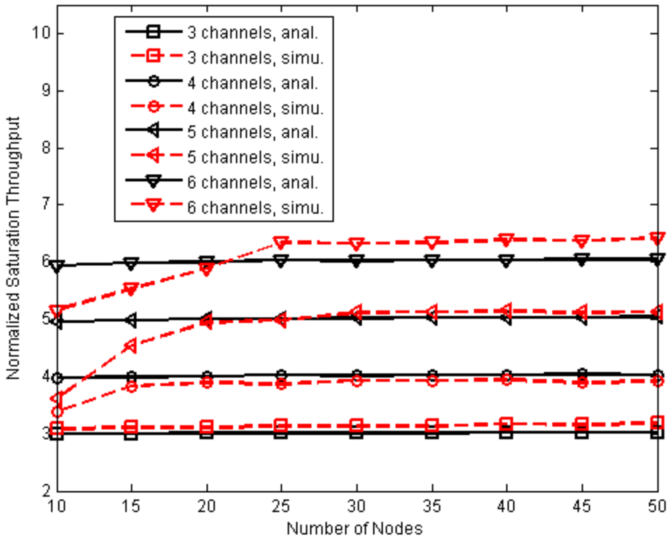
Table 5.1: System Parameters [1, 2]

Carrier sense threshold	$1.56 * 10^{-8}$ mW
Receiver sensitivity	$3.65 * 10^{-7}$ mW
Maximum transmission power (P_{max})	281.8 mW
T_{DIFS} (μs)	50
T_{SIFS} (μs)	10
PHY_{hdr} (bits)	192
Slot Time σ (μs)	20
MAC_{hdr} (bits)	272
CW_{min}	32
CW_{max}	1024
Channel bit rate	1 Mbps
ACK (bits)	112 + PHY_{hdr}
RTS (bits)	160 + PHY_{hdr}
CTS (bits)	112 + PHY_{hdr}
Hello packet (bits)	320 + PHY_{hdr}
Propagation delay δ (μs)	1
Slow hopping time (ms)	100
Fast hopping time (ms)	1
Switching delay time (μs)	100

as discussed in the previous section. Figure 5.4 shows two instances of the expect number of nodes over different channels for different nodes in the network. The first bar is the analytical result (the expect number of nodes over any channel is $\lfloor n/k \rfloor$, where $\lfloor . \rfloor$ is the floor operation), the second bar is the expect number of nodes over channel index 1, the third bar is the expect number of nodes over channel index 2, and so on. The last bar is the average number of nodes from all channels (i.e., the sum of expect number of nodes over channel index 1, channel index 2, . . . , channel index k divided by k). From the figure, we can see the node distribution over channels is valid. Recall that we only track the slow hopping interface because the fast hopping interface of a transmitter follows the slow hopping interface of a receiver.

