Code division multiple access based multi-channel medium access control protocols and topology control for mobile ad hoc networks

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**CODE DIVISION MULTIPLE ACCESS BASED
MULTI-CHANNEL MEDIUM ACCESS CONTROL
PROTOCOLS AND TOPOLOGY CONTROL FOR
MOBILE AD HOC NETWORKS**

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A Thesis Submitted To the Nanyang Technological University
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Summary

Excessive quantity of control overhead can constitute a major cause of degradation in throughput for wireless mobile ad hoc networks (MANETs). To date, Code Division Multiple Access (CDMA) based multi-channel medium access control (MAC) algorithms in MANETs, rely on the periodic exchange of neighborhood information within two-hop separation to assign a transmission code to a node, in order to avoid the hidden terminal problem (HTP). However, this results in an expensive communication overhead and hence aggravates the network performance with the bandwidth under-utilization, energy inefficiency and creating large end-to-end latency. To effectively combat the excessive exchange of control packets for code assignment, this thesis proposes a novel code assignment scheme, termed as two-phase coding scheme, and develops it under two different network scenarios, i.e., one is cell-based where location information is available whereas the second case is clustering-adaptive with a dynamic clustering algorithm employed.

Location-aware two-phase coding multi-channel MAC protocol (LA-TPCMMP) employs the first-phase code to differentiate between multiple adjacent cells and the second-phase code is used to identify each node in one cell. This method elimi-

nates the HTP during data transmission in MANETs without periodical exchange of neighborhood information. Next, the thesis extends the work to a cluster-adaptive two-phase coding multi-channel MAC protocol (CA-TPCMMP) and integrates two-phase coding scheme with the concept of dynamic clustering, where the first-phase code is used to differentiate between neighboring clusters and the second-phase code is used to distinguish nodes within one cluster. CA-TPCMMP not only mitigates the heavy control overhead but also eliminates the original dependence to the location information. It is also effective in combating the HTP during data transmission. For both protocols, the theoretical analysis on the upper bounds and extensive simulations are done to demonstrate that LA-TPCMMP and CA-TPCMMP significantly outperform the existing CDMA-based algorithms with regards to control overhead and delay performance.

It is well known, that there exists unavoidable fading and interference phenomena in CDMA wireless ad hoc networks, and this causes time-varying channel conditions. Therefore, a key problem for such a network is to maintain the acceptable multiple access interference (MAI) performance over wireless channels experiencing fading with as more as possible simultaneous packet transmission. This thesis examines the multi-code multi-packet transmission (MCMPT) scheme for wireless CDMA ad hoc networks operating in a generic Nakagami-m fading channel. Based on the instantaneous good channel conditions in a Nakagami-m fading channel, a node can initiate a flexible number of parallel transmissions of multiple packets with multiple codes. By exploiting the inherent time-varying channel conditions, MCMPT gains

a substantial performance improvement, in terms of expected forward progress per hop. In contrast, conventional single packet transmission ignores the varying channel conditions and thus suffers significant performance degradation with regard to the maximum forward progress.

Finally, this thesis addresses the topology control in wireless multi-hop ad hoc networks with respect to k -connectivity property. Most existing work relies on a simplistic channel propagation model to investigate the critical transmission range for k -connectivity. This thesis studies the network performance in terms of successful link probability and k -connectivity probability by adopting a realistic channel model that takes into account log-normal shadowing and Nakagami-m fading. With the shadowing and fading environment, it examines the critical density to ensure that the probability of k -connectivity is close to 1. The impacts of the shadowing parameters and fading characteristics on the k -connectivity property are examined.

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List of Abbreviations

ABCP	Access-Based Clustering Protocol
ACK	positive Acknowledgement
ARQ	Automatic Request Repeat
AWGN	Additional White Gaussian Noise
BER	Bit Error Rate
BTMA	Busy Tone Multiple Access
CA	Code Acquisition
CABC	Channel Access-Based Clustering
CACK	Code Acknowledgement
CAM	Code Assignment Message
CA-TPCMMP	Cluster-Adaptive Two-Phase Coding Multi-channel MAC Protocol
CBR	Constant Bit Rate
CBRP	Cluster Based Routing Protocol
cdf	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CH	Cluster Head

CHMA	Channel Hopping Multiple Access
CL	Cell Leader
CM	Cell/Cluster Member
COS	Confirmation of Slot
CPT	Conventional Packet Transmission
CREP	Code Reply
CREQ	Code Request
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear to Send
DBTMA	Dual Busy Tone Multiple Access
DCF	Distributed Coordination Function
DIFS	Distributed Inter-Frame Space
DS/BPSK	Direct Sequence/Binary Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
ETP	Exposed Terminal Problem
FAMA	Floor Acquisition Multiple Access
FAMA-NCS	Floor Acquisition Multiple Access Non-persistent Carrier Sense
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FPRP	Five Phase Reservation Protocol
GAMA	Group Allocation Multiple Access

GPS	Global Positioning System
HACK	Handover Acknowledgement
HAGR	Agree to Handover
HAMA	Hybrid Activation Multiple Access
HREA	Ready to Handover
HREQ	Handover Request
HRMA	Hop-Reservation Multiple Access
HTP	Hidden Terminal Problem
IID	Independent and Identical Distributed
IETF	Internet Engineering Task Force
IFS	Inter-Frame Space
LA-TPCMMP	Location-Aware Two-Phase Coding Multi-channel MAC Protocol
LD	Leader Declaration
LH	Leadership Handover
LLC	Logical Link Control
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
MACAW	Multiple Access Collision Avoidance for Wireless
MAI	Multiple Access Interference
MANET	Mobile Ad hoc Networks
MCMPT	Multi-Code Multi-Packet Transmission
NACK	Negative Acknowledgement

NAV	Network Allocation Vector
NS	Network Simulator
PAMAS	Power Aware Multiple-Access Protocol
PCF	Point Coordination Function
PDA	Personal Digital Assistant
pdf	Probability Density Function
PN	Pseudo Noise
QoS	Quality of Service
RCC	Random Competition-based Clustering
RFS	Request for Slot
RI-BTMA	Receiver-Initiated Busy Tone Multiple Access
RICH-DP	Receiver-Initiated Channel Hopping with Dual polling
RTS	Request to Send
SIFS	Short Inter-Frame Space
SINR	Signal to Interference and Noise Ratio
SMPT	Simultaneous MAC Packet Transmission
SNMS	Sequence Neighbor Multiple Access
ST	Switching
TA	Traditional Algorithms
TBMAC	Time Bounded Medium Access Control
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access

UDP User Datagram Packet

UxDMA Unified Time/Frequency/Code Division Multiple Access

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Chapter 1

Introduction

A spontaneous self-organization and self-configuration of a collection of wireless nodes that share a common wireless radio spectrum, are now referred to as wireless ad hoc networks (also called packet radio networks or multi-hop wireless networks). An ad hoc network could provide a temporary wireless network to accomplish some tasks in scenarios where pre-deployment of a fixed communication infrastructure is difficult or unavailable. If the nodes are freely moving, it is termed as mobile ad hoc networks (MANETs). As shown in Fig. 1.1, a wireless ad hoc network is distinctive from the traditional wireless infrastructure network, typically e.g. cellular network, in that it is a purely distributed wireless network without central control and fixed infrastructure, instead with an emphasis on distributed coordination. In a traditional cellular network, the base stations are able to manage the radio access of the wireless users within their cells and coordinate with each other to control handoff as well as informing the users the appropriate transmission power to mitigate interference. All the communications occur between the mobile nodes and the base stations or access points, which hence can be accomplished within one hop. In contrast, for a MANET, there is no base stations to deploy and manage and hence

Figure 1.1: A snapshot of cellular network and ad hoc network

wireless nodes have to instantly self-deploy without any central administration. Due to the inherent characteristics of ad hoc networks, many challenges arise from it. Since the topology is dynamically changing without any predictable pattern, the nodes have to efficiently and dynamically reorganize the network with the flexible topology knowledge. Besides, mobile nodes are essentially power supplied with the limited-lifetime batteries and can not be recharged in time, which leads to the transmission power constraint for a transmitter. Accordingly, a source node has to either directly communicate with its destination node if they are close enough or coordinately conduct the data transmission via the intermediate nodes to relay, which hence gives rise to the issues of how to cooperate to discover the route and forward data, i.e. routing problem. In a MANET, wireless nodes share a common radio resource and always compete for the limited wireless bandwidth resource. The dynamic changing topology coupled with the sharing of the scarce wireless radio spectrum brings forward the new problem of contentions and collisions. This

naturally poses a fundamental issue of how to coordinate the access of the common medium efficiently without central administration.

An exploding demand for the emerging military and civilian applications has fueled significant development of MANETs in recent years. In the case of the battle fields and natural disaster area by earthquake or hurricane, it is very possible that the infrastructure network is damaged. Hence, rapid deployment and rescue operations of ambulances, tanks, or planes, necessitate a MANET to provide an instantaneous communication. In a wireless point-to-point meeting or distributed scientific experiment on a campus, there is a large amount of mobile data exchange between the users that carry some commercially available computing devices, such as laptops and personal digital assistants (PDAs). This requires the platform of a MANET to quickly self-organize and cooperatively perform data exchange, instead of a pre-configured infrastructure network. Furthermore, the developing technologies of mobile computing as well as the widespread availability of portable computing devices, will facilitate more and more applications of MANET technology.

The implicit characteristics of ad hoc networks bring up a set of new underlying assumptions and hence require new protocol design which extends beyond those design for cellular networks. There are growing interests and importance for research in MANETs. Specific organization such as Internet Engineering Task Force (IETF) [1] has been formed to deal with the issues for MANET and extensive work has been devoted in these fields to improve the network performance.

1.1 Motivation and Objective

As shown in Fig. 1.2, the simplified TCP/IP protocol stack of a MANET, that is similar to the ISO OSI seven-layer network structure [2] that has been developed for building a protocol stack architecture for the communication network, consists of the physical layer, data link layer, network layer, transport layer and application layer with each layer serving for a particular purpose. Data link layer interacts between physical layer, that specifies the characteristics of the transmission medium and addresses the issues such as modulation as well as coding etc., and network layer, that takes the task of discovering a route from the source node to the destination node. Since the wireless communication channel is inherently prone to error, logical link control (LLC) layer, referred to as a sub-layer of data link layer, provides the functionality to protect the data against the channel errors by adding the redundant information bits to the data bits, e.g., forward error correction (FEC). The lower sub-layer, i.e., medium access control (MAC), fits as the other part of the data link layer, responsible for coordinating the access of the nodes to the shared resource. Since the MAC layer has an immediate impact on the efficient and fair utilization of the wireless channel, it determines the network performance, to a large extent. To efficiently utilize the precious wireless resource and avoid excessive collisions, nodes within the neighborhood should cooperate with each other. Towards this end, it is critical to design a good medium-access protocol to ensure efficient channel utilization under the constraint of a limited bandwidth resource.

Several central problems related with MAC in wireless ad hoc networks are the

Figure 1.2: The simplified TCP/IP protocol stack of a MANET

hidden terminal problem (HTP) and exposed terminal problem (ETP) [3], which can cause a significant system performance degradation. The problem of how to eliminate them remains to be a big concern to the research communities. Although the classical IEEE 802.11 distributed coordination function (DCF) access [4] has been proposed, it focuses on single channel MAC protocol, which however is not good enough to deal with some of these problems. Instead, one of these problems provides the motivation for us to explore the utilization of multiple channels in a MAC protocol. Indeed, the IEEE 802.11b standard specifies 14 channels available for communications and IEEE 802.11a standard specifies 4 channels for outdoor and 8 channels for indoor applications. Nevertheless, IEEE 802.11 DCF is designed only for single channel and ignores such multi-channel resource, which causes throughput degradation and latency to increase under heavy traffic load. Multiple channel MAC protocol is a better approach as it can enable concurrent transmission via the technologies, including time division multiple access (TDMA) [5] and frequency

division multiple access (FDMA) [5] as well as code division multiple access (CDMA) [5], and hence substantially overcome these problems. Based upon this, one would seek to design a multi-channel MAC protocol for MANETs to eliminate the HTP and ETP and achieve better system performance. In this thesis, the focus is on the design and analysis of CDMA based multi-channel MAC protocol considering that orthogonal codes are a rich resource [6] compared with frequency bands and time slots.

A remarkable fact in a MANET is that mobile nodes are with a limited amount of energy supply. The sudden expiry of some nodes may jeopard the connectivity of the entire network, not to mention that the node itself is out of the function. Hence, a network should be designed so that energy can be conserved as more as possible. In fact, large quantity of control overhead constitutes a major cause and source of additional energy consumption. In a CDMA-based multi-channel MAC protocol for MANETs, the criteria of distributed code assignment is that nodes within two-hop separation should adopt different transmission codes, in order to avoid the HTP. Based upon it, traditional protocols require the exchanges of neighborhood information within two-hop separation to do the code assignment, which leads to numerous control overhead, especially under a heavy traffic load. It becomes important in the context of energy-constrained nodes, to mitigate such expensive control overhead for code assignment, as it can significantly degrade the network performance with regard to bandwidth under-utilization and energy inefficiency as well as large delays. To date, there is no an efficient code assignment scheme for CDMA-based

multi-channel MAC protocol in MANETs.

Nowadays, the location information is easy to be available through GPS [7] [8]. We, hence, are inspired to develop a new location-based approach for CDMA-based multi-channel MAC protocol, with the purpose of mitigating the heavy control overhead. Furthermore, the concept of the dynamic clustering [9] has been widely explored in MANETs to alleviate the control overhead. Considerable work [10] [11] [12] has been dedicated to building up a hierarchical structure in a large-scale MANET. The research into this topic provides the insight into a new design and algorithm of combining the multi-channel MAC protocol with the dynamic clustering, in order to develop a comprehensive and promising protocol that can not only combat the heavy control overhead but also be well-suited for some particular cases where the location information is difficult to be obtained.

As it is well known, wireless propagation environment is subject to serious multipath fading phenomena as well as interference [5] and hence the channel conditions are time-varying. Actually, time-varying channel conditions offer numerous opportunities to exploit the substantial system performance improvement. There is an straightforward insight to increase the number of parallel transmission in an instantaneous good channel condition while to decrease it in an impaired channel condition when satisfying required signal to interference plus noise ratio (SINR) [5] for the correct packet reception and recovery. However, none of the existing work addresses the issues of the network performance improvement, in terms of one important performance metric, called expected forward progress, by exploiting the time-varying

channel conditions in a fading channel. Naturally, we are motivated to examine the tradeoff between having several simultaneous transmission and acceptable SINR, and to find the optimal number of parallel transmission in each channel state in order to maximize the expected forward progress per hop.

Extension of this work occurs in similar cases related to one fundamental property in topology control of wireless ad hoc networks, i.e., connectivity property [13]. Under the channel conditions of shadowing and fading, k -connectivity [14], one important topological property used to ensure a node in the network to be connected with at least k neighbors with high probability, remains to be an open issue rather than the simple range assignment problem [14]. Even though considerable studies have discussed about k -connectivity for topology control, most of them relies on a simplistic channel propagation model. Unfortunately, wireless channel is suffering from the propagation impairments such as multi-path fading, shadowing and path loss. Hence, it is more reasonable to study the k -connectivity performance with respect to the impact of channel impairment characteristics.

1.2 Contribution of the Thesis

This thesis is composed of three pieces of work. The first major work of this thesis is to propose two CDMA-based multi-channel MAC protocols to mitigate the heavy control overhead of code assignment in MANETs. The second major work of this thesis is to investigate the physical layer aspect of a proposed transmission scheme by taking into channel conditions. The third piece of work of this thesis is to study

the topology control with respect to k -connectivity.

The most important contribution of this thesis is that it proposes a novel scalable code assignment algorithm for large-scale MANETs, termed as two-phase coding scheme, wherein the first-phase code is used to broaden the spatial reuse and the second-phase code is employed to distinguish between different nodes in one specific area. Specifically, it is developed under two different network backgrounds, i.e., location-dependent and clustering-adaptive.

For the case that the location information is available, a new location-aware two-phase coding multi-channel MAC protocol (LA-TPCMMP) is presented for large-scale dense MANETs. A cell-based configuration for two-phase coding scheme is introduced to enable the simultaneous transmissions, where the first-phase codes are used for differentiating the adjacent cells and the second-phase codes are employed for distinguishing the nodes in one specific cell. The proposed scheme eliminates the HTP during data transmission without requiring periodical exchange of neighborhood information. Furthermore, the mechanism of collision resolution in the control channel is presented. The performance of the proposed protocol is analyzed in terms of control overhead and delay. The theoretical results are confirmed by extensive simulations and it is demonstrated that the new protocol significantly outperforms the traditional CDMA-based multi-channel MAC protocols.

Furthermore, two-phase coding scheme is integrated with clustering to eliminate the dependence to the location information and the cluster-adaptive two-phase coding multi-channel MAC protocol (CA-TPCMMP) is introduced for MANETs. Now,

the first-phase codes are used for differentiating the neighboring clusters and the second-phase codes are employed to distinguish the nodes in a specific cluster. CA-TPCMMP effectively incorporates the procedure of code assignment with dynamic clustering and thus substantially reduces the control overhead of code assignment in a CDMA-based multi-channel MAC protocol while simultaneously combating the HTP. The confliction detection and confliction resolution mechanisms for the allocation of the first-phase codes as well as the collision avoidance mechanism for the allocation of the second-phase codes in the control channel, are also introduced. Furthermore, the theoretical analysis in terms of control overhead and delay are presented. Extensive simulation results verify that substantial improvement can be achieved by the proposed protocol over the traditional distributed CDMA-based multi-channel MAC algorithms with or without clustering.

For the third part of this thesis, the probability density function of multiple access interference (MAI) [5] power is derived under a generic Nakagami-m fading channel model. The previous MAI distribution in the Rayleigh fading channel [15] is shown to follow as a special case of the derivation of this thesis. Furthermore, considering that conventional packet transmission (CPT) only adopts the single-code single-packet transmission, a multi-code multi-packet transmission (MCMPT) scheme is proposed for wireless CDMA ad hoc networks operating in a Nakagami-m fading channel to increase the performance in terms of one important network performance metric, i.e., the expected forward progress. Based on the instantaneous good channel conditions in a Nakagami-m fading channel, a node can initiate

a flexible number of parallel transmission of multiple packets on multiple codes. By exploiting varying channel conditions, the analytical model is developed to examine the maximum expected progress per hop and optimum number of parallel transmission in MCMPT under the Nakagami- m fading channel. Numerical results show that adaptive MCMPT considering varying channel conditions not only outperforms the nonadaptive CPT, but also achieves a better progress improvement with the increasing values of parameter m in a slowly-varying Nakagami- m fading channel.

Finally, the topology properties with respect to link successful probability and k -connectivity probability, are studied, by taking into account both log-normal shadowing and Nakagami- m fading in wireless ad hoc networks. Given a certain number of nodes distributed according to a spatial probability density function, the critical density to keep the probability that the entire network is k -connected close to 1, is examined. The impacts of the fading characteristics and shadowing parameters on the k -connectivity are illustrated and discussed.

1.3 Outline of the Thesis

The rest of this thesis is organized as follows. Chapter 2 summarizes the background literature and shows the motivation for the later studies. Chapter 3 introduces the two-phase coding scheme and proposes LA-TPCMMP. The detailed mathematical model is developed and extensive simulations are given to compare it with the traditional CDMA-based multi-channel MAC protocols. Chapter 4 integrates the

two-phase coding scheme with the concept of the clustering and proposes the CA-TPCMMP. The performance is examined by the detailed theoretical analysis. Furthermore, simulations are provided to verify that CA-TPCMMP outperforms the traditional CDMA-based multi-channel MAC protocols with or without clustering. Chapter 5 generalizes the MAI distribution in a Nakagami-m fading wireless CDMA ad hoc networks and proposes a scheme of MCMPT for wireless CDMA ad hoc networks. Numerical results are provided. Chapter 6 studies the topology control with respect to k -connectivity by taking into account the log-normal shadowing and Nakagami-m fading phenomena. Chapter 7 summarizes this thesis and points out the further areas of research stipulated in these directions.

Chapter 2

Literature Overview

This chapter provides an overview into the issues addressed in this thesis and explains the background and motivation. Section 2.1 begins by summarizing the medium access modes of MAC work, then proceeds to define the classical problems, and surveys the existing work of collision avoidance in single channel and multi-channel approaches. Next, it presents the related work of CDMA-based multi-channel MAC protocols and introduces the knowledge of two different network backgrounds as well as explains the ensuing natural possibility to explore a new multi-channel protocol. Section 2.2 reviews the adaptive techniques by considering the channel conditions in wireless networks and describes the existing multi-code systems as well as the ensuing possibility to explore the MCMPT. Section 2.3 discusses the topology control with respect to the simple range assignment problem and k -connectivity in a simplistic channel model, and hence shows the open problem.

2.1 Background of MAC Protocols

MAC protocols regulate the access of wireless terminals to the shared medium resource and play a critical role in the efficient and fair utilization of the wireless

channel. The features of a MANET, such as the lack of centralized control, limited bandwidth resource, flexible topology, energy-constrained terminals and the inherent nature of the wireless channel, brings forward new issues like collision avoidance, which translates into new challenges. The design of MAC protocols for these types of networks is of utmost importance.

2.1.1 Medium Access Modes

In general, MAC layer protocols¹ can be classified as two categories, i.e., centralized access mode and distributed access mode, as shown in Fig. 2.1. Centralized access mode employs (1) polling, (2) token-passing to ensure data transmission free of collisions. The IEEE 802.11 point coordination function (PCF) [4] is one common example of a centralized algorithm used to provide contention-free service. Although a centralized access design is free of contention and close to the optimum with each channel access under the central control, it does not apply to MANETs, due to the absence of centralized administration. Contention-based distributed access mode is usually targeted for MANETs, as it can achieve good-degree scalability. Whenever there is a demand for data transmission, nodes will contend to specify a channel in the shared wireless radio resource before a transmission is initiated. As a consequence, collision is caused by simultaneous transmissions in the vicinity and thus significant interference may occur. This, in turn, seriously degrades the throughput performance. The IEEE 802.11 DCF access is a typical distributed MAC protocol.

¹The comprehensive classification can be referred to [16].

Figure 2.1: Basic medium access modes of MAC layer protocols

2.1.2 Classical Problems

To date, there are many ground-breaking research carried out in the field of wireless ad hoc networks to reduce collisions. However, the most difficult problems associated with MAC in MANETs are the notorious HTP and ETP [3], as shown in Fig. 2.2 and Fig. 2.3 respectively. A hidden node is one that is within the range of the intended receiver but out of the range of the transmitter. In Fig. 2.2, node A is hidden from node C . When node A is transmitting to node B , node C , being within the transmission range of node B while out of the transmission range of node A , cannot detect the carrier and may therefore send data to node B simultaneously. As a consequence, data collisions occur at node B and packet is lost. Instead, an exposed node is one that is within the range of the transmitter but out of the range of the receiver. As shown in Fig. 2.3, node C is exposed to node B . When node B is transmitting to node A , node C , being within the transmission range of node B while out of the transmission range of node A , senses the busy channel and hence defers its own transmission to node D . However, this is unnecessary because in no

Figure 2.2: Hidden terminal problem

Figure 2.3: Exposed terminal problem

sense the transmission from node *C* to *D* will interfere the transmission from node *B* to *A*. As a result, it can not make the best of the channel. The classical HTP and ETP act as the bottleneck and exert an adverse influence so that the throughput is significantly limited in MANETs. It is challenging to avoid collisions in a network fraught with HTP and ETP.

