

PERFORMANCE ANALYSIS OF THE BEACON PERIOD CONTRACTION
MECHANISM IN WIMEDIA MAC FOR UWB

by

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I would also like to take this opportunity to dedicate this thesis to my parents.

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ABSTRACT

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The WiMedia MAC for UWB based WPANs is currently preferred among standards for wireless network since it requires non-infrastructure for ad hoc network, and also supports for Quality of Service (QoS). Without infrastructure, coordination of devices within radio range is achieved by the exchange of beacon frames, which is an overhead in WiMedia MAC, since no data transmission is allowed during Beacon Period (BP). In a dynamic network, devices might leave or join in, so beacon slots will be released or reoccupied with the changing of network. And BP contraction mechanism is aimed at reusing the released beacon slots in a dynamic network by shifting the latest movable beacon slot to the earliest empty beacon slot, so that more time slots will be saved for data transmission. In this thesis we investigate the

performance of BP Contraction Mechanism in WiMedia MAC by modeling it as distance-2 coloring problem, and On-Line First-Fit algorithm is applied to solve the problem. We carry out different scenarios of simulation for dynamic ad hoc networks to study the stability of BP contraction mechanism, and also the maximum propagation times of BP contraction. The simulation results demonstrate that BP contraction mechanism has a stable performance in dynamic networks, and the nodes' joining/leaving order has small influence on the behave of BP contraction. The propagation of BP contraction can be terminated in a few times, which shows the network will become stable very soon after devices joining or leaving.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Ultra Wide Band (UWB) technology has attracted tremendous interests recently by promising untethered communications in conjunction with sumptuous bandwidth. Currently, two key technologies have dominated the UWB physical layer [1], namely the time pulse approach driving by Time domain (acquired by Motorola), and the Multi-Band OFDM Alliance (MBOA) [4] backed by major powerhouses including Intel, Texas Instruments, SONY, and Microsoft. Regardless of the physical layer technology employed, the vast data rate imposes an unprecedented challenge to design a media access control (MAC) mechanism. Firstly, the MAC layer must be capable of efficiently utilizing the available bandwidth while maintaining reasonable power consumption. Secondly, confronting a plethora of (envisioned) multimedia applications typified by video and imaging, the MAC layer must be capable of satisfying stringent QoS requirements. Thirdly, due to the limited transmission range constrained by stiff power regulation, the MAC layer must be capable of naturally embracing an ad-hoc, multi-hop network configuration.

While the IEEE 802.15.3 MAC layer specification has been well established and in the process of being standardized, it is designed originally for high data rate

envisioned at less than 50Mbps. Furthermore, the master/slave approach adopted in 802.15.3 MAC protocols [22] cannot accommodate the multi-hop, ad-hoc setup as envisioned for UWB devices in ubiquitous and in particular high-speed personal area networks.

Motivated thereby, the MBOA has developed a MAC protocol specifically for high speed WPANs. Furthermore, by abandoning the master/slave, the proposed MAC protocol can accommodate the infrastructure-less setup in nature. In addition, the proposed MAC protocol provides inherent QoS provisioning mechanism through support for both reservation and service differentiation. Two distinguish features in WiMedia MAC are beaconing and distributed reservation protocol (DRP). Instead of central coordinator, WiMedia devices coordinate with each other by sending beacons. In WiMedia MAC, time is divided into superframes, which starts with variable length of beacon period (BP) and the rest will be used for data transmission. In the beacon period, no data transmission is allowed except sending beacons. Therefore beacon period is an overhead in WiMedia MAC. BP contraction mechanism is aimed at shrinking the length of BP in order to spare more slots to transmit data.

Because of the infrastructure-less character of WiMedia MAC, beacons act as coordinators among devices. It is important for beacons to have a stable performance in WiMedia MAC in order to guarantee the stability of the whole network. Therefore BP contraction mechanism, which is used for beacons, should also be robust for dynamic networks. In this thesis, we make our efforts on the performance analysis of BP

contraction mechanism and our results shows that this mechanism has a very stable and efficient performance in WiMedia MAC.

To give a brief idea, here we give a general introduction for BP contraction mechanism. In BP contraction mechanism, devices get information about the utilization of beacon slots from beacons received in previous superframes, and mark themselves as movable if there is one or more beacon slot available before their own. And the latest movable device will shift its own beacon to the earliest empty beacon slot. And BP contraction mechanism will terminate when all of the active devices become unmovable in the network.

To evaluate the performance of BP contraction mechanism, we formulate the BP contraction mechanism into distance-2 coloring problem, and we use two metrics to analyze the maximum and average BP lengths theoretically. Furthermore we apply On-Line First-Fit algorithm, which is a typical algorithm for distance-2 coloring problem, for our evaluation of the mechanism. Since BP contraction will not terminate until all of the devices become unmovable, we also evaluate the propagation times of BP contraction. We carry out different scenarios of simulation based on the two metrics we formulate and investigate the propagation times of BP contraction mechanism. Our results illustrate that the BP contraction mechanism is very efficient for saving the length of beacon period and also has a stable performance in WiMedia MAC. In the following section, we will give a brief introduction about the outstanding features of WiMedia MAC, as one of which beaconing plays an important role in the whole standard.

1.2 Overview of WiMedia MAC

Besides various enhancements as compared to existing WPAN MAC protocols, the MBOA MAC introduces two new distinct features, namely beaconing used for devices announcing presence, coordination with neighbors and scheduling traffic in the medium, the other is distributed reservation protocol (DRP), a new decentralized reservation mechanism, which manages the channel time allocation reservations for each device by involving all neighbors participants. These two features allow devices to operate in a true ad-hoc manner without relying on improvised coordinators in order to realize infrastructure-less.

1.2.1 Preliminaries

In the MBOA MAC protocol, refer to [3], time is divided into superframes, each of which is comprised of 256 medium access slots (MASs). Each superframe starts with beacon period (BP) followed by data period. The duration of beacon period called BP length varies for each device. No data transmission but beacons are allowed during beacon period. Each device announces its presence by sending a beacon in the beacon period and also listens to beacons from other devices within transmission range. According to the beacon slot allocation, devices schedule the order of accessing medium correspondingly. The remainder of the superframe is termed data period, dedicated to data communications and miscellaneous operations. Data is passed between devices in MAC service data units (MSDUs), fragment and reassemble is adopted to reduce the error rate.

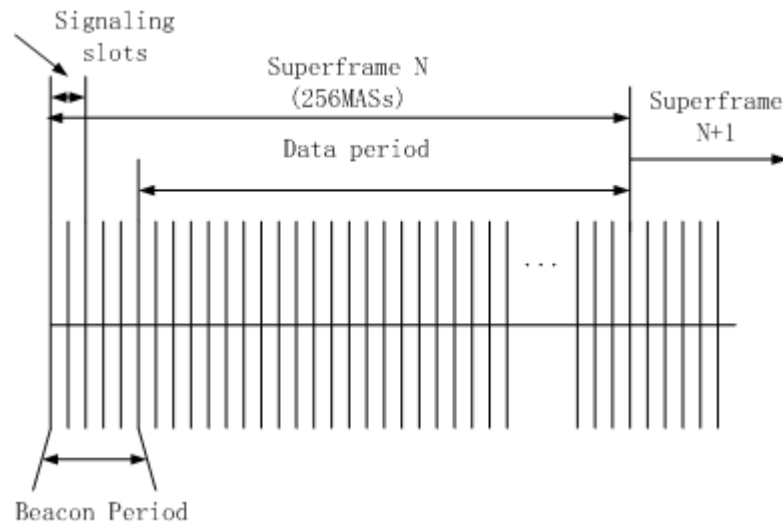


Figure 1.1 Superframe Structure

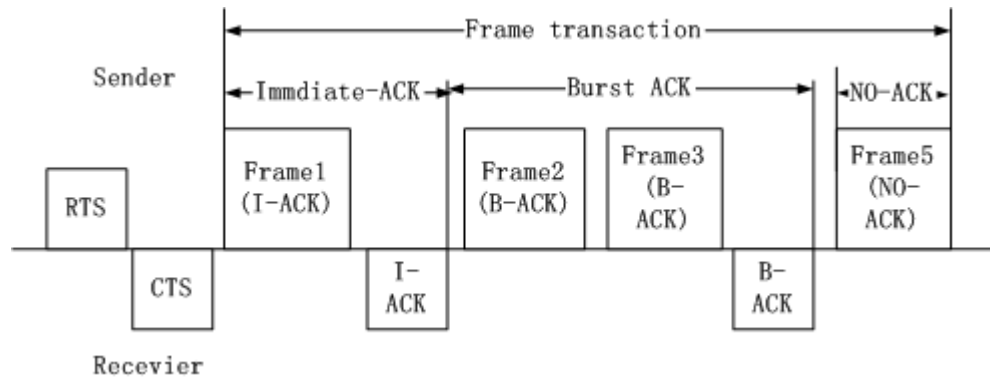


Figure 1.2 Frame Transaction Using Three Different Acknowledgements

Three acknowledgement mechanisms are available to verify the delivery of a frame, which is termed in No-ACK, B-ACK, Imm-ACK. The basic packet exchange sequence follows the 802.11 rules [5], [12], namely RTS-CTS-Data-ACK, where all frames except for data are optional and ACK policy can be chosen from the three. Accordingly, each packet carries the duration field for other devices to setup the network allocation vector in order to perform virtual carrier sensing. Figure 1.1

illustrates the composition of a superframe while Figure 1.2 details a typical exchange sequence including RTS, CTS, Data, and ACK Frames.

1.2.2 Channel Access Control

In MBOA MAC, a device can either obtain transmission opportunity over the wireless medium through random access or reservation since two access mechanisms are available in this standard.

1.2.2.1 PCA

The random access, defined as prioritized channel access (PCA), resembles the Enhanced DCF protocol as specified in 802.11e [16]. In this mechanism, each traffic category residing on a single device corresponds to a traffic queue. In turn, each traffic queue independently performs contention on the channel following the backoff rule similar to that of IEEE 802.11. In particular, each traffic queue employs different parameters in this channel contention procedure, for example, minimum contention window (CW_{min}) size, maximum contention window (CW_{max}) size and arbitration inter-frame space (AIFS). Devices access medium using PCA, and starts transmit when they get transmission opportunity (TXOP) which presents an interval of time when a device gets the right to initiate its transmission and its duration is limited to TXOPLimit. PCA is a contention-based CSMA/CA protocol. Collision Avoidance (CA) contributes to reduce the probability of collision happening by invoking a backoff procedure. Each device has a number of virtual stations (VS) in it. Each virtual station has a definite priority and a type of traffic attached to it. After the packet arrives to this virtual station and before every transmission attempt a virtual station has to sense the

channel as idle for a static period calls Arbitration Interframe Space (AIFS). This time period is dependent on the priority level allotted to the virtual station. And each virtual station has a fixed AIFS value for itself. After that it invokes the backoff counter inherent in each AC. The duration of the backoff counter for the AC is drawn from a uniformly distributed interval of $[0, CW]$. And the size of contention window (CW) should be set an integer between minimum contention window (CW_{min}) and maximum contention window (CW_{max}), both of which depend on the priority of the backoff.