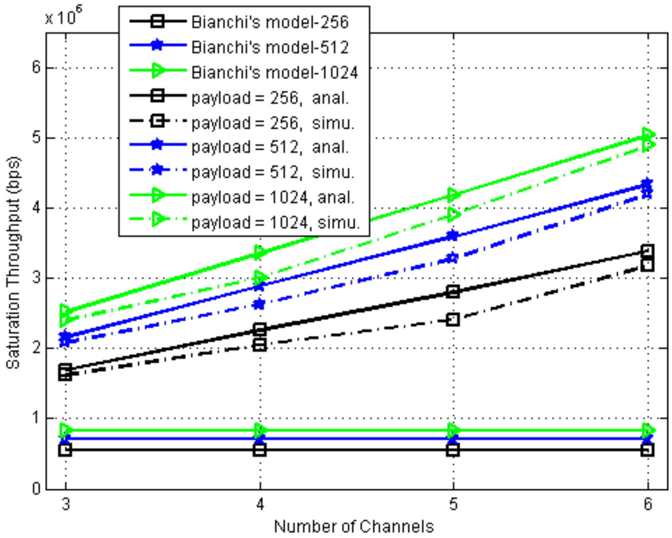


(a) Throughput

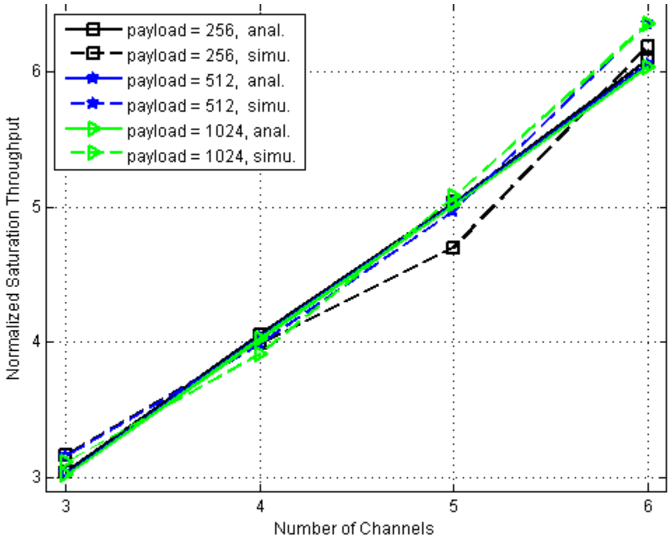


(b) Normalized throughput

Figure 5.2: Saturation throughput vs. different numbers of nodes and channels

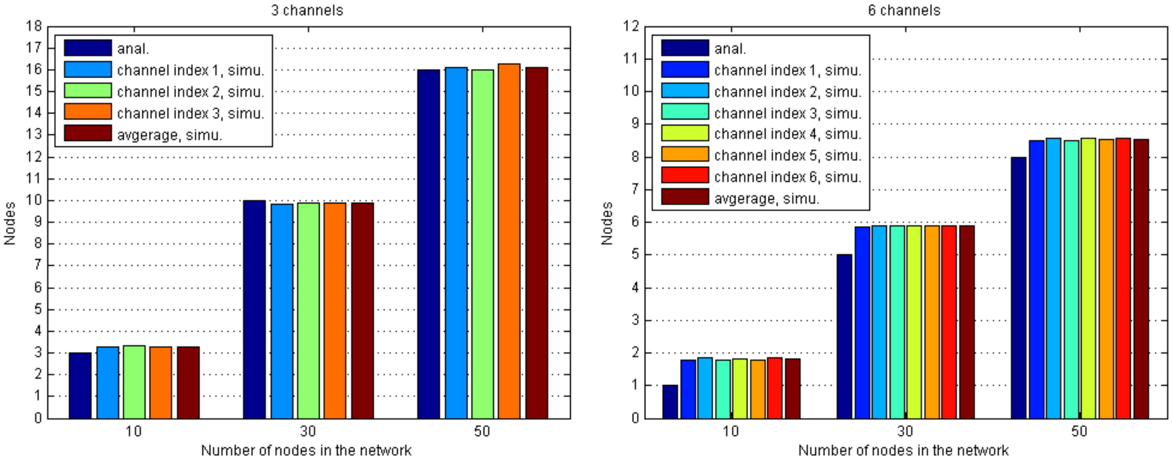


(a) Throughput



(b) Normalized throughput

Figure 5.3: Saturation throughput vs. different numbers of channels and payloads.



(a) Three channels (b) Six channels

Figure 5.4: Expected number of nodes over different channels

5.5 Maximum Saturation Throughput

In this section, we determine the maximum throughput, and what parameters can affect the achievable network throughput to compute the optimal transmission probability τ.