Figure 2.4: The diagram of distributed contention-based MAC protocols

2.1.3 Review of Existing Related Work

Fig. 2.4 gives the diagram of the various distributed contention-based MAC protocols.

Single Channel MAC Approaches

There have been a large body of single channel MAC approaches among the contention-based distributed MAC protocols for the MANETs. The readers are advised to refer to [17] [18] for a list of protocols.

The ALOHA protocol [19] was one of the earliest random access protocols for

wireless communication. Nodes send data whenever they have data traffic, irrespective of the state of the channel. As a consequence, it is vulnerable to the period of twice a packet length, which causes that the maximum channel throughput is very low. Slotted ALOHA [20][21] improves pure ALOHA by dividing the overall time into many slotted time segments. Nodes only transmit at the beginning of a time slot to achieve the time synchronization, which hence reduces the vulnerability period of a transmission and doubles the throughput, relative to the pure ALOHA.

Furthermore, carrier sense, including physical carrier sense by physical layer and virtual carrier sense in MAC layer through network allocation vector (NAV), reduces collisions by deferring transmission if any of the carrier sense mechanisms senses that the channel is busy and proceeds to generate random back-off before the initiation of next transmission attempt.

The classical example in this case is carrier sense multiple access (CSMA) [22], which tries to avoid collisions through physical carrier sensing before data transmission. In CSMA, the deferring duration can be determined by various methods such as n -persistent algorithms [22]. The operations of n -persistent algorithms work as follows. In 1-persistent CSMA, the node keeps listening until the channel is free and then transmits its data packet. In non-persistent CSMA, after sensing that the channel is busy, the node enters a back-off state by setting a randomized timer and continues to sense the channel until the timer expires. If the channel is busy, the node resumes the timer. Otherwise, it transmits the data packet. In p -persistent CSMA, the channel is assumed to be time slotted. Unlike the 1-persistent CSMA,

the node transmits its packet during the sensed free slot with probability p and stays silent during the busy slot with probability $1 - p$. Although CSMA yields a markedly good performance over ALOHA when the network is with low traffic load, it is prone to collisions, in particular the HTP, when the transmitters sense that the channel is free and attempt to transmit simultaneously. As a result, the performance may degrade to that of ALOHA.

Multiple access collision avoidance (MACA) [23] is one scheme based on virtual carrier sense, where nodes depend on RTS/CTS/DATA (request to send /clear to send) three-way handshake mechanism to inhibit collisions to the upcoming data transmissions. A transmitter first sends a short-length RTS control packet to the receiver, who responds with a short-length CTS control packet. Only after receiving CTS successfully, the transmitter may commence the data packet transmission immediately. Other neighboring nodes that overhear the RTS packet have to defer their transmission for a long enough interval to refrain from the collisions to the upcoming CTS packet, and other nodes that overhear the CTS packet defer for the duration of the upcoming data transmissions. The apparent problem with MACA lies in that nodes within the transmission range of a transmitter do not know if the RTS/CTS exchange was successful and therefore the binary exponential back-off algorithm before next transmission attempt is not fair. MACAW [24] does the enhancement by adding ACK signal to solve the problem that MACA suffers from. In addition, it does the complement with a distributed binary exponential back-off algorithm to achieve fairness. However, these kinds of handshaking mechanism only

prevent the HTP and ETP to some extents, rather than completely eliminate them, as proven in [25].

Floor acquisition multiple access (FAMA) [26][27] first uses both physical carrier sensing and RTS/CTS handshake mechanism to ensure the acquisition of the floor, in its sense, before data transmission. FAMA was further extended to FAMA non-persistent carrier sensing (FAMA-NCS) [28] by employing a longer CTS packet to serve as a busy tone to ensure correct floor acquisition and collision-free data packet reception. Although FAMA-NCS inhibits the HTP, it does not solve the ETP. Moreover, FAMA and its evolutions are still based on reservations, which is not efficient under heavy loads due to frequent contentions. A more complete single-channel solution [25] suggests enhancements to RTS/CTS handshaking. Even though this solution increases the number of the hidden nodes that can be eliminated, it pays the cost of increasing the overhead due to more involved handshaking.

IEEE 802.11 DCF access method [4] extends the FAMA with an addition of ACK control packet to the basic RTS/CTS dialogue and implements CSMA with collision avoidance (CSMA/CA) [29] that is originally designed for wired local area networks. Fig. 2.5 shows the basic operation mechanism of IEEE 802.11 DCF access. There are several types of inter-frame spacing (IFS) slots, i.e., respectively the short IFS (SIFS) and distributed IFS (DIFS) in an increasing order of length. Different types of packets can require the medium to be free for the duration of a different type of IFS. IEEE 802.11 DCF access works as follows. A node in request for data transmission first senses the channel and if the channel is free for a duration of DIFS, it can

transmit immediately. Otherwise, it defers its transmission, enters the state of collision avoidance and backs off from transmitting for a specified interval. During the collision avoidance, if the node still senses that the channel is busy, it will suspend its back-off timer until the channel is sensed free for a duration of DIFS. Afterwards, it employs the same medium sense and resumes the back-off for a random amount of time. After executing CSMA/CA, the node then employs RTS/CTS/DATA/ACK handshake mechanism to do the data exchange with the receivers. The transmitter sends a RTS control packet followed by the receiver replying a CTS packet correspondingly to indicate its readiness for the data transmission. Then the transmitter can send its data packet and the receiver confirms using ACK packet. The control packets such as RTS, CTS or ACK are transmitted after the medium has been free for a duration of SIFS. Each control packet contains a duration information up to which the wireless channel is expected to be busy. Thus each node maintains a network allocation vector (NAV) that is correspondingly updated according to the overheard duration message. Upon hearing RTS or CTS, other nodes defer their access to the channel for a duration indicated by NAV to prevent a collision with the existing data transmission until ACK message is received.

Although IEEE 802.11 DCF is targeted at solving the HTP, there are serious contentions and collisions from RTS/CTS control packets as the number of nodes increases. As a consequence, the network performance significantly aggravates with the channel under-utilization and unbounded maximum delay for data transmission. As reported in [30], there is serious instability and unfairness problems when trans-

- A transmitter send RTS message after waiting for DIFS
- The receiver acknowledge via CTS after SIFS upon receiving RTS
- The transmitter can now send data at once
- The receiver acknowledge via ACK message
- Other nodes stay silent when hearing NAV message

Figure 2.5: IEEE 802.11 DCF access method

mission control protocol (TCP) is used on top of 802.11 DCF, which is attributed to the fact of inefficiency in dealing with the HTP and ETP.

Multi-Channel MAC Approaches

Multi-channel MAC protocols have been recommended to combat collisions and increase simultaneous transmissions. One approach is to use a dedicated channel for control packets exchange [3] [31] [32] [33]. Negotiation for data exchange is accomplished in the control channel with a small bandwidth, thus providing the possibility that ongoing data transmissions are free of interference by the control packets. Another approach is by dividing the available radio spectrum into multiple channels by means of frequency bands (in FDMA) [34] [35] [36], time slots (in TDMA) [37] [38] or orthogonal codes (in CDMA) [39][6]. With the use of multiple channels, data can

be transmitted simultaneously in the same region with different channels free of interference. In the latter approach, the central design issues have been attributed to two aspects, i.e., how to assign different channels such as different frequency bands or orthogonal codes to different nodes without central administration and how to resolve the contention and collision problems, in particular, the HTP and ETP.

Power aware multi-access protocol with signaling for ad hoc network (PAMAS) [31] first separates the signaling channel (i.e. control channel) with the data channel, which avoids collisions from control packets and data packets. Data transmission is commenced on the data channel only after successful RTS/CTS negotiations on the control channel. Another approach known as busy tone multiple access (BTMA) [3] employs an out-of-band busy tone to inform the busy status of the specific channel, thereby inhibiting the collision from the hidden terminals. BTMA eliminates the HTP at the expense of aggravating the ETP. Receiver initiated busy tone multiple access (RI-BTMA) [32] improves it by inhibiting the nodes within the receiving range of the receiver to initiate data transmission. However, the packet transmission is vulnerable to collisions in the duration that one data packet is correctly decoded as it takes a long time for RI-BTMA to initiate the busy tone. As a result, RI-BTMA reduces the number of exposed terminals to some extent at the cost of not completely inhibiting the hidden terminals. Recently, dual busy tone multiple access (DBTMA) [33] proposes that two busy tones are employed to indicate that the channel is busy and inhibit the data collisions. However, it requires more transceivers, which is not economical from the perspective of practicability.

The group allocation multiple access (GAMA) [37] protocol proposes that nodes in demand for data transmission will compete to become a member of a transmission group at the intended receiver in order to transmit a collision-free data packet. It specifies that nodes share the floor in a orderly manner and establish variable-length frames based on traffic demand. Whenever there is low traffic load in the network, GAMA behaves almost like CSMA. Under heavy traffic load, it tends to perform similar to TDMA. More recently, five phase reservation protocol (FPRP) [38] proposes that multiple reservations of time slots may be made simultaneously throughout the network to enable faster convergence of the transmission procedure. However, it requires the network-wide time synchronization, which is easy to be achieved in centralized networks by referring to base stations, instead of a distributed network for a large-scale MANET.

Both hop-reservation multiple access (HRMA) [34] and channel hopping multiple access (CHMA) [35] regulate that all nodes follow a common frequency hop pattern and employ the sender-initiated collision avoidance handshake to determine which sender-receiver pair should dwell in the same hop in order to exchange data while other nodes continue to hop. They reduce the collisions of control packets from RTS and CTS to some extent, but require the strict clock synchronization. Receiver initiated channel-hopping with dual polling (RICH-DP) [40] is the first MAC protocol based on a receiver-initiated collision avoidance mechanism, where all nodes listen to a common control channel that may be a frequency band, a spreading code or a combination of both. The polling and polled nodes can transmit data after a

successful handshake to ensure the reception at the receiver free of collision in the presence of hidden terminals.

Multi-channel CSMA protocol presented in [36] assumes that each mobile node has multiple receivers concurrently listening on multiple available frequency channels such that nodes can adjust their receiving frequency to multiple frequency channels. A transmitter uses carrier sensing to detect a free channel and tends to prefer its latest used channel, instead of randomly choosing a new channel. Similar approach is employed in [41] with the addition that the best channel is selected according to the channel condition at the receiver side. However, they incur a higher hardware cost due to the requirement of multiple transceivers, e.g., the transceiver number is set to 10 or 20 referring to their simulations, which is impractically commercially.

Sequence neighbor multiple access (SNMS) [42] employs a sender-based data transmission strategy to promote multi-cast transmission with the assumption that the channels of any two nodes are different and have been successfully pre-assigned in the networks. However, the problem of how to assign these channels is not addressed in that paper, which is a difficult issue in a multi-channel MAC protocol design.

Although multiple time slots and frequency bands have been exploited to increase throughput and reduce collisions in the presence of heavy traffic in MANETs, the network capacity is limited by the strict requirement of the excessive coordination. Ideally, the pre-allocation of the resources prevents neighboring nodes from interfering with each another during the data transmission, as each node is assigned a unique time slot or frequency band to transmit its data. However, it is not always

possible to have as many data channels as there are nodes in the network, due to the limited spectrum resource. Furthermore, when the network is with low traffic or the number of active nodes in request for data transmission is small, it incurs the serious channel under-utilization with the scarce resource allocated to the inactive nodes. In order to reduce resource waste, the reallocation of wireless bandwidth translates into significant overhead, as the nodes in request to transmit have to be identified by exchanging control packets. Moreover, FDMA-based multi-channel MAC protocols require some additional guard frequency bands to ensure that the signal transmissions between the neighboring frequency bands do not interfere with each other, besides the fact of high hardware cost. Likewise, TDMA-based multi-channel MAC protocols incur large latency when the network is heavy-loaded as nodes have to wait for their specific time slots for transmission, besides the fact that clock synchronization is often difficult to be achieved in the context of a large-scale MANETs due to the absence of central administration.

Beyond all doubt, some protocols have been presented to utilize direct sequence spreading codes to enable simultaneous transmissions [39][6]. Indeed, such CDMA systems provide more flexibility as it allows the simultaneous transmission of several spread-spectrum waveforms over the same bandwidth by using approximately orthogonal codes, typically a *pseudo noise* (PN) sequence, with the graceful performance degradation, thereby leading to better channel utilization compared to TDMA/FDMA systems. Along with other benefits, such as an increasing tolerance to jamming and narrow band interference as well as multi-path effect, CDMA has

attracted much attentions. For this thesis, therefore, the focus is on CDMA-based multi-channel MAC protocol design for MANETs.

CDMA Techniques

In the direct sequence spread spectrum (DSSS) system, the spread spectrum signals are generated by spreading (i.e., multiplying) the digital data signal with a PN code [5], namely a unique spreading code, specifically assigned to each node. A PN code is statistically random sequence, e.g., the Walsh codes based on a Walsh matrix [5]. The intended receiver is required to know the spreading code hold by the transmitter, *a priori*. The receiver recovers the original data signal by de-spreading the received signal (i.e., multiplying the received signal with a de-spreading PN code). The data information may only be restored at the receiver due to the perfect auto-relation property, when the de-spreading PN code is identical to the spreading code used at the transmitter. Multiple transmissions based on multiple orthogonal codes can be separated, due to the correlation property of the PN codes. This allows several concurrent transmitter-receiver pairs to communication over the same radio spectrum, provided that each transmitter employs its distinct PN code to do modulation, which is referred to as CDMA. In CDMA techniques, the unperfect orthogonality, i.e., nonzero cross-correlations, between different CDMA codes may induce MAI [5].

Code Assignment Criteria in CDMA-Based Multi-Channel MAC Protocols

Based on it, a critical design issue in a MANET using CDMA is to determine an appropriate transmission code *a priori* for the chosen transmitter-receiver pair. For example, in cellular networks, the base stations take the responsibility of the code assignment to the mobile stations that request for voice/data transmission. However, the question of how to identify a definite transmission code for a transmitter-receiver pair before communication occurs in a MANET, is difficult, due to the absence of central administration. Limited by the number of the available orthogonal codes, the efficient code assignment with spatial reuse becomes to be of utmost importance in a large-scale MANET.

Various distributed code assignment schemes are discussed in [43], including transmitter-oriented code assignment, receiver-oriented code assignment and pairwise-oriented code assignment. For a transmitter-oriented code assignment, the transmitters adopt their own code as transmission code to do data modulation and the receivers tune into this corresponding code to receive the data. Instead, for a receiver-oriented code assignment, the transmitters use the receiver's codes as the transmission code and the receivers listen on their own code. As shown in Fig. 2.6 and Fig. 2.7, obviously, the interference occurs when two nodes within two-hop separation adopt the same transmission code and transmit at the same time. In Fig. 2.6, when two transmitters A and C are two-hop away, transmitter-oriented code assignment scheme incurs interference at node B because the same codes $C1$ are adopted

Transmitter-Oriented Code Assignment:

When node A and C adopt the same transmission code $C1$ as shown in the bracket and transmit simultaneously, the interference occurs at node B , even though they transmit for different receivers B and D respectively.

Figure 2.6: Interference occurs when two transmitters within two-hop separation use the same code

at A and C . Likewise, in Fig. 2.7, when two receivers B and D are two-hop away, receiver-oriented code assignment scheme incurs interference at node B because the same codes $C2$ are adopted at B and D . In order to avoid this kind of HTP, it is essential that no two nodes should share the same code for the spatial reuse of code if they are within two-hop separation.

2.1.4 Code Assignment Approaches in CDMA-Based Multi-Channel MAC Protocols

So far, considerable work has focused on code assignment in a CDMA-based multi-channel MAC design for MANETs. In order to avoid the HTP, the basic criterion of code assignment in such protocols is that the same codes are reused more than

Receiver-Oriented Code Assignment:

When node A and C transmit simultaneously for the receivers B and D respectively,
the interference occurs at node B, since the same code C2 is adopted in their respective receivers B and D.

Figure 2.7: Interference occurs when two receivers within two-hop separation use the same code

two hops away. A unified framework for (T/F/C)DMA channel assignment, called UxDMA algorithm, is exploited in [44], which extracts the common constraints for channel assignment and converts the channel assignment problem into a graph coloring problem known to be NP complete as well as proposes the collision-free scheduling approaches. Obviously, the requirement of the complete topology knowledge of the entire network poses a major challenge. Moreover, distributing the corresponding schedule across the entire network is workable in ad hoc networks. In order to solve this problem, a novel distributed neighbor-aware contention resolution algorithm, called hybrid activation multiple access (HAMA) [45], is introduced by defining different priorities to nodes and determining the channel access schedule for each time slot. However, HAMA requires promptly detecting and notifying the changes within a two-hop separation in order to harmonize code scheduling that

can avoid the HTP. Transmitter-oriented code assignment [46] explains that quasi-orthogonal codes are assigned to transmitters in a packet-radio network in such a way to eliminate the HTP. It also derives the bound on the minimum number of codes for correct code assignments. Code assignment was proven to be NP-hard and the optimal code assignment schemes for networks with special topologies and heuristic distributed code assignment algorithms are proposed in [47] with the aim of minimizing the number of orthogonal codes and eliminating the hidden terminal interference. SEEDEx algorithm [48] proposes that nodes exchange the seeds of their pseudo-random number generators within two-hop separation to know the schedules of each other such that the hidden terminals and exposed terminals can be identified in advance and reduced. The algorithm in [49] considers the case that nodes determine their transmission codes through broadcasting to neighbors within two-hop separation when it has data to transmit and gives the communication complexity of distributed assignment of codes in the worst case.

Although all these work [43] [45] [47] [48] [49] [50] [51] [52] have been devoted in distributed code assignment to avoid the HTP, they all assume that the complete neighborhood information is known, i.e., nodes broadcast their holding codes to their one-hop and two-hop neighbors such that nodes within two-hop separation adopt different codes as their transmission codes. The encountered problem is that as the user density in the network increases, there will be more collisions in broadcasting the codes even in a separated control channel. Furthermore, when the mobility of the network is particularly high, it is difficult for a node to obtain its accurate neigh-

neighborhood information in real time. As a consequence, some nodes within two-hop separation may select the same codes and the HTP can not be avoided. Moreover, frequent neighborhood exchanges in code assignment under high density and mobility incur heavy overhead and large delay, which seriously degrades the network performance. Regardless of the application, an efficient distributed code assignment algorithm is indispensable to reduce the control overhead and eliminate the HTP as well as achieve the scalability.

Location Based Protocols

Today, the outdoor location information can be easily obtained from the popularly used global positioning system (GPS) [7] [53]. Considering that location information has been widely utilized in routing protocols [8] [54], it is natural to exploit the location information for the distributed code assignment in a multi-channel MAC protocol.

Several location-based multi-channel MAC protocols have been proposed in the literature [55] [56]. Time bounder MAC (TBMAC) [55] employs the cellular structure to differentiate frequency bands distribution among the cells. In each cell, nodes in demand for data exchange contend for their specific time slots for data communications. GRID with channel borrowing (GRID-B) [56] proposes a dynamic channel allocation scheme with location awareness, where the physical area is partitioned into many squares called as grids with each grid assigned a default channel. A mobile node, upon in request for data transmission, dynamically computes the channels that it could borrow from the neighboring grids, based on the specific grid

where it is currently located. However, when the location accuracy is inadequate, a node near the border of the adjacent grids may incorrectly identify the grid where it is located. This will cause different nodes in the adjacent grids to choose the same channel allocated to that grid. As a consequence, HTP might still exist. Hence, we are inspired to design a location-based distributed code assignment scheme in a multi-channel MAC protocol.

Clustering Based Protocols

Nowadays, in the presence of dynamically changing network topologies due to nodes mobility, clustering [10] [12] appears to be an important mechanism employed to build up a hierarchical structure, which may achieve good scalability and alleviate the heavy control overhead in the context of a large-scale MANET. Through clustering, the total network topology is partitioned into small groups. Hence, the topological changes within a cluster do not affect the total network structure, which can mitigate the impact of the mobility on the network performance. In particular, clustering facilitates the control of transmission power [57], which therefore may reduce the interference and energy consumption. However, most of the existing literatures only focus on the pure algorithm design [9] [58] and hierarchical topology control [59] [60] as well as clustering-based routing protocol [11] [61] [62], without taking the medium access into account. Therefore, it makes sense to exploit an integrative cluster-based distributed code assignment scheme in a multi-channel MAC protocol.

2.2 Adaptive Techniques and Multi-Code System

Adaptive techniques, that consider the varying channel conditions, have been the promising approaches to increase wireless spectral efficiency and also satisfy the required communication quality for the specific applications. So far, much interest has been paid on the adaptive modulation and coding [63], constellation size [64] and packet length [65] [66] as well as adjusting the FEC coding rate [67] [68] under varying channel conditions in a wireless network. Recently, the benefit of adaptive modulation is investigated in [69] by considering varying channel state information in a CDMA multi-hop packet radio network. However, few of them considers a flexible number of parallel packet transmission based on the varying channel conditions in wireless CDMA ad hoc networks.

In fact, nowadays, many existing wireless systems, by referring to [70] [71], are multi-code CDMA systems, which provides the possibility that a transmitter sends multiple packets to a receiver by using several code channels. However, the conventional transmission is designed to transmit one packet after the other and thus do not take advantage of the multiple parallel CDMA code channels. Even though simultaneous MAC packet transmission (SMPT) [70] proposes the scheme of transmitting multiple packets in parallel according to packet loss resulting from the unreliable wireless link, it aims at stabilizing the link layer throughput to ensure high-quality multimedia services over wireless links. With the assumption that multiple codes are available at a node, we are inspired to study the physical performance of parallel multi-packet transmission on multiple codes for wireless CDMA ad hoc networks

operating in a generic fading channel. For instance, under a given spreading gain factor, we try to answer the question as to how many parallel transmissions are allowed for a node within a specific region to maintain the acceptable MAI performance over wireless channels experiencing fading. The flexible number of multi-packet transmission scheme regulates that each node monitors whether its packet transmission is successful or not depending on the interference level and reacts accordingly. Hence, it is especially well suited for wireless ad hoc networks without the requirement of a central administration to schedule packet transmission.

2.3 Topology Control

Considerable studies have discussed the issues such as the multi-path routing and the capacity [72] [73] in wireless ad hoc networks, where connectivity problem [74] [75] [76] [77] is a fundamental property and design metric. To date, connectivity has received quite a lot of attentions in the context of ad hoc networks. In particular, there have been much interest devoted in how many neighbors are necessary to achieve a certain performance requirement. Kleinrock and Silvester [78] argue that six is the magic number to maximize the one-hop forward progress of a packet. Furthermore, Takagi and Kleinrock [79] extend it and present that the number can be revised to eight. However, these results rely on the assumption that the transmission range of each node is fixed. Furthermore, Hou and Li [80] develop it and demonstrate that the magic number is six and eight when nodes are allowed to adjust their transmission range individually. Based on them, Hajek [81] shows that to

Figure 2.8: The propagation impairments of wireless channel and the actual coverage area of a node

maximize the transmission efficiency, namely the ratio of the expected progress to the transmission range, each node should have three nearest neighbors on average. Later, Ni and Chandler [82] prove that with the number of nodes in the network increasing, six or even eight neighbors on average is not enough to bring the network connected. More recently, Wan and Yi [14] take the connectivity into account and study the asymptotic transmission radius and critical neighbor number for k -connectivity in wireless ad hoc networks. However, existing work relies on a simplistic channel propagation model with the assumption that two nodes are connected if and only if their distance is less than a deterministic transmission radius.

