利用可動態轉向之有向性天線改善IEEE 802.16(d)網狀網路之效能

Using Steerable Directional Antennas to Improve the Performances of IEEE 802.16(d) Mesh Networks

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摘要

IEEE 802.16(d)網狀網路很有希望成爲下一代的無線骨幹網路，在該網路中的節點皆須配備一隻全向性天線（或是由多隻有向性天線所構成的天線陣列）來送收無線訊號。在此網路下，有效發揮有向性天線空間重複利用的特性將會是一個很大的挑戰。

在本篇論文中，相對於原本使用多隻有向性天線所構成的天線陣列去模仿全向性天線的功能，我們提出了一個全新的設計，使得每個網路節點只須配備一隻可動態轉向的有向性天線，我們的設計可以更佳的發揮有向性天線的優勢並且大量減少網路部署的成本。

由我們在媒體存取控制（Media Access Control）層的模擬結果，可以觀察到我們的設計有效的提升可使用之控制頻寬的利用率。另一方面，應用程式所能得到的傳輸流量顯示，我們的設計可以提升整體網路TCP傳輸流量7.506倍以及UDP傳輸流量2.436倍。

關鍵字：有向性天線、網狀網路、無線都會區域網路、IEEE 802.16、WiMAX。

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ABSTRACT

The IEEE 802.16(d) mesh network is a promising next-generation wireless backbone network. This network requires that all network nodes should be equipped with an omni-directional antenna (or an directional antenna array emulating it). Exploiting the spatial reuse property of directional antennas in such networks is a great challenge.

In this thesis, instead of collocating directional antennas to emulate omni-directional antennas, we propose a novel design using only one steerable directional antenna for each node. Our design can better exploit the advantages of directional antennas and greatly reduce the deployment cost of the network.

Our MAC-layer simulation results show that our design significantly increases the utilization of the control-plane bandwidth. The application throughput results show that our design can increase the aggregate TCP throughputs by a factor of 7.506 and the aggregate UDP throughputs by a factor of 2.436, respectively.

Keywords: directional antenna, mesh network, wireless metropolitan area networks, IEEE 802.16, WiMAX.

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最後要感謝我的父母以及一直伴隨我的人，你們總是能在各方面無條件地支持我關心我鼓勵我，讓我無需擔心生活上的問題，並且在我心情低落時不厭其煩地聆聽我的抱怨，在我煩惱時不間斷的給我鼓勵，讓我能一直努力至今天。

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Chapter 1

Introduction

The IEEE 802.16(d) standard (WiMAX) [5] is a promising candidate for next-generation wireless broadband technology. In this standard, two operational modes are defined. One is the point-to-multipoint (PMP) mode, which provides one-hop communications between a base station and several subscriber stations. The other is the mesh mode, which supports multi-hop and peer-to-peer communications. Using the mesh mode, subscriber stations can directly communicate with each other without the aid of the base station.

The directional antenna technology features the well-known spatial reuse property for wireless signal. It can increase network capacity and data transmission concurrency. The IEEE 802.16(d) standard has defined the adaptive antenna system (AAS) for error resilience and transmission concurrency in the PMP mode. AAS exploits a set of directional sector antennas to form an antenna array. In contrast, the mesh mode is defined based on the omni-directional-antenna assumption and operates using broadcast control messages. To emulate the broadcasting function of an omni-directional antenna, the standard allows collocating sector antennas to emulate an omni-directional antenna for each network node. In such a way, however, the spatial reuse property of directional antennas cannot be exploited in the mesh mode and therefore network capacity cannot be substantially increased.

In this thesis, we propose a novel design to better exploit the advantages of directional antennas for the IEEE 802.16 mesh network. The proposed design is based on the mesh distributed coordinated scheduling (MSH-DSCH) mode and only requires that each network node be only equipped with a steerable directional antenna. This design employs our proposed innovative management processes, which are extended from the original standard, to eliminate the need of emulating control message broadcasting.

Such a novel design has two advantages. First, compared with the sector antenna array design, the deployment cost of our design can be much reduced because using our design each network node is equipped with only one directional antenna. Second, the spatial reuse property can be efficiently exploited. Thus, the capacity and data transmission concurrency of a network can be much increased.