Equation (5.7) determines the saturation throughput analytically. By rearranging (5.7), we get

$$\psi_l = \frac{E[P]}{T_s - T_c + \frac{\sigma P_i/(1-P_i)+T_c}{P_s}} = \frac{E[P]}{T_s - T_c + \sigma y}. \tag{5.11}$$

Since $T_s, T_c, E[P]$, and σ are constants, ψ_l depends on y. When ψ_l is maximized, $1/y$ is maximized as follows:

$$\frac{1}{y} = \frac{P_s}{P_i/(1-P_i) + T_c/\sigma} = \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{T_c^* - (1-\frac{\tau}{k})^n (T_c^* - 1)}, \tag{5.12}$$

where $T_c^* = T_c/\sigma$ is the time duration of a collision measured per σ unit. By taking the derivative of (5.12) with respect to τ and imposing it equal to 0, we obtain

$$(1-\frac{\tau}{k})^n - T_c^*\{\frac{n\tau}{k} - [1-(1-\frac{\tau}{k})^n]\} = 0. \tag{5.13}$$

Under the condition $\tau \ll 1$,

$$(1-\frac{\tau}{k})^n \approx 1 - \frac{n\tau}{k} + \frac{n(n-1)}{2}(\frac{\tau}{k})^2 \tag{5.14}$$

holds and leads to the following approximate solution:

$$\tau = k\frac{\sqrt{[n+2(n-1)(T_c^*-1)]/n}-1}{(n-1)(T_c^*-1)} \approx \frac{k}{n\sqrt{T_c^*/2}}. \tag{5.15}$$

Equation (5.13) and its approximate solution (5.15) indicate that the optimal transmission probability τ should consider the number of channels. In (5.15), within a given network, τ depends on the network size n, the number of channels k, and the system parameters m and CW_{min}. Since n and k are not a directed controllable variable, m and CW_{min} are the only way to achieve maximum throughput. This conclusion has been also stated in [130], and unfortunately, the values m and CW_{min} are fixed, as specified in the IEEE 802.11 standard.

Let $K = \sqrt{T_c^*/2}$ and use (5.15), from (5.5) and (5.6), we have

$$P_i = (1-\frac{\tau}{k})^n = (1-\frac{1}{nK})^n \approx e^{-1/K} \tag{5.16}$$

and

$$P_s = \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{1-P_i} \approx \frac{n}{(nK-1)(e^{1/K}-1)} \approx \frac{1}{K(e^{1/K}-1)}, \tag{5.17}$$

when n is sufficiently large. Thus, the maximum achievable throughput ψ_l^{max} of channel l can be approximated as

$$\psi_l^{max} = \frac{E[p]}{T_s + \sigma K + T_c(K(e^{1/K} - 1) - 1)}, \tag{5.18}$$

which is independent of n and k, and the maximum achievable throughput of all channels is the summation of the maximum throughput of each channel and given

$$\Psi^{max} = \sum_{l=1}^{k} \psi_l^{max}, \tag{5.19}$$

which depends on the number of channels in the network, but not the number of nodes. To determine the improvement of the proposed protocol, the improvement gain $\wp$ can be determined

$$\wp = \frac{\Psi^{max}}{S_{max}} = k, \tag{5.20}$$

where S_{max} is the maximum achievable throughput of single-channel networks obtained in [130].

5.6 Saturation Throughput Limit

In the previous section, we determine the maximum achievable throughput, and how the system parameters and network topology (i.e., the number of stations and channels) affect the maximum throughput. In this section, we compute the throughput limit when we have a large number of channels, i.e., $k \to \infty$, to investigate the performance bottleneck of the proposed protocol.

Assume the number of channels is large ($k \to \infty$) for a fixed number of nodes n, the question is what is the upper limit throughput that we can achieve? The following remarks summarize the results:

Remark 1. When the number of channels is large ($k \to \infty$), from (5.3), the transmission probability τ is only depends on the minimum window size (no exponential backoff)

$$\tau = \frac{2}{CW_{min} + 1}. \tag{5.21}$$

Remark 2. From (5.8), the total throughput of all channels is given by

$$\begin{aligned} \Psi &= \lim_{k \to \infty} \frac{kP_s(1 - P_i)E[P]}{P_i\sigma + P_s(1 - P_i)T_s + (1 - P_s)(1 - P_i)T_c} \\ &= \frac{n\tau E[P]}{\sigma} = \frac{2nE[P]}{(CW_{min} + 1)\sigma}. \end{aligned} \tag{5.22}$$

Equation (5.22) proves that the proposed protocol does not have any bottleneck issue.