Unfortunately, wireless channel is suffering from the propagation impairments such as path loss, multi-path fading and shadowing [5], as shown in Fig. 2.8(a). Due to the obstructions and irregularities in the surroundings of the transmitter and receiver, the radio signal is subject to severe degradation. As a result, as shown in

Fig. 2.8(b), the coverage area of a node is irregular rather than simply circular. It is essential to capture the channel impairment characteristics to formulate a realistic channel model. In some applications, we have to ensure a certain k –connectivity for the purpose of route diversity in ad hoc networks, in order to enhance the reliability of data communication and satisfy the quality of service (QoS) requirements. Hence, it is practical for us to investigate k –connectivity in a realistic channel model to provide insight to the design of wireless ad hoc networks.

Chapter 3

Location-Aware Two-Phase Coding Multi-Channel MAC Protocol for MANETs

3.1 Introduction

In this chapter, we provide the first contribution of our work, where we propose a novel location-aware multi-channel MAC protocol, termed as LA-TPCMMP. It is formulated for a large-scale dense MANET based on a scalable two-phase coding scheme. The first-phase code is used for differentiating adjacent cells and the second-phase code is employed for distinguishing nodes inside the specific cell. One salient feature of this protocol is that it completely eliminates the HTP during data transmission without requiring periodical exchange of neighborhood information. The sender obtains its first-phase code according to its location information, and exchanges a few control packets with its cell leader (CL) in the control channel to obtain its unique second-phase code. Contentions and collisions only occur in the

control channel when nodes contend to obtain the second-phase codes. In the data channel, no HTP will exist since any two nodes within two-hop separation, will adopt their unique quasi-orthogonal transmission codes. Furthermore, the mechanism of collision resolution in the control channel is explained in detail. Next, the performance analysis of the proposed protocol, in terms of control overhead and delay, is provided. Finally, the theoretical results are confirmed by extensive simulations and it is demonstrated that the new protocol significantly outperforms the traditional CDMA-based multi-channel MAC protocols.

The remainder of this chapter is organized as follows. Section 3.2 describes the design of LA-TPCMMP in detail. Section 3.3 presents the analysis of the control overhead of LA-TPCMMP. Section 3.3.4 gives the analysis of the average delay. Section 3.4 reviews the traditional code assignment algorithms and approximately analyzes their performance. Section 3.5 explains the simulation model, examines the performance of LA-TPCMMP in terms of average control overhead and delay and compares it with that of the traditional CDMA-based multi-channel algorithms. Section 3.6 concludes the chapter.

3.2 Protocol Design

LA-TPCMMP is proposed for a large-scale dense MANET, where the whole network is sub-divided into cells of hexagonal geographic structure with radius R , as shown in Fig. 3.1. Nowadays, GPS-related applications [8] are quickly gaining the popularity and the location information can be easily obtained by positioning devices such as

Figure 3.1: Cell distribution

GPS. Hence, in LA-TPCMMP, each node is equipped with some positioning devices such as GPS. A node can know its location information from positioning devices, and there is a predefined mapping from its location to the cell which it stays in.

The wireless channel is divided into the control channel and data channel. We assume that through the control channel all the nodes are able to operate in time-slotted mode and are correctly synchronized. LA-TPCMMP consists of five basic mechanisms including 1) initial CL election, 2) leadership handover, 3) code acquisition, 4) code reacquisition and 5) data transmission. The first four functions are implemented in the control channel whereas the last one is implemented in the data channel. Next, we describe the operations of the protocol.

Figure 3.2: Cell structure

3.2.1 Two-Phase Coding Scheme

This protocol introduces two-phase coding scheme, where the first-phase code is used for differentiating adjacent cells and the second-phase code is employed for distinguishing nodes in one specific cell. Similar to frequency reuse in cellular communications, different first-phase codes are required to cover the whole network. The reuse of the first-phase codes greatly increases the scalability of LA-TPCMMP.

Suppose each node in the network has its location information by means of some positioning technologies such as GPS. The CL is responsible for maintaining and assigning the second-phase codes to its cell members (CMs). The circular central part with radius R' of each cell is defined as the leader residence area as shown in Fig. 3.2, where G is the cell center and E is the CL.

Let us assume there exist a set of finite PN orthogonal codes for data transmission. We divide it into m sub-sets with n codes in each sub-set. Let C_1^i denote the

i_{th} sub-set and C_2^j denote the j_{th} PN code in the i_{th} sub-set, then the set of the first-phase codes is defined as $C_{FC} = \{C_1^i | i = 1, 2, \dots, m\}$ and the set of the second-phase codes is defined as $C_{SC} = \{C_2^j | j = 1, 2, \dots, n\}$. The set of the transmission codes is defined as $C_{TC} = \{(C_1^i, C_2^j) | C_1^i \in C_{FC}, C_2^j \in C_{SC}\}$ with each element being a joint first-phase and second-phase code and any two elements in C_{TC} are orthogonal. A Fig. 3.2 shows a CM A in cell i with its code (C_1^a, C_2^a) .

3.2.2 Sizes of Cell and Leader Residence Area

Let R_d denote the default transmission range of the nodes. As shown in Fig. 3.2, since a CL is located in the leader residence area with radius R' , it should satisfy $R + R' \leq R_d$ to ensure that all nodes in its cell are within its transmission range. Considering all cells are of the same radius R , it is easy to know that the minimal distance between any two nodes in different cells with the same first-phase codes is $\sqrt{7}R$ as shown in Fig. 3.1. In order to ensure that the same transmission codes appear at least two hops away, it is required that $\sqrt{7}R > 2R_d$. Accordingly, one has the lower and upper bound of R ,

$$\frac{2}{\sqrt{7}}R_d \doteq 0.7559R_d < R \leq R_d. \quad (3.1)$$

Thereby, the upper bound of R' can be derived from the following inequality

$$R' \leq R_d - R < (1 - \frac{2}{\sqrt{7}})R_d \doteq 0.244R_d. \quad (3.2)$$

Figure 3.3: Priority region partition in leader residence area

3.2.3 Operations of LA-TPCMMP

Let us divide the leader residence area into N_p different priority regions as shown in Fig. 3.3, which is used by the initial CL election and leadership handover. A node inside the leader residence area is located in region i ($i = 0, 1, \dots, N_p - 1$) when its distance R_c to the geographical center of the current cell follows $i = \lfloor \frac{R_c}{\delta} \rfloor$, where $\delta = R'/N_p$ and $\lfloor x \rfloor$ denotes the biggest integer smaller than x . Here, define $d_i = i\delta$. The priority level starts from 0. During the initial CL election and leadership handover, a node located in region i has higher priority to another node located in region j if $i < j$.

Initial CL is elected from the CMs inside the leader residence area in a distributed way. If a node within region i cannot get any response from the CL after ξ trials for code acquisition, it assumes that there is no CL in the current cell and begins the competition by broadcasting a Leader Declaration (LD) message to declare itself as

a CL after deferring a priority region-dependent period

$$T_i = T_{Li} + T'_{Ui}, \quad (3.3)$$

where T_{Li} is the minimal deferring value related to the priority region i and T'_{Ui} is the incremental deferring value which is randomly selected from $[0, T_{Ui})$ with T_{Ui} being the upper bound of T'_{Ui} . Obviously, $T_{Li} \leq T_i < T_{Li} + T_{Ui}$. Since nodes closer to the cell center is more favored, T_{Ui} and T_{Li} are respectively defined as

$$T_{Ui} = \omega(1 - e^{-(d_{i+1}^2 - d_i^2)/R'^2}) \quad (3.4)$$

and

$$T_{Li} = \begin{cases} 0, & i = 0 \\ \sum_{j=0}^{i-1} \omega(1 - e^{-(d_{j+1}^2 - d_j^2)/R'^2}), & i \geq 1 \end{cases} \quad (3.5)$$

where ω is a pre-defined parameter which should be determined by the density of nodes and transmission time of the specified control packets. The normalized ratio of area of region i can be derived as $(d_{i+1}^2 - d_i^2)/R'^2 = ((i+1)^2 - i^2)/N_p^2$. Thus, with these definitions, nodes within different priority regions adopt different T_{Li} and nodes within the same priority region adopt the random values between $[0, T_{Ui})$ for competition.

If a node inside the leader residence area hears the LD message from another node before it sends its own LD message, it gives up its competition without broadcasting its own LD message. The first node, which broadcasts the declaration, upgrades

Figure 3.4: The operations of leadership handover

itself as the CL. It is easy to see that if $i < j$, then $T_i < T_j$. Hence, a node within higher priority region always owns higher competition priority. In this way, the elected node is usually closer to the geographic center of its cell and more suitable to act as a CL. However, for the nodes within the same priority region, a random competition strategy is adopted.

If necessary, a CL will hand over the leadership and available second-phase code set to a more suitable member. As shown in Fig. 3.4, it initiates the leadership handover procedure by broadcasting a HandoverRequest (HREQ) message when it moves out of the leader residence area of its current cell and suspends its code allocation operations. CMs within the leader residence area of the current cell will respond according to the above-mentioned priority-based random competition strategy, where a node with a higher priority level has more chances to send a ReadytoHandover (HREA) message and the node that successfully transmits the HREA will become the new CL. After receiving HREA message, the CL

replies with the AgreetoHandover (HAGR) message with the available code set information piggybacked. Upon receiving the HAGR message from the original leader, the inherited node will upgrade itself to the CL by duplicating the information of the available code set, resume its right of code allocation and send the HandoverAcknowledgement (HACK) message. When the original CL receives the HACK message, it will downgrade itself as a normal CM and discard its information of the available code set. If a CL can not receive the responses from its CMs after a predefined period of τ_{to} , it will try to hand over the leadership again.

A transmitter-oriented data transmission similar to [46] is adopted. In LA-TPCMMP node i determines its first-phase code C_1^i according to the aforementioned predefined mapping as it knows its location information, and acquires its unique second-phase code C_2^i from its CL by sending the CodeRequest (CREQ) message with its reservation period $T_{sc(i)}$ piggybacked, as shown in Fig. 3.5. After receiving the CREQ message successfully, the CL allocates an unique available second-phase code from the available code set, records $T_{sc(i)}$ and replies with the CodeReply (CREP) message to the requesting CM. When node i hears the CREP message, it sends the CodeAcknowledgement (CAACK) message which includes the information of the selected second-phase code such that the CL can update the available code set and record the expiration time of node i to use the assigned code. Meanwhile, node j gets the information of the transmission code of node i and hence achieves the code synchronization. Then node i can start its data transmission to node j in the data channel. Otherwise, it will retransmit CREQ until CREP is received or ξ

Figure 3.5: The operations of code acquisition

times code acquisitions trials are reached.

A second-phase code for a node can only be used for the reserved period $T_{sc(i)}$. After this period, if node i still needs the second-phase code for data transmission, it should reacquire the code from the CL for another period of $T_{sc(i)}$ using the CREQ message. The CL will take over the code allocated to node i and add it to the available code set after the period of $T_{sc(i)}$. That is, the valid period of an allocated second-phase code of node i is $T_{sc(i)}$. In this way, the second-phase code can be reused by other nodes.

When a node migrates from one cell to another, it should tune its first-phase code corresponding to the new cell and obtain its new second-phase code from the CL of the new cell.

Figure 3.6: Control channel access and collision avoidance

3.2.4 Collision Resolution in the Control Channel

Let us suppose nodes operate in time-slotted mode in the control channel and each time slot is of duration τ_1 . As shown in Fig. 3.6, there are four different modes, i.e., code acquisition (CA) mode, leadership handover (LH) mode, switching 1 (ST1) and switching 2 (ST2) modes. CA mode consists of several time frames and each frame is divided into three time slots respectively dedicated for CREQ, CREP and CACK messages. CREQ is only initiated in the first slot, followed by CREP and CACK messages are respectively initiated in the subsequent slots. If a CL wants to hand over its leadership, it will send a HREQ in the second slot of a frame of CA mode, which forms the ST1 mode. If a CM under the coverage of more than two CLs sends CREQ, the CLs within its coverage either encounter collisions or receive its CREQ message. Since only its CL that successfully receives the CREQ will respond to the CM, the CM will receive CREP message that is free of interference. Therefore, whenever CREQ of a node wins the contention in its cell, it will definitely acquire its second-phase code in the subsequent slots unless CREP is interrupted by HREQ.

The code acquisition procedure is initiated only when a node has data transmission requirement and does not hold any second-phase code. However, there exists the contention and collision among the CREQ messages from multiple CMs. The binary splitting strategy [83] is employed to resolve the collision problems, i.e., each node will decide with probability 0.5 whether it will continue to transmit CREQ in the next frame and wait for the response. A successful reception of CREP means that the node wins the contention and other nodes involved in the collision will restart the contention following this strategy. Otherwise, they continue to decide whether to transmit in the subsequent CREQ slot as before. As pointed out by [83], this procedure will terminate in several frames with high probability. Additionally, if collisions are not resolved within the ξ trials for code acquisition, nodes will abort by themselves.

LH mode has a higher priority than CA mode. Whenever a CL wants to hand over its leadership, it switches the cell to the LH mode by immediately initiating the HREQ in the corresponding slot. The CMs within the coverage of this CL should defer their control messages for code acquisition in the control channel once they hear HREQ until HACK is received. The CMs that hear HREA also defer until HAGR is successfully received plus an additional slot such that CMs under the coverage of the new CL while it is out of the coverage of the former CL refrain from interfering with the reception of HREA messages. When there is no collisions of HREA occurring at the CL, CMs within leader residence area can hear HAGR in the subsequent slot after they transmit HREA. Then, they can transmit HACK.

Thus, the leadership handover, which is composed of several unsuccessful HREA trials and one successful HREA contention, can be accomplished free of interference. Since leadership handover can be completed in any slot, the length of a frame of CLs is variable with its frame terminating either at a new frame of CA mode or at CREP or CACK slot that forms the ST2 mode, after which nodes in the cell change to CA mode and start the new frame for contention.

3.2.5 Elimination of HTP in the Data Channel

Suppose the transmission codes of nodes A and B are $C^a = (C_1^a, C_2^a) \in C_{TC}$ and $C^b = (C_1^b, C_2^b) \in C_{TC}$ respectively. Actually, when A and B are within two hops and transmitting simultaneously to the same receiver, there are two cases that HTP may happen: 1) A and B are in the same cell, then $C_1^a = C_1^b$ and $C_2^a \neq C_2^b$, thus $C^a \neq C^b$. 2) A and B are in different cells, then the maximum distance between A and B is $2R_d$. Since the minimal distance between any two nodes in different cells with the same first-phase codes is $\sqrt{7}R$ and $\sqrt{7}R > 2R_d$, one has $C_1^a \neq C_1^b$. Thus, no matter what second-phase codes nodes A and B use, one always has $C^a \neq C^b$. In both cases, C^a and C^b are always quasi-orthogonal. Therefore, with this kind of assignment of transmission codes, HTP is eliminated in LA-TPCMMP.

3.3 Analysis of LA-TPCMMP

3.3.1 Assumptions

It is assumed that nodes are Poisson distributed in the network with density ρ . The traffic arrival process is Poisson with mean arrival rate λ . Nodes operate in half-duplex mode. Let us choose a time interval τ_2 which is long enough to resolve a collision, i.e., the duration of slots required to resolve a collision when k nodes are involved in the contention and binary splitting strategy is employed to resolve the collision. Then, one can have the assumption that there is no other new nodes to participate in the contention during this interval. In the following analysis, the average incurred control overhead is the accumulative count of control packets over the predefined τ_2 interval for a node.

3.3.2 Mobility Model and Handover Probability

The random walk-based mobility model [60] is adopted here, where each node's movement consists of a sequences of random length mobility intervals called epochs. The epoch lengths are independent and identically distributed (IID) and exponentially distributed, the direction of a mobile node during each epoch is IID uniformly distributed over $[0, 2\pi)$ and the speed of a mobile node is an IID uniformly distributed random variable between $[0, V_{max})$ and remains constant during each epoch. Suppose R_{eq} is the radius of a circle with the same area as the hexagonal cell. It is easy for the reader to calculate that $R_{eq} = \sqrt{\frac{3\sqrt{3}}{2\pi}}R$.

From [60] [84], one knows that there are two kinds of activation models, i.e., node activation model and link activation model. Node activation model usually refers to that nodes become active in a cell at a specified moment. Whereas, link activation model refers to that mobile nodes move into a cell at a specified moment. The former tends to represent the status of CL handover and initial status of CM migration, while the latter approximates to the steady status of CM migration. Let $f_{T_{mh}}(t)$ denote the *probability density function* (pdf) of the residence time in a cell of a mobile node that hands over from a neighboring cell before crossing into another cell and $f_{T_{lh}}(t)$ denote pdf of the average residence time in the leader residence area of a CL. Thus, one has

$$f_{T_{mh}}(t) = \begin{cases} \frac{4R_{eq}}{\pi V_{max} t^2} \{1 - \sqrt{1 - (\frac{V_{max} t}{2R_{eq}})^2}\}, & 0 \leq t \leq \frac{2R_{eq}}{V_{max}} \\ \frac{4R_{eq}}{\pi V_{max} t^2}, & t \geq \frac{2R_{eq}}{V_{max}} \end{cases} \quad (3.6)$$

$$f_{T_{lh}}(t) = \begin{cases} \frac{8R_{eq}}{3\pi V_{max} t^2} \{1 - \sqrt{1 - (\frac{V_{max} t}{2R_{eq}})^2}\}, & 0 \leq t \leq \frac{2R_{eq}}{V_{max}} \\ \frac{8R_{eq}}{3\pi V_{max} t^2}, & t \geq \frac{2R_{eq}}{V_{max}} \end{cases} \quad (3.7)$$

according to [60]. Thereby, the mean cell residence time $E[T_{mh}]$ for a mobile node handing over from one cell into another cell and the mean residence time $E[T_{lh}]$ in the leader residence area for a CL can be computed as

$$E[T_{mh}] = \int_0^{\infty} t f_{T_{mh}}(t) dt, \quad (3.8)$$

$$E[T_{lh}] = \int_0^{\infty} t f_{T_{lh}}(t) dt. \quad (3.9)$$

Let the CM handover probability $P_{mh}(\tau_2)$ and CL handover probability $P_{lh}(\tau_2)$ respectively denote the probability of the CMs to walk out of the current cell and probability of the CL to walk out of the leader residence area of its cell in interval τ_2 . Then, one has

$$P_{mh}(\tau_2) = \frac{1}{E[T_{mh}]} \tau_2, \quad (3.10)$$

$$P_{lh}(\tau_2) = \frac{1}{E[T_{lh}]} \tau_2. \quad (3.11)$$

3.3.3 Analysis of Control Overhead of LA-TPCMMP

In LA-TPCMMP, the overall control overhead results from code acquisition, code reacquisition and leadership handover.

Overhead Analysis of Code Acquisition and Reacquisition

Let $N = \rho\pi R_d^2$ be the average number of nodes in the transmission range. A successful code acquisition requires the correct reception of the CREQ, CREP and CACK messages. However, CREQ may encounter collisions, since the nodes in the coverage area of a CL may initiate their communications at the same time. According to the Poisson distribution, the probability that there are i nodes within the transmission range of a CL is $P(N, i) = e^{-N} N^i / i!$. The probability that among i nodes there are k nodes simultaneously participating in the contentions with the probability p_1 follows the Binomial distribution involved in the contention simultaneously is $\sum_{i=0}^{\infty} B(i, p_1, k) P(N, i)$, where p_1 is determined by the transmission probability and handover probability. According to the Poisson distribution, the probability that

there is no traffic arrival during τ_2 is $e^{-\lambda\tau_2}$. Hence, one has the contention probability $p_1 = (1 - e^{-\lambda\tau_2})P_{mh}(\tau_2)$ during interval τ_2 . Given ζ_k as the average number of CREQ slots required to resolve one collision, it follows the recursive relationship

$$\zeta_k = \begin{cases} 1, & k = 1 \\ \frac{1+2^{-k} \sum_{j=1}^{k-1} \binom{k}{j} \zeta_j}{1-2^{-k+1}}, & k > 1 \end{cases} \quad (3.12)$$

according to the conclusion of binary splitting strategy in [83]. Consequently, the average number β_k of the CREQ messages to resolve the collisions within the interval τ_2 can be computed as

$$\beta_k = \sum_{j=0}^{\zeta_k-1} k \left(\frac{1}{2}\right)^j. \quad (3.13)$$

After the successful reception of CREQ, CREP and CACK messages will be transmitted correspondingly for only once, which add 2 to the overhead. Therefore, denoting χ_1 as the average number of required control packets to win the contention for each node involved in the contention, one has

$$\chi_1 = \sum_{i=1}^{\infty} \sum_{k=1}^i B(i, p_1, k) P(N, i) (\beta_k + 2). \quad (3.14)$$

Thus, the average number $\phi_{CA}(\tau_2)$ of required control packets for a successful code acquisition of a node is

$$\phi_{CA}(\tau_2) = \chi_1. \quad (3.15)$$

Recall that the second-phase code allocated to node i will be recycled after $T_{sc(i)}$ and a node in request for data transmission has to re-obtain its code after the currently holding code is invalid. For the simplification of analysis, the period $T_{sc(i)}$ is chosen as the average duration for node i in a cell. Thus, one can equivalently consider the probability of initiating code reacquisition as p_1 . Hence, the average numbered control overhead $\phi_{CR}(\tau_2)$ for code reacquisition is also

$$\phi_{CR}(\tau_2) = \chi_1. \quad (3.16)$$

according to the above-mentioned computations.

Overhead Analysis of Leadership Handover

During the leadership handover, the CMs within the leader residence area send HREA messages according to the priority order determined by their distances to the center of the leader residence area. The deferring timer T_{Li} ensures two nodes respectively from different priority regions free of collision and T'_{Ui} is used to avoid the HREA collisions between two nodes within the same priority regions since it is a random multiple of $2\tau_1$ in $[0, T_{Ui})$. Define $x_i = \rho\pi(d_{i+1}^2 - d_i^2)$. To ensure the successful reception of HREA, it requires only one HREA message is initiated in a slot with the probability $w_i = \frac{2\tau_1}{T_{Ui}}$. Therefore, given that $W_I = \lceil \frac{1}{w_i} \rceil$, the average number of HREA messages of y_i within priority region i is

$$y_i = s_i \frac{x_i}{2} + (1 - s_i)x_i, \quad (3.17)$$

where $s_i = \binom{W_I}{1} w_i (1 - w_i)^{x_i - 1}$.