To the best of our knowledge, in the literature no papers have studied how to use steerable directional antennas for IEEE 802.16(d) mesh networks. As such, our thesis has two contributions. First, this thesis is the first paper proposing a novel design to make the steerable-directional-antenna system feasible in an IEEE 802.16(d) mesh network. Second, the proposed design can much increase network capacity and data transmission concurrency for the IEEE 802.16(d) mesh network.

The rest of this thesis is organized as follows. In Chapter 3, an overview of the IEEE 802.16 mesh network are introduced. The preliminary fundamentals and related work are also presented. In Chapter 4, we elaborate on our proposed design. In Chapter 5, we compare the performances of the IEEE 802.16(d) mesh networks using our design and the original omni-directional-antenna design. In Chapter 6, advanced issues and improvements for our design are addressed. Finally, in Chapter 7 we conclude this thesis.

Chapter 2

Related Work

In recent years, using directional antennas to increase capacity and spatial reuse of wireless networks has been extensively studied. However, most of previous studies are based on IEEE 802.11(b) networks. These papers deal with issues of using directional antennas in a CSMA/CA based networks, such as neighboring node discovery, antenna orientation, and routing. To the best of our knowledge, our work is the first paper studying issues of using steerable directional antennas in IEEE 802.16(d) mesh networks.

In [4], the authors propose a new network architecture with multi-channel multi-sector directional antennas (MCMSDA WLAN). Based on the proposed architecture, they also propose a Lagrangian Relaxation based algorithm for balancing loads in the vicinity of several neighboring access points. This work deals with the load-balancing problem for links in an IEEE 802.11(b) WLAN; thus, the scope of this paper is far from that of ours.

In contrast to WLANs, using directional antennas in ad hoc networks is much more challenging, requiring additional mechanisms to discover potential neighboring nodes and coordinate antenna orientation. In addition to these two essential problem, “deafness” is another problem that greatly decrease the performance gain when using directional antennas. [19],[2], [9], [6], [7], [13], and [14] propose modifications to the IEEE 802.11(b) MAC protocol to address the above issues. These variants of the IEEE 802.11(b) MAC standard are CSMA/CA based protocols and, therefore, much differ from our work, which aims to using directional antennas in IEEE 802.16(d) mesh networks.

In [19], the authors modify the original IEEE 802.11(b) virtual carrier sensing mechanism that utilizes the RTS and CTS control messages. They present a directional virtual carrier sensing mechanism (DVCS), in which MAC frames (RTS, CTS, DATA, and ACK frames) are directionally transmitted. The DVCS mechanism records the angle-of-arrival information of incoming packets sent by neighboring nodes to optimally adjust the orientation of antennas when transmitting packets back to those nodes.

The DVCS mechanism also modifies the network allocation vector control message (NAV message), defined by the IEEE 802.11(b) standard, to be a directional-antenna-version variant (DNAV message). The NAV message is used to inform neighboring nodes of a duration of forthcoming packet transmission, during which nodes other than the transmitting node should suspend their packet transmission to avoid packet collisions. The NAV message is designed to be omni-directionally transmitted while the DNAV message can be directionally transmitted. As a result, the DNAV message can reduce the number of neighboring nodes that should suspend their data transmission, as compared with the NAV message, therefore increasing the spatial reuse level of a network.

[7] proposes a modified IEEE 802.11(b) MAC protocol, named directional MAC (DMAC). This version of DMAC comprises two schemes. Using the first scheme, a transmitting node transmits RTS messages directionally (DRTS) to the intended receiving node. On receiving the DRTS message, the receiving node should omni-directionally send a CTS message to notify its neighboring nodes of the forthcoming packet reception, if the channel is clear for packet reception. Using the second scheme, a transmitting node can send RTS messages either directionally or omni-directionally depending on two rules. (1) if any antennas of the transmitting node and its neighboring nodes are suspended due to the CSMA/CA mechanism (for example, one neighboring node is going to transmit or receive packets.), this transmitting node should directionally send its RTS message to the intended re-

ceiving node. (2) In other cases, the transmitting node should omni-diretionally transmit its RTS message. The use of DRTS increases the spatial reuse degree of a wireless network and thus increases the capacity of the network.