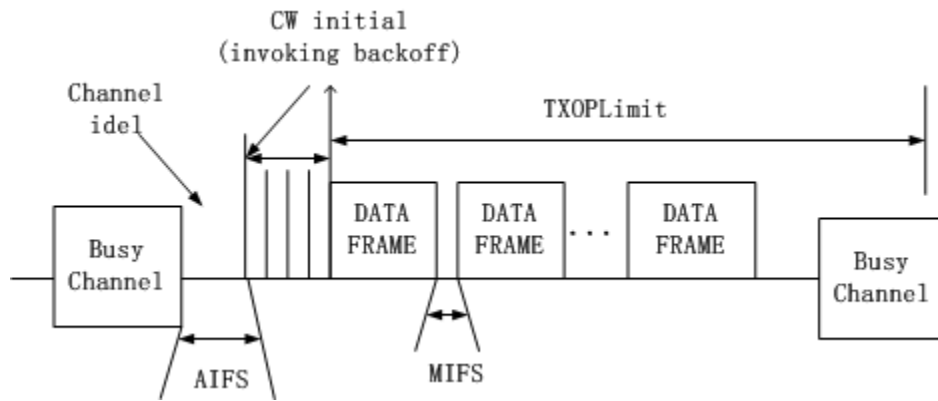


Figure 1.3 Prioritized Channel Access

During the slot counting phase whenever the station senses the channel as idle it decreases its slot counter by one. If the slot counter reaches zero its representative AC obtained a TXOP for the wireless medium and the device will start to transmit the data packet. Otherwise, device senses the channel as busy; it freezes its slot counter. The station then has to start the process of sensing channel for AIFS period again. If the channel is sensed as idle for another AIFS period again, the backoff procedure start

counting down the remaining slots. Once a collision happens, the contention window will double its size to reduce the probability of collision occurrence again. The channel access procedure for prioritized channel access is depicted in Figure 1.3.

1.2.2.2 DRP

While PCA can effectively provide service differentiation among different traffic categories, it cannot provide any service guarantee for real time traffic exemplified by video and voice. Motivated thereby, MBOA MAC specifies another media access method based on reservation, termed distributed reservation protocol (DRP). In DRP, a device, on its own, can request the reservation of a certain number of time slots on the channel. It is very similar to the working nature of the TDMA protocol [18]. Devices involved in transmission using DRP should announce their presence and reservation in their beacons. During the beacon period, each device sends a beacon in which its intended reservation MASs is indicated. And devices within transmission range should listen to each other's beacon during the beacon period without any dataframe transmission. Each device has two kinds of reservation. A device can start immediately transmitting at the beginning of the reserved time slots (hard reservation) [17] or perform channel contention using the highest priority without backoff (soft reservation). In a hard reservation, the slot owner by reservation should start transmission at the beginning of its reserved MASs without any initiation procedure for the frame transactions since all of the other transmission should terminate at least pSIFS plus mGuardTime before. No other transmission but the owner is allowed in that period. In soft reservation all the devices compete for the channel access using PCA

mechanism. However the reservation owner gets the access to its reserved slot with the highest priority at the very beginning of that communication slot without doing any backoff. Therefore, if the reserved slot leaves some remaining time which lasts enough to other frames transaction by other devices, devices in slot owner's neighborhood can reuse the remaining by performing PCA procedure. The option of soft reservation provides possibility of leveraging unused time slots by other devices, as the channel is open for contention as long as it is not busy after an AIFS under the PCA mechanism. How to negotiate the reservation in DRP? It either can be done explicitly by sending out a request reservation frame or implicitly embedding the request in the beacon frame. Correspondingly, the intended receiver, deeming the reservation acceptable, can indicate confirmation either through replying the reservation frame directly or embedded in its own beacon message.

1.2.3 Beaconing

The beacon mechanism is vital in the operation of MBOA MAC. As there is no coordinator in the network, beacon serves as the main method for performing key functions of the network including neighbor discovery, channel reservation, and topology control. According to the MBOA MAC, each device shall announce its presence by transmitting a beacon frame in the beacon period. The beacon period is slotted and each beacon, with additional guard time, shall occupy one third of a single MAS. Each beacon contains the device ID of its originating device, and IDs of all its direct neighbors whose beacons can be heard by the device in the former superframes [2].

Therefore, each device, by hearing the beacons of its neighbors and decoding the device ID therein, possesses the knowledge of all its two hop neighbors. Notice that this is still a localized knowledge and hence will not hinder the protocol from scaling toward large networks. To avoid collision of beacon frames [6], in conjunction with the device ID, a device's beacon also contains slot information about immediate neighbors' beacons. Therefore, a device when first powering up and scanning the channel will be capable of determining available beacon slots for beacon transmission.

In the WiMedia MAC spec, beacon slots are numbered in sequence starting from 0. Devices occupy their own beacon slots by sending a beacon at the beginning of that beacon slot. As mentioned above, the length of BP should include all of the necessary beacon slots for a device and its neighbors, so when new devices come up, additional beacon slots will be needed. Signaling slots at the beginning of BP are used to extend the length of BP in the future.

Before any transmission, a device shall scan for beacons for at least one superframe, if it cannot receive any beacon from its neighbors, it will create a new BP, in which it will send a beacon in the first beacon slot after the signaling beacon slots. Otherwise, if a device hears one or more beacons from other devices during the BP, it will not create a new BP, but use the same BP and transmit a beacon after the last unavailable beacon slot. In its own beacon, device shall claim its BP length, which includes its own beacon slot and all of the beacon slots occupied by its neighbors heard in the former superframes. Collisions might happen when devices send beacons in the other devices' beacon slots. Therefore, devices sometime need to skip beacon

transmission and only listen in their own beacon slots. Once collision happens, device should relocate its beacon slot different from the former one.

In a dynamic wireless network, devices may join and leave periodically. When new devices join, signaling beacon slots will be used to do BP extension to enlarge the current BP so that new devices can have their own beacon slots to send beacons. On the other hand, when existing active devices leave the network or fall down because of some reasons, their beacon slots will be released and available for other active devices. BP contraction algorithm is designed to do this job in order to compress the BP length.

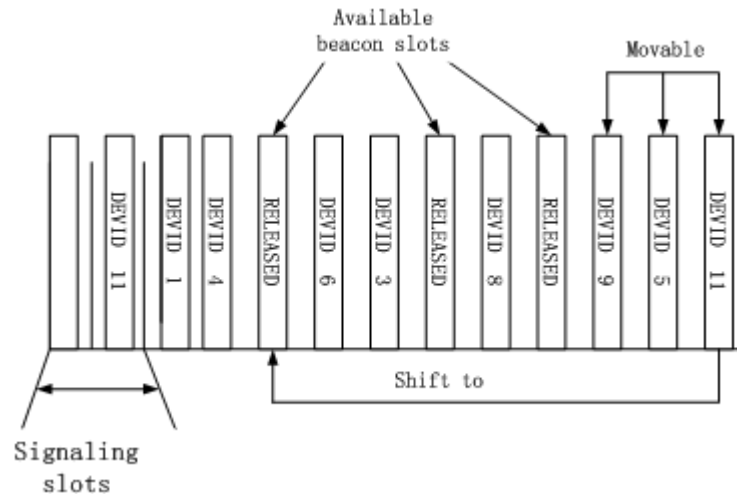


Figure 1.4 BP Contraction Mechanism

In BP contraction, a device will consider its beacon slot movable in the current superframe when it finds at least one beacon slot other than signaling slots before its beacon slot is unoccupied. Otherwise it will mark itself unmovable. Both 'movable' and 'non-movable' information will be broadcast by sending beacons. In the following superframe, the latest movable beacon slot will be shifted to the earliest available

beacon slot if no collision happens. Figure 1.4 illustrates the BP contraction mechanism and information possessed by each node.

1.3 Overview of Thesis

The two distinguish features of WiMedia MAC are both related to the performance of beacons. BP contraction mechanism is an essential part of the beaconing both on saving the lengths of BP and reusing the released the beacon slots. In this thesis, we investigate the performance of BP contraction mechanism used in WiMedia MAC by modeling it as distance-2 coloring problem. Furthermore we use two metrics to analyze the maximum and average BP lengths theoretically. We apply On-Line First-Fit algorithm, which has a good performance for minimizing the amount of chromatic colors in a graph, to our model. We also carry out different scenarios of simulation to take a look into the performance of BP contraction mechanism and also its propagation problem.

The rest of the thesis is organized as follows. Chapter 2 will give some information about beacon period in WiMedia MAC. Chapter 3 will give some theoretical analysis for modeling the BP contraction mechanism and also some problems which might happen with this mechanism. Chapter 4 will focus on the experimental setup for BP contraction mechanism, and by different scenarios of simulation, we did analysis for the performance of BP contraction mechanism and its propagation. Chapter 5 will conclude the thesis discussion.

CHAPTER 2

BEACON PERIOD

In WiMedia MAC, time is divided into superframes, which is comprised of 256 Medium Access Slots (MAS). Each MAS lasts 256us, and can transmit three beacons. Each superframe starts with a varied length of time slots called Beacon Period (BP), which is used to transmit beacons only, no data transmission is allowed in this period. And the rest of the superframe is used to transfer data. Each device has its own BP, which has a maximum length of mMaxBPLenght beacon slots, which is a multiple of MASs. The length of each beacon slot is mBeaconSlotLength. Beacon slots in the BP are numbered in sequence, starting at zero. The first mSignalSlotCount beacon slots of a BP are referred to as signaling slots and are used to extend the BP length of neighbors. Every active device in a network shall broadcast a beacon in the BP and listen for neighbor's beacons in all beacon slots specified by its BP length in each superframe. When transmitting in a beacon slot, a device shall start transmission of the superframe on the medium at the beginning of that beacon slot. A device shall transmit beacons at pBeaconTransmitRate, which is equal to 55Mb/s currently. Each beacon cannot exceed a length of mMaxBeaconLength which is equal to mBeaconSlotLength plus SIFS plus mBeaconGuardTime.

2.1 Purposes of Beacons

Since WiMedia MAC is infrastructure-less, all the devices coordinate with each other by sending beacons during BP. In WiMedia MAC, devices announce their existence by sending beacons and also discover their neighbors by receiving beacons during BP. And beacons also can be used to synchronize superframe time. If devices access medium channel using DRP, it will use beacons to reserve their future transmission slots and inform other devices about the reservation within the neighborhood so that to achieve collision-free. Additionally, beacons can also be used for managing Traffic Indications Map (TIM) Information and interference mitigation.

2.2 Beacon Slot State

Each BP is a multiple of MASs, and every MAS can transmit three beacons. Every active device in the network should send a beacon in some beacon slot during the BP. Before a device transmits a beacon, it should sense the channel for receiving beacons from its neighbors so that it will get the information about the beacon slots occupation. In the specification, if in the latest $mMaxLostBeacons+1$ superframes the beacon slot was never encoded as occupied in the BPOIE of the beacons transmitted or received by the device. For all other cases, if devices sense the beacon slots reserved by other devices, those beacon slots state should be unavailable. In a dynamic network, after some existing devices leave the network because of some reasons, their occupied the beacon slots will change their state from occupied to idle.