In turn, nodes within region i initiate the HREA messages only if there is no successful reception within region $i - 1$. Hence, when $i \geq 1$, the conditional probability of nodes within region i to initiate HREA is $\prod_{k=0}^{i-1} (1 - s_k)$. Then, one has

$$z_i = \begin{cases} y_i, & i = 0 \\ \prod_{k=0}^{i-1} (1 - s_k) y_i, & i \geq 1 \end{cases} \quad (3.18)$$

Given χ_2 as the average number of HREA messages for one successful reception at the CL, one has

$$\chi_2 = \sum_{i=0}^{N_p-1} z_i. \quad (3.19)$$

Recall that HREQ owns higher priority than CREP and nodes will defer their access for the control channel as soon as they hear any control message of leadership handover. Consequently, HREQ, HAGR and HACK are initiated without collisions and these add 3 to the overall overhead. Therefore, the average overhead $\phi_{LH}(\tau_2)$ of leadership handover is

$$\phi_{LH}(\tau_2) = \chi_2 + 3. \quad (3.20)$$

Average Total Control Overhead

The probabilities of a node to be the CM and CL are assumed to be $p_3 = \frac{N'-1}{N'}$ and $p_4 = \frac{1}{N'}$ respectively, where $N' = \rho\pi R_{eq}^2$. Note that the probabilities of initiating code acquisition and code reacquisition are both equal to the contention probability

Figure 3.7: Demonstration of cell members under the coverage of different cell leaders

p_1 . Therefore, within the interval τ_2 , the total average control overhead ϕ of LA-TPCMMP is

$$\phi(\tau_2) = p_3 p_1 \chi_1 + p_4 P_{lh}(\tau_2) \phi_{LH}(\tau_2). \quad (3.21)$$

3.3.4 Analysis of Average Delay of LA-TPCMMP

To simplify the analysis, let us assume the CLs are at the centers of their respective cells. As shown in Fig. 3.7, the shaded areas S_1 , S_2 and S_3 are respectively the areas covered by one CL, two CLs and three CLs. The probabilities that nodes stay within S_1 , S_2 and S_3 are respectively denoted as p_{S1} , p_{S2} and p_{S3} . Since the nodes are uniformly distributed, one can get the probability of a node to be in S_1 , S_2 or

S_3 as

$$p_{S1} = S_1/(\pi R_d^2),$$

$$p_{S2} = 6S_2/(\pi R_d^2),$$

$$p_{S3} = 6S_3/(\pi R_d^2).$$

Let S_f denote the area of the pie slice centered at CL_2 and with radius R_d and angle $\alpha = 60^\circ$, and S_t denote the area of the equilateral triangle with $d = \sqrt{3}R$, then one has $S_t = 3S_f - 3(\frac{S_2}{2} + S_3) + S_3$. Given S_o as the cross area of two circles with radius R_d and distance of the circle centers d , one has $S_o = 4(\frac{\arccos \frac{d/2}{R_d}}{2\pi} \pi R_d^2 - \frac{1}{2} \frac{d}{2} \sqrt{R_d^2 - (\frac{d}{2})^2})$.

Remark that

$$S_f = \frac{\pi R_d^2}{6},$$

$$S_t = \frac{\sqrt{3}d^2}{4},$$

$$\frac{S_2}{2} + S_3 = \frac{S_o}{2}.$$

Thus one has

$$S_3 = S_t - 3S_f + 3\frac{S_o}{2} = \frac{\sqrt{3}d^2}{4} - \frac{\pi R_d^2}{2} + 3\frac{S_o}{2},$$

$$S_2 = 2(\frac{S_o}{2} - S_3),$$

$$S_1 = \pi R_d^2 - 6S_2 - 6S_3.$$

The probability that a node in S_k hears i leadership handover is $\binom{k}{i} P_{lh}(\tau_2)^i (1 - P_{lh}(\tau_2))^{k-i}$ ($k = 1, 2, 3$). Given that $\psi_{LH}(\tau_2)$ is the upper bound of the average delay of leadership handover, one has the delay of the node suffering from leadership handover is upper bounded by $i\psi_{LH}(\tau_2)$. For the simplification of analysis, we suppose the duration of each control packet τ_3 is equal to τ_1 . Since the code acquisition requires the correct reception of the CREQ and CREP messages and a node wins

the contention after the average ζ_k CREQ slots, the upper bound $\psi(\tau_2)$ of average delay spent in code acquisition for a node can be computed as

$$\begin{aligned} \psi(\tau_2) = & \sum_{k=1}^3 p_{Sk} \sum_{i=0}^k \binom{k}{i} P_{lh}(\tau_2)^i (1 - P_{lh}(\tau_2))^{k-i} (i\psi_{LH}(\tau_2)) \\ & + \sum_{i=1}^{\infty} \sum_{k=1}^i (3(\zeta_k - 1) + 2)\tau_3 B(i, p_1, k) P(N, i). \end{aligned} \quad (3.22)$$

Now let us proceed to compute $\psi_{LH}(\tau_2)$. Recall that nodes have to defer one slot after transmitting HREA. When the HREA messages of nodes within region 0 are received by the corresponding CL with probability s_0 , the delay is upper bounded by T_{L1} . Otherwise, according to the conditional probability $1 - s_0$, the delay is correspondingly upper bounded by T_{L2} . Thus, when the HREA messages of nodes within region i are received by the corresponding CL, one has the upper bound of $\prod_{k=0}^{i-1} (1 - s_k) T_{Li}$. In addition, the delay due to the HREQ, HAGR and HACK messages is $3\tau_3$. Thereby, one has

$$\psi_{LH}(\tau_2) = s_0 T_{L1} + \left(\sum_{i=1}^{N_p-1} \left(\prod_{k=0}^{i-1} (1 - s_k) T_{Li} \right) \right) + 3\tau_3. \quad (3.23)$$

3.4 Analysis of Traditional CDMA-Based Multi-Channel Algorithms

In traditional algorithms (TAs), code assignment requires the exchanges of two-hop neighborhood information. Based on the criterion that nodes need to know the

information of nodes within two-hop separation, the algorithm by J. J. Garcia in [49] gives the communication complexity of distributed assignment of codes in the worst case as $O(N_n d_m^2)$, where N_n is the total number of nodes and d_m is the network degree. Actually, the control overhead results from the number of broadcasting packets for the refresh each time and updating frequency. Since there is always a minimal interval to obtain the neighborhood information under a certain mobility and density in case of conflict in adopting codes, let us derive this appropriate interval to ensure the timely neighborhood updating and compare the incurred control overhead and delay with LA-TPCMMP.

According to [49], a node sends a Code Assignment Message (CAM) to all its one-hop neighbors when a new node comes into transmission range. All receivers are required to acknowledge the sender to ensure the reliable transmission of CAM. Let N_{h1} denote the average number of one-hop neighbors and $N_{m,h1}$ denote the total number of nodes which migrate into the one-hop distance in the pre-specified small timer $\varepsilon = \tau_2$. Note that $v\varepsilon$ is far smaller than R_d . Therefore, given l as the distance between two nodes, the average number of new coming one-hop neighbors can be approximately derived as

$$N_{m,h1} = \int_{R_d}^{R_d+v\varepsilon} \theta \rho(2\pi l) dl, \quad (3.24)$$

where $\theta = \frac{2 \arccos((l-R_d)/(v\varepsilon))}{2\pi}$ denotes the angle along which nodes can migrate into the required area. Thereby, the control overhead $\phi_{CA}(\tau_2)$ of TAs within the interval

τ_2 is at least

$$\phi_{CA}(\tau_2) = (1 - e^{-\lambda\tau_2})N_{m,h1}(N_{h1} + 1). \quad (3.25)$$

Before initiating its transmission, a node should first listen to the neighborhood broadcast for at least a period of $\tau_c = (1 - e^{-\lambda\tau_2})N_{m,h1}(r+1)\tau_3$ to ensure the adopted code is appropriate to avoid the HTP. The chosen value of r of a node should ensure that each neighbor within transmission range at least broadcasts once for acknowledgement. According to the occupancy problem in combinatorial mathematics in [45][85], the probability that u nodes get no chance to successfully broadcast itself is

$$p(u; r, N_{h1}) = N_{h1}^{-r} C_{N_{h1}}^u \sum_{v=0}^{N_{h1}-u} (-1)^v C_{N_{h1}-u}^v (N_{h1} - u - v)^r. \quad (3.26)$$

Thus, to ensure $p(0; r, N_{h1}) \doteq 1$, i.e., almost each node can successfully broadcast itself in this duration, a node should defer τ_c before initiating its data transmission. Therefore, the delay $\psi_{CA}(\tau_2)$ of TAs is lower bounded by τ_c .

3.5 Numerical and Simulation Results

The simulations are conducted using network simulator (NS2) [86] with CMU wireless extensions combined with our own C++ models, which implement all the details of LA-TPCMMP. When doing NS2 simulations, the assumption on Poisson distribution in the analytical model may be relaxed. The performance is evaluated in terms of control overhead and delay versus the varying density and mobility under different traffic load. The mean value of control overhead and delay is calculated

over the predefined τ_2 interval for a node to get average control overhead and delay. To ensure that the simulation does not suffer from the influences of the borders as presented in [60], let us assume that two opposite borders of the simulated area are wrapped around to form a closed area, which approximates an area without border with the uniform distribution of nodes. Although it is desired that the whole area is divided into the complete hexagonal cells consistent with 7 first-phase codes reuse in the closed area, in this chapter, due to the scalability limitation of our simulation tool, the topology is chosen as $800m \times 700m$ and $R = 100m$ with nodes and traffic flows randomly distributed and the impact of inconsistent first-phase code reuse near the border is ignored. (Noted that the density is the total number of nodes per unit area (m^2).) A two-ray ground model is used as the propagation model. The channel rate is $2Mbps$ with control channel rate of $0.3Mbps$. The traffic type is user datagram packet (UDP) with packet size $512bytes$. Assume all the control packets are of the same length $50bytes$. Accordingly, one has $\tau_1 = \tau_3 = 0.00133s$. We choose $\tau_2 = 0.05s$. The simulation time is $500s$ and to approximate the effect of the steady status, the first $100s$ is discarded. The simulation results are averaged 8 runs with different movement patterns for each value of the traffic arrival rate, speed and density. The previously mentioned parameters $\xi = \beta_k$ and $\tau_{to} = 2\chi_2\tau_1$. In the partition of the priority regions, we choose the parameter $\omega = 2\rho\pi\delta^2\tau_1/(1 - e^{-1/N_p^2})$.

Fig. 3.8 and Fig. 3.9 show average delay and control overhead for leadership handover versus density for different number of priority regions. Average delay and control overhead increase when the density increases and decrease with the incre-

Figure 3.8: Average delay versus density in leadership handover under different number of priority regions in LA-TPCMMP

mental number of priority regions. When $\rho \geq 0.001$, they are sensitive to the density. Whereas, with N_p increasing, they are not significantly affected by the density. This is due to with more partition of priority regions there is less chances of collisions from the HREA messages even under high density. Consequently, there is less ensuing delay and control packets. However, for a fixed density, there is no significant reduction of delay and overhead with more partition of priority regions when N_p is very large. Moreover, increasing regions partition is unpractical due to the additional computation overhead. Hence, in the following analysis and simulation, when $N_{h1} \leq 30$ we adopt N_p as 1. When $30 < N_{h1} \leq 50$, N_p is chosen as 2.

In Fig. 3.10, the number of one-hop neighbors is varied to observe average control

Figure 3.9: Average control overhead versus density in leadership handover under different number of priority regions in LA-TPCMMP

overhead under varying traffic load when the speed $V = 10m/s$. Obviously, the control overhead of TAs is worse than that of LA-TPCMMP with the increasing number of one-hop neighbors and almost aggravates exponentially with the increasing density. When the network is considerably loose with $N_{h1} = 5$, the control overhead of TAs when $\lambda = 2Pks/s$ is even less than that of LA-TPCMMP. This is due to that when the network is loose, the neighborhood update of TAs is less frequent and the probability of collisions is small. Whereas, in LA-TPCMMP, extra control overhead is caused by CLs migration and leadership handover, which makes it less advantageous. Although TAs show a superior performance for the loose distribution, they are vulnerable to the network density. LA-TPCMMP significantly outperforms TAs

Figure 3.10: Average control overhead versus the number of one-hop neighbors in both algorithms when $V = 10m/s$

when the network is becoming dense. When $N_{h1} = 50$, the control overhead incurred in TAs is almost 16 times that of LA-TPCMMP when $\lambda = 2Pkts/s$. Furthermore, when $\lambda = 10Pkts/s$, the control overhead incurred in TAs is almost 162 times that of LA-TPCMMP. Control overhead of LA-TPCMMP is not affected significantly by density since there is small handover probability $P_{mh}(\tau_2) \doteq 0.00422225$ when $V = 10m/s$ and $R = 100$ which causes less contentions even under high density. The performances in both algorithms become worse when the offered load increases since bigger transmission probability causes more contentions and collisions among control packets.

Due to the scalability of y axis, the simulation and numerical results of aver-

Figure 3.11: Average control overhead versus the number of one-hop neighbors under different traffic load in LA-TPCMMP when $V = 10m/s$

age control overhead of LA-TPCMMP are separately illustrated in Fig. 3.11. The simulation data of LA-TPCMMP confirm our analysis. Control overhead of LA-TPCMMP is not affected significantly by the offered load due to the small handover probability. However, as shown in Fig. 3.10, the performance of TAs almost aggravates linearly with the increasing traffic load since bigger transmission probability requires more frequent neighborhood update. Therefore, LA-TPCMMP substantially reduces control overhead for a sufficiently dense or heavy-loaded network.

Fig. 3.12 shows average control overhead versus average speed under different traffic load when $N_{h1} = 30$. The average speed V is varied from $2m/s$ to $15m/s$ to observe the impact on the control overhead. With the speed increasing, there is big-

Figure 3.12: Average control overhead versus average speed in both algorithms when $N_{h1} = 30$

ger chance for the CMs and CLs to migrate out of the cell and leader residence area, i.e. the CMs handover probability and CL handover probability increase. Consequently, the control overhead of LA-TPCMMP increases when the speed increases. In TAs, with increasing speed there is more chances for a new node migrating into two-hop separation, which results in more updating of neighborhood information. Therefore, TAs also requires more control packets in response to increasing mobility. However, the upward trend of TAs is significantly worse than that of LA-TPCMMP.

Fig. 3.13 shows how average delay varies with density in both algorithms. There is substantial reduction of average delay of LA-TPCMMP due to less exchanges of control packets. Average delay of TAs almost aggravates exponentially with

Figure 3.13: Average delay versus the number of one-hop neighbors in both algorithms when $V = 10m/s$

the increasing density and the delay of LA-TPCMMP is minimally affected by the density. Fig. 3.14 compares the simulation and numerical results of average delay of LA-TPCMMP for different traffic load. It is shown that simulation results match well with the analysis.

Fig. 3.15 shows average delay versus average speed under different traffic load when $N_{h1} = 30$. With the increasing speed, the increasing CMs and CL handover probabilities cause the delay increase of LA-TPCMMP. Whereas, in TAs, more updating of neighborhood information results in the delay increase. LA-TPCMMP incurs less delay and it rises significantly less sharply than that of TAs.

Fig. 3.16 demonstrates average control overhead and delay of LA-TPCMMP

Figure 3.14: Average delay versus the number of one-hop neighbors under different traffic load in LA-TPCMMP when $V = 10m/s$

versus speed when $\lambda = 10Pkts/s$ and $N_{h1} = 30$. Both the overhead and delay increase linearly with the increasing speed. The simulation data verify the numerical results.

3.6 Conclusions

The basic idea of CDMA-based multi-channel algorithms is that nodes within two-hop separation should adopt different transmission codes such that the HTP can be avoided. However, TAs rely on the periodic exchange of neighborhood information to assign transmission code, which results in expensive control overhead. Heavy exchange of control packets for code assignment aggravates the network perfor-

Figure 3.15: Average delay versus average speed in both algorithms when $N_{h1} = 30$

mance with the bandwidth under-utilization, energy inefficiency and large latency. In this chapter, we present an efficient multi-channel MAC protocol named as LA-TPCMMP, where the first-phase code is used to differentiate between different cells and the second-phase code is used to differentiate between nodes in one cell. This approach eliminates the HTP during data transmission in MANETs without periodical exchange of neighborhood information.

We analyze the constraints that the cell size should be satisfied to ensure the same transmission codes appear more than two hops away, and show the priority-based random competition strategy for the initial CL election and leadership handover, as well as, present the mechanism of collision resolution to reduce control overhead and delay. Furthermore, we provide the comprehensive theoretical analysis of average

Figure 3.16: Average control overhead and delay versus average speed in LA-TPCMMP when $\lambda = 10 Pkts/s$ and $N_{h1} = 30$

overhead and delay according to the migration probability of nodes. Simulation results verify the theoretical analysis and it is shown that LA-TPCMMP significantly outperforms the existing CDMA-based algorithms with regards to control overhead and delay performance.

Chapter 4

Cluster-Adaptive Two-Phase

Coding Multi-Channel MAC

Protocol for MANETs

4.1 Introduction

Although LA-TPCMMP outperforms TAs, its application is partially limited by the dependance to the location information. Clustering is an important mechanism employed to build up a hierarchical structure and alleviate the heavy control overhead in a large-scale MANET. Traditional distributed clustering algorithms [9][58] have been proposed based on node ID or node degree. More recently, the mobility-based framework [60] adaptively organizes (α, t) clusters by estimating the path availability. The max-min D-cluster algorithm [59] presents a heuristic to form d-hop clusters to achieve the fair distribution of load. Access-based clustering protocol (ABCP) [87] minimizes the overhead on cluster formation with the consideration of broadcast scheduling of control messages. Channel access-based protocol (CABC) [88]

maximizes the worst-case control channel efficiency by using the randomized control channel broadcast access method. To the best of our knowledge, only MAPLE clustering scheme proposed in [89] takes the medium access of adjacent clusters into account during the clustering establishment and maintenance, where the cluster heads (CHs) of adjacent clusters respectively occupy their particular time frames to broadcast their beacon messages and maintain their clusters. However, it does not explain how to allocate multi-channel resources by making use of clustering information to make the efficient channel spatial reuse.

This sheds a light to develop a comprehensive protocol by enabling TPCMMP with dynamic clustering. In this chapter, we present a new protocol, termed as CA-TPCMMP, for general large-scale MANETs. CA-TPCMMP assigns the first-phase codes and second-phase codes respectively for adjacent clusters and different cluster members (CMs) in one specific cluster. The key characteristic of CA-TPCMMP is that code assignment is efficiently incorporated with cluster maintenance and thus significantly reduces the control overhead due to less number of exchanges of neighborhood information. In CA-TPCMMP, each frame is related to a specific first-phase code and each CH occupies its particular frame to broadcast its beacon messages. Meanwhile, each CM in a cluster acquires its unique time slot within the frame of its cluster to broadcast for cluster maintenance and whenever it requests for data transmission, it achieves its second-phase code in its cluster using its time slot free of contentions. The CHs that are spatially separated can use the same frame.

To summarize, CA-TPCMMP adaptively assigns the transmission codes based on dynamic clustering by utilizing two-phase coding scheme without the requirement of the location information. Furthermore, we introduce the confliction detection and confliction resolution mechanisms for the first-phase code assignment as well as the collision avoidance mechanism of CMs during the contention for their respective time slots are also presented. The theoretical analysis with respect to the control overhead and delay are provided as well and further verified by extensive simulations.

The remainder of this chapter is organized as follows. Section 4.2 introduces CA-TPCMMP in detail and presents the confliction detection and confliction resolution mechanisms as well as collision avoidance mechanism. Section 4.3 gives the theoretical analysis of CA-TPCMMP. Section 4.4 describes traditional approaches. Section 4.5 provides a simulation study and examines the performance of CA-TPCMMP. Section 4.6 discusses and concludes the chapter.

4.2 Protocol Design

4.2.1 Preliminaries

In CA-TPCMMP, similar two-phase coding scheme is employed except that the first-phase codes are used for differentiating the adjacent clusters and the second-phase codes are used for distinguishing the nodes in a specific cluster. Let $\mathcal{C}(i)$ denote the set of nodes of cluster i and $C_{1,i}$ denote the first-phase code of cluster i . Then we have $C_1^a = C_{1,i}$ for any node $A \in \mathcal{C}(i)$ with its code $C^a = (C_1^a, C_2^a)$. We call cluster

i and cluster j ($i \neq j$) are neighboring clusters if there exists $u \in \mathcal{C}(i)$ and $v \in \mathcal{C}(j)$ such that u and v are one-hop away from each other. The set of neighboring clusters of cluster i is denoted as $\mathcal{NC}(i)$.

4.2.2 Code Confliction and Criteria for Code Assignment

We denote that two nodes within two-hop separation are in code confliction when they adopt the same transmission codes since collision may happen at their common neighbors if they transmit data packets simultaneously. In order to avoid the confliction, we introduce the following criteria for code assignment in CA-TPCMMP.

Criterion 1: For any two nodes $A \in \mathcal{C}(i)$ and $B \in \mathcal{C}(i)$ in a given cluster i , their second-phase codes should be assigned such that $C_2^a \neq C_2^b$.

Criterion 2: For any two neighboring clusters i and j , their first-phase codes should be assigned such that $C_{1,i} \neq C_{1,j}$.

Criterion 3: For any two clusters i and j , if there exists a cluster k that satisfies cluster $i \in \mathcal{NC}(k)$ and cluster $j \in \mathcal{NC}(k)$, their first-phase code should be assigned such that $C_{1,i} \neq C_{1,j}$.

Considering the above criteria for code assignment, a cluster i maintains a set of permitted first-phase codes $C_{PFC}(i) = C_{FC} - \{\bigcup C_{1,j} | \forall j \in \mathcal{NC}(i)\}$ which consists of all the first-phase codes that are different from those of its neighboring clusters.

4.2.3 Operations of CA-TPMMP

We assume that there exist three different states for nodes, respectively namely CM, CH and cluster candidate, where a CH is responsible for maintaining and assigning the second-phase codes to its CMs in each cluster and each CM is one-hop away from its CH. The wireless channel is divided into a control channel and a data channel.

The selection of the first-phase codes and second-phase codes can be based on various kinds of initial clustering algorithms. Here, without loss of generality, we take the example that nodes initially employ the random competition-based clustering (RCC) [59] to establish the clusters, for our explanation of CA-TPCMMP. During the cluster maintenance, we minimize the event that two CHs are within the communication range of each other to reduce the overlapping of the clusters. For the case of that, the CH with lower ID will notify its one-hop neighbors not within the overlapped area to re-compete for the CH. We deem that a CM will definitely joins a cluster if it is within half of the communication range of the corresponding CH.

Access Mechanism of Control Channel

In this subsection, we give the access format of control channel and basic idea of CA-TPCMMP. The control channel is time-slotted and divided into several super-frames and frames as shown in Fig. 4.1. Each super-frame consists of M_1 frames, wherein each frame is dedicated for one cluster with M_1 being the available number of frames that can be used for the adjacent clusters. Each frame is composed of

Figure 4.1: Control Channel Access Format

one *beacon slot* followed by some fixed number of M_2 *maintenance slots*, wherein the beacon slot is dedicated to election, probing as well as beacon of a CH and the *maintenance slot* $_i$ ($1 \leq i \leq M_2$) is dedicated for a CM within a cluster with M_2 being the supported number of CMs in a cluster. Each maintenance slot is further composed of three mini-slots, where the first two mini-slots are dedicated to Request for Slot (RFS) message and Confirmation of Slot (COS) message respectively and the third mini-slot is for *broadcasting message* of a CM. There is a flag that indicates code request and code release in the RFS message and broadcasting message respectively.