In [2] and [14], Choudhury et al. propose another version of directional MAC protocol for exploiting the advantages of using directional antennas in IEEE 802.11(b) networks. This version of DMAC directionally transmits all types of MAC frames to increase spatial reuse of an IEEE 802.11(b) network and allows a multi-hop RTS operation to establish multi-hop links between distant nodes (The DMAC with multi-hop RTS operation is referred to as MMAC in [2].). Using the multi-hop RTS operation, a transmitting node can initiate a multi-hop RTS frame destined to a node several hops away from it. This multi-hop RTS frame can be relayed by intermediate nodes and set up a direct packet transmission from the transmitting node to the receiving node. As a result, MMAC can reduce the number of packet transmissions for multi-hop links, as compared to DMAC.

On the other hand, to solve the deafness problem, for each transmission pair (a transmitting and a receiving nodes), [7] categorizes other transmission pair into two types: related and unrelated traffic to it. Related traffic is defined as the set of transmission pairs that may interfere with each other. In the MAC protocol proposed in [7], a transmitting node of a transmission pair should adjust its antenna beamwidth to cover nodes that are proceeding data packet transmission/reception. In such a design, nodes belonging to the same related traffic set can be aware of data packet transmission/reception that may interfere with their own traffic. As such, data packet collisions can be avoided with the original CSMA/CA MAC mechanism.

Choudhury and Vaidya propose a tone-based MAC protocol (ToneMAC) to solve the deafness problem in [13]. Besides the original CSMA/CA protocol, ToneMAC uses an additional out-of-band tone signal to help network nodes differentiate transmission failures due to collisions from those due to deafness. Using ToneMAC, RTS, CTS, DATA, and ACK frames are transmitted directionally to exploit the spatial reuse advantage of directional antennas. Besides, a receiving node should omni-directionally transmit an out-of-band tone signal after it sends an ACK frame out and, similarly, a transmitting node should omni-directionally transmit the tone signal after it receives an ACK frame acknowledging the DATA frame it has transmitted. For nodes neighboring to transmitting and receiving nodes, they can tell MAC frame collisions from the node deafness condition. If they receive tone signals from its intended receiving node, they will know that the intended receiving node pointed its antenna to another direction for data transmission/reception, thus causing a deafness condition.

In [9], Ramanathan et al. summarize issues of using directional antennas in IEEE 802.11(b) networks for the data link layer, MAC layer, and routing protocol. They also propose a generic frame for neighboring node discovery and power control in [9].

Regarding routing protocol for directiona-antenna networks, [12] proposes a new CSMA/CA based MAC protocol with the aid of topology and packet transmission information. Before starting data frame transmission/reception directionally, each transmitting/receiving node should omni-directionally transmit RTS/CTS frames to help its neighboring nodes keep track of the information of topology and on-going communication pair. Such a MAC protocol design enables use of antenna-pattern-aware routing protocol for better load-balancing, as compared to previously proposed routing protocols. [12] also proposes such a antenna-pattern-aware protocol to find routing paths that can minimize the interference with other communication pairs, thereby effectively balancing network loads over all network nodes.

Besides proposing modifications and enhancements to the IEEE 802.11(b) MAC protocol, several works have proposed alternative MAC protocols for wireless ad hoc networks. In [15], the authors present a slotted-aloha-based MAC protocol with adaptive array smart antennas. The performance evaluation is carried out in both analytical and simulation approaches. The performances of the proposed slotted-aloha protocol are studied using varied number of antenna elements and network loads in terms of throughputs and packet delay. Performance comparison between the proposed protocol and the original IEEE 802.11(b) is also given in this work.

In [10], Raman and Chebrolu design and implement the 2P MAC protocol to replace the existent IEEE 802.11 CSMA/CA protocol in the context of wireless mesh networks. The 2P MAC protocol uses a token-based approach to coordinate network nodes' transmission and reception. With the aid of expiration timers, 2P is capable of synchronizing network nodes for successful packet transmission and reception. The authors build a real-world testbed to compare the performances of the 2P and CSMA/CA protocols in terms of UDP and TCP throughputs. The experiment results show that 2P outperforms the CSMA/CA protocol regarding application throughputs.

In [8], Navda et al. design and implement a beam steering framework using steerable directional antennas (MobiSteer) to improve performances of IEEE 802.11 links between a moving vehicle and roadside access points. The results of field trials show that the link quality (in terms of SNR value) obtained by MobiSteer is better than the network using omni-directional antennas.