2.3 Beacon Period Length

In BP, beacon slots are numbered in sequence. Each device will announce its BP length, measured in beacon slots, in its beacon. And the maximum BP length cannot exceed mMaxBPLength. For each device, the BP length should include all of the beacons received in the prior superframe and also its own beacon slot, but not more than mBPExtension beacon slots after the last reserved beacon slots. Power-sensitive devices generally should not include any beacon slots after the last unavailable beacon slot in their announced BP length. The BP length announced by each device varies according to the neighborhood each device might involve in. And BP length of each device might change due to the dynamic of network, as new devices might power up and extend the beacon group, on the other hand, active devices might move out of coverage of network or power off so that some beacon slots might be released.

2.4 Beacon Frame

In WiMedia MAC, one of the purposes by sending beacons is to announce the existence of devices and also reserve the future transmission slots. In each BP, devices shall broadcast information like BP length, occupation of beacon slots and also other information. In this section, we will take a look into the information provided in a beacon frame. Table 2.1 illustrates the MAC header field settings for beacon frames.

Information elements (IE) can appear in beacons and certain command frames. Beacon period occupancy IE (BPOIE), included in beacon frames, can provide information observed by the device sending the IE. A device should always include a

BPOIE in its beacon. In the BPOIE, a device shall indicate the beacons received from other devices in the previous superframes. The format of BPOIE is illustrated in Table 2.2.

Table 2.1 MAC Header Field Values For Beacon Frames

Header field	Value
Protocol Version	0
ACK Policy	0(No-ACK)
Frame Type	0(beacon frame)
Frame Subtype / Delivery ID	Reserved
Retry	Reserved
DestAddr	BcstAddr
SrcAddr	DevAddr of the transmitter
Sequence Control	
Duration	
More Frames	Reserved
Access Method	Reserved

Table 2.2 BPOIE Format

Octets:1	1	1	k	2	...	2
Element ID	Length(=1+ K+2N)	BP Length	Beacon Slot Info Bitmap	DevAddr 1	...	DevAddr N

IEs are included in order of increasing Element ID, except for ASIEs. ASIE do not appear prior to any IE with Element ID zero through seven, but may appear anywhere after those IEs. DRP IEs that have the same Target DevAddr and Stream Index are adjacent to each other in the beacon. The Beacon Parameters field is illustrated in Table 2.3.

Table 2.3 Beacon Parameters Field Format

Octets : 6	1	1
Device Identifier	Beacon Slot Number	Device Control

Table 2.4 indicates the Device Control field format. The Beacon Slot Number field is set to the number of the beacon slot where the beacon is sent within the beacon period (BP), in the range of [0, mMaxBPLength-1], except in beacons sent in signaling slots. In signaling slots it is set to the number of the device's non-signaling beacon slot.

Table 2.4 Device Control Field Format

bits : b7-b6	b5-b2	b1	b0
Security Mode	Reserved	Signaling Slot	Movable

The Movable bit is set to ONE if the beacon is movable if there is any beacon slot available before its beacon slot, and is set to ZERO otherwise. The Signaling Slot bit is set to ONE if the beacon is sent in a signaling beacon slot, and is set to ZERO otherwise. The Security Mode field is set to the security mode at which the device is currently operating.

2.5 Beacon Collision Detection

Collisions might happen when WiMedia devices chose beacon slots to send their beacons. Therefore four ways can be used to detect beacon collision. The first one is that a device receives a beacon in the current superframe, in which its beacon slot appears occupied in the BPOIE whereas the corresponding DevAddr is neither its own nor BcstAddr. The second one is that its beacon slot has been reported as occupied and the corresponding DevAddr has been BcstAddr in the BPOIE of a beacon it received in the same beacon slot in each of the latest mMaxLostBeacons superframes. The third way, some time devices need to skip some beacon transmission, and listen to the beacon collision. And after skipping beacon transmission in the previous superframe, its beacon slot is reported as occupied in the BPOIE of any beacon it receives in the current superframe. The last way to find out the beacon collision, while skipping beacon transmission in the current superframe, a device receives in its beacon slot in the current superframe: a MAC header of type beacon frame, or a PHY indication of medium activity that does not result in correct reception of a MAC header.

2.6 Beacon Transmission and Reception

Before we start to introduce the procedure of beacon transmission, we will briefly present some terms which will be mentioned in this section later. FCS represents Frame Check Sequence. It contains a 32-bit value which represents a CRC, used for verifying the validation of the beacon frame at the receiver. HCS represents Header

Check Sequence, which can protect the combination of PHY header and the MAC header.

For any WiMedia device, before it attempts to transmit any non-beacon frame, it should broadcast a beacon to reserve the future transmission slots. And before it transmits the beacon, it should sense the channel as idle for at least one superframe. If during the last superframe, it does not receive any beacon from other devices, it will create a new beacon period and send its own beacon in the first beacon slot after the signaling beacon slots, and broadcast to its neighbors. On the other hand, it receives one or more beacon headers, but no beacon frames with a valid FCS during the scan, the device should scan for an additional superframe. If the device receives one or more beacons during the scan, it will not create a new BP, but transmit its own beacon in a beacon slot randomly chosen after the largest unavailable numbered beacon slot, but not exceed the end of the BP.

If beacon collision is detected by a device, it shall choose a different beacon slot for its subsequent beacon transmissions from up to mBPExtension beacon slots located after the highest-numbered unavailable beacon slot it observed in the last superframe and within mMaxBPLength after the beacon period start time. If there is no beacon slot available in the BP, a device shall use signaling beacon slots to extend the existing BP by setting the signaling slot bit to one, randomly choosing a signaling beacon slot in the BP. Each BP starts with signaling beacon slot, and the signaling slot is used under the above conditions regardless of whether a device is sending a beacon for the first time in an existing BP or changing the beacon slot after detecting a beacon collision. A device

shall send a beacon in the signaling slot until its neighbors extend their BP lengths to include its beacon slot but only up to $mMaxLostBeacons+1$ superframes. After transmitting a beacon in a signaling slot for $mMaxLostBeacons+1$ superframes, a device shall wait for at least $mMaxLostBeacons+1$ superframes before sending a beacon in a signaling slot again. However, since two BPs overlapping might happen, a device may wait for a random number of superframes before sending a beacon in a signaling slot to reduce potential collisions. A device communicating with other devices shall listen for beacons during the BP length it announced in the last superframe. Once a device received a beacon in a signaling beacon slot in the previous superframe, it shall enlarge its BP Length to include the beacon slot indicated in the beacon received in the signaling slot. If a device received a beacon with invalid FCS, or detected a medium activity that did not result in reception of a frame with valid HCS, in a signaling slot in the previous superframe, it shall listen for beacons for an additional $mBPExtension$ beacon slots after its last announced BP length, but not more than $mMaxBPLength$ beacon slots. In order to detect beacon collisions with neighbors, a device shall skip beacon transmission periodically, and listen for a potential neighbor in its beacon slot. Device shall skip beacon transmission at least every $mMaxNeighborDetectionInterval$. With the exception of transmitting its own beacon as described in this Clause, a device shall not transmit frames during the announced BP length of any of its neighbors. If a device does not receive a beacon from a neighbor in the current BP, it shall use information contained in the most-recently received beacon from the neighbor as if the beacon were received in the current superframe, except when determining the contents

of the Beacon Slot Info Bitmap and DevAddr fields in its BPOIE. If a device does not receive a beacon from another device for more than mMaxLostBeacons consecutive superframes, it shall not consider the device as a neighbor.

2.7 Beacon Period Contraction Mechanism

Before a WiMedia device attempts to transmit, it shall scan the channel to receive beacons from others. If one or more beacons received, it will not create a new BP, but randomly transmit a beacon in a beacon slot randomly selected after the highest unavailable beacon slot but up to mBPMaxLength. Therefore, the beacon slot selected might not be the one just after the highest unavailable beacon slot, and if not, some beacon slots might not be used in the BP, which results in the waste of BP length. Since no data transmission is allowed during BP, it is an overhead. The shorter the BP length is, the longer the data transfer period will be. In order to enlarge the usage of BP, BP contraction mechanism is adopted in WiMedia MAC to shrink the BP.

Briefly, BP contraction mechanism is to shift the later beacons to the earlier available beacon slots. A device shall mark its beacon to be movable if in the current superframe it finds at least one unreserved beacon slot between the signaling slots and its own beacon slot. However, a device will still consider its own beacon unmovable when it includes a Hibernation Mode IE during the announced hibernation period. Several devices might mark themselves as movable, but only the device not involved in a beacon collision or a BP merge and also the latest movable one shall shift its beacon into the earliest available beacon slot following the signaling beacon slots in the BP of

the next superframe. In another word, two conditions fulfill the requirements of BP contraction mechanism. First, its beacon has been movable and second, all the beacon slots after the device's own and within the device's BP length have been encoded as non-movable in the BPOIE of the beacons transmitted or received by the device.

2.8 Merge of Multiple BPs

In dynamic network, changes caused by mobility, devices moving in or out might happen, and also other effects, which will results in that devices using two or more unaligned beacon period start time (BPST) may come into each other's range. This causes overlapping superframes. A received beacon with valid HCS and FCS that indicates a BPST that is not aligned with a device's own BPST is referred to as an alien beacon. The BP defined by the BPST and BP length in an alien beacon is referred to as an alien BP. Synchronization problems could cause the beacon of a fast device to appear to be an alien beacon. Once a device detect a BPST has a difference from its own by less than $2 \times mGuardTime$, it will consider that to be aligned. If a device detects that its BPST falls within the alien BP or if the alien BPST falls within its own BP, it shall consider an alien BP to overlap its own. But, a beacon with the Signaling Slot bit set to ONE will not be considered to be an alien beacon.

After a device receive one alien beacon, for up to $mMaxLostBeacons$ superframes, if the device does not receive any other alien beacon, it shall use information contained in the most recently received beacon as if the alien beacon were received at the same offset within the current superframe. The BPST offset identifies

the BPST of the alien BP where the device will move. A device should include a BP Switch IE in its beacon prior to changing its BPST. The BP Switch IE is used to indicate a device will change its BPST to align with an alien BP, illustrated in table 2.5.

Table 2.5 BP Switch IE Format

Octets:1	1	1	1	2
Element ID	Length (=4)	BP Move Countdown	Beacon Slot Offset	BPST Offset

The BP Move Countdown field should be set to the amount of superframes after which the device will modify its BPST. And once it reaches zero, the following transmitted beacon frame shall be set to the time indicated in this IE. The Beacon Slot Offset field is a positive number by which a device should adjust its beacon slot number while adjusting its BPST. And when it is set to zero, it means the device will join the alien BP using normal BP join rules. The BPST Offset field is equal the amount of time the device will delay its BPST, measured in microseconds, and should be positive.

2.8.1 Overlapping BPs

It is important for energy conservation to establish a single, joint BP with overlapping WPANs, because the BP is the only period a device should stay awake and be able to receive frames. Therefore, only during BP and DRP periods devices are involved in, they need to power up but in other time powered off. Devices which detect alien BPs have to refrain from the interference to alien BPs and DRP reservations. WiMedia MAC provides a procedure to merge coexisting BPs. Briefly speaking, after announcing a protection DRP period for the alien WPAN, devices start shifting their

beacons so that to merge BPs into a single BP. We will provide more details in the following. If the BPST of a device falls within an alien BP, the device shall relocate its beacon to the alien BP according to the following procedures. The device shall change its BPST to the BPST of the alien BP. After changing its BPST, if the device is required to send a beacon in a signaling slot, it should wait for a random number of superframes before sending the beacon in the signaling slot. The device should choose the random number with equal probability in the range zero to the BP Length declared in its last beacon before relocating to the alien BP. The device shall adjust its beacon slot number so that its new beacon slot number is its old beacon slot number plus one, plus the number of the highest occupied beacon slot indicated in any beacon received in the alien BP, minus mSignalSlotCount. Alternatively, it shall follow normal BP join rules to relocate its beacon to the alien BP. The device shall not send further beacons in its previous BP.