Each frame is related to a specific cluster and its corresponding first-phase code. Different frames of a super-frame are dedicated to different clusters and clusters that are spatially separated enough can use the same frame with the same first-phase codes. All the maintenance slots are used by the CMs for maintaining clusters, negotiating the appropriate first-phase codes and allocating the second-phase codes. Different CMs of a cluster will contend to obtain their different maintenance slots in

their respective frames to send their broadcasting messages. Therefore, there exists no collisions from broadcasting message of the adjacent clusters if their adopted first-phase codes are different.

The basic idea of CA-TPCMMP is that each cluster is related to a specific frame with its corresponding first-phase code and the CMs within a cluster use their corresponding maintenance slots in their respective frame to obtain their specific second-phase codes. Different frames of a super-frame are dedicated to different clusters, and thus clusters that are spatially separated enough can use the same frame with the same first-phase codes. The beacon slot is used by a CH for cluster maintenance that simultaneously broadcasts their adopted first-phase code. All the maintenance slots are used by the CMs for the purpose of broadcasting messages to maintain clusters and negotiating the appropriate first-phase codes for their frame as well as allocating the second-phase codes. Hence, the first-phase and second-phase code acquisition for a node is embedded into the the frame acquisition and slot acquisition respectively, which effectively integrates code assignment with clustering. In this way, there exists no collisions from broadcasting message of the adjacent clusters if their adopted first-phase codes are different. In the following, we recite how to select the first-phase and second-phase codes.

Selection of The First-Phase Codes and Confliction Detection and Resolution Mechanisms

The selection of the first-phase code for one specific cluster is determined by the first-phase codes held by its neighboring clusters. The first-phase code of a cluster

is acquired through negotiating during the cluster maintenance.

CH election is completed in the beacon slot. Whenever a cluster candidate successfully contends to be the CH of a cluster i , it listens for a duration of a super-frame, waits until the beginning of a new free frame and sends the *probing message* in the beacon slot. The CMs of cluster i that receive the probing message check their stored tables that record the first-phase codes held by their neighboring clusters and initiate opposition by sending *broadcasting messages* that convey the code inconsistency indication if the neighboring clusters are adopting the same first-phase code. The stored table of each CM is updated according to the information overheard from the broadcasting message of the CMs of its neighboring clusters. Upon collecting the broadcasting messages of its CMs, the CH updates its $C_{PFC}(i)$ and randomly chooses one free first-phase code from its $C_{PFC}(i)$ to continue to probe its appropriate first-phase code which should not be in conflict with any neighboring clusters to satisfy Criterion 2. Alternatively, it periodically broadcasts the probing message with the adopted first-phase code piggybacked. The procedure of the negotiation of the first-phase codes is named as conflict detection and conflict resolution. We call the probing of the first-phase code with the probability $\frac{1}{|C_{PFC}(i)|}$ as the probability-based conflict resolution scheme.

If the CH does not receive the opposition messages continuously, it considers the current first-phase code to be suitable and periodically broadcasts the *beacon message* that disseminates its cluster ID (determined by its CH ID), first-phase code and the number of its CMs. Otherwise, it should adjust its first-phase code such

that Criterion 2 can be satisfied. The CMs, which hear the beacon messages, will record the corresponding first-phase code information. Since the CMs send their broadcasting messages conveying the neighboring cluster ID, their first-phase codes and the number of their CMs, a CH may detect that its neighboring clusters with different cluster ID occupy the same frame and adopt the same first-phase code. Let S_u denote the number of CMs within a CH u . Therefore, to ensure Criterion 3 is satisfied, we introduce another criterion,

Criterion 4: For any two clusters i and j that satisfy $i \in \mathcal{NC}(j)$ or there exists a cluster k that satisfies cluster $i \in \mathcal{NC}(k)$ and cluster $j \in \mathcal{NC}(k)$, if $C_1^i = C_1^j$ and $S_i < S_j$, we assume cluster j keeps the original first-phase code and cluster i obtains its first-phase code according to the probability-based confliction resolution scheme.

As shown in Fig. 4.2, we observe three cases of confliction in the negotiation of the first-phase codes of neighboring clusters, i.e., confliction with neighboring, star and chain structures. In case (a), when cluster i detects $C_{1,i} = C_{1,j}$, it will re-compete for its frame if $S_i < S_j$ while the cluster j keeps the original frame, i.e., it keeps the original first-phase code. In case (b), when cluster l detects $C_{1,h} = C_{1,i} = C_{1,j}$, if $S_h < S_i < S_j$, it notifies that cluster j keeps the original frame and clusters h and i re-compete for their frames. The first-phase codes of all neighboring clusters k , m and n are piggybacked in the broadcasting messages such that clusters h and i can update their respective C_{PFC} . Consequently, clusters h and i may again select the same frame in the following contention. However, within a limited number of

Figure 4.2: Three cases of the first-phase code confliction

trials as proved later, the first-phase code confliction between clusters *h* and *i* will be resolved. In case (c), when cluster *l* detects $C_{1,i} = C_{1,j}$ and cluster *m* detects $C_{1,h} = C_{1,i}$, in the worst case, there is a chain reaction, e.g., $S_h < S_i$ and $S_i < S_j$. Then cluster *j* keeps the original frame and clusters *h* and *i* re-compete for their frames. Similarly, the confliction can be resolved within a finite number of trials as proved in Section 4.3.

Selection of The Second-Phase Codes and Collision Avoidance Mechanism

Whenever a cluster is established, a CH maintains its available slot set in its cluster and periodically broadcasts it in the beacon message. Meanwhile, the CMs that

have joined this cluster contend to obtain their respective maintenance slots in the specific frame of this cluster. Since it is difficult for all CMs to coordinate their response and not collide with each other in each frame, we employ binary splitting strategy [83] to resolve collisions during the slot acquisition, i.e., when there exist the collisions from RFS messages during contention, the senders that can not hear COF message will decide with equal probability $p = 1/2$ whether it will continue to transmit RFS in the next maintenance slot. A CH will send COS after a successful reception of RFS and update its available slot set. The CM that transmitted RFS knows it wins its maintenance slot after it receives the COS. Other nodes involved in the collision will restart the contention following this strategy. Usually, a CM can obtain its slot in the frame of its cluster within a limited number of trials. New CMs will always listen for a period of their respective frame to know the available slot set from the beacon message before participating in the contention for their maintenance slots.

The second-phase code of a node is allocated by its CH. A CM that has obtained its slots can acquire its second-phase code from its CH free of contention. A CH records the available second-phase codes in its cluster. Whenever a CM is in request for data transmission, it transmits the RFS message by marking the code request field in it. Upon receiving the RFS message, the CH sends COS message to allocate code. The CM listens to the COS message of its CH to acquire its second-phase code and acknowledges its CH by sending broadcasting message in its allocated slot such that its CH can update the available second-phase codes. The broadcasting message

of a CM disseminates its ID, cluster ID, its first-phase code, the first-phase codes hold by neighboring clusters and other parameters such as remaining energy and the number of nodes within coverage with the same first-phase codes that reflect its appropriateness of being a CH. In addition, it conveys its destination ID and second-phase code such that the destination node overhears the code information and achieves code synchronization. Transmitter-oriented data transmission [46] is adopted. As soon as the data transmission finishes, the CM will return its second-phase code to its CH by marking the code release field in its broadcasting message. When a CM migrates into another cluster, usually it releases its original second-phase code to the former CH and re-obtains its new second-phase code in the new cluster. As a complementary measure, the CH will recycle the allocated second-phase codes to facilitate the efficient reutilization of codes if it can not receive the broadcast from a node which indicates the adopted second-phase code of the node is in use after a interval.

4.2.4 Effectiveness in Combating HTP during the Data Transmission

Since there may exist overlapping among the clusters for CA-TPCMMP, we will demonstrate the cases that the HTP may happen through the following Lemma.

Lemma 1: In CA-TPCMMP, any two nodes A and B that are in different clusters and within two-hop separation belong to two clusters which are either neighboring clusters or neighbors of another common cluster.

Figure 4.3: Diagram of HTP in CA-TPCMMP

Proof: Let CH_i and $d(A, B)$ denote the CH of cluster i and the distance between nodes A and B respectively. If $d(A, B) \leq R$, $A \in \mathcal{C}(1)$ and $B \in \mathcal{C}(2)$, then cluster 1 $\in \mathcal{NC}(2)$. Otherwise, assume $d(A, C) \leq R$ and $d(B, C) \leq R$, i.e., node C is the common one-hop neighbor of nodes A and B . If $A \in \mathcal{C}(1)$, $B \in \mathcal{C}(2)$ and $C \in \mathcal{C}(1) \cup \mathcal{C}(2)$, then cluster 1 $\in \mathcal{NC}(2)$. However, if $A \in \mathcal{C}(1)$, $B \in \mathcal{C}(2)$ and $C \in \mathcal{C}(3) \in \overline{\mathcal{C}(1) \cup \mathcal{C}(2)}$, we still have cluster 3 $\in \mathcal{NC}(1)$ and cluster 3 $\in \mathcal{NC}(2)$ since $d(A, C) \leq R$ and $d(B, C) \leq R$. Consequently, nodes A and B belong to two clusters which are either neighboring clusters or neighbors of another common cluster. $\square$

Next, according to Lemma 1, the total cases that HTP may happen can be illustrated in Fig. 4.3. Suppose the transmission codes of nodes A and B are $C^a = (C_1^a, C_2^a) \in C_{TC}$ and $C^b = (C_1^b, C_2^b) \in C_{TC}$ respectively. As shown in Fig. 4.3 (a), when A and B are in the same cluster 1, then $C_1^a = C_1^b$ and $C_2^a \neq C_2^b$ according to Criterion 1, thus $C^a \neq C^b$. In Fig. 4.3 (b), when A and B are in the adjacent clusters 1 and 2, then $C_1^a \neq C_1^b$ according to Criterion 2. In Fig. 4.3 (c), when A

and B are respectively in cluster 1 and 3 that are the neighbors of cluster 2, then $C_1^a \neq C_1^b$ according to Criterion 3. Thereby, no matter what second-phase codes nodes A and B use in the second and third cases, one always has $C^a \neq C^b$. In all three cases, C^a and C^b are always quasi-orthogonal. Therefore, if three criteria are always observed, there is no HTP in CA-TPCMMP.

4.3 Theoretical Analysis of CA-TPCMMP

4.3.1 Control Overhead and Delay Analysis

Assume that nodes are Poisson distributed in the network with density ρ . Let $N = \rho\pi R^2$ be the average number of nodes within the transmission range R .

Control Overhead and Delay in the Slot Acquisition

The successful slot acquisition requires the correct reception of the RFS and COS messages. However, it faces the collisions in the reception of RFS messages, since nodes within the communication range of a CH may initiate their contentions for their respective maintenance slots at the same time.

Initially, among N nodes, the probability of k contenders follows a Poisson distribution $\mathcal{P}_1(k) = e^{-N} N^k / k!$. Given ζ_k as the average number of contention slots

Table 4.1: χ_1 versus transmission range

TxRange	100m	150m	200m	250m
χ_1	3.30659	7.18795	12.6519	19.6893

required to resolve one collision, it follows the recursive relationship

$$\zeta_k = \begin{cases} 1, & k = 1 \\ \frac{1 + 2^{-k} \sum_{j=1}^{k-1} \binom{k}{j} \zeta_j}{1 - 2^{-k+1}}, & k > 1 \end{cases} \quad (4.1)$$

according to the conclusion of binary splitting strategy in [83]. Consequently, χ_1 average number of the RFS messages to win one contention can be computed as

$$\chi_1 = \sum_{k=1}^{\infty} \frac{\mathcal{P}_1(k)}{k} \sum_{l=1}^k l \sum_{j=0}^{\zeta_l-1} \left(\frac{1}{2}\right)^j. \quad (4.2)$$

Table 4.1 shows χ_1 varies with the transmission ranges. Unless otherwise mentioned, without loss of generality, we assume $\rho = 10^{-4}$ in the following analysis. It can be seen that the upward slope of χ_1 increases with the incremental transmission ranges.

Recall that the CMs contend to obtain their maintenance slots of their cluster only in their specific frames. Given χ_2 as the average total number of frames required for k nodes that participate in the contention to obtain their respective slots, we have

$$\chi_2 = \frac{1}{M_2} \sum_{k=1}^{\infty} \sum_{j=1}^k \zeta_j \mathcal{P}_1(k). \quad (4.3)$$

Fig. 4.4 shows χ_2 varies with the transmission ranges and M_2 . We observe that

Figure 4.4: χ_2 versus transmission range and M_2

although χ_2 increases with the incremental transmission ranges under a certain M_2 , it quickly decreases with the increasing of M_2 under a certain transmission range.

In steady state, the number of nodes simultaneously participating in the contention can be computed according to the number of nodes that migrate into the communication range of a CH within the interval of a super-frame. Let v denote the average speed and $N_{m,h1}(\varepsilon)$ denote the total number of nodes which migrate into the one-hop distance of a CH in the pre-specified small time interval ε . Notice that $v\varepsilon$ is far smaller than R which can be easily shown later. Therefore, given l as the distance between two nodes, the average number of new coming nodes can be

approximately derived as

$$N_{m_h1}(\varepsilon) = \int_R^{R+v\varepsilon} \theta \rho(2\pi l) dl, \quad (4.4)$$

where $\theta = \frac{2 \arccos((l-R)/(v\varepsilon))}{2\pi}$ denotes the angle along which nodes can migrate into the required area.

Denote the duration to transmit a RFS, a COS, a beacon message from a CH and broadcasting message from a CM respectively as τ_r , τ_c , τ_{bh} and τ_{bm} seconds. In the following, unless otherwise stated, we assume $\tau_{bh} = \tau_{bm}$, $\tau_r = \tau_c$ and the length of the broadcasting message is 50 bytes with $\tau_{bm} = 0.00133s$. Since a node sends RFS message which disseminates only its ID and a bit which indicates if the second-phase code is required or not and a CH sends COS message that conveys the sequence number of the allocated slot or code, the duration of these mini-slot is less than that of mini-slot for broadcasting message. We define a variable $\kappa = \frac{\tau_r}{\tau_{bm}}$. Let τ_{sf} and τ_f denote the duration of a super-frame and a frame respectively, then we have $\tau_{sf} = M_1\tau_f$ and $\tau_f = \tau_{bh} + M_2(\tau_r + \tau_c + \tau_{bm}) = \tau_{bh} + M_2(1 + 2\kappa)\tau_{bm}$. When M_1 adopts the maximal value 20, $M_2 \doteq \rho\pi(250)^2$ and $\kappa = 1/5$, we have $\tau_{sf} = 0.7714s$. Usually, the average speed is less than $20m/s$. Hence, we have $v\varepsilon = v\tau_{sf} \ll R$ when $R \geq 100m$.

As shown in Fig. 4.5, we observe $N_{m_h1}(\tau_{sf})$ versus v and R_d . As the transmission range and speed increase, $N_{m_h1}(\tau_{sf})$ increases quickly. However, when $R \leq 250m$, we observe that the number of nodes migrating into the transmission range of a CH within τ_{sf} is less than 1. Hence, in the steady status, it takes less contention for a

Figure 4.5: Average number of nodes migrating into the transmission range of a CH within the duration of a super-frame versus transmission range under the varying average speeds

new coming node to obtain its maintenance slot.

Since the CH acknowledge the CMs only when it wins the contention, it adds 1 to the overall overhead due to the successful contention. Thus, the average number ϕ_S of required RFS and COS messages for a successful slot acquisition of a node is

$$\phi_S = \chi_1 + 1. \quad (4.5)$$

The average total delay of ψ_S spent in the appropriate slot acquisition can be

Figure 4.6: Average control overhead of slot acquisition versus $1/\kappa$

approximately derived as

$$\psi_S = \lfloor \chi_2 \rfloor \times \tau_{sf} + \frac{\tau_f}{2} + \tau_{bh} + (\chi_2 - \lfloor \chi_2 \rfloor) \times \tau_{bm}. \quad (4.6)$$

As shown in Fig. 4.6 and Fig. 4.7, we observe the relation of average incurred control overhead and average total delay versus $1/\kappa$. Both average control overhead and average total delay decrease with the incremental κ .

Control Overhead and Delay in the Frame Acquisition

Let us assume that there are averagely x clusters probing their first-phase codes and y free frames are available within the neighborhood of any given cluster (including

Figure 4.7: Average total delay of slot acquisition versus $1/\kappa$

this cluster). Now we proceed to compute the average number of required control packets for a successful first-phase code broadcast of a node and the average total number of super-frames required to resolve a confliction.

Let $\alpha_{k,i}$ denote the number of clusters which have chosen the i_{th} frame in the k_{th} probing and $\nu_{k,i}$ denote the number of times that different number repeatedly appears in $\alpha_{k,1}, \dots, \alpha_{k,y}$ in turn, then we have $\alpha_{k,i} = 0, 1, 2, \dots, x$ and $\nu_{k,i} = 1, 2, \dots, y$ for any $1 \leq i \leq y$. According to the classical occupancy problem [90], the probability to obtain the given occupancy number $\alpha_{k,1}, \dots, \alpha_{k,y}$ equals

$$\mathcal{P}_2(x, y, k) = \frac{x!}{\alpha_{k,1}! \alpha_{k,2}! \dots \alpha_{k,i}! \dots \alpha_{k,y}!} \times \frac{y!}{\nu_{k,1}! \nu_{k,2}! \dots \nu_{k,i}! \dots \nu_{k,y}!} y^{-x}, \quad (4.7)$$

where $\sum_{i=1}^y \alpha_{k,i} = x$ for any $1 \leq k \leq y_0$. Here, y_0 is the pre-specified maximal number of probing after which there is no confliction in the frame acquisition of the neighboring clusters.

Let α_k and β_k denote the number of the clusters whose first-phase codes should be re-acquired in the k_{th} probe and the number of the available frames that have not been occupied by the neighboring clusters respectively, then we have

$$\alpha_{k+1} = \sum_{i=1}^y (1 - \delta(\alpha_{k,i} - 1) - \delta(\alpha_{k,i}))(\alpha_{k,i} - 1) \quad (4.8)$$

and

$$\beta_{k+1} = \beta_k - \sum_{i=1}^{\beta_k} (1 - \delta(\alpha_{k,i})), \quad (4.9)$$

where $\alpha_1 = x$, $\beta_1 = y$, $1 \leq k \leq y_0$ and $\delta(\cdot)$ is the Dirac function with $\delta(0) = 1$ and $\delta(z) = 0$ if $x \neq 0$.

Let ϑ_k denote the probability that there is the confliction that two clusters choose the same frame in the k_{th} probe. According to the conditional probability, we have

$$\vartheta_{k+1} = \delta\left(\prod_{i=1}^y (\delta(\alpha_{k,i} - 1) + \delta(\alpha_{k,i}))\right) \vartheta_k \mathcal{P}_2(\alpha_k, \beta_k, k), 1 \leq k \leq y_0 \quad (4.10)$$

with $\vartheta_1 = 1$.

Thus, the average number of required control packets of ϕ_F for a successful first-

Figure 4.8: χ_3 versus x and y (plot only $y \geq x$)

phase code broadcast of a node is

$$\phi_F = \chi_3 = \sum_{t=1}^{y_0} \sum_{s=1}^t \sum_{\sum_{i=1}^y \alpha_{s,i} = \alpha_s} \alpha_s \prod_{k=1}^t \mathcal{P}_2(\alpha_k, \beta_k, k) \delta(\vartheta_{t+1}). \quad (4.11)$$

Fig. 4.8 shows χ_3 varies with x and y . We observe that χ_3 increases with the incremental x and decreases with the incremental y .

The average total number of super-frames of χ_4 required to resolve a confliction

Figure 4.9: χ_4 versus x and y

and satisfy Criteria 2-3 is

$$\chi_4 = \sum_{t=1}^{y_0} \sum_{s=1}^t \sum_{\sum_{i=1}^y \alpha_{s,i} = \alpha_s} \prod_{k=1}^t \mathcal{P}_2(\alpha_k, \beta_k, k) t \delta(\vartheta_{t+1}). \quad (4.12)$$

As shown in Fig. 4.9, χ_4 decreases quickly with the increasing y given a certain x when it is required that x clusters find their appropriate frames in y available frames.

The average delay of ψ_F for a CH to obtain its appropriate frame is upper

bounded by

$$\psi_F = \chi_4 \tau_{sf} / x. \quad (4.13)$$

Average Total Control Overhead and Delay

Let P_{CH} and P_{CM} denote the probability of a node to be a CH and a CM respectively, then we approximately have

$$P_{CH} = \frac{1}{N} \quad (4.14)$$

and

$$P_{CM} = \frac{N-1}{N}. \quad (4.15)$$

Define the average lifetime of a CH or CM, i.e., T_{CH} and T_{CM} , as the average duration of a node to be a CH or CM within a cluster continuously. Instead of average total delay, we get the average delay ψ_S in slot acquisition with χ_2 replaced with $\chi'_2 = \frac{1}{M_2} \sum_{k=1}^{\infty} \sum_{j=1}^k \zeta_j \frac{\mathcal{P}_1(k)}{k}$ in Eq. 4.6. Therefore, the control overhead ϕ_{CA} of CA-TPCMMP in unit time is upper bounded by

$$\phi_{CA} = P_{CH} \frac{\phi_F + \lceil \frac{T_{CH} - \psi_F}{\tau_{sf}} \rceil}{T_{CH}} + P_{CM} \frac{\kappa \phi_S + 1 + \lceil \frac{T_{CM} - \psi_S}{\tau_{sf}} \rceil}{T_{CM}}. \quad (4.16)$$

The average delay ψ_{CA} of code acquisition is upper bounded by

$$\psi_{CA} = P_{CH} \frac{\psi_F}{T_{CH}} + P_{CM} \frac{\psi_F + \psi_S}{T_{CM}}. \quad (4.17)$$

4.3.2 The Selection of Parameters

Given N_c as the maximal number of neighboring clusters, y should be an appropriate value that satisfy the delay requirement during the negotiation and adjustment of the first-phase codes. In the worst case, $x = N_c + 1$ clusters are contending for their appropriate first-phase codes and $y = M_1$ frames are available. Then, given the pre-specified average delay requirement d_1 , we can determine the appropriate value of M_1 according to

$$\psi_F \leq d_1 \quad (4.18)$$

referring to Eq. 4.12 and Eq. 4.13.

Under a certain κ and M_1 , we require the suitable value of M_2 which satisfy

$$\psi_S \leq d_2, \quad (4.19)$$

where d_2 is the required average maximal delay for a node to obtain its slot. Since M_2 implies the supported number of CMs in a cluster, in our simulation, we determine the total number of slots under the control of a CH of M'_2 is $\mu + \sigma$ with the reasonable delay, where μ and σ are respectively the mean value and standard deviation of the number of CMs within the communication range of a CH. As shown in Table 4.2, we observe the chosen value M'_2 and ensuing delay of slot acquisition under increasing transmission ranges.