Instead of designing or implementing new MAC protocols for directional antennas, [11] and [18] evaluate the performance of existing antenna technologies and protocols. In [11], Ramanathan compares the performances of steerable antennas and switched antennas using antenna patterns. Simulations with a realistic radio and propagation model were conducted to study maximum achievable throughputs and delays of networks using these two antennas with varied gains and node density. In [18], Ueda et al. built a real-world testbed for evaluating wireless ad hoc network with smart antennas. They realized and evaluated a spatial division multiple access (SDMA) protocol, which periodically collects the direction and signal level of neighboring nodes, stores them into an angle-signal-table (AST), and determines the used antenna pattern according to the information of AST.

Most of the literature is based on IEEE 802.11(b) CSMA/CA protocol. [1] is one of few papers discussing the IEEE 802.16(d) mesh network using directional antennas. The authors assume that each network node is equipped with directional antennas and propose an integer programming approach to minimize the deployment cost of an IEEE 802.16-based backhaul network. However, this paper does not consider the coordination overhead of control message transmissions, when using directional antenna in IEEE 802.16(d) mesh networks. Such coordination of control message transmission is essential to solve the deafness problem. The reason is that the IEEE 802.16(d) mesh network is a coordinated network; thus, each node can compute the transmission timing of its neighboring nodes. With the aid of this information, a receiving node can point its antenna to the intended transmitting node at the correct timing. Nonetheless, the IEEE 802.16(d) mesh-mode MAC protocol coordinates control message transmissions with the assumption of the broadcasting nature of wireless signal. As such, adapting the original IEEE 802.16(d) mesh-mode MAC in the context of directional antennas becomes a challenging issue. Unlike [1], our work aims to solve MAC protocol issues for using directional antennas in IEEE 802.16(d) mesh networks.

Differing from the previous work, our work does not enhance the CSMA/CA based MAC protocol. The IEEE 802.16(d) mesh network employing a novel distributed election-based algorithm, and thus using directional antennas for such networks should use quite different techniques to solve the issues mentioned previously. To best of our knowledge, our paper is the first work employing steerable directional antenna for the IEEE 802.16(d) mesh mode. We design an enhanced version of the distributed election algorithm to solve the contention of control message transmissions and the deafness problem, when adopting directional antennas in the IEEE 802.16(d) networks. To initialize such an IEEE 802.16(d) mesh directional network, we also propose a hash-function-based scheme to perform neighboring node discovery and initial synchronization.

Chapter 3

Background

In this chapter, we first take an overview of the IEEE 802.16(d) mesh network. Second, the effect of the holdoff time value will be discussed. Lastly, we will introduce some works relative to using directional antennas in the IEEE 802.16 network.

3.1 Overview of IEEE 802.16(d) Mesh Networks

The IEEE 802.16(d) standard[5] defines an air interface of fixed broadband wireless access (BWA) system specifications providing high network throughput and low packet loss rate broadband communications. The BWA system uses the median based on the single-carrier modulation in the 10-66 GHz licensed bands or the orthogonal frequency division multiplexing (OFDM) in frequencies below 11 GHz.

In the reference model of the standard, two protocol layers are defined. First, the median access control (MAC) layer comprises three sublayers, namely the service-specific convergence sublayer, the MAC common part sublayer (MAC CPS), and the security sublayer. Second, the physical layer defines multiple specifications for different frequency ranges and applications.

The MAC layer of the IEEE 802.16 network supports two operation modes for sharing wireless media. First, the point-to-multipoint (PMP) architecture is designed for one-hop communication between a base station (BS) and multiple subscriber stations (SS). Second, the mesh topology mode is designed for a multi-hop wireless network in which any pair of one-hop distancing SSs (including the BS) can communication with each other. In the mesh mode, the BS has a direct connection to backhaul services for SSs to communication with hosts outside the mesh network.

To avoid data transmission collisions, the IEEE 802.16 mesh mode provides two scheduling modes — the centralized and the distributed modes. The distributed mode is further divided into the coordinated and the uncoordinated scheduling, respectively. In this thesis, the proposed design is dedicated for the distributed coordinated scheduling mesh mode using directional antennas.