Remark 3. A special case is when the number of channels is equal to the number of nodes ($k = n$), and n goes to infinity. Under the condition $\tau \ll 1$, p_c from (5.4) can be derived by

$$p_c = 1 - e^{-\tau} \approx 0. \tag{5.23}$$

From (5.7), We can obtain the throughput of a given channel

$$\psi = \frac{\tau e^{-\tau}E[P]}{\sigma e^{-\tau} + \tau e^{-\tau}T_s + (1 - e^{-\tau} - \tau e^{-\tau})T_c} \approx \frac{\tau E[P]}{\sigma + \tau(T_s - T_c)}. \tag{5.24}$$

5.7 Simulation Results

In Section 5.4, we have validated the analytical model presented in Section 5.3 in single-hop networks. In this section, simulation results are given to evaluate the proposed protocol in multi-hop networks. We study the performance of the unmodified Dynamic Source Routing (DSR) [133] over DSP. We select the following three performance metrics:

1. *Average aggregate throughput.* To achieve k times the throughput of a single-channel network, one may say that each node should have k interfaces, which is unpractical. In single-hop networks (Sections 5.3 and 5.4), we show that the proposed protocol approximately achieves k times the throughput of IEEE 802.11 single channel MAC protocol with only two interfaces per node. In multi-hop networks, the proposed protocol utilizes all channels by frequency hopping and achieves about k times the capacity of the IEEE 802.11 MAC protocol as discussed in the following.

2. *Average end-to-end packet delay.* The end-to-end packet delay is important for real time applications, and it is the time duration for a packet to be received correctly by its destination. The delay occurs because of queueing, backoff, propagation, access, switching, and transmission times. The MAC queueing size of each node is 50 packets, and packets will be dropped after reaching a retry limit, i.e., 7. We do not take into account the dropped packets.

3. *Normalized routing overhead.* Most routing protocols use broadcast information to determine a routing path from any source node to any destination node. In the proposed protocol, nodes could be over different channels and thereby affecting the routing protocols. In addition, any broadcast packet is transmitted through two interfaces. The normalized routing overhead is the

total transmitted routing packets normalized by the total received packets. For any routing packet sent over multiple hops, we count each hop as two using the proposed protocol and as one using the IEEE 802.11 MAC scheme. At the same time, we only count the received packets at destination nodes.

5.7.1 Simulation Settings

The ns-2 simulator (ns-2.30) [122] is used for simulations, and the simulation parameters are presented in Table 5.1. In addition, the retry limit is set to 7, i.e., after 7 retransmissions of a packet without succeeding, the packet is dropped and the next packet in the queue is scheduled for the next transmission. The two-ray path loss model is adopted in the simulations, and the radio transmission range and the carrier sensing range of each node of each channel is 250 meters and 550 meters, respectively.

We simulate multi-hop wireless networks by randomly deploying 100 mobile nodes into two different network sizes: $250m$x$250m$ and $500m$x$500m$ square areas. We refer to the $250m$x$250m$ square area as the dense network and the $500m$x$500m$ square area as the sparse network. A node movement is simulated using the random waypoint model [134] with speed uniformly distributed in the range [0, 20] m/s, and the simulation results are shown with five different pause times: 60, 120, 300, 600, and 900 seconds. The simulation time is 900 seconds, so a pause of 900, the length of the simulation time, means no mobility. Each simulation scenario is run for five different movement patterns. Thus, we have a total of 50 different scenarios.

There are 50 flows with rate of 500 Kbps in the simulations, and source and destination pairs are randomly chosen. Each traffic flow in the network uses the constant bit rate (CBR) traffic model, and the packet size is 1024 bytes. We assume the switching delay time is 100 μs. Existing wireless interfaces can switch between channels with a delay of 130 μs [95], and it is expected that the channel switching delay of wireless interfaces will be reduced to 40-80 μs [58, 36].