2.8.2 Non-overlapping BPs

When a device detects an alien BP, but that does not overlap in time with its own BP, it shall merge BPs following other rules other than the overlapping BPs. The device shall include in its beacon a DRP IE with Reservation Type set to Alien BP for the alien BP. Since the MAS boundaries may not be aligned, the device may need to include an additional MAS in the reservation to completely cover the alien BP. If the device received multiple beacons from the alien BP, it shall include all MASs used by the largest reported BP length in the reservation. If the MASs occupied by the alien BP change over time, the device shall update the DRP IE accordingly. The device shall

relocate its beacon to the alien BP, within $mBPMergeWaitTime$ if the alien BPST falls within the first half of the superframe, or within $1.5 \times mBPMergeWaitTime$ if the alien BPST falls within the second half of the superframe, but shall not relocate to the alien BP if a beacon received in that alien BP includes a BP Switch IE.

A device that transmits or receives a beacon in its own BP that contains a DRP IE with Reservation Type set to Alien BP shall observe the following rules. The device should not change beacon slots except as required by merge rules, unless a collision is detected. The device shall listen for beacons during the MASs indicated in the reservation.

2.8.3 Beacon Relocation

If a device starts or has started the beacon relocation process and receives an alien beacon, it shall follow these rules:

If the device did not include a BP Switch IE in its last beacon, it shall include a BP Switch IE in its beacon in the following superframe with the fields set as follows: The device shall set the BP Move Countdown field to $mInitialMoveCountdown$. The device shall set the BPST Offset field to the positive difference in microseconds between the alien BPST and the device's BPST. That is, the field contains the number of microseconds that the device must delay its own BPST to align with the alien BPST. If multiple alien beacons are received, the device shall set the BPST Offset field to the largest calculated value. The device shall set the Beacon Slot Offset field to: One plus the number of the highest occupied beacon slot indicated by any beacon received in the alien BP, based on the Beacon Slot Number field and BPOIE, minus $mSignalSlotCount$;

or Zero to indicate the device will join the alien BP using normal join rules. If the device included a BP Switch IE in its last beacon, it shall modify the BP Switch IE in the following superframe as follows: If the elapsed time between the device's BPST and the following alien BPST is larger than the device's BPST Offset field + $2 \times mGuardTime$, the device shall set the BP Move Countdown field, the BPST Offset field, and the Beacon Slot Offset field as described above respectively. If the elapsed time between the device's BPST and the following alien BPST is larger than the device's BPST Offset field - $2 \times mGuardTime$ and smaller than the device's BPST Offset field + $2 \times mGuardTime$, the device shall set the BPST Offset field. It shall set the Beacon Slot Offset field as described in A3 if the value in the field would be increased, or leave it unchanged otherwise. It shall set the BP Move Countdown field to one less than the value used in its last beacon if the Beacon Slot Offset field is unchanged, or set it as described in A1 if the Beacon Slot Offset field is changed. If a device receives a neighbor's beacon that contains a BP Switch IE, it shall follow these rules: If the device did not include a BP Switch IE in its last beacon, it shall include a BP Switch IE in its beacon in the following superframe with the fields set as follows: The device shall set the BP Move Countdown field to the BP Move Countdown field of the neighbour's BP Switch IE. The device shall set the BPST Offset field to the value of the same field contained in the neighbor's beacon. The device shall set the Beacon Slot Offset field to: The larger of: one plus the number of the highest occupied beacon slot indicated by any alien beacon received in the alien BP identified by the neighbour's BP Switch IE, based on the Beacon Slot Number field and BPOIE, minus $mSignalSlotCount$; or the Beacon

Slot Offset field contained in the neighbour's beacon; or Zero, to indicate the device will join the alien BP using normal join rules.

If the device included a BP Switch IE in its last beacon, it shall modify the BP Switch IE as follows: If the BPST Offset field contained in the neighbour's beacon is larger than the device's BPST Offset field + $2 \times \text{mGuardTime}$, the device shall set the BP Move Countdown field, the BPST Offset field, and the Beacon Slot Offset field as described in C1, C2 and C3 above respectively. If the difference between the BPST Offset field contained in the neighbour's beacon and the device's BPST Offset field is smaller than $2 \times \text{mGuardTime}$, the device shall modify its BP Switch IE as follows: If the Beacon Slot Offset field contained in the neighbour's beacon is larger than the device's Beacon Slot Offset field, the device shall set the BP Move Countdown field, the BPST Offset field, and the Beacon Slot Offset field as described above respectively. If the Beacon Slot Offset field contained in the neighbour's beacon is equal to or smaller than the device's Beacon Slot Offset field, the device does not receive alien beacons from the alien BP indicated by its current BPST Offset field, and the BPMoveCountdown field contained in the neighbour's beacon is less than the device's BPMoveCountdown field, then the device shall set the BPST Offset field as described above. It shall not change the Beacon Slot Offset field. It shall set the BP Move Countdown field to one less than the value used in its last beacon. If a device included a BP Switch IE in its last beacon and none of the conditions within B or D apply, the device shall not change the BPST Offset field or the Beacon Slot Offset field, and shall set the BP Move Countdown field to one less than the value used in its last beacon.

If a device includes a BP Switch IE in its beacon, it shall continue to do so until it completes or halts the relocation process. If a device receives an alien beacon that indicates relocation earlier than its planned relocation, the device shall halt the relocation process. If a neighbour halts the relocation process, the device shall halt the relocation process.

To halt the relocation process, a device shall include a BP Switch IE in its beacon with BPST Offset field set to 65535, Beacon Slot Offset field set to zero, and BP Move Countdown field set to mInitialMoveCountdown. In following superframes, it shall follow the rules above.

At the end of the superframe in which a device includes a BP Switch IE with a BP Move Countdown field equal to zero, the device shall adjust its BPST based on its BPST Offset field. It may transmit a beacon in that superframe, or delay one superframe to begin beacon transmission in its new BP. After relocating its beacon to the alien BP, the device shall include neither the BP Switch IE nor the alien BP DRP IE in its beacon. If the Beacon Slot Offset field was non-zero, the device shall transmit a beacon in the beacon slot with number equal to its prior beacon slot number plus the value from the Beacon Slot Offset field. If this beacon slot number is greater than or equal to mMaxBPLength, the device shall follow the normal BP join to relocate its beacon to the alien BP.

2.8.4 BP Extension

A device that receives an alien beacon with a BP Switch IE with Beacon Slot Offset field greater than zero shall set its BP length to at least the sum of the Beacon

Slot Offset field and the BP length reported in the alien beacon, but not greater than mMaxBPLength.

CHAPTER 3

MODEL DESIGN

In WiMedia MAC, if a device wants to transmit a data frame, it should broadcast a beacon to reserve the transmission slots in advance, and also receives beacons from all neighbor devices to get information about the occupation of the time slots. WiMedia MAC restricts that two devices within two hops cannot transmit beacon in the same beacon slot, so the BP length of a device should be able to include all of its two-hop neighbors' beacon as well as itself. However, if a device gets powered off or leaves the network, its occupied beacon slot will be released and should become available by other devices within its neighborhood. Thus reusing the released beacon slot can reduce the BP length by using BP contraction algorithm. In this Chapter, we model the BP contraction mechanism as a distance-2 coloring algorithm, formulate the optimal BP contraction problem using two metrics, and On-Line First-Fit coloring algorithm is applied to our model. Since BP contraction mechanism will not terminate until all of the devices become unmovable in the network, it will propagate to other neighborhood. We also give some illustration about this problem.

First of all, we give some introduction about the coloring problem and algorithm we will use in our modeling.

3.1 Coloring Algorithm

3.1.1 Vertex Coloring

A vertex coloring is an assignment of labels or colors to each vertex of a graph such that no edge connects two identically colored vertices. The most common type of vertex coloring seeks to minimize the number of colors for a given graph. The minimum number of colors which with the vertices of a graph G may be colored is called the chromatic number [7].

3.1.2 Distance-2 Coloring Problem

In a graph, two distinct vertices are said to be distance-2 neighbors if the shortest path connecting them consist of at most 2 edges. A distance-2 coloring of a graph $G = (V, E)$ is a mapping C : such that $C(u) \neq C(v)$ whenever u and v are distance-2 neighbors. C represents the color index set [8].

3.2 Model of BP Contraction Mechanism

Briefly the BP contraction mechanism in WiMedia MAC has three major steps [18]. 1) A device marks itself movable if it observes an available slot before its own slot. 2) The movable information is relayed by its neighbors to its two-hop neighbors. 3) If a device is not involved in a beacon collision and its beacon is the latest movable one among its two-hop neighbors', the device shall shift its beacon to the earliest available beacon slot.

BP is an overhead in MBOA MAC. BP contraction mechanism is used to compress the BP length since some released beacon slots can be reused by other two

hop neighbors. According to BP contraction mechanism, the latest movable beacon slot will be shifted to the earliest beacon slot.

As described in the first section of this chapter, we can model BP contraction mechanism as distance-2 coloring problem. Two hop neighbors cannot be colored the same. We use an undirected graph $G = (V, E)$ to model the devices' spatial distribution, where V is the device set and E denotes the neighbor set. $E = (e_{ij})_{|V| \times |V|}$. Let $e_{ij} = 1$ if device i and j are neighbors of each other, and $e_{ij} = 0$ otherwise. A beacon slot must not be assigned to two devices within two hop neighbors, so the beacon slot assignment problem can be modeled as the distance-2 coloring problem. Therefore the chromatic number of colors used in the distance-2 coloring problem should be equal to the length of BP in the BP contraction mechanism.

We formulate the BP contraction mechanism as distance-2 coloring problem, furthermore we model the optimal BP contraction as linear programming problem. There are two fundamental metrics to measure the performance of BP contraction algorithms. The first one is the average BP length, which reflects the overall performance of the algorithm and the second one is the maximum BP length, which reflects the worst case. In the next subsection, we will formulate BP contraction mechanism under these two metrics.