3.1.1 Node, Neighbor, Neighborhood, and Extended Neighborhood

A node is a generic term for a BS and a SS in the mesh network. Stations with which a node can directly communicate are called the node's one-hop neighbors or neighbors in brief. Neighbors of a node form a neighborhood and all the neighbors of the nodes in the neighborhood form a extended neighborhood. A node's two-hop neighbors are the nodes in the extended neighborhood excluding one-hop neighbors.

3.1.2 Network Entry

In the mesh network, each SS is called a new node before finishes the network entry procedure. A new node cannot schedule data transmission until it finishes the network entry procedure and becomes a functional node. (The BS is a functional node when the mesh network starts.)

In the network entry procedure, a new node first listens to the mesh network configuration (MSH-NCFG) message in the air. While receiving MSH-NCFG messages, the new node shall maintain a physical neighborhood list according to the information carried in the MSH-NCFG message. The new node then selects a potential sponsoring node from its neighborhood and asks for opening a temporary sponsor channel by sending a mesh network entry (MSH-NENT) message to the sponsoring node. After the sponsoring node opens the sponsor channel, the new node can communication with its sponsoring node by the sponsor channel.

With the sponsor channel, the new node can start the registration procedure by transmitting a registration request (REG-REQ) message to the sponsoring node. When the sponsoring node received a REG-REQ message from the sponsor channel, it tunnels the message by prepending a UDP header and a IP header to the registration node, usually collocated with the BS. Then the registration node shall assign a unique mesh node ID in the same network for the new node and sends a registration response (REG-RSP) message to the sponsoring node. When sponsoring node receives the REG-RSP message from the registration node, it forwards the message to the new node. The new node completes the registration procedure as receiving the REG-RSP message, then it will ask the sponsoring node to close the sponsor channel and finishes the network entry procedure.

3.1.3 Contention Resolution for Transmitting Control Messages

In the distributed coordinated scheduling mode, a functional node periodically broadcasts MSH-NCFG or MSH-DSCH messages to its one-hop neighbors on the transmission opportunity won in the previous contention. A functional node carries its next transmission time and its one-hop neighbors' next transmission time in the control message. When a node received a control message, it can update the neighborhood list, which contains one-hop and two-hop neighbors, with next transmission opportunities carried in the received control message.

In the standard, instead of a precise number, each transmission opportunity carried in the control messages is expressed by a 5-bit *mx* and a 3-bit *exponent* as follows:

$$\begin{aligned} 2^{exponent} \cdot mx < \text{transmission opportunity} \leq 2^{exponent} \cdot (mx+1), \\ \text{where } 0 \leq mx \leq 30,\ 0 \leq exponent \leq 7 \end{aligned} \tag{3.1}$$

A node can derive a transmission interval from mx and $exponent$ unless the mx value is 31. In the case that the mx value is 31, the node shall consider the transmission interval of the corresponding neighbor is unknown.

In the mesh network, a node transmits control messages only on the transmission opportunity won in the mesh election algorithm, which is defined in the standard. The mesh election algorithm uses an eligible nodes list as an input to determine whether a node wins a certain transmission opportunity. The mesh election algorithm can ensures the resultant transmission opportunity is collision free within the extended neighborhood.

A functional node performs the mesh election algorithm to contend for a specific transmission opportunity. First, the functional node has to derive the eligible nodes list from its neighborhood list. If the contended transmission opportunity is in a neighbor's transmission interval, the node should consider the neighbor as a eligible node and add the neighbor into the eligible nodes list.

Additionally, when a node determines the eligibility of a neighbor, it shall consider the neighbor's holdoff time, which will be explained in Section 3.2.1. The neighbor's holdoff time plus $2^{exponent} \cdot mx$ is the earliest subsequent transmission opportunity of the neighbor. A node shall exclude the neighbor from the eligible nodes list when it contends for a transmission opportunity before the neighbor's earliest subsequent transmission opportunity.

3.1.4 Distributed Coordinated Data Transmission Scheduling

Three different types of the information element (IE) can be carried by the MSH-DSCH message for the distributed coordinated data transmission scheduling. Each data transmission is established by exchanging these IEs between a requesting node and a granting node in a three-way handshake procedure. A node can start a data transmission after it completes the three-way handshake procedure. We explain these IEs as follows:

Request IE

It carries the amount of the requesting resource.

Availability IE

It indicates free mini-slot ranges in which the granting node can issue a grant.