5.7.2 Simulation Results

Figure 5.5 and Figure 5.6 show the performance of the proposed DSP in multi-hop environments. DSP-3, DSP-6, and DSP-12 mean that the proposed DSP has 3, 6, and 12 channels, respectively. Figure 5.5a shows the average aggregate throughput of the dense network. The throughput of DSP is higher than the throughput of IEEE 802.11, and the two protocols achieve steady throughput values with different mobility patterns because the size of the network is small. To examine the achievement of the proposed protocol, the proposed DSP achieves 3.63, 9.57, and 20.88 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively, when there is no mobility, i.e., the pause time is 900 seconds. These achievements are due to k available channels and channel reuse.

Figure 5.5b presents the average end-to-end delays of the dense network. The proposed DSP achieves less delay with more channels. The uncertainty of the delay using the IEEE 802.11 strategies is high because the network has only a single channel and all nodes compete over the shared channel.

Since our proposed protocol transmits any broadcast packet through two interfaces, this approach increases the likelihood of discovering neighboring nodes and determines shorter routing paths, but increases routing messages. In Figure 5.5c, we show the normalized routing overhead and observe that the proposed protocol encounters less normalized routing overhead with more available channels due to better network performance and resolving the congestion.

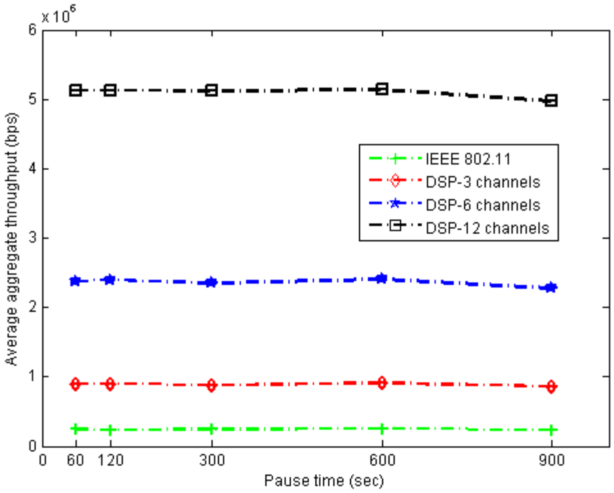
In Figure 5.6a, the throughput of the protocols increases and then decreases due to the mobility patterns and spatial reuse [135]. However, the proposed DSP provides better performance, and the more channels the network has, the better performance will be. When there is no mobility, for instance, the proposed DSP achieves 2.99, 6.37, and 12.33 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively. When the pause time is 300 seconds, the proposed DSP achieves 3.22, 7.05, and 14.12 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively. Thus, the capacity of the proposed MCMAC protocol approximately achieves k (the total number of channels in the network) times the capacity of the IEEE 802.11 MAC protocol.

In Figure 5.6b, the end-to-end delay of the IEEE 802.11 MAC strategies encounter higher delay than the proposed DSP because the IEEE 802.11 MAC protocols use a single channel. Comparing the dense network as shown in Figure 5.5b with the sparse network as shown in Figure 5.6b, the delay differences of the DSP between the sparse and dense networks are small, but the delay differences of the IEEE 802.11 MAC protocol are high.

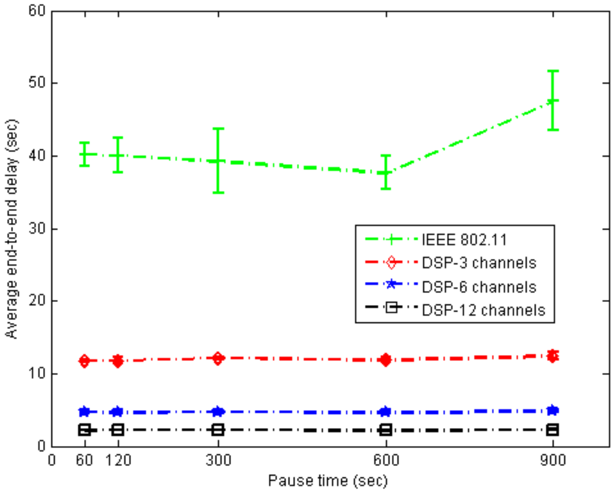
Figure 5.6c shows the normalized routing overhead in the sparse network. The IEEE 802.11 incurs high routing overhead when the mobile nodes are in fast mobility. However, when there is less or no mobility, the IEEE 802.11 protocol has the same routing overhead ratio as the proposed DSP with three channels. As the number of channel increases, the routing overhead of DSP has less effect.