3.2.1 Minimizing Maximum BP Length

Minimizing the maximum beacon period length can be formulated as finding the minimum colors to distance-2 coloring graph, since the maximum BP length is the same as the maximum beacon slot assigned to devices. Let the square of MBOA

devices topology $G_2 = (V, E_2)$, and S be the set of independent sets (IS) in G_2 . An independent set of G is a set of vertices such that there is no edge in E connecting any pair. Clearly, in any coloring of G , all vertices with the same label comprise an independent set. A maximal independent set is an independent set that is not strictly included in any other independent set. We use S_i to denote the set of ISs including device i . It is obvious that finding the minimum colors for distance-2 coloring G is same as finding the chromatic number of G_2 . Let the Boolean variable δ_s represent whether we select ISs in graph coloring or not, and the problem of minimizing maximum BP length can be formulated as:

$$\min \sum_{s \in S} \delta_s, \quad \text{subject to}$$

$$\sum_{s \in S_i} \delta_s = 1, \quad \forall i \in V$$

$$\delta_s \in \{0, 1\}, \quad \forall s \in S$$

3.2.2 Minimizing Average BP Length

We use a Boolean matrix $B = (b_{ik})_{|V| \times M}$ to denote the beacon slot assignment in minimizing average BP length, where $b_{ik} = 1$ if device i uses the k -th slot, and vice versa. Because each device transmits exactly one beacon, the number of beacons is equal to the number devices, $|V|$. Therefore, $|V|$ slots is always enough and we set $M = |V|$. Let C_i be the index of the i -th device's beacon slot, and L_i be the BP length of device i . Our objective is to minimize the average BP length, which

$\min \sum_i L_i / |V|$, subject to:

$$\sum b_{ik} = 1 \quad (3)$$

$$L_i = \max_{d_{ij} \leq 2} C_j \quad (4)$$

$$C_i = \sum_k k * b_{ik} \quad (5)$$

$$b_{ik} \in \{0,1\}, i, k \in \{1, \dots, |V|\} \quad (6)$$

In the above formulation, d_{ij} is the distance (measured in hops) between devices i and j . Constraint (3) means that each device occupies exactly one beacon slot, and constraint (4) is gotten from its definition. Furthermore, it is easy to check that constraint (5) is also correct under (3). Finally, constraint (6) gives the range of the variables used in the formulation.

3.3 Solution for the optimal BP Contraction Mechanism

We model the BP contraction mechanism as distance-2 coloring problem, and in the two metrics we mentioned above, we want to find a minimum value for each metric. However, for distance-2 coloring algorithm, finding a minimum coloring is NP-complete. Therefore we should find an approximation algorithm for the distance-2 coloring. On-line First-Fit coloring algorithm is a well known algorithm used on the

distance-2 coloring problem. And many researchers have extensively studied on-line coloring algorithms [26, 27, 28, 29]. Most of their work is devoted to the proof of upper bounds for the chromatic amount of colors for a graph, that is, the worst-case behavior of the coloring algorithm First-Fit [26, 28] and also they showed that First-Fit has better performance than other on-line coloring algorithms. In [30], it also shows that comparing to the other on-line coloring algorithms the First-Fit has a slower growing waste utilization with the increasing of measurement scale, which means for our simulation, with the density of network increasing, the First-Fit will have a slower increase on the chromatic amount of colors than the other methods.

3.3.1 On-line First-Fit Coloring Algorithm

The coloring problem is to color a graph with as few colors as possible [11]; that is, to minimize the number of colors. An on-line coloring of a graph G is a procedure that immediately colors the vertices of G taken from a list without looking ahead or changing the colors already assigned. More precisely, an on-line coloring of G is an algorithm that properly colors G by receiving its vertices in some order V_1, V_2, \dots, V_n . The color of V_i is assigned by only looking at the subgraph of G induced by the set $\{V_1, V_2, \dots, V_i\}$, and the color of V_i never changes thereafter.

Let G be a graph with an ordering $V_1 < V_2 < \dots < V_n$ of its vertices and let A be an on-line coloring algorithm with input $(G, <)$. Over all such possible orderings $<$, let $X_A(G)$ denote the maximum number of colors used by A to color G . Clearly, $X_A(G)$ measures the worst-case behavior of A on G . The minimum number of colors required to color G off-line is called chromatic number of G and is denoted by $X(G)$.

One of the on-line coloring algorithms is First-Fit algorithm (also sometimes called “the Greedy algorithm”); Given $(G, <)$ as input, First-Fit works by receiving the vertices of the graph G one vertex at time in the given order $V_1 < V_2 < \dots < V_n$ and assigning the smallest possible integer from Z as the color to vertex $V_i (1 \leq i \leq n)$; that is, the smallest color not yet assigned to any vertex adjacent to V_i among the previously colored vertices. We note that if the vertices of G are considered in an ideal sequence then $X_{ff}(G) = X(G)$; to construct a sequence first find an optimal coloring of G and then put all vertices with the same color in consecutive positions in the sequence.

3.3.2 BP Contraction Mechanism Optimization

BP contraction algorithm can be modeled as distance-2 coloring problem and specifically can be solved by On-Line First-Fit coloring. In On-Line First-Fit coloring algorithm, each node is given in order and will be colored according to the sequence with the smallest available color index. Two nodes connecting to each other should be colored differently.

We map it to the BP contraction algorithm. Each device will be numbered in their powering up order and sequentially allocated by the earliest available beacon slot according to the beacon slots occupation of its neighbors. Devices within radio range in wireless network cannot use the same beacon slot for any pair. And the length of BP for each device includes all of the unavailable beacon slots and itself.

In a dynamic wireless network, we take each device as a node in On-Line First-Fit coloring algorithm. Beacon slot number is represented by color index in natural number order. Each device use On-Line First-Fit coloring algorithm to do the slot

reservation with getting a color index as its own beacon slot. While new device joining, it checks all of the nodes' color within radio range and color itself by the smallest available color index. Once active devices leaving, its former owned color index will be released and will be available for nodes within two hop neighborhood. Therefore, BP length of each device should be the largest color index among its neighborhood and itself.

Given the coloring model of beacon slot assignment, we can now study how the BP contraction algorithm colors the graph. For a device just powering up, it scans for beacons first. After receiving one or more beacons with valid header checksum, it tries to transmit a beacon in the beacon period after all two hop neighbors' transmissions. Since the beacon slot the new comer occupying must be the last one within two hop neighborhood, the device proceeds to observe available slots and it will shift beacon to the first available slot. For a device leaving the network, the released slot will be reoccupied soon by some of its two hop neighbors. The contraction algorithm terminates only when all devices are not movable, i.e., for each device, all beacon slots before its own slot are unavailable. Therefore, we can see that the BP contraction mechanism is a greedy coloring algorithm, which can be further modeled as On-Line First-Fit coloring algorithm. On-Line First-Fit coloring scheme maps a vertex order into a color assignment by coloring each vertex in the given order and selecting the smallest available color index in each step. Given a network topology, the performance of the algorithm only depends on the device ordering, which is a function of device joining/leaving sequence. It is hard to model the device joining/leaving behavior and

find its relationship with the device ordering; however, we could generate a large number of different random device orderings and use them as the input of the algorithm to study its impact on the BP contract algorithm performance.

3.4 BP Contraction Propagation

In a dynamic network using WiMedia MAC, with the changing of network, devices reuse the released beacon slots in order to save the overhead of superframe for data transmission. Once the BP Contraction Mechanism being triggered by a device's leaving the network, will the BP contraction be done once or will be propagated? Here we give a simple example of a dynamic network.

According to BP contraction algorithm, the lasted movable beacon slot will be shifted to the earliest beacon slot. We take Figure 3.1 as an example. Devices 9, 5, 11 mark themselves as movable, and three released beacon slots are available. The latest movable device 11 will shift its beacon slot to the first available beacon slot.

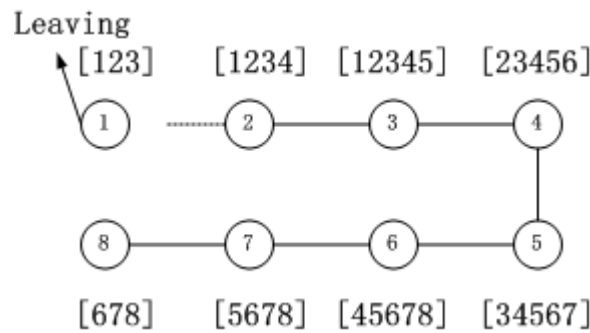


Figure 3.1 A Simple Network

In MBOA MAC, BP contraction will terminate when all of the devices mark themselves as unmovable. From this perspective, the contraction usually cannot be done

once but will be propagated till no unreserved beacon slot exists. In Figure 3.1 we illustrate a very simple wireless network. The number in each circle represents the powering up ordering and also the device ID. Lines between two nodes do not really exist but only drawn to show they are one hop neighbors. In this wireless network, two hop neighbors can communicate with each other. Numbers above each node are its two hop neighbors and also represent the composition of its BP, in which devices IDs arranged in order of their occupation for beacon slots. Once device 1 leaves, according to BP contraction algorithm, its two hop neighbors, device 2 and device 3, will sense beacon slot 1 released and mark themselves as movable. As shown in the figure, device 3 in the BP should be the latest movable one, which means it will shift its beacon slot to the beacon slot released by device 1. Sequentially, after device 3 shifts to the first beacon slot, its former beacon slot 3 will be released and then sensed by its two hop neighbors, device 2, 4, 5, but only device 4, 5, whose beacon slots after device 3, will mark themselves movable. BP contraction will be done by device 5 shifting its beacon slot to beacon slot 3. Consequently, this BP contraction will be propagated till there is no device movable. In our network, after BP contraction of device 5, device 7 will shift its beacon slot to beacon slot 5, and finally the BP contraction algorithm will be terminated by the last contraction of device 8 moving its own beacon slot to the beacon slot 7. Therefore the total propagation times under this network topology is 4. Obviously, the propagation times will have some difference according to the different devices ordering. If we exchange the powering up order between device 1 and device 3, the beacons in the BP will be sent in the sequence as 231, and the leaving of device 1

will not cause any BP contraction propagation since it sends beacon in the last beacon slot in its BP, which means none of its two hop neighbors' beacons is behind it and sequentially no one will be marked movable.

CHAPTER 4

SIMULATION

4.1 Network Setup

We carry out a simulator to evaluate the performance of BP contraction mechanism. In our simulator, we set up a dynamic ad hoc network, 300 nodes are randomly distributed in a square area 30m * 30m. All of the devices are ordered in sequence by their powering up order.

For each device, two states 'on/off' to represent device active/dead. Each device will have its initial state when it gets powered up, and the percentage of active devices could be changed according to requirement when they are initialed.

For each device, its initial state has a duration period after which it will automatically switch to the other opposite state, and generally it is in exponential distribution. By changing the states of devices, we simulate the device joining/leaving and also change device orderings periodically.

The transmission range is varied from 2 meters to 6 meters and identical for each device, and in reality the maximum transmission range is not longer than 10 meters. Devices within two hop neighbors can receive beacons from each other and also communicate with each other. In order to take consideration of the influence of device ordering, we generate a large number of different networks with different spatial

distribution, therefore devices orderings are determined by both the distribution and periodical network changing.

4.2 Experimental Analysis

4.2.1 Average BP Length and Maximum BP Length

In scenario 1, for each fixed transmission range, we generate 5000 random devices' orderings, and calculate the best/average/worst performance of the BP contraction algorithm. Figure 4.1 illustrates the simulation results under the metrics as we mentioned in Chapter 3, average BP length with and without BP contraction mechanism.