Grants IE

It carries the information about a granted mini-slot range if the IE is sent by the granting node. If the IE is sent by the requesting node, it confirms a grant.

The three-way handshake procedure is performed between two nodes for establishing a data transmission. The requesting node first transmits a MSH-DSCH message containing a request IE and one or more availability IEs. When receiving this message, the granting node finds a free mini-slot range, if exists, which is included in the mini-slot range indicated in the received availability IE. If a proper mini-slot range is found, the granting node grants this request by transmitting a grant IE to the requesting node. Lastly, the requesting node sends a MSH-DSCH message including the copy of the received grant IE to confirm the grant.

3.2 Dynamic Holdoff Time Setting

3.2.1 The Holdoff Time in the IEEE 802.16 Mesh Network

In the IEEE 802.16 mesh network, each node determines the next transmission opportunity by the mesh election algorithm introduced in Section 3.1.3. In this election algorithm, a network node cannot contend for the transmission opportunity immediately following the current one. The standard requires it to refrain

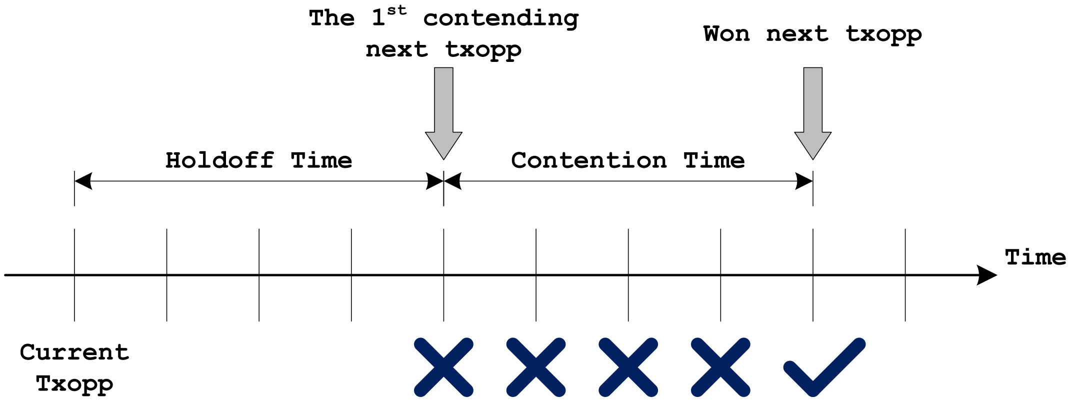


Figure 3.1: The holdoff time before contending for next transmission opportunity.

from contending in a certain number of consecutive transmission opportunities, which is called the holdoff time as shown in Fig 3.1.

$$\begin{aligned} &\text{Holdoff Time} = 2^{exponent+base}, \\ &\text{where } base = 4,\ 0 \leq exponent \leq 7 \end{aligned} \tag{3.2}$$

In the standard, the holdoff time value is defined as Equation (3.2). Although the exponent value can be variant in different networks, all nodes in the same network are required to be consistent in the holdoff time exponent value.

3.2.2 Dynamic Holdoff Time Approach

In [16], authors propose a two-phase holdoff time setting scheme that uses different holdoff time values in its network initialization phase and its data transmission phase. The proposed holdoff time setting scheme ensures success of network initialization. Additionally, two versions of the holdoff time setting scheme in the data transmitting phase are also proposed in the article.

Static Holdoff Time Value Setting

In the static version defined in [16], each node is assigned a different holdoff time based on its two-hop neighborhood node number. A node with a dense extended neighborhood is assigned a larger holdoff time. Contrarily, a node with sparse extended neighborhood is assigned a smaller holdoff time. The improved performance of this static holdoff time assignment approach is shown in the article.

Dynamic Holdoff Time Value Setting

A dynamic holdoff time assignment approach is proposed in [16]. In this approach, a node adjusts its holdoff time according to the bandwidth requirement in time. This approach can effectively decrease roundly half required time of the three-way handshake procedure used for distributed coordinated data scheduling in the mesh network.

Discussion on Holdoff Time Base

In [16], the effect of fixed holdoff time base required by the standard[5] is discussed. The authors propose how to change the holdoff time base without losing standard compliance and explain advantages of setting the holdoff time base to zero.