5.8 Discussions

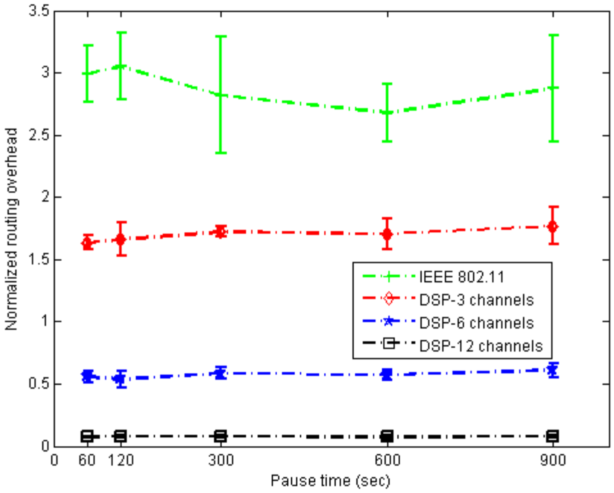
The proposed protocol exploits multiple channels using independent frequency hopping, so it resolves the congestion of the common channel. This approach results in significantly high network performance. The proposed DSP requires only two interfaces per node to avoid the busy receiver problem because one interface never deviates from its default hopping sequence. As a result, it increases the cost and