Table 4.2: Chosen Value M'_2

TxRange	100m	150m	200m	250m
M'_2	4.78935	9.71925	16.1112	24.0661
χ_2	1.67675	2.45136	3.03536	3.64412

4.4 Traditional Algorithms

We simulate the traditional algorithms (TAs) without clustering according to [49], i.e., a node sends a Code Assignment Message (CAM) to all its one-hop neighbors when a new node comes into transmission range and all receivers are required to acknowledge the sender to ensure the reliable transmission of CAM. In TAs with clustering, the same code assignment algorithm is employed except the underlying clustering mechanism, where each node has to wait for its maintenance slot to send its CAM.

4.5 Performance Evaluation

The simulation is done in NS2 [86] with the setup as shown in Table 4.3. When doing NS2 simulations, the assumption on Poisson distribution in the analytical model may be relaxed. The performance is evaluated in terms of control overhead, delay, throughput and energy efficiency versus transmission range and average speed. We vary the transmission range R to get the various number of one-hop neighbors and calculate the mean value of control overhead and delay per second for a node to get average control overhead and delay. The simulation results are averaged 10 runs with different movement patterns for each value of traffic arrival rate of λ , v

Table 4.3: Simulation Model

Parameters	Values
Platform	NS2 with CMU wireless extensions
Propagation Model	Two-ray ground model
Routing Protocol	AODV
Channel rate	2Mbps
Scenario	100 nodes and 30 traffic flows in $1000m * 1000m$
Mobility model	Random way point mobility model
Average Speed	Up to $20m/s$ with 0 pause time
Simulation time	$500sec$
Traffic type	CBR UDP with packet size $512bytes$
Control channel rate	$0.3Mbps$
Control packets	$50bytes$
κ	$1/5$
M_1	20
x	8

and R .

Fig. 4.10 and Fig. 4.11 show the average lifetime of a CH and CM in our clustering algorithm. As the speed increases, the average lifetime of a CH and CM both decreases. Incremental transmission range can prolong their average lifetime.

Fig. 4.12 shows average control overhead with 95% confidence interval [91] versus the transmission ranges when $\lambda = 50Pks/s$ and $v = 10m/s$. Obviously, the control overhead of TAs is worse than that of CA-TPCMMP and aggravates seriously with the increasing transmission ranges no matter it is based on flat topology or clustering. When the network is considerably loose with $N \doteq 3$ ($R = 100m$), the control overhead of TAs without clustering is even less than that of CA-TPCMMP. This is due to that when the network is loose, the neighborhood update of TAs is

Figure 4.10: Average lifetime of a CH versus average speed under the varying transmission ranges in CA-TPCMMP

less frequent and the probability of collisions is small. Whereas, in CA-TPCMMP, extra control overhead is caused by cluster establishment and maintenance and the appropriate frame and slot acquisition, which makes it less advantageous. TAs with clustering show a superior performance than TAs without clustering with the increasing number of one-hop neighbors. However, CA-TPCMMP significantly outperforms TAs when the network is becoming dense. When $N = 20$ with $R = 250m$, the control overhead incurred in TAs with clustering is almost 11 times higher than that of CA-TPCMMP. Furthermore, the control overhead incurred in TAs without clustering is almost 23 times higher than that of CA-TPCMMP. Moreover, the confidence interval of CA-TPCMMP is much smaller than those of TAs with clustering

Figure 4.11: Average lifetime of a CM versus average speed under the varying transmission ranges in CA-TPCMMP

and without clustering. Control overhead of CA-TPCMMP is not affected significantly by density since the acquisition of the first-phase and second-phase codes is completely incorporated in the clustering maintenance.

In Fig. 4.13, average speed is varied from $5m/s$ to $20m/s$ for observation of the average control overhead with 95% confidence interval when $R = 200m$ and $\lambda = 50Pks/s$. As the average speed increases, there is higher chance for a new node to migrate into transmission range, which requires more updating of neighborhood information in TAs. Consequently, the control overhead of TAs under both topology almost aggravates linearly with the increasing speed. CA-TPCMMP also requires more control packets in response to increasing speed since high mobility requires

Figure 4.12: Average control overhead with 95% confidence interval versus transmission range in CA-TPCMMP compared with TAs with/without clustering when $v = 10m/s$

more cluster maintenance. However, the upward trend of TAs is significantly worse and the confidence interval is much bigger than those of CA-TPCMMP. Therefore, CA-TPCMMP substantially reduces control overhead for a sufficiently dense or high mobility network.

As shown in Table 4.4 and Table 4.5, the simulation results of CA-TPCMMP match well with the numerical results. The control overhead first decreases with the incremental transmission ranges and then increase slightly with the incremental transmission ranges since the average lifetime of the CH and CM both increases with the incremental transmission ranges.

Fig. 4.14 shows how average delay varies with the transmission ranges under the

Figure 4.13: Average control overhead with 95% confidence interval versus average speed in CA-TPCMMP compared with TAs with/without clustering when $R = 200m$ and $\lambda = 50Pks/s$

Table 4.4: Average control overhead versus transmission range when $v = 10m/s$ in CA-TPCMMP

R(m)	100	150	200	250
simulation results	1.9613	0.7393	0.5885	0.6327
numerical upper bound	2.1593	0.8996	0.7171	0.7801

Table 4.5: Average control overhead versus average speed when $R = 200m$ in CA-TPCMMP

v(m/s)	5	10	15	20
simulation results	0.3850	0.5885	0.7837	0.9663
numerical upper bound	0.4970	0.7171	0.9310	1.1458

Table 4.6: Average delay versus transmission range under varying average speed in CA-TPCMMP

R(m)	100	150	200	250
simulation results ($v=10\text{m/s}$)	0.0354	0.0320	0.0570	0.0730
numerical upper bound ($v=10\text{m/s}$)	0.0530	0.0451	0.0695	0.0871
simulation results ($v=20\text{m/s}$)	0.0541	0.0494	0.0903	0.1151
numerical upper bound ($v=20\text{m/s}$)	0.0730	0.0621	0.1032	0.1302

varying average speed. Average delay of both CA-TPCMMP and TAs with clustering is worse than that without clustering since with clustering a node has to wait for its appropriate slot in the appropriate frame of its cluster to transmit its neighborhood information. However, the lower delay of TAs without clustering is obtained at the cost of higher overhead from frequent updating of neighborhood information. Moreover, average delay degrades quickly with the increasing transmission ranges while the upward slope in CA-TPCMMP and TAs with clustering is decreasing. In CA-TPCMMP, with the increasing speed, there are more CMs to migrate into a new cluster, which causes more collisions in the appropriate slot assignment for the acquisition of the second-phase code. Meanwhile, the first-phase codes of the adjacent clusters have to be adjusted timely to avoid the HTP. Consequently, the delay of CA-TPCMMP increases. Nonetheless, CA-TPCMMP incurs less delay and rises less sharply than TAs with clustering due to less exchanges of control packets. Table 4.6 shows the simulation results of CA-TPCMMP match well with the numerical results.

Figure 4.14: Average delay versus transmission range under the varying average speeds in CA-TPCMMP compared with TAs with/without clustering

4.6 Discussions and Conclusions

Here, we concentrate on the CDMA-based multi-channel MAC protocol due to the fact that heavy control overhead is incurred in the code assignment of the traditional CDMA-based multi-channel protocol. However, based on the point of channel spatial reuse, the proposed models also applies to TDMA and FDMA based multi-channel MAC protocol as well as their combinations. It is noteworthy that the ideas in CA-TPCMMP are radically different from the channel allocation of a cellular-type network with mobile base stations [92] in that mobile BSs are always preassigned and enriched with abundant energy supply as well as high processing power. Henceforth, mobile base stations establish the backbone link in a different radio level with much

bigger transmission power than the mobile hosts. Whereas, in CA-TPCMMP, nodes are of the same transmission power and thus the CHs are randomly chosen and dynamically change. Apparently, the intra-cluster communication is via the relaying of the CMs. Hence, the question of how to coordinate the channel assignment of the adjacent clusters, is very important in the context of MANETs. Overall, CA-TPCMMP provides us a useful framework of jointly designing clustering and channel assignment in a multi-channel MAC protocol, which is of significance in reducing the control overhead and henceforth energy consumption. Even though it pays the cost of not minimizing the required quasi-orthogonal codes compared to identifying a different code within two-hop separation via neighborhood exchanges, in the context of MANETs, this tradeoff may be acceptable, as reducing control overhead is of vital importance than minimizing the required codes in some specific applications that are strictly restricted by power supply.

This chapter proposes a novel multi-channel MAC protocol for MANETs named as CA-TPCMMP, which integrates two-phase coding scheme with the concept of dynamic clustering. For this algorithm, to decide an appropriate confliction-free transmission code, complete two-hop neighborhood information of a node is not necessary, which makes it immune from serious overhead that TAs suffer from. Although one-hop neighborhood of clusters is indispensable, relative to the code assignment of nodes within two-hop separation, the probability of selecting an appropriate first-phase code that is not in confliction with neighboring clusters greatly increases since the impact of code identification of clusters suffering from the increas-

ing density and mobility is much less than that incurred by nodes within two-hop separation.

Through the process of detection and resolution of code confliction, CA-TPCMMP mitigates the HTP during data transmission. We also introduce the collision avoidance mechanism during the acquisition of the second-phase code in the control channel. Furthermore, we present the theoretical analysis of the control overhead and delay of CA-TPCMMP. Extensive simulation results demonstrate that CA-TPCMMP substantially improves the system performance in terms of control overhead, throughput and energy efficiency.

Chapter 5

Multi-Code Multi-Packet

Transmission in Nakagami-m

Fading Wireless Ad Hoc Networks

5.1 Introduction

In CDMA techniques, there is MAI when employing the incompletely orthogonal spreading codes. The serious fading and interference phenomena in wireless CDMA ad hoc networks cause a time-varying channel condition. Therefore, a key problem for such a network is to maintain the acceptable MAI performance over wireless channels experiencing fading with as more as possible simultaneous packet transmission. To date, the expected forward progress per hop, which considers both the local throughput and the number of hops, has been investigated in the literatures [59] [78] [93] as an important performance measure of packet forward in wireless CDMA ad hoc networks.

Sousa and Silvester [93] derive the optimum transmission range for a CDMA mul-

ti-hop network over an additive white Gaussian noise (AWGN) channel to maximize the expected progress per hop. Zorzi and Pupolin [94] extend the channel model by considering both fading and shadowing to evaluate the optimum transmission range. Furthermore, Souryal et al. [15] derive the distribution of the interference power for a Rayleigh fading channel and explore the benefit of route diversity in such a channel. However, the existing work only gives the interference distribution in the special cases of non-fading AWGN channel and Rayleigh fading channel instead of a general fading channel. Moreover, none of the existing work considers the forward progress improvement by exploiting the varying channel conditions in a fading channel. Although a framework of SMPT is proposed in [70] to stabilize the link-layer throughput, it focused on automatic request repeat (ARQ) component and only studied the link-layer buffer occupancy and code usage.

In this chapter, firstly we generalize the fading model and derive the pdf of MAI power in the wireless CDMA ad hoc networks under a Nakagami- m fading channel. We show that the previously known results of Rayleigh fading channel follow as the special cases of our analysis. Secondly, we propose MCMPT scheme for wireless CDMA ad hoc networks operating in a Nakagami- m fading channel and investigate the benefit of MCMPT for the varying parameter m . We seek to maximize the expected progress per hop by adapting the number of parallel transmission of multiple packets on multiple codes according to varying channel conditions in a Nakagami- m fading channel. Under the instantaneous good channel conditions, more number of parallel transmission can be initiated simultaneously while satisfy required SINR

for the correct packet reception and recovery. We argue that there is an optimum number of parallel packet transmission under a certain channel condition of the Nakagami-m fading channel to maximize the expected forward progress per hop.

The remainder of the chapter is organized as follows. Section 5.2 explains the system model. Section 5.3 derives the pdf of MAI power at a given node for the Nakagami-m fading model. Section 5.4 introduces the MCMPT and analytically examines the performance, in terms of the expected forward progress, by utilizing the Markov partitioning of the channel states. Section 5.5 gives the numerical results and compares it with the CPT. Section 5.6 concludes the chapter.

5.2 System Model

Let us consider a wireless CDMA ad hoc network operating under heavy traffic conditions, where nodes are Poisson distributed in the network with average density λ . Then,

$$Prob(\text{finding } k \text{ nodes within the region with radius } a) = \frac{e^{-\lambda\pi a^2} (\lambda\pi a^2)^k}{k!}$$

The transmission system is time slotted and each node transmits data independently with successful transmission probability p in each slot.

We assume that the system operates in an asynchronous direct sequence scheme of binary phase shift keying (DS/BPSK) with rectangular chip pulse, and that nodes transmit at the same transmission power. Following [95][93], SINR μ is represented

as,

$$\mu = \left(\frac{2Y}{3GP_r} + \frac{1}{\mu_0} \right)^{-1} \quad (5.1)$$

where P_r is the received signal power, Y is the total interference power, G is the processing gain and μ_0 is the SINR at the receiver in the absence of MAI. The total MAI power Y is assumed to be a Gaussian random variable.

Let μ_t denote the threshold value of SINR for successful packet reception. Then, according to [93], the unconditional packet success probability can be given by

$$\begin{aligned} P_s &= \int_0^\infty p_M(\mu) f_M(\mu) d\mu \\ &= \int_0^\infty p'_M(\mu) (1 - F_M(\mu)) d\mu \\ &= 1 - F_M(\mu_t) \end{aligned} \quad (5.2)$$

where $f_M(\mu)$ and $F_M(\mu)$ are respectively the pdf and *cumulative distribution function* (cdf) of the random variable M , and the packet success probability $p_M(\mu)$ is a step function

$$p_M(\mu) = \begin{cases} 1, & \mu \geq \mu_t \\ 0, & \mu < \mu_t \end{cases} \quad (5.3)$$

We use a complex channel model, which considers both large-scale path loss with path loss exponent n and multi-path fading. We use a generic Nakagami- m fading distribution to characterize the multi-path fading, since it is a two-parameter distribution with parameter m and Ω and it can give the best fit to the statistics of signals transmitted over multi-path channels in a land-mobile and indoor-mobile environments via the m parameters. We consider the slowly-varying flat fading and

hence the channel remains roughly constant over a time slot. Let P_t and P_r denote respectively the transmission power and the receiving signal strength. Then, we have

$$P_r = \frac{\alpha^2 P_t}{d^n}$$

where α is the channel fading amplitude and d is the distance between the transmitter and receiver. The channel fading amplitude α follows Nakagami-m fading [5] and the pdf of the Nakagami-m fading random variable A is given by

$$f_A(\alpha) = 2\left(\frac{m}{\Omega}\right)^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-m\alpha^2/\Omega}, \alpha \geq 0 \quad (5.4)$$

where Ω is the average received power, m is the Nakagami-m fading parameter ($m \geq 1/2$) and $\Gamma(\cdot)$ is the gamma function defined by

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt, z \geq 0$$

The parameter m characterizes the severity of the fading. As m increases, the fading becomes less severe. As a special case of $m = 1$, the Nakagami-m distribution represents the Rayleigh distribution. The case $m = 1/2$ gives the one-side Gaussian fading which is the fading in the worst case. Moreover, the Nakagami-m distribution can approximate Rice and log-normal distribution when $m > 1$ [96].

Performance is measured in terms of the expected progress per hop [78][93]

$$\sqrt{\lambda}Z = \sqrt{\lambda}\zeta R_0,$$

where ζ is the one-hop local throughput of a transmitter and R_0 is the distance between the transmitter and receiver. Referring to [93], Appendix A shows that ζ is the product of the probability of successful packet transmission P_s and the tendency of two nodes to pair up, which is given by $\zeta = (1 - p)(1 - e^{-p})P_s$. Define N as the average number of nodes that are closer to the receiver than transmitter, then we have $N = \lambda\pi R_0^2$. Hence, the expected progress per hop can be expressed as

$$\begin{aligned}\sqrt{\lambda}Z &= \sqrt{N/\pi}(1 - p)(1 - e^{-p})P_s \\ &= \sqrt{N/\pi}(1 - p)(1 - e^{-p})(1 - F_M(\mu_t))\end{aligned}\tag{5.5}$$

and this result will be used in Section IV.

5.3 MAI Power Distribution in a Generic Nakagami-m Fading Channel

Referring to the previous work [93][59] that derive the MAI power distribution under the non-fading AWGN channels and Rayleigh fading channels respectively, in this section, we will derive the MAI power distribution of wireless CDMA ad hoc networks in a generic Nakagami-m fading channel.

Since we assume that nodes transmit at the same transmission power, we have the normalized interference power $g(r_i)$ from a node i expressed as $g(r_i) = \alpha^2 P_t / r_i^n$, where r_i is the distance between node i and the given receiver. Then we have total

interference Y_a at the given node within the disk D_a with radius a expressed as

$$Y_a = \sum_{r_i \leq a} g(r_i) \quad (5.6)$$

Let ϕ_{Y_a} be the characteristic function of Y_a , then we have

$$\phi_{Y_a}(\omega) = \mathbf{E}(e^{j\omega Y_a}) \quad (5.7)$$

According to the conditional expectations, Eq. 6.6 can be expressed as

$$\begin{aligned} \phi_{Y_a}(\omega) &= \mathbf{E}(e^{j\omega Y_a}) \\ &= \mathbf{E}(\mathbf{E}(e^{j\omega Y_a} / k \text{ nodes in } D_a)) \\ &= \sum_{k=0}^{\infty} \frac{e^{-\lambda_t \pi a^2} (\lambda_t \pi a^2)^k}{k!} \mathbf{E}(e^{j\omega Y_a} / k \text{ nodes in } D_a) \end{aligned} \quad (5.8)$$

where $\lambda_t = \lambda p$. Let r denote the distance between an interferer and a given node.

Considering that nodes are uniformly distributed, we have the pdf of the random variable R given by

$$f_R(r) = \frac{2r}{a^2}, 0 < r \leq a$$

With the assumption that the fading attenuation of each interferer is *independent and identically distributed* (i.i.d), Eq. 6.7 can be further expressed as

$$\phi_{Y_a}(\omega) = \sum_{k=0}^{\infty} \frac{e^{-\lambda_t \pi a^2} (\lambda_t \pi a^2)^k}{k!} \{ \mathbf{E}(e^{j\omega g(r)}) \}^k \quad (5.9)$$

where

$$\mathbf{E}(e^{j\omega g(r)}) = \int_0^a \int_0^\infty e^{j\omega\alpha^2/r^n} f_{R,A}(r, \alpha) d\alpha dr \quad (5.10)$$

Assuming that the fading is independent of the distance, Eq. 6.8 can be written as

$$\begin{aligned} \mathbf{E}(e^{j\omega\alpha^2/r^n}) &= \int_0^a \int_0^\infty e^{j\omega\alpha^2/r^n} f_R(r) dr f_A(\alpha) d\alpha \\ &= \int_0^a \frac{2r}{a^2} \int_0^\infty 2\left(\frac{m}{\Omega}\right)^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-m\alpha^2/\Omega} e^{j\omega\alpha^2/r^n} d\alpha dr \end{aligned} \quad (5.11)$$

As noted in [93], only the path loss exponent $n = 4$ can give the closed-form expression of density. Hence, we use $n = 4$ thereafter. Note that $\phi_{Y_a}(\omega)$ is not convergent for $m < 1$ when $a \rightarrow \infty$. Therefore, we obtain $\mathbf{E}(e^{j\omega\alpha^2/r^n})$ for the typical values of $m = 1, 2, 3$ and 4 (referring to m values used by Proakis [5] and Alouini [63]) in Eq. 5.12 respectively, where $m = 1$ represents Rayleigh fading.

Substituting it for Eq. 5.9, we obtain $\phi_{Y_a}(\omega)$ in Eq. 5.13, where $\beta = e^{-\lambda_t \pi a^2}$. Since we have the total MAI power Y at a given node

$$Y = \lim_{a \rightarrow \infty} Y_a,$$

correspondingly, we have the characteristic function of Y

$$\phi_Y(\omega) = \lim_{a \rightarrow \infty} \phi_{Y_a}(\omega)$$

$$\mathbf{E}(e^{j\omega\alpha^2/r^n}) =$$

$$\begin{cases} \frac{a^2 - (1-j)\sigma\sqrt{\omega}\text{ArcTan}[\frac{a^2(1+j)}{2\sigma\sqrt{\omega}}]}{a^2}, & m = 1 \\ \frac{2a^6 - j3a^2\sigma^2\omega + 3(-1)^{1/4}\sigma\sqrt{\omega}(ja^4 + \sigma^2\omega)\text{ArcTan}[\frac{(-1)^{1/4}a^2}{\sigma\sqrt{\omega}}]}{2a(a^5 - ja\sigma^2\omega)}, & m = 2 \\ \frac{6a^2(12a^8 - j25a^4\sigma^2\omega - 10\sigma^4\omega^2) + 5(1-j)\sigma\sqrt{3\omega}(j3a^4 + 2\sigma^2\omega)^2\text{ArcTan}[\frac{\sqrt{3}(1+j)a^2}{2\sigma\sqrt{\omega}}]}{8a^2(3a^4 - j2\sigma^2\omega)^2}, & m = 3 \\ \frac{2a^2(384a^{12} - j924a^8\sigma^2\omega - 560a^4\sigma^4\omega^2 + j1056\sigma^6\omega^3) - 105(1+j)\sigma\sqrt{\omega}(j2a^4 + \sigma^2\omega)^3\text{ArcTan}[\frac{(1+j)a^2}{\sigma\sqrt{\omega}}]}{96a^2(2a^4 - j\sigma^2\omega)^3}, & m = 4 \end{cases} \quad (5.12)$$

$$\phi_{Y_a}(\omega) =$$

$$\begin{cases} e^{-\lambda_t\pi(1-j)\sigma\sqrt{\omega}\text{ArcTan}[\frac{a^2(1+j)}{2\sigma\sqrt{\omega}}]}, & m = 1 \\ e^{-\lambda_t\pi a^2 + \lambda_t\pi \frac{(2a^6 - j3a^2\sigma^2\omega + 3(-1)^{1/4}\sigma\sqrt{\omega}(ja^4 + \sigma^2\omega)\text{ArcTan}[\frac{(-1)^{1/4}a^2}{\sigma\sqrt{\omega}}])}{2(a^4 - j\sigma^2\omega)}}, & m = 2 \\ e^{-\lambda_t\pi a^2 + \lambda_t\pi \frac{(6a^2(12a^8 - j25a^4\sigma^2\omega - 10\sigma^4\omega^2) + 5(1-j)\sigma\sqrt{3\omega}(j3a^4 + 2\sigma^2\omega)^2\text{ArcTan}[\frac{\sqrt{3}(1+j)a^2}{2\sigma\sqrt{\omega}}])}{8(3a^4 - j2\sigma^2\omega)^2}}, & m = 3 \\ e^{-\lambda_t\pi a^2 + \lambda_t\pi \frac{(2a^2(384a^{12} - j924a^8\sigma^2\omega - 560a^4\sigma^4\omega^2 + j1056\sigma^6\omega^3) - 105(1+j)\sigma\sqrt{\omega}(j2a^4 + \sigma^2\omega)^3\text{ArcTan}[\frac{(1+j)a^2}{\sigma\sqrt{\omega}}])}{96a^2(2a^4 - j\sigma^2\omega)^3}}, & m = 4 \end{cases} \quad (5.13)$$

which one can show as

$$\phi_Y(\omega) = \begin{cases} e^{-\lambda_t\pi^2\sigma\sqrt{\omega/2}e^{-j\pi/4}}, & m = 1 \\ e^{-\frac{3}{4}\lambda_t\pi^2\sigma\sqrt{\omega}e^{-j\pi/4}}, & m = 2 \\ e^{-\frac{5}{8}\lambda_t\pi^2\sigma\sqrt{3\omega/2}e^{-j\pi/4}}, & m = 3 \\ e^{-\frac{35}{32}\lambda_t\pi^2\sigma\sqrt{\omega/2}e^{-j\pi/4}}, & m = 4 \end{cases} \quad (5.14)$$

As a result, using the inverse Fourier transform, one can obtain the pdf and cdf

Table 5.1: Additional factor η for various m

m	1	2	3	4
η	$\sqrt{\frac{\pi}{2}}\sigma$	$\frac{3}{4}\sqrt{\pi}\sigma$	$\frac{5}{8}\sqrt{\frac{3\pi}{2}}\sigma$	$\frac{35}{32}\sqrt{\frac{\pi}{2}}\sigma$

of Y respectively as

$$f_Y(y) = \begin{cases} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-\lambda_t^2 \pi^4 \sigma^2 / 8y}, & m = 1 \\ \frac{3}{8} \lambda_t \sigma \left(\frac{\pi}{y}\right)^{3/2} e^{-9\lambda_t^2 \pi^4 \sigma^2 / 64y}, & m = 2 \\ \frac{5}{8} \sqrt{3} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-75\lambda_t^2 \pi^4 \sigma^2 / 512y}, & m = 3 \\ \frac{35}{32} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-1225\lambda_t^2 \pi^4 \sigma^2 / 8192y}, & m = 4 \end{cases} \quad (5.15)$$

and

$$F_Y(y) = \begin{cases} \text{Erfc}\left(\frac{\lambda_t \pi^2 \sigma}{2\sqrt{2y}}\right), & m = 1 \\ \text{Erfc}\left(\frac{3\lambda_t \pi^2 \sigma}{8\sqrt{y}}\right), & m = 2 \\ \text{Erfc}\left(\frac{5\sqrt{3}\lambda_t \pi^2 \sigma}{16\sqrt{2y}}\right), & m = 3 \\ \text{Erfc}\left(\frac{35\lambda_t \pi^2 \sigma}{64\sqrt{2y}}\right), & m = 4 \end{cases} \quad (5.16)$$

for $y > 0$. We observe that Eq. 5.16 is consistent with Sousa's result in [93] with an additional factor η for various m illustrated in Table 5.1 for different values of parameter m . We also observe that the result when $m = 1$ is complying with Souryal's result of Rayleigh fading in [59].