Chapter 4

Protocol Design

This chapter proposes a protocol design for the IEEE 802.16 mesh mode MAC layer. The protocol aims to provide a comprehensive suite of modifications for using directional antennas in the IEEE 802.16 mesh network. We first define problems of using directional antennas in the mesh network. We then go through the original implementation of standard[3] over the NCTUns platform[17]. In the following, we define some terminologies used in this chapter. Finally, we will describe modifications to each component of the MAC-layer module in detail.

4.1 Difficulty of using Directional-antenna in IEEE 802.16 Mesh Network

In the IEEE 802.16 mesh network, each network node should use the mesh election algorithm mentioned in Section 3.1.3 to determine its control message transmission timing. This algorithm requires a list of eligible contending nodes as an input to determine the wining node for each transmission opportunity. A network node should maintain its extended neighborhood (defined in Section 3.1.1) to derive the eligible contending node list for each transmission opportunity. The maintenance of a node's extended neighborhood relies on periodically exchanging control messages among neighboring nodes. In an omni-directional-antenna network, the control

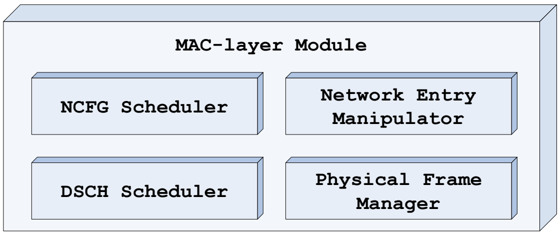


Figure 4.1: Components of the MAC-layer Module

messages transmitted by a network node can be received by its neighboring nodes due to the broadcast nature of wireless radio. But in a directional-antenna network, only neighbors in the coverage of the transmitting node's antenna can receive its control message. The neighbors out of the coverage cannot update its maintained extended neighborhood from the information in the control message sent by the transmitting node. If network nodes do not exchange control messages with their neighbors in time, the contention resolution is likely to fail in a directional-antenna network. The failure of contention resolution will incur the collision of control messages and then the network cannot operate accurately. Even worse, the network cannot be successfully initialized at the beginning. In the following sections we describe how the IEEE 802.16 mesh network works well using directional antennas. Furthermore, it works more efficiently and capably under our design.

4.2 Introduction to the Omni-direction-antenna MAC layer

To clearly explain our modifications to the omni-directional-antenna MAC-layer implementation, we first introduce the essential components of the MAC-layer module in this section.

As shown in Fig 4.1, the MAC-layer module is mainly divided into four components — NCFG scheduler, DSCH scheduler, network entry manager, and physical frame manager. In the following, we explain how these four components are modified to realize a directional-antenna version of the MAC-layer module.

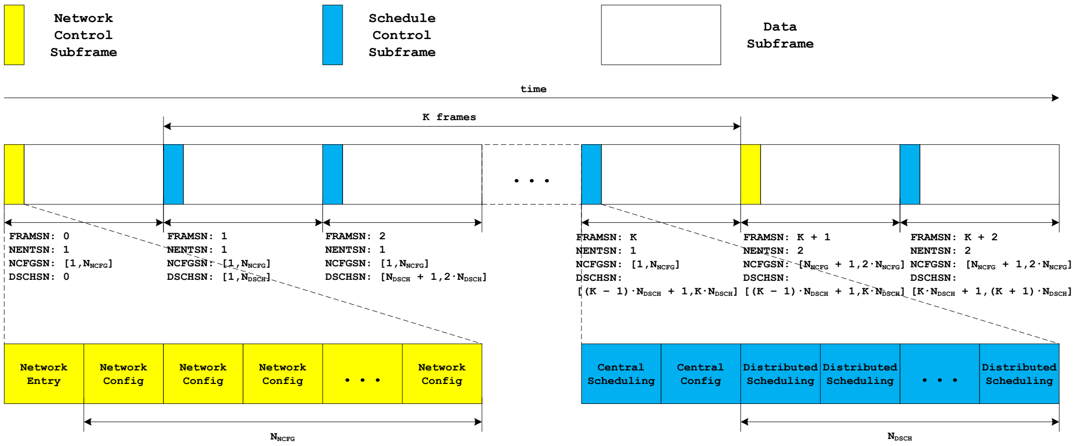


Figure 4.2: Mesh Frame Structure.

Physical Frame Manager