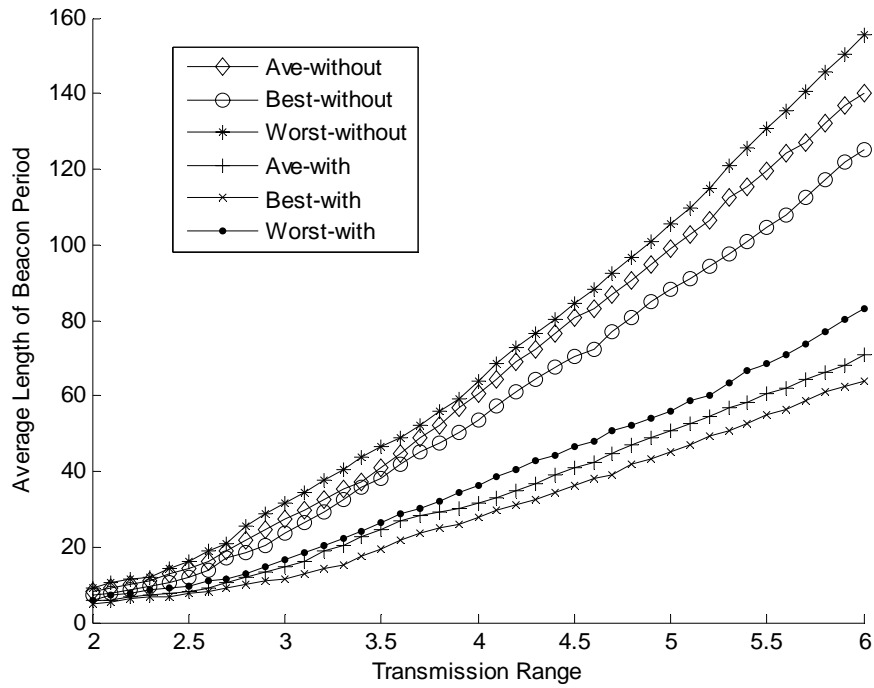


Figure 4.1 Average BP Length Without And With BP Contraction

Figure 4.2 illustrates maximum BP length with and without contraction with random device ordering. At first glance, we can see that BP contraction always halves BP length under different transmission ranges in both metrics. Next the impact of the device ordering on the BP contraction mechanism (which is calculated by $100\% * (\text{worst} - \text{best})/\text{best}$ for each fixed transmission range) is always less than 20%. Devices' ordering does not have a significant influence on the performance of BP contraction mechanism.

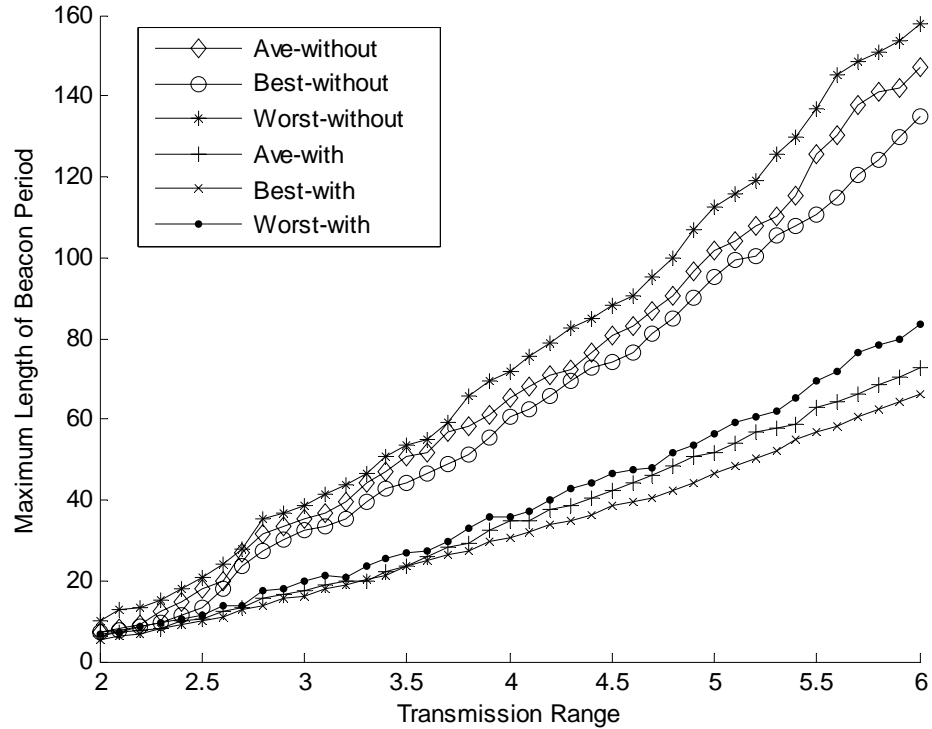


Figure 4.2 Maximum BP Length Without And With BP Contraction

Furthermore, we take a look at the gap between the average BP length and the best BP length. The gap is very small, less than 10% most of the cases. According to reference [7], this result confirms that the average number of colors used by randomized First-Fit is always very close to its lower bound.

For the 5000 different network topologies, we calculate the standard deviation of BP lengths for the different metrics we discussed above. Figure 4.3 illustrates the standard deviation of the average BP lengths in the maximum metric.

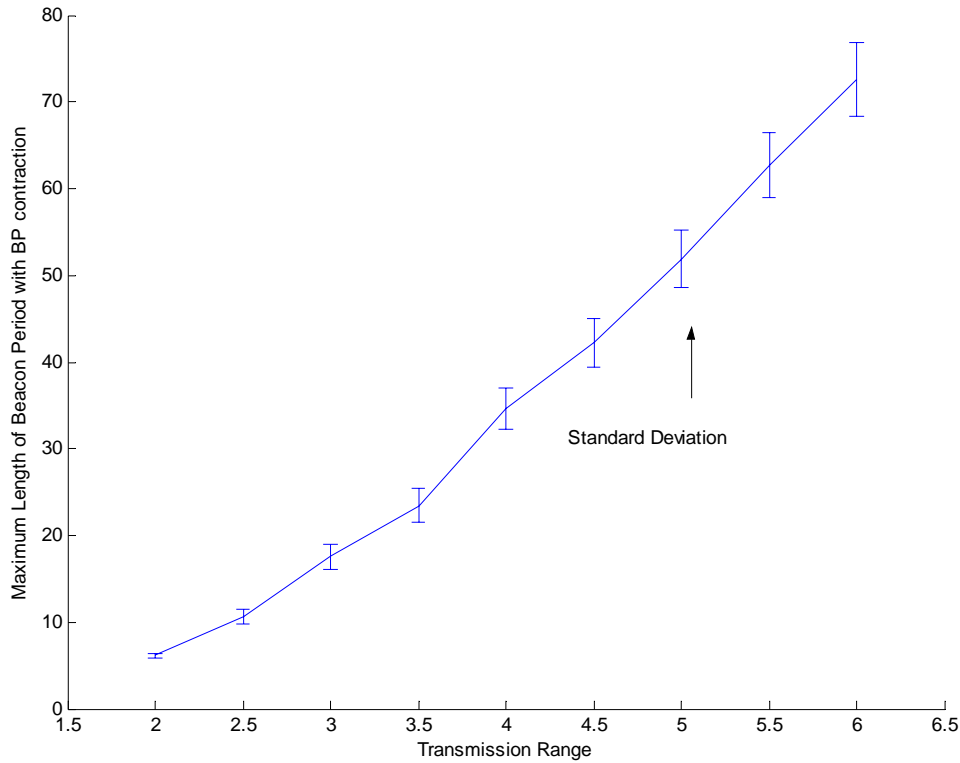


Figure 4.3 Average BP Lengths With Standard Deviation In Maximum Metric With Transmission Range

In our figure we put the average BP lengths in maximum metric for comparison. For the standard deviation, each bar represents the standard deviation for the average

BP lengths with the same transmission range. From the figure, we can see the standard deviation is increasing with the transmission range increasing.

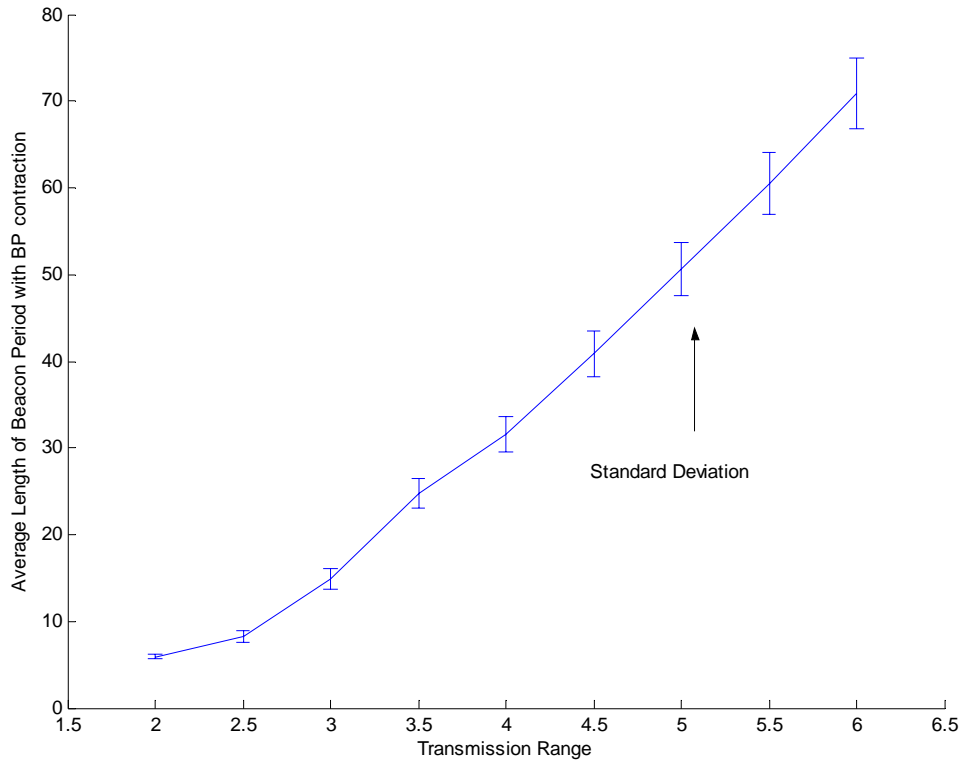


Figure 4.4 Average BP Lengths With Standard Deviation In Average Metric With Transmission Range

When transmission range increases, network density becomes higher so that the impact of the network topology will become more significant. The more devices get involved in a neighborhood, the more different the devices ordering will be, which will result in more difference of BP lengths. Therefore, the standard deviation of BP lengths will increase with the transmission range increasing. We take two examples here. When the transmission range is 2 meters, only around 5 nodes are within a neighborhood, the difference of the devices' orderings will not change too much with only around 5 nodes

involving, which results in that the difference of the BP length will not have a big difference. However, with the increasing of the transmission range, when the transmission range reaches 6 meters, theoretically there should be around 50 nodes in one neighborhood, actually more than that, so the variance of devices' orderings will be significant. Since the coloring algorithm can be influenced by the topology of a graph, the amount of chromatic colors by using On-Line First-Fit coloring algorithm will vary more with the change of the networks.