5.4 MCMP

CPT employs the sequential transmission of packets, i.e., the transmitter sends at most one packet on a code anytime, without considering the channel conditions.

MCMPT exploits the parallel packet transmission on multiple code channels provided by multi-code CDMA. In MCMPT, based on the instantaneous good channel conditions and acceptable MAI, the sequential transmission of packets in CPT is transformed into a flexible number of parallel transmission of multiple packets on multiple codes according to the fading conditions to increase the expected forward progress. There is a tradeoff between more number of simultaneous transmission and increased MAI. We consider slow Nakagami-m fading channel. Thus, CPT can be evolved into adaptive MCMPT according to varying channel conditions of Nakagami-m fading channels.

5.4.1 Channel States Partitioning according to Markov Model for Nakagami-m Fading Channels

In MCMPT, we partition the channel states according to the $Q+1$ -state Markov model with one sample path shown in Fig. 5.1, where Q is the partitioned number of good channel conditions of a Nakagami-m fading channel and additional 1 is for the bad channel conditions. Denote α_q^l and α_q^u respectively as the lower and upper threshold values of α for the q ($q = 0, 1, \dots, Q$) channel state interval, where $q = 0$ denotes the bad channel state and incremental q means better channel conditions. For each good channel state, there is corresponding number of parallel packet transmission to maximize the expected progress per hop. Note that for the bad channel state, no packets are transmitted. The thresholds of the partitioned channel states will be determined later.

Figure 5.1: A sample path of a Nakagami-m fading channel that shows the relationship between the channel fading amplitude α and the corresponding channel state q in a discrete and homogeneous $Q+1$ -state Markov model

5.4.2 Analysis of Expected Progress Per Hop

Let κ denote the flexible number of parallel transmission in MCMPT from a node which is active with the attempt probability p at a slot, we have the actual SINR

$$\mu = \left(\frac{2(\kappa Y + (\kappa - 1)P_r)}{3GP_r} + \frac{1}{\mu_0} \right)^{-1} \quad (5.17)$$

where for simplification we only consider the case that κ is the same. Substituting Eq. 5.17 in Eq. 5.16 in terms of Y , we can obtain the conditional cdf of M on A as

$$F_{M|A}(\mu|\alpha) = \begin{cases} 1 - F_Y\left[\frac{3G}{2\kappa R_0^4}\left(\frac{\alpha^2}{\mu} - \frac{1}{\mu_0} - \frac{2\alpha^2(\kappa-1)}{3G}\right)\right], & \mu < \alpha^2\mu_0 \\ 1, & \mu \geq \alpha^2\mu_0 \end{cases}$$

where A follows a Nakagami-m probability distribution.

Define the multiple-access capability

$$K(\mu, \alpha, \kappa) = \frac{3G}{2\kappa} \left(\frac{A^2}{M} - \frac{1}{\mu_0} - \frac{2A^2(\kappa - 1)}{3G} \right)$$

Thus, we can obtain

$$\begin{aligned} F_M(\mu) &= \int_0^\infty F_{M|A}(\mu|\alpha) f_A(\alpha) d\alpha \\ &= \int_0^{\sqrt{\mu/\mu_0}} f_A(\alpha) d\alpha + \int_{\sqrt{\mu/\mu_0}}^\infty (1 - F_Y[\frac{1}{R_0^4} K(\mu, \alpha, \kappa)]) \cdot f_A(\alpha) d\alpha \\ &= 1 - \sum_{q=0}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R_0^4} K(\mu, \alpha, \kappa)] f_A(\alpha) d\alpha \end{aligned} \quad (5.18)$$

where $\alpha_q^u = \alpha_{q+1}^l$. Note that $\alpha_q^l = \min\{\alpha_q^l, \sqrt{\mu/\mu_0}\}$.

As a result, the expected progress per hop can be expressed as

$$\begin{aligned} \sqrt{\lambda}Z &= \sqrt{N/\pi\kappa}(1-p)(1-e^{-p})(1-F_M(\mu_t)) \\ &= \sqrt{N/\pi\kappa}(1-p)(1-e^{-p}) \sum_{q=0}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R_0^4} K(\mu, \alpha, \kappa)] \cdot f_A(\alpha) d\alpha \end{aligned} \quad (5.19)$$

Therefore, the adaptation mechanism can be defined as

$$\begin{aligned} \arg_{\forall(\kappa_q, p_q)} \max\{\sqrt{\lambda}Z\} &= \sum_{q=0}^Q \arg_{\forall(\kappa_q, p_q)} \max\{\sqrt{N/\pi\kappa}(1-p)(1-e^{-p}) \\ &\quad \cdot \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R_0^4} K(\mu, \alpha, \kappa)] f_A(\alpha) d\alpha\} \end{aligned} \quad (5.20)$$

where κ_q and p_q are respectively the variables κ and p in the q -th channel state. Let

us define

$$(\sqrt{\lambda}Z)_q = \sqrt{N/\pi\kappa}(1-p)(1-e^{-p}) \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R_0^4} K(\mu, \alpha, \kappa)] f_A(\alpha) d\alpha \quad (5.21)$$

Eq. 5.21 is a concave function in the variables p and κ and hence there exists an optimum (κ_q, p_q) pair to maximize $(\sqrt{\lambda}Z)_q$. Therefore, we can find the optimum (κ, p) pair for each channel state to maximize $\sqrt{\lambda}Z$ in Eq. 5.20 such that transmitter can initiate κ parallel packet transmission with acceptable MAI to any ongoing transmission to achieve the maximum expected progress per hop. For the special case of $m = 1$ and $\kappa = 1$, we observe that Eq. 5.20 is consistent with Souryal's result in [59].

5.4.3 Determination of Thresholds

We know that the steady state probability of channel conditions can be derived as

$$\begin{aligned} Pr[\alpha_q^l < \alpha \leq \alpha_q^u] &= \int_{\alpha_q^l}^{\alpha_q^u} f_A(\alpha) d\alpha \\ &= (\Gamma(m, \frac{m\alpha_q^{l2}}{\Omega}) - \Gamma(m, \frac{m\alpha_q^{u2}}{\Omega})) / \Gamma(m) \end{aligned} \quad (5.22)$$

There are many partitioning schemes for determining the thresholds of state intervals in the finite-state Markov channel [97][98]. In the following numerical results, we simply apply equally probable partition [99] of channel states. Taking the case $m = 1$ as the reference, we determine the thresholds according to

$$Pr[\alpha_q^l < \alpha \leq \alpha_q^u] = \frac{1}{Q+1} \quad (5.23)$$

where $\alpha_0^l = 0$ and $\alpha_Q^u \doteq 3$ (this value is chosen by referring to [99]).

Table 5.2: Thresholds for the partitioned channel state intervals

Q	α_0^l	$\alpha_0^u(\alpha_1^l)$	$\alpha_1^u(\alpha_2^l)$	$\alpha_2^u(\alpha_3^l)$	$\alpha_3^u(\alpha_4^l)$	α_4^u
1	0.1	0.8325	3	-	-	-
2	0.1	0.6367	1.048	3	-	-
3	0.1	0.5364	0.8326	1.1777	3	
4	0.1	0.4730	0.7168	0.9646	1.2878	3

5.4.4 Implementation Issues

The adaptation of appropriate number in MCMPT is based on the estimation of channel states, which is feedback by the receiver to the transmitter by comparing the measured signal attenuation to a set of channel gain thresholds in a separate control channel. Existing work has investigated the impact of channel estimation and suggests that it is practical. In [65], the channel is estimated for its adaptation mechanism based on number of positive/negative acknowledgement (ACK/NACK). In [66], more reliable channel estimation is done by using different ACK/NACK observation intervals and weighting factors. Therefore, it is practical in MCMPT that the receiver notifies the transmitter of the channel conditions according to its measured signal such that the transmitter can select appropriate (κ, p) pair to maximize the expected progress per hop based on the instantaneous channel state information. As explained in [70] [71], the existing multi-code systems provides the feasibility for MCMPT.

Figure 5.2: Expected progress per hop versus transmission probability under varying G in MCMPT compared with CPT when $N = 7$ and $Q = 3$ in the Rayleigh fading channel

5.5 Numerical results

By referring to the direct-sequence mobile packet radio network [100][101], we choose the same system parameters $\mu_t = 6.6dB$ (required $BER = 10^{-5}$ and CRC code gain $= 1dB$), $\mu_0 = 26.6dB$ and $G = 128$. According to [59], the parameter σ is set to be $1/\sqrt{2}$. Hence, $\Omega = 2\sigma^2 = 1$. The thresholds for the partitioned channel state intervals are illustrated in Table 5.2, where we replace $\alpha_0^l = 0$ with $\alpha_0^l = \sqrt{\mu_t/\mu_0} = 0.1$ as noted in Eq. 5.18. Thereafter, unless specifically mentioned, the expected progress per hop in MCMPT is obtained through adopting the optimum number of parallel packet transmission in each channel state for each transmission probability.

Fig. 5.2 shows that expected progress per hop versus transmission probability under varying G in MCMPT compared with CPT when $N = 7$ and $Q = 3$ in

Figure 5.3: Expected progress per hop versus transmission probability under varying Q in MCMPT compared with CPT when $N = 7$ and $G = 128$ in the Rayleigh fading channel

the Rayleigh fading channel. With the increasing values of Q , there is a bigger benefit of expected forward progress per hop. This is attributed to the increasing multiple access capability with a bigger spreading factor. Next, we specify G as 128 to investigate the performance of MCMPT over CPT.

Fig. 5.3, Fig. 5.4 and Fig. 5.5 show that expected progress per hop versus transmission probability p under varying number of state partitions of Nakagami- m fading channels respectively in the cases of $m = 1$, $m = 2$ and $m = 4$ when $N = 7$ and $G = 128$. Obviously, when we consider the varying channel conditions and adapt the optimum number of parallel packets transmission, there is significant improvement of expected progress per hop than that of CPT. With more number of partitions of channel states, there is better expected progress per hop due to more accurate

Figure 5.4: Expected progress per hop versus transmission probability under varying Q in MCMPT compared with CPT when $N = 7$ and $G = 128$ in the Nakagami-m ($m=2$) fading channel

Figure 5.5: Expected progress per hop versus transmission probability under varying Q in MCMPT compared with CPT when $N = 7$ and $G = 128$ in the Nakagami-m ($m=4$) fading channel

Figure 5.6: Expected progress per hop versus transmission probability in MCMPT with $Q = 3$ compared with CPT under varying N when $G = 128$ in the Rayleigh fading channel

channel states. However, the increasing slope becomes less, which is attributed to more number of partition approximates the perfect estimation of the instantaneous channel states. There exists an optimum value of p under the different number of state partitions of Rayleigh fading channel in MCMPT, in agreement with CPT. The result in the case of $m = 1$ is consistent with that of MCMPT in the Rayleigh fading channels. With the increasing values of parameter m , there is better $\sqrt{\lambda}Z$ under the same other parameters, due to less severe fading.

In Fig. 5.6, Fig. 5.7 and Fig. 5.8, we vary the transmission probability to observe the benefit of MCMPT over CPT under varying number of nodes N respectively in the cases of $m = 1$, $m = 2$ and $m = 4$ when $G = 128$ and $Q = 3$. There is significant improvement of $\sqrt{\lambda}Z$ in MCMPT. We observe that, as in the case of

Figure 5.7: Expected progress per hop versus transmission probability in MCMPT with $Q = 3$ compared with CPT under varying N when $G = 128$ in the Nakagami-m ($m=2$) fading channel

Figure 5.8: Expected progress per hop versus transmission probability in MCMPT with $Q = 3$ compared with CPT under varying N when $G = 128$ in the Nakagami-m ($m=4$) fading channel

Figure 5.9: Expected progress per hop versus transmission probability under varying κ in MCMPT when $N = 7$, $G = 128$, $Q = 3$ and $q = 1$ in the Rayleigh fading channel

CPT, under different transmission probability, there is different optimum value of N which maximizes the expected progress per hop for any case of m . As shown in Fig. 5.6, the illustrated values of $N = 20, 10, 7$ and 3 show maximum $\sqrt{\lambda}Z$ within the corresponding interval of $p \in [0, 0.04)$, $[0.04, 0.07)$, $[0.07, 0.12)$ and $[0.12, 1)$ respectively. With the increasing transmission probability p and N , there is no much progress benefit due to limited multiple-access capability. Instead, there is even worse $\sqrt{\lambda}Z$ under high transmission probability in MCMPT than that in CPT, which is further attributed to the supposition in MCMPT that there is no packet transmission when $q = 0$. The benefit of expected forward progress increases with the increasing values of m under the same parameter N .

Fig. 5.9, Fig. 5.10 and Fig. 5.11 show that expected progress per hop versus transmission probability under varying κ in MCMPT respectively in the cases of

Figure 5.10: Expected progress per hop versus transmission probability under varying κ in MCMPT when $N = 7$, $G = 128$, $Q = 3$ and $q = 2$ in the Rayleigh fading channel

Figure 5.11: Expected progress per hop versus transmission probability under varying κ in MCMPT when $N = 7$, $G = 128$, $Q = 3$ and $q = 3$ in the Rayleigh fading channel

Figure 5.12: Expected progress per hop versus κ in MCMPT when $N = 7$, $G = 128$ and $Q = 3$ under varying m and q in the Rayleigh fading channel

$q = 1$, $q = 2$ and $q = 3$ when $N = 7$, $G = 128$, $Q = 3$ and $q = 1$ in the Rayleigh fading channel. We observe that for different transmission probability, there is different optimum value of κ even for different channel states. For instance, in Fig. 5.9, expected progress per hop when $\kappa = 7$ outperforms that when $\kappa = 3, 5$ and 11 , in the presence of $p \in [0.18, 0.24)$. Whereas, expected progress per hop when $\kappa = 5$ outperforms that when $\kappa = 3, 7$ and 11 , in the presence of $p \in [0.24, 0.31)$. Next, we specify p as 0.27 to investigate the optimum value of κ in different channel states.

Fig. 5.12, Fig. 5.13 and Fig. 5.14 show the optimum κ in different states respectively in the cases of $m = 1$, $m = 2$ and $m = 4$ when $N = 7$, $G = 128$ and $Q = 3$ for the optimum transmission probability $p = 0.27$ of CPT. The optimum value of

Figure 5.13: Expected progress per hop versus κ in MCMPT when $N = 7$, $G = 128$ and $Q = 3$ under varying m and q in the Nakagami-m ($m=2$) fading channel

Figure 5.14: Expected progress per hop versus κ in MCMPT when $N = 7$, $G = 128$ and $Q = 3$ under varying m and q in the Nakagami-m ($m=4$) fading channel

κ in the partitioned channel state q can be obtained by differentiating $(\sqrt{\lambda}Z)_q$ with respect to κ . There exists an optimum κ to maximize $\sqrt{\lambda}Z$ for each channel state. In the case of Rayleigh fading ($m = 1$), when q increases, the optimum number of parallel transmission of MCMPT increases due to the good channel conditions. As m increases, there is less improvement of $\sqrt{\lambda}Z$ of $q = 3$ than that of $q = 2$, and when $m = 4$, $\sqrt{\lambda}Z$ of $q = 3$ is even less than that of $q = 2$. This is attributed to that the pdf of Nakagami- m fading attenuation varies with the parameter m . With the increasing values of m and our supposition of the equally probable partition with the reference of $m = 1$, there is bigger cumulative distribution when $q = 2$ than that when $q = 3$ in Nakagami- m fading.

5.6 Conclusions

In this chapter, the pdf of MAI power in wireless CDMA ad hoc networks is derived for a generic Nakagami- m fading channel. Furthermore, an adaptive parallel packet transmission scheme named as MCMPT is proposed for wireless CDMA ad hoc networks operating in a slow Nakagami- m fading channel by considering varying channel conditions. Performance is analyzed in terms of the expected progress per hop and it is shown that MCMPT outperforms CPT and with increasing values of m there is better benefit of packet progress. Moreover, there is an optimum number of parallel packet transmission under a certain channel condition to maximize the expected forward progress per hop.

Chapter 6

An Analysis of k -Connectivity in Nakagami- m Fading and Shadowing Wireless Ad Hoc Networks

6.1 Introduction

This chapter takes a close look at k -connectivity. Previous work [102] analyzes the connectivity of multi-hop radio networks in a log-normal shadowing environment and gives the tight lower bound for the minimum nodes density that is necessary to obtain an almost surely connected network. [103] derives the outage probability by taking into account the shadowing and Rayleigh fading. [104] studies the impact of interferences on the connectivity of a large-scale ad-hoc network, using percolation theory and shows that there is a critical value of interference coefficient above which the network is made of disconnected clusters of nodes. [105] investigates the isola-

tion probability and thereby the coverage and connectivity probability by taking the shadowing and fading into account and further exploits the channel randomness by means of diversity. However, all these existing work only consider 1-connectivity or isolation probability, and none of them investigate k -connectivity ($k > 1$) property. Although [106] derives the minimal transmission range that could create an almost surely k -connected network for a given density, and [14] studies the asymptotic critical transmission radius for k -connectivity and asymptotic critical neighbor number for k -connectivity in a wireless ad hoc network, they consider only a simplistic channel model and ignore the severe channel impairment characteristics.

The key features of wireless propagation environments bring up a series of complex issues, such as channel distortions, which causes the network design particularly challenging. Actually, it is more reasonable to study the k -connectivity performance with respect to the impact of channel impairment characteristics. It is not complete without capturing the channel characteristics that has the direct bearing on the link connectivity. In order to account for a realistic channel model, we, hence, develop a fairly generic mathematical model, by taking into account both the log-normal shadowing and Nakagami- m fading, and present an analytical procedure for the computation of the k -connectivity in an ad hoc network in the presence of log-normal shadowing and Nakagami- m fading. We argue that the shadowing increases the successful link probability and thereby k -connectivity. We show that with m increasing in the Nakagami- m fading channel, the probability of k -connectivity increases also. Given nodes are Poisson distributed, we compute

the probability that there is at least k neighbors for a node, and thereby the total probability of k –connectivity for the entire network. This yields sight into how one designer should set the density to ensure the k –connectivity. Alternatively, when the density is certain, it reveals what is the probability to achieve k –connectivity.

The remainder of the chapter is organized as follows. Section 6.2 describes the system model in our study. Section 6.3 analyzes the successful link probability and thereby k –connectivity probability in the corresponding radio propagation model, which includes the log-normal shadowing and Nakagami-m fading channel model. Section 6.4 does the conclusion.

6.2 System Model

Let us consider a wireless ad hoc network where nodes are Poisson distributed in the network with average density λ . Then the probability $\mathcal{P}(N, k)$ of finding k nodes within the region with radius a is

$$\mathcal{P}(N, k) = \frac{e^{-\lambda\pi a^2} (\lambda\pi a^2)^k}{k!}, \quad k \geq 0,$$

where $N = \lambda\pi a^2$. As nodes are uniformly distributed over the region, we have the pdf of the distance R between a chosen transmitter-receiver pair follows

$$f_R(r) = \frac{2r}{a^2}, \quad 0 \leq r \leq a$$

For the sake of simplicity, we assume that all nodes are with the same transmission power.

Wireless transmissions are severely impaired by the multi-path propagation effect that arises due to the reflection, refraction and diffusion of the transmitted signal around the scattering objects during the propagation [5]. Wireless signals that propagate over long distances seriously attenuates, which is called path-loss. When a receiver receives multiple attenuated and time-delayed versions of the transmitted signal, with the additional corruption by noise and interference, the transmitted signal might be enhanced, thereby translating into the increasing SINR, or weakened, thereby translating into the decreasing SINR. This is called multi-path fading and can be further divided into large-scale fading (slow fading) and small-scale fading (fast fading). The shadowing phenomena considers the case that the received signal strength may be different due to the different propagation conditions in their surroundings even though the distance between two transmitter-receiver pairs is the same. Hence, it is referred to as large-scale fading. Typical obstacle examples include mountains, buildings, trees, and other moving objects etc.. On the other hand, the transmitted signals are experiencing rapid fluctuation of the amplitude over a short time interval, hence referred to as small-scale fading.