(a) average throughput

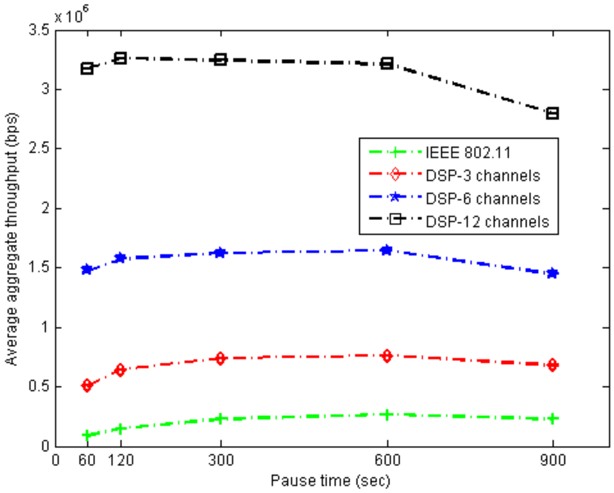


(b) average end-to-end delay

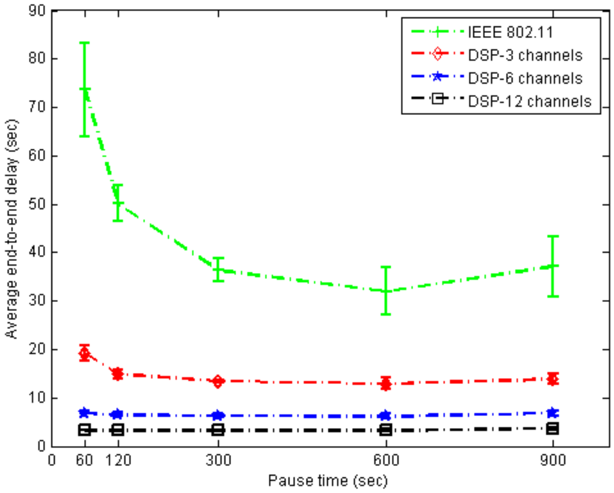


(c) normalized routing overhead

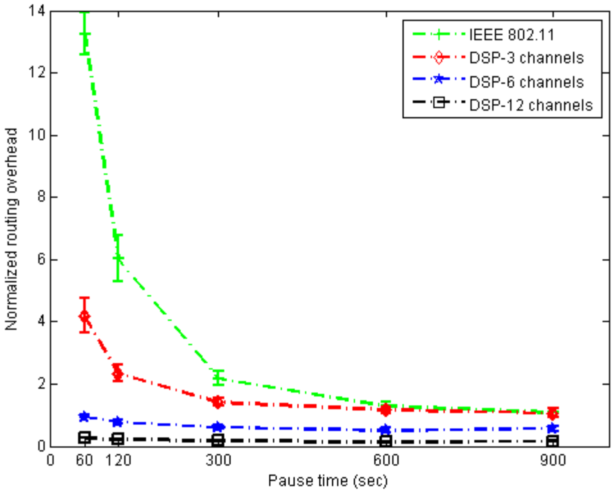
Figure 5.5: The performance of the dense network



(a) average throughput



(b) average end-to-end delay



(c) normalized routing overhead

Figure 5.6: The performance of the sparse network

consumes more energy. Other multi-channel MAC protocols based on independent frequency hopping needs only one interface per node (e.g., [89, 71, 58]), and therefore it is cost-effective, but suffers from the busy receiver problem discussed in Section 2.2.3.

In DSP, any node can transmit only one unicast packet even through there are two radio interfaces per node. This strategy reduces the complexity of the proposed MAC protocol. One may suggest that a node can transmit two unicast packets at the same time because the node has two interfaces. This suggestion is possible, but it increases the complexity.

To the best of our knowledge, all protocols based on the parallel rendezvous approach (i.e., independent frequency hopping) require clock synchronization, and the proposed DSP is no exception. Although global clock synchronization is difficult, the DSP requires pairwise clock synchronization between neighboring nodes [128, 129].

5.9 Summary

In this chapter, we have proposed a novel MCMAC protocol based on the fast and slow hopping approaches. Our protocol does not change the legacy IEEE 802.11 MAC strategies and employs two radio interfaces per node. The fast hopping interface is mainly for transmission, whereas the slow hopping interface is for reception. In particular, whenever a transmitter has a packet for a receiver, the fast hopping interface of the transmitter follows the slow hopping interface of the receiver. The proposed protocol is based on the multiple rendezvous approach and avoids the busy receiver problem because the slow hopping interface never deviates from its hopping sequence. In addition, an analytical study has been presented to evaluate the network throughput. Simulation results have been provided to validate the analytical model and to demonstrate the improvement in the capacity of the network. In addition, the upper throughput limit is computed in the context of an infinite number of channels.

Chapter 6

Conclusions and Further Work

The performance of single-channel ad hoc networks is limited due to a number of major issues. One such major issue is interference among nodes. Using unlicensed multiple channels is a potential solution to enhance the limited performance of single-channel networks because that reduces the level of contention and allows multiple communications to occur simultaneously. Using multiple channels with power control boosts the network performance even more because adjusting transmission power decreases interference over the channels. The aim of this thesis is to improve the network performance using unlicensed multiple channels. In this chapter, we summarize the thesis major research contributions and briefly discuss some potential future research topics.

6.1 Major Research Contributions

The main contributions of this thesis are summarized as follows:

- We have investigated the deficiency of uncontrolled asymmetrical transmission power over multiple channels in ad hoc environments. Additionally, we have proposed a novel distributed TPC scheme called the distributed power level (DPL) for multi-channel ad hoc networks without requiring clock synchronization. Specifically, different transmission power levels are assigned to different channels so that nodes search for an idle channel based on the received power such that the maximum allowable power of the preferred data channel is larger than or equal to the received power. If the most preferred channel of the least maximum power is busy, the nodes are able to select the next channel, etc. As a result, interference is reduced over channels. Two TPC modes are introduced for DPL: symmetrical and asymmetrical. For the symmetrical DPL mode, nodes transmit at the same power level assigned to the selected channel. However, for the asymmetrical DPL mode, nodes are allowed to transmit at a lower or equal power level as that assigned to the selected channel.