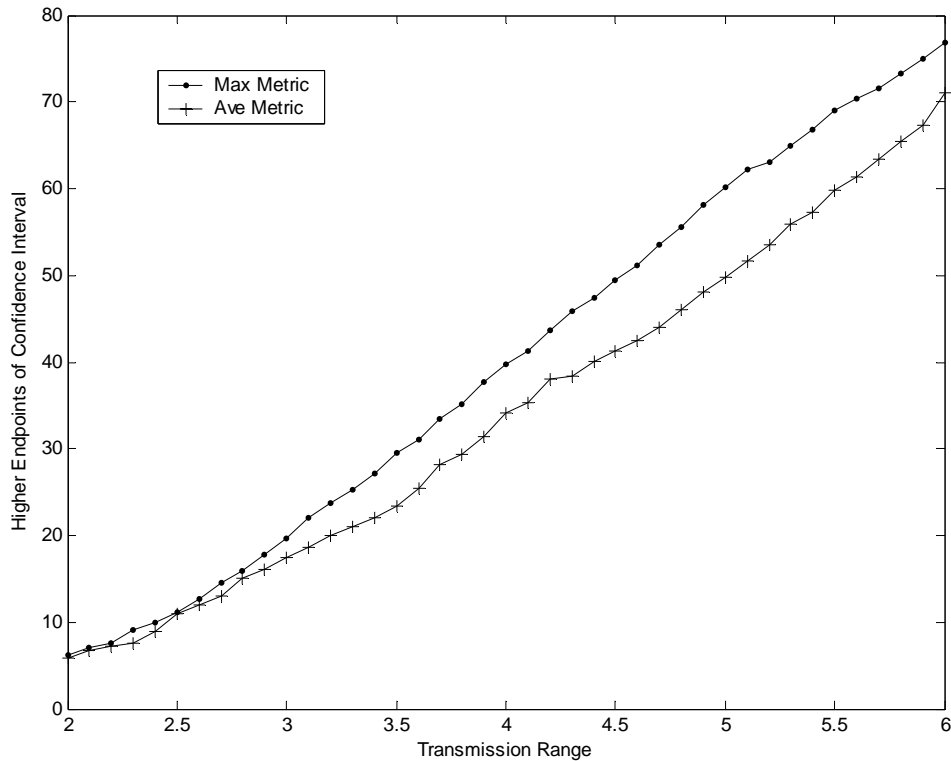


Figure 4.5 Higher Endpoints Of Confidence Interval Of BP Lengths In Two Metrics

Figure 4.4 shows the average BP lengths with standard deviation in average metric with different transmission ranges. From the figure we can see the standard deviation has the same trend as it in maximum metric.

Furthermore, from our simulation, the average BP length for a network topology can be considered to be a random variable X . The distribution of X is assumed here to be a normal distribution with unknown expectation μ and known standard deviation we got in Figure 4.3 and Figure 4.4. And we set our confidence level to be 95%, we calculated the confidence interval for both metrics of BP lengths described above.

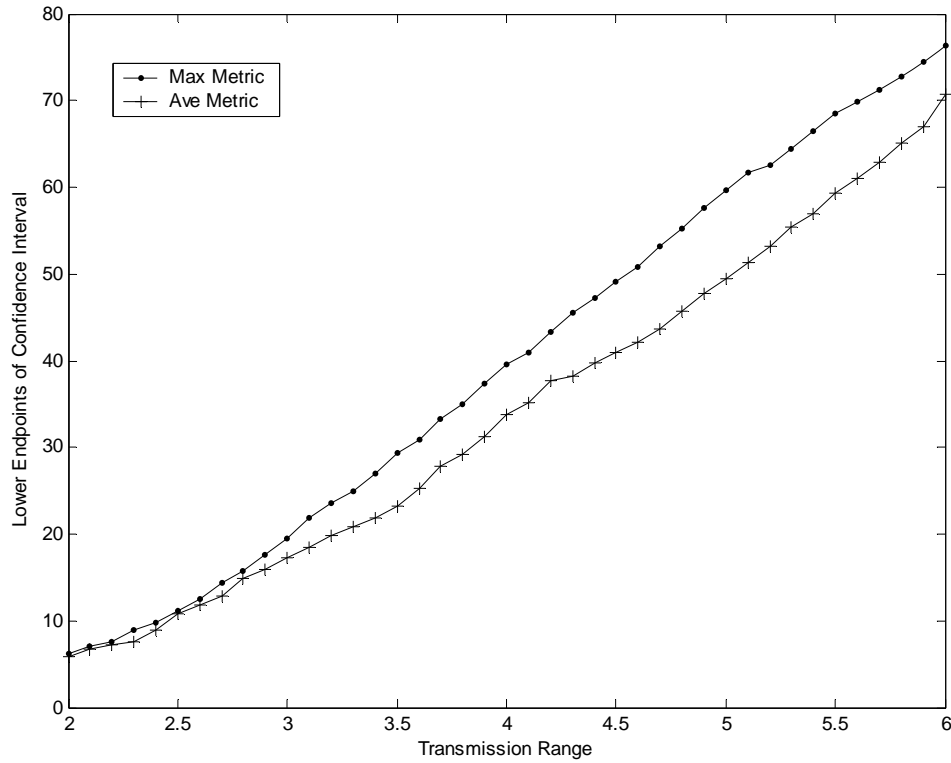


Figure 4.6 Lower Endpoints Of Confidence Interval Of BP Lengths In Two Metrics

Figure 4.5 shows the higher endpoint of the BP lengths in the two metrics, and Figure 4.6 show the lower endpoint of the BP lengths in the two metrics.

4.2.2 *Propagation Times of BP Contraction*

Since the BP contraction will not be terminated once, the propagation times should be considered as an important aspect to evaluate its performance. And given a network, the topology will have some influence on the performance of BP contraction mechanism. Generally, the density of the network, and also the average nodal degree will directly diversify the BP lengths so that the propagation times of BP contractions will also vary. Therefore, in our simulation, the network topology is in uniform distribution, and we randomly generate 1000 different device orderings.

Figure 4.7 illustrates the minimum/average/maximum BP contraction propagation times with different transmission range. Since the topology of the network has significant influence on the BP contraction propagation times, we initial 1000 different devices deployments in our network and turn off each node sequentially, let the rest active nodes do the BP contraction, then we calculate the maximum/average/minimum BP contraction propagation times. At first glance, the variation of the BP contraction propagation times with the transmission range is less than 1. The average propagation times increases slowly with the transmission range. However the maximum propagation times varies with the trend of decreasing with transmission range. For the minimum propagation times, absolutely when the leaving devices transmit in the last beacon slot in the BP, the BP contraction will not happen, which results in 0 in our figure.

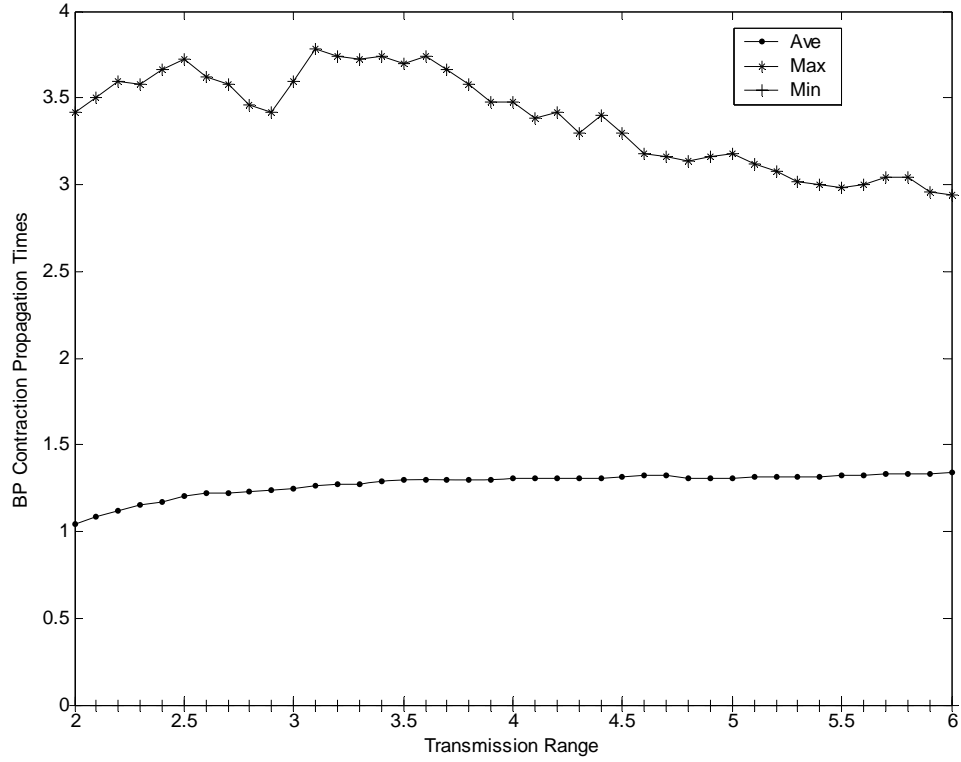


Figure 4.7 Propagation Times Of BP Contraction With 300 Nodes

Furthermore, Figure 4.8 illustrates the average nodal degree changing with increasing transmission range. For each node, with the changing of transmission range, the amount of neighbors will be varied. Average nodal degree represents the average amount of neighbors for each node in the network. We evaluate the network variance through the average nodal degree since the BP length will be influenced by the amount of neighbors.

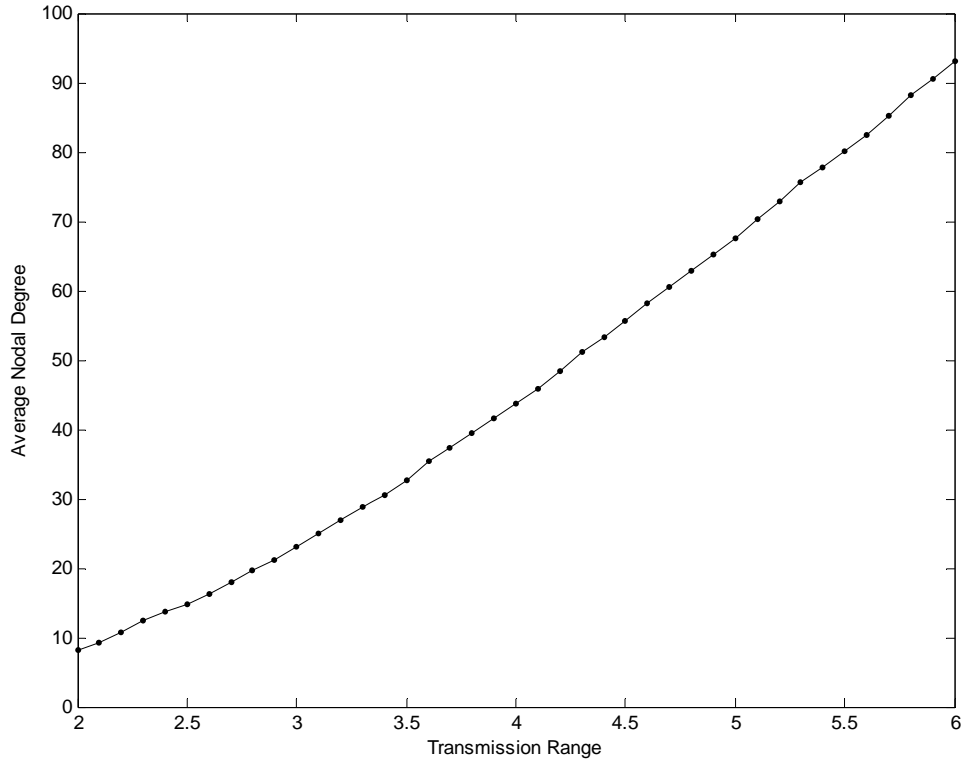


Figure 4.8 Average Nodal Degree With Different Transmission Ranges

Theoretically, we can calculate the density of the network, when the transmission range is set to 2, in the condition of two hop neighbors being able of communicating, the size of one neighborhood is around 5.4, and 48 when transmission range is set to 6. From Figure 4.8, it turns out that the average nodal degree is higher than our theoretical result. However, from Figure 4.9, we can see the average nodal degree does not have too much impact on the average BP contraction propagation times. Though the average nodal degree was changing from around 8 to more than 90, the difference between the BP contraction propagation times is still within 0.5, which

means, the BP contraction mechanism has a very stable performance, and it can be terminated in a short time despite of the amount of average nodal degree.