6.3 k-Connectivity Analysis

We first apply a result on the property of geometric random graphs [107], i.e., in a random distributed geometric graph of n nodes, if the corresponding links are

added in turn to the empty graph and n is large enough, then the probability that the resulting graph becomes k -connected almost approaches 1 at the moment that it achieves a minimum degree of k . Let d_{min} denote the minimal number of neighbors that a node can have a connection, i.e., a minimum degree per node, then one has

$$\mathcal{P}(A \text{ homogenous ad hoc network is } k - \text{connected}) \approx \mathcal{P}(d_{min} \geq k)$$

with k being a predefined value of connectivity. Hence, we seek to investigate the probability $\mathcal{P}(d_{min} \geq k)$ referring to it.

Let p_s denote the successful link probability, then we can express $\mathcal{P}(d_{min} \geq k)$ as a double sum over j and m , i.e.,

$$\mathcal{P}(d_{min} \geq k) = \sum_{m=k}^{\infty} \sum_{j=k}^m \lim_{R \rightarrow \infty} \mathcal{P}(N, i) C_i^j p_s^j (1 - p_s)^{i-j} \quad (6.1)$$

Hence, next, we derive p_s in the presence of various channel conditions.

6.3.1 The Simplistic Channel Model

Let P_t and P_r denote respectively the transmission power and the receiving signal strength. Then, we have

$$P_r = \iota(d) P_t,$$

where $\iota(d)$ is the path loss with d being the distance between the transmitter and receiver. Two nodes can communicate directly with each other only when

$$P_r \geq \mu_t,$$

where μ_t is the receiving threshold value for successful packet reception. In the simplistic path loss model, we have $\iota(d) = \frac{K}{d^\alpha}$, where K is a constant determined by antenna height and gain, and α is the path-loss exponent. The path loss exponent α depends on the environment and can vary between 2 in free space and 6 in heavily built urban areas. Hence, given R_0 as the transmission range in the absence of fading and shadowing, we have $R_0 = (\frac{KP_t}{\mu_t})^{1/\alpha}$.

In the simplistic channel model, two nodes can communicate only when they are within the transmission range of each other. Thus, the probability that a randomly chosen node has at least k neighbors is

$$\sum_{i=k}^{\infty} \frac{e^{-\lambda\pi R_0^2} (\lambda\pi R_0^2)^i}{i!}$$

6.3.2 The Channel Model in the Presence of Shadowing

In this subsection, we use a more realistic channel model, which considers path loss with large-scale shadowing. The log-normal shadowing process has been widely adopted to model the shadow fade attenuations. Then, with the assumption that the shadow fade attenuations between any two chosen transmitter-receiver pairs follow the *independent and identical distributed* (iid) log-normal shadowing process,

we have

$$P_r = \iota(d)P_t 10^{z/10},$$

where $10^{z/10}$ is the log-normal distributed shadow fade attenuation. The pdf of the log-normal shadowing variable Z is

$$f_Z(z) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{z^2}{2\sigma^2}\right) \quad (6.2)$$

where σ is the log-normal spread, i.e., the standard deviation of the Gaussian distribution that describes the shadowing phenomenon. Note that the simplistic channel model actually corresponds to the log-normal shadowing with a marginal value of σ approaching to [105].

We, henceforth, have the probability that there is a connection between two nodes as

$$\begin{aligned} p_s &= \mathcal{P}(R \leq R_0 \exp(\beta z / \alpha)) \\ &= \int_{-\infty}^{\infty} f_Z(z) dz \int_0^{\min\{a, R_0 \exp(\beta z / \alpha)\}} f_R(r) dr \\ &= \frac{R_0^2 \exp(\frac{2\beta^2 \sigma^2}{\alpha^2})}{a^2} \end{aligned} \quad (6.3)$$

according to [108], where $\beta = \ln 10 / 10$ and a is a very large value.

Substituting Eq. 6.3 into Eq. 6.1, we have $\mathcal{P}(d_{min} \geq k)$ in the presence of log-normal shadowing as

$$\mathcal{P}(d_{min} \geq k) = \sum_{m=k}^{\infty} \sum_{j=k}^m \lim_{R \rightarrow \infty} \mathcal{P}(N, i) C_i^j \left(\frac{R_0^2 \exp(\frac{2\beta^2 \sigma^2}{\alpha^2})}{a^2} \right)^j \left(1 - \frac{R_0^2 \exp(\frac{2\beta^2 \sigma^2}{\alpha^2})}{a^2} \right)^{i-j} \quad (6.4)$$

Fig. 6.1 shows $\mathcal{P}(d_{min} \geq 3)$ versus the node density for various shadowing spread

Figure 6.1: $Prob(d_{min} > 3)$ versus node density for different values of σ when $\alpha = 3.5$, $K = 10$ and $R_0 = 100$

when $\alpha = 3.5$, $K = 10$ and $R_0 = 100$. We observe that $\mathcal{P}(d_{min} \geq 3)$ increases steeply toward 1 as the average density increases. For instance, average node density $\lambda = 10^{-4}$ creates a connected network with the $\mathcal{P}(d_{min} \geq 3) = 0.80$, when $\sigma = 6$. If we increase λ to $2 * 10^{-4}$, then we obtain $\mathcal{P}(d_{min} \geq 3) = 0.99$. This is consistent with the conclusion drawn in [106]. Meanwhile, we note that with the shadowing factor σ increasing, there is a bigger 3-connectivity probability for the same density and other system parameters. This is due to that there is higher probability of being able to communicate with nodes at farther distances as shadowing becomes serious. The increases in the average node degree directly translate to the increases in the connectivity. We, hence, may draw the conclusion that the presence of log-

Figure 6.2: $\text{Prob}(d_{\min} > 3)$ versus σ for different values of α when $\lambda = 10^{-4}$, $K = 10$ and $R_0 = 100$

normal shadowing increases the probability of k -connectivity, as have been argued in previous results [105] on coverage and isolation probability. We plot 3-connectivity probability for the varying values of $\sigma = 1, 3, 6, 8, 10$.

Fig. 6.2 shows $\mathcal{P}(d_{\min} \geq 3)$ versus shadowing spread for various path loss exponent when $\lambda = 10^{-4}$, $K = 10$ and $R_0 = 100$. With the shadowing increasing, there is a bigger $\mathcal{P}(d_{\min} \geq 3)$ and under the same shadowing, $\mathcal{P}(d_{\min} \geq 3)$ decreases as path loss factor α increases. We observe that for a big value of σ , 3-connectivity almost equals to 1, which indicates that the path loss α can not have much impact for the 3-connectivity for the big shadowing. As the connectivity coincides with the average node degree, we have the conclusion that the path loss plays a big role in

k -connectivity properties only for a range of medium values of σ , rather than for a big or small σ . This is also consistent with the conclusion in [105].

6.3.3 The Channel Model in the Presence of Shadowing and Nakagami-m Fading

Furthermore, we take into account both large-scale shadowing and small-scale fading. We use a generic Nakagami-m fading distribution, a two-parameter distribution with parameter m and $\bar{\gamma}$, to characterize the small-scale fading. The instantaneous received carrier to noise ratio Γ on a Nakagami-m fading channel is a continuous stochastic variable with gamma distribution. The pdf for it is given by

$$p_{\Gamma}(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp\left(-m\frac{\gamma}{\bar{\gamma}}\right)$$

where $\bar{\gamma}$ is the average received power, m is the Nakagami fading parameter ($m \geq 1/2$) and $\Gamma(\cdot)$ is the gamma function defined by

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt, x \geq 0$$

The parameter m characterizes the severity of the fading.

According to [105], the probability that there is a connection between two nodes

is derived as

$$\begin{aligned}
 \mathcal{P}(\gamma \geq \mu_t) &= \int_{\mu_t}^{\infty} p_{\Gamma}(\gamma) d\gamma \\
 &= 1 + \left(\frac{\bar{\gamma}}{\mu_t}\right)^m \left(\frac{\Gamma(m, \frac{m\mu_t}{\bar{\gamma}})}{\Gamma(m)} - 1\right) \\
 &= \begin{cases} \exp(-\mu_t/\bar{\gamma}), & m = 1 \\ \frac{1}{\bar{\gamma}} \exp(-2\mu_t/\bar{\gamma})(2\mu_t + \bar{\gamma}), & m = 2 \\ \frac{1}{3\bar{\gamma}^3} \exp(-4\mu_t/\bar{\gamma})(32\mu_t^3 + 24\mu_t^2\bar{\gamma} + 12\mu_t\bar{\gamma}^2 + 3\bar{\gamma}^3), & m = 4 \end{cases} \quad (6.5)
 \end{aligned}$$

where $\bar{\gamma} = \frac{KP_t 10^{z/10}}{d^\alpha} = \frac{\mu_t R_0^\alpha 10^{z/10}}{d^\alpha}$.

Define $\psi = \frac{d^\alpha}{R_0^\alpha 10^{z/10}}$. Hence, the upper equation can be further simplified to

$$\mathcal{P}(\gamma \geq \mu_t) = \begin{cases} \exp(-\psi), & m = 1 \\ \exp(-2\psi)(2\psi + 1), & m = 2 \\ \frac{1}{3} \exp(-4\psi)(32\psi^3 + 24\psi^2 + 12\psi + 3), & m = 4 \end{cases} \quad (6.6)$$

Therefore, we have

$$p_s = \int_{-\infty}^{\infty} \mathcal{P}(\gamma \geq \mu_t) f_Z(z) dz \int_0^{\min\{a, R_0 \exp(\beta z/\alpha)\}} f_R(r) dr \quad (6.7)$$

Substituting Eq. 6.7 into Eq. 6.1, we have

$$\begin{aligned}
 &\mathcal{P}(d_{min} \geq k) \\
 &= \sum_{m=k}^{\infty} \sum_{j=k}^m \lim_{R \rightarrow \infty} \mathcal{P}(N, i) C_i^j \left(\int_{-\infty}^{\infty} \mathcal{P}(\gamma \geq \mu_t) f_Z(z) dz \int_0^{\min\{a, R_0 \exp(\beta z/\alpha)\}} f_R(r) dr \right)^j \\
 &\quad \left(1 - \int_{-\infty}^{\infty} \mathcal{P}(\gamma \geq \mu_t) f_Z(z) dz \int_0^{\min\{a, R_0 \exp(\beta z/\alpha)\}} f_R(r) dr \right)^{i-j} \quad (6.8)
 \end{aligned}$$

Figure 6.3: $\text{Prob}(d_{\min} > 3)$ versus node density for various channel models when $\sigma = 1$, $\alpha = 3.5$, $K = 10$ and $R_0 = 100$

Fig. 6.3, Fig. 6.4 and Fig. 6.5 show $\mathcal{P}(d_{\min} \geq 3)$ versus the node density when $\alpha = 3.5$, $K = 10$ and $R_0 = 100$ under shadowing channel condition and shadowing plus various fading channel conditions, for $\sigma = 1$, $\sigma = 3$ and $\sigma = 6$ respectively. We observe that the probability that the minimal degree is bigger than 3 decreases with the additional fading, compared to with only shadowing, for various values of σ . For instance, in Fig. 6.5, when $\lambda = 10^{-4}$, $\mathcal{P}(d_{\min} \geq 3)$ is 0.80, 0.60, 0.68 and 0.72 for the shadowing, shadowing plus Rayleigh fading and Nakagami-m fading with $m = 2$ and $m = 4$, respectively. Correspondingly, the minimal average node density 1.75×10^{-4} , 2.08×10^{-4} , 1.95×10^{-4} and 1.87×10^{-4} are respectively required to ensure that the probability of the minimal degree bigger than 3 exceeds 0.95. This suggests that

Figure 6.4: $Prob(d_{min} > 3)$ versus node density for various channel models when $\sigma = 3$, $\alpha = 3.5$, $K = 10$ and $R_0 = 100$

Nakagami-m fading reduces the connectivity properties of the network, which holds for any σ . Therefore, we get the conclusion that fading is not dependent on the shadowing. However, with m increases, $\mathcal{P}(d_{min} \geq 3)$ also increases, which implies that the fading does not change much the connectivity properties. We also note that as σ increases, $\mathcal{P}(d_{min} \geq 3)$ monotonously increases for a certain fading plus shadowing. In order to achieve that a node has at least 3 neighbors with probability 0.95, the average density 2.91×10^{-4} , 2.76×10^{-4} and 2.08×10^{-4} are required for the case of shadowing plus Rayleigh fading in Fig. 6.3, Fig. 6.4 and Fig. 6.5, respectively. This further shows that shadowing increases connectivity properties, in the presence of a certain fading.

Figure 6.5: $Prob(d_{min} > 3)$ versus node density for various channel models when $\sigma = 6$, $\alpha = 3.5$, $K = 10$ and $R_0 = 100$

Fig. 6.6 shows that for the increasing range of mean degree k , the probability $\mathcal{P}(d_{min} \geq k)$ decreases, for various kinds of shadowing plus fading phenomena under a certain density with the system parameters $\sigma = 3$, $\alpha = 3.5$, $K = 10$ and $R_0 = 100$. For instance, $\mathcal{P}(d_{min} \geq k)$ is almost 1 for $k = 1$ when $\lambda = 2 * 10^{-4}$ with only shadowing, while decreases to 0.96, 0.81 and 0.51 as k increases to 3, 5 and 7 respectively. This coincides with the conclusion in [106] that considers neither shadowing nor fading. We observe that for a certain value of k , increasing node density causes a bigger value of $\mathcal{P}(d_{min} \geq k)$, e.g., with shadowing plus Nakagami-m fading ($m=4$), $\lambda = 10^{-4}$ for $k = 3$ can achieve that the probability of the minimal degree bigger than 3 is about 0.57, whereas $\lambda = 2 * 10^{-4}$ can achieve that at about

Figure 6.6: $\text{Prob}(d_{\min} > k)$ versus k for various channel models when $\sigma = 3$, $\alpha = 3.5$, $K = 10$ and $R_0 = 100$

0.95. This yields the same conclusion as subsection B.

6.4 Conclusion

In this chapter, we study the network performance in terms of the successful link probability and k -connectivity probability by taking into account shadowing and fading in wireless multi-hop ad hoc networks. We show that k -connectivity probability increases as the log-normal spread σ increases. We investigate the impacts of the fading characteristics and system parameters on the k -connectivity property. Given a certain number of nodes distributed according to a spatial probability

density function, we examine the critical density to keep the k -connectivity of the network close to 1. These results can be practically used by a network designer to estimate the critical density to ensure a certain network connectivity.

Chapter 7

Conclusions

This chapter does a summarization of the contributions of this thesis and highlight some of the future work that is worth while to be explored.

7.1 Contributions

In conclusion, in this thesis, we have presented a new multi-channel MAC scheme, termed as two-phase coding multi-channel MAC protocol, which significantly reduces the control overhead of code assignment in a CDMA-based multi-channel MAC design for MANETs. We have developed it under two different network backgrounds, which is respectively cell-based when location information is available and clustering-adaptive when dynamic clustering is employed. LA-TPCMMP employs the first-phase code to differentiate between different cells and the second-phase code to differentiate between nodes in one cell, which eliminates the HTP, fraught in ad hoc networks, during data transmission. Furthermore, CA-TPCMMP integrates two-phase coding scheme with the concept of dynamic clustering, wherein the first-phase code is used to differentiate between neighboring clusters and the second-phase code is used to distinguish nodes within one cluster. CA-TPCMMP can eliminate

the dependence to the location information and is effective in combating the HTP during data transmission. LA-TPCMMP and CA-TPCMMP can lead to substantial reduction of control overhead and hence prolong the lifetime of an ad hoc network. Both of the proposed protocol framework apply to TDMA and FDMA as well as their combinations.

Moreover, previous work studying the distribution of MAI power in wireless CDMA ad hoc networks assumes a non-fading channel or Rayleigh fading channel. We, therefore, generalize the fading channel model and derive the distribution of MAI power under a generic Nakagami- m fading channel model. It is shown that the previous results follow as the special cases of our derivation. Furthermore, by considering the time-varying channel conditions, we propose a MCMPT scheme for wireless CDMA ad hoc networks operating in a Nakagami- m fading channel to increase the performance, in terms of the expected forward progress. Based on the instantaneous good channel conditions in a Nakagami- m fading channel, a node can initiate a flexible number of parallel transmission of multiple packets on multiple codes. By exploiting varying channel conditions, we develop the analytical model to examine the maximum expected progress per hop and optimum number of parallel transmission in MCMPT under the Nakagami- m fading channel. It is proved that adaptive MCMPT considering varying channel conditions outperforms the nonadaptive CPT.

Finally, we discuss the topology control in wireless multi-hop ad hoc networks with respect to k -connectivity. By considering log-normal shadowing and Nakagami-

m fading, we study the network performance in terms of successful link probability and k –connectivity probability under a realistic channel model. We examine the critical density to ensure that the probability that a node is k –connected is close to 1 in the shadowing and fading environment. The results can be practically used for the design of wireless ad hoc networks.

7.2 Future Research

Further work stipulated in these directions is illustrated as follows. In LA-TPCMMP, the bandwidth and energy efficiency resulting from significant reduction of control packets is worth to be investigated. In addition, during the priority-based random competition strategy, other factors such as the remaining power of a node as well as the mobility might be comprehensively considered to prolong the network life. The overall system performance by combining CA-TPCMMP with some more advanced clustering algorithms such as cluster-based routing protocol (CBRP) [1] can be investigated. Transmission power control for mitigation of MAI in both protocols can also be studied. Moreover, it is assumed that there is perfect channel estimation in MCMPPT for wireless CDMA ad hoc networks operating in a Nakagami fading channel. In the future, the impact of imperfect channel estimation is worth to be considered. Finally, the discussion of k –connectivity can be applied in the background of multi-channel diversity. By exploiting the inherent diversity of the multi-channel networks, the redundant data information can be propagated over multiple paths to allow the destination node collect information over average

channel variations to build the original information, which can thereby enhance the reliability of data communication as well as guarantee QoS. Also, it can be exploited to balance the channel load and mitigate the traffic crowd that obviously require the knowledge of network topology and channel state.

Author's Publications

Journal Publications

1. L. L. Zhang, B. H. Soong, and W. D. Xiao, "Two-Phase Coding Multi-Channel MAC Protocol with MAI Mitigation for Mobile Ad Hoc Networks," *IEEE Communications Letters*, Vol. 8, No. 9, Sep. 2004, pp. 597-599.
2. L. L. Zhang and B. H. Soong, "Multi-Code Multi-Packet Transmission (MCMPT) in Wireless CDMA Ad Hoc Networks under Rayleigh Fading Channels," *IEEE Communications Letters*, Vol. 9, No. 11, Nov. 2005, pp. 985-987.
3. L. L. Zhang, B. H. Soong, and W. D. Xiao, "Location-Aware Two-Phase Coding Multi-Channel MAC Protocol for MANETS," To appear in *IEEE Trans. on Wireless Communications*.
4. L. L. Zhang, B. H. Soong, and W. D. Xiao, "An Integrated Cluster-Based Multi-Channel MAC Protocol for MANETs," Submitted to *IEEE Trans. on Wireless Communications*.
5. L. L. Zhang and B. H. Soong, "A New Multi-Packet Transmission Scheme in

Nakagami Fading Wireless Ad Hoc Networks,” Submitted to *IEEE Trans. on Wireless Communications*.

6. L. L. Zhang and B. H. Soong, “An Analysis of k-Connectivity in Nakagami Fading and Shadowing Wireless CDMA Ad Hoc Networks,” Submitted to *IEEE Trans. on Vehicular Technology*.

Conference Publications

1. L. L. Zhang, B. H. Soong, and W. D. Xiao, “A New Multi-Channel MAC Protocol for Ad Hoc Networks Based on Two-phase Coding with Power Control (TPCPC),” In Proc. IEEE ICICS-PCM, Singapore, Dec., 2003.
2. L. L. Zhang, B. H. Soong, and W. D. Xiao, “Overhead Analysis of Location-Aware Two-Phase Coding Multi-Channel MAC Protocol for MANETS,” In Proc. IEEE 29th LCN, Temper, Florida, USA, Nov., 2004.
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5. L. L. Zhang and B. H. Soong, "k-Connectivity in Wireless Multi-Hop Networks with Shadowing," In Proc. IEEE GLOBECOM, San Francisco, USA, Nov., 2006.

Appendix A

Expected Forward Progress

In a multi-hop network, a small transmitter-receiver distance can increase the probability that a packet is successfully transmitted. Whereas, it requires more number of hops for a packet to arrive at the destination node, which instead decreases the packet success probability. The expected forward progress, a performance metric that provides a tradeoff between the packet successful probability and the number of hops, is first introduced for determining the optimum transmission range in a multi-hop network. The dimensionless expected forward progress is expressed as

$$\sqrt{\lambda}Z = \sqrt{\lambda} \cdot \zeta \cdot R_0 \quad (\text{A.1})$$

where ζ is the local throughput computed as follows.

A.1 Local Throughput

The local throughput is the rate that a node successful send its packets, which can be expressed as a function of transmitter-receiver distance R_0 , the average density λ , the transmission probability p and the spreading factor G . Assume the network

is with uniform traffic. i.e., each node transmit independently with probability p in each time slot. The local throughput ζ can be expressed as

$$\begin{aligned}\zeta &= P[A \text{ Transmit}] \cdot P[B \text{ not transmit}] \cdot P[\text{Packet received}/B \text{ not transmit}] \\ &= p(1-p) \cdot P[B \text{ chooses the transmission from } A] \cdot P_s\end{aligned}\tag{A.2}$$

where P_s is the probability that a packet is correctly received, i.e., the SINR of this packet exceeds the threshold of correct packet recovery.

Assume the number of potential transmitters to node B is n , and each of these transmitters may transmit to n nodes, then one has the probability of a transmission to node B is p/n . Furthermore, if i nodes are transmitting to node B , the probability that node B receives the transmission from node A is $1/i$. Accordingly, one has

$$\begin{aligned}&P[B \text{ chooses the transmission from } A] \\ &= \sum_{i=0}^{n-1} \binom{n-1}{i} \left(\frac{p}{n}\right)^i \left(1 - \frac{p}{n}\right)^{n-1-i} \frac{1}{i+1} \\ &= \frac{1}{p} \left(1 - \left(1 - \frac{p}{n}\right)^n\right)\end{aligned}\tag{A.3}$$

Substituting Eq. A.3 into Eq. A.2, one obtains

$$\begin{aligned}\zeta &= (1-p) \left(1 - \left(1 - \frac{p}{n}\right)^n\right) \cdot P_s \\ &\triangleq \tau_n(p) \cdot P_s\end{aligned}\tag{A.4}$$

Let $n \rightarrow \infty$ in Eq. A.4, one further obtains

$$\begin{aligned}\zeta &= \tau_n(p) \cdot P_s \\ &\triangleq \tau_\infty(p) \cdot P_s \\ &= (1 - p)(1 - e^{-p}) \cdot P_s\end{aligned}\tag{A.5}$$

Alternatively, ζ can be regarded as the product of the tendency that two nodes are paired up and the availability of a channel, wherein τ is the tendency to pair up for a node and P_s is the availability of the channel with SINR bigger than a predefined threshold.

Substituting Eq. A.5 in Eq. A.1, one obtains the expected forward progress

$$\sqrt{\lambda}Z = \sqrt{\lambda}R_0(1 - p)(1 - e^{-p}) \cdot P_s\tag{A.6}$$

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