- We have proposed a MCMAC protocol, called multi-channel MAC with hopping reservation (MMAC-HR), to resolve the multi-channel exposed terminal problem. MMAC-HR uses two radio interfaces: one interface is fixed over the control channel and the other interface switches dynamically between data channels. The fixed interface supports broadcasting information and reserves a data channel for any data transmission. The switchable interface, conversely, is for data exchanges and follows independent slow hopping without requiring clock synchronization. The proposed protocol is also a distributed one.
- In Chapter 5, we have proposed a novel MCMAC protocol that increases the network capacity using frequency hopping called the dynamic switching protocol (DSP). Different from the existing MCMAC protocols, the proposed MCMAC protocol follows the parallel rendezvous approach and avoids the

busy receiver problem. It also does not change the IEEE 802.11 standards. The basic principle of the proposed DSP is that one interface follows fast hopping and is for transmission, and the other interface follows slow hopping and is primarily for reception.

- For DSP, an analytical model has been developed and is validated using the ns-2 simulator for single-hop networks. The maximum saturation throughput of each channel is achieved by computing the optimal transmission probability considering the number of channels, and the total maximum throughput of DSP achieves as many channels as the maximum saturation throughput of single-channel networks. We have also derived the upper limit throughput when the number of channel is large.

6.2 Further Research Work

This thesis focuses on designing TPC and MCMAC protocols and analyzing their performance. Nonetheless, a number of research directions needs to be investigated

- In Chapter 3, the power assignment is fixed and known prior to the nodes in the network (i.e., the power assignment is configured before the nodes join the network). In addition, we have studied impact of power assignment of the network throughput and shown that inappropriate power assignment can degrade the network throughput. Finding the best power assignment is an open problem, and in the future, we will develop an adaptive scheme to assign transmission power levels to different channels based on node density and the number of channels. The new adaptive power control should be stable and fast converge.

- The transmission power of the proposed protocols in Chapters 4 and 5 over all channels is fixed and equal. Studying power control with these proposed protocols is still an open issue.

- Research presented in this thesis fixes the transmission data rate over all channels. Applying data rate adaptation will enhance the network performance and should be investigated. For example, in Chapter 3, it is interesting to consider TPC with data rate adaptation, so a node selects a channel with the highest data rate.

- The protocol proposed in Chapter 4 utilizes independent channel hopping. For our future work, we will develop an intelligent channel selection (dependent channel hopping) for MMAC-HR so that the network load is balanced over multiple channels, thereby enhancing the network performance.

- In this research work, we consider all nodes always listen to any channel without adapting energy saving strategies. Designing such strategies in multi-channel systems is an important topic for future investigation. All protocols in this thesis have two radio interfaces per node. A simple power management technique is to turn off one interface while keeping the other interface on if nodes do not have packets to transmit. This simple scheme has a significant impact on power consumption.

- In this thesis, we consider only unlicensed frequency channels. It has been proven that licensed channels are underutilized by licensed users due to static frequency allocation. Therefore, a new concept of spectrum allocation called Dynamic Spectrum Access (DSA) (cognitive networks) has been proposed with prioritized spectrum access [136]. Exploring licensed frequency channels has recently begun, and more research is required.

6.3 Final Remarks

Multi-channel multi-hop networks are the future architecture for the next generation wireless networks. In this architecture, it is expected that the number of wireless radio interfaces per node is less than the number of channels and can be more than one. A number of researches are focusing on exploiting multiple channels to enhance the network performance using multiple radio interfaces. However, there is little attention in integrating more than one approach (e.g., using multiple channels with adaptive rate and power control or using more than one smart antenna to exploit multiple channels) to increase the network capacity. The integration of more than one approach is worth further investigation.

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