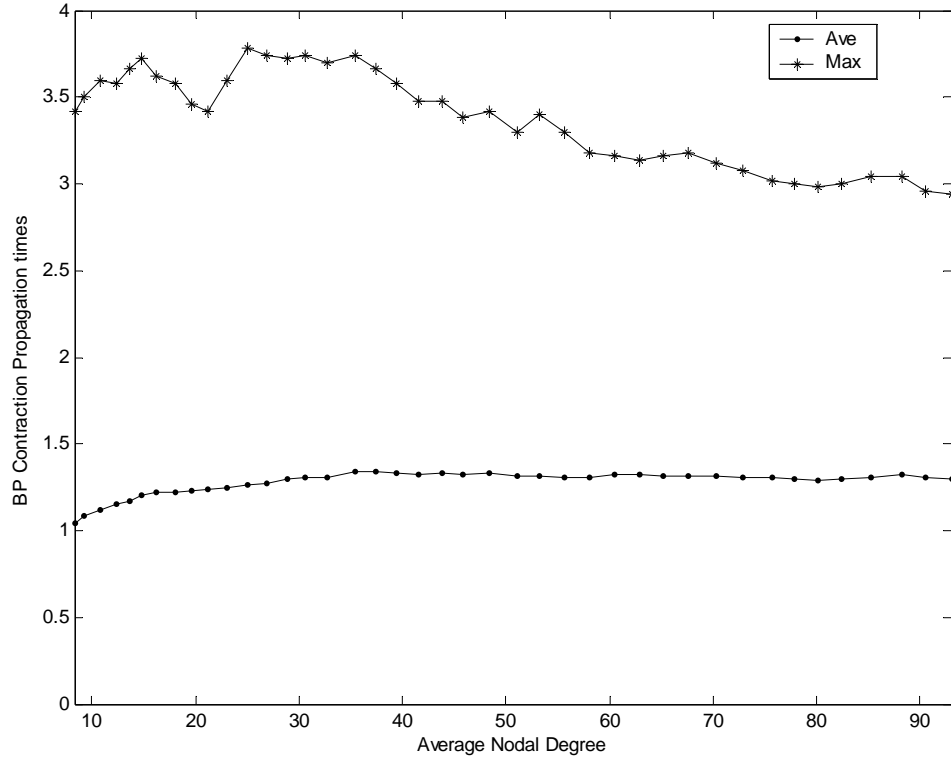


Figure 4.9 BP Contraction Propagation Times With Different Average Nodal Degrees

As analyzed in Chapter 3, BP contraction can be propagated, and will terminate until all of the devices become unmovable. The BP contraction propagation times can be influenced by two aspects, layout of a device's neighborhood including the amount and distribution of neighbors, the other is the position of device's beacon slot. Therefore reflected in the figure, the maximum propagation times decreases with the transmission range since more neighbors will be involved with the increasing of transmission range, which results in decreasing of the clusters of neighborhood. If we assume all of the

nodes are in one neighborhood, then BP contraction will be done only once without broadcasting to any other cluster of neighborhood. But in average, with the increasing of transmission range, more and more clusters of neighborhood can communicate with each other, BP contraction propagation times will increase.

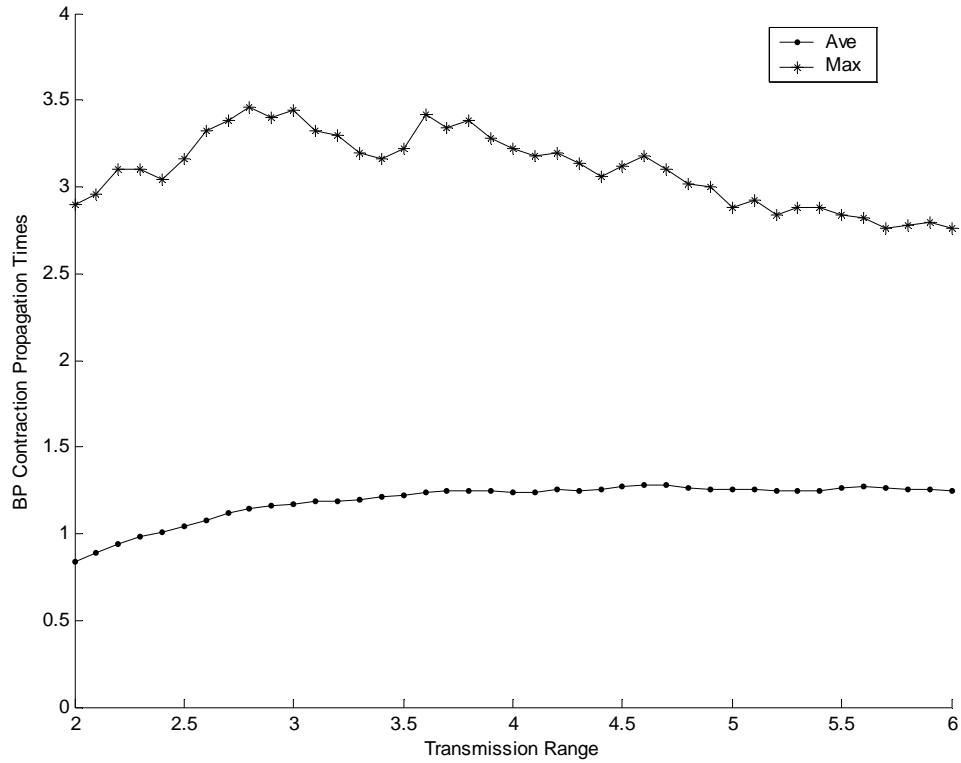


Figure 4.10 Propagation Times Of BP Contraction With 200 Nodes

We take an example when the transmission range is set to be 2 meters. When we set the transmission range as 2 meters, some clusters of neighborhood get isolated from other clusters of nodes because of the short transmission range, but they will become able to communicate with those clusters of nodes when the transmission range increases. From the figure, we can see that the maximum propagation times of BP

contraction is less than 4, which means that the BP contraction algorithm has a very stable performance in ad hoc network.

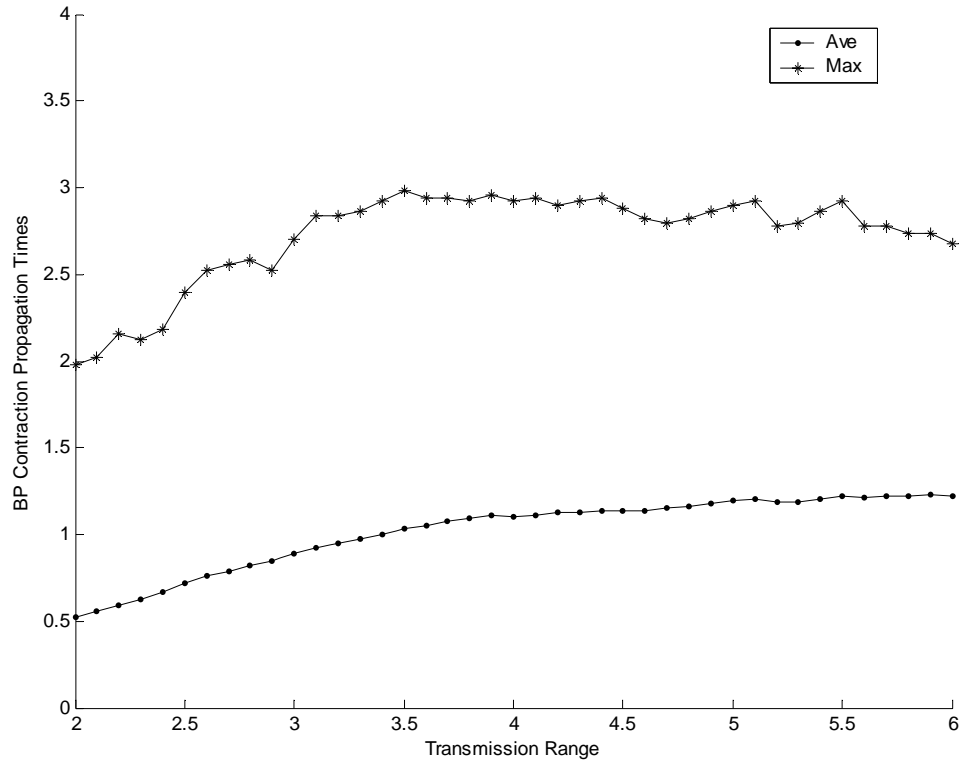


Figure 4.11 Propagation Times Of BP Contraction With 100 Nodes

In the above scenario, 300 nodes are active in our network. In order to see the impact of network density on the BP contraction propagation times, we decrease the amount of nodes to 200, and Figure 4.10 illustrates similar trend as it is with 300 nodes in the network. And we can see that the maximum propagation times is always less than 4. Average propagation times is always around 1, and has little difference from Figure 4.11. However, when the amount of nodes comes to 100, the trend of maximum propagation times becomes different from what we have for 200 and 300 nodes in the

network. Maximum propagation times is also increasing with the transmission range increasing. In a low density network, the increasing of transmission range has little influence on the decreasing of the total amount of clusters of neighborhood, in another word, the impact of the decreasing of neighborhood clusters cannot be significant enough to exceed the impact of increasing of clusters which get connected.

CHAPTER 5

CONCLUSION

In this thesis, we evaluate the performance of BP contraction mechanism in WiMedia, and carry out different scenarios of simulation in dynamic networks. From our results, we can see that BP contraction mechanism has a very good performance in dynamic network, in which it can halve the BP length in a network without using BP contraction mechanism. And devices' ordering has little impact on the performance of BP contraction, which is shown to be that the variance of BP lengths in different network topologies is always less than 20% in our simulation. At last we evaluate the propagation times of the BP contraction, and it shows up that in our network BP contraction can always terminate within four times, which means a dynamic network can become stable within a short time by using BP contraction mechanism. In high density network, the maximum propagation times of BP contraction will decrease with the transmission range increasing, however, in low density network, the maximum propagation times of BP contraction will increase with the transmission range increasing. For average propagation times of BP contraction, it is always increasing with the transmission range increasing in any network with different density.

Above all, BP contraction mechanism adopted in the WiMedia MAC has a very stable performance on dynamic wireless networks, and also can efficiently save the time slots for data transmission.

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BIOGRAPHICAL INFORMATION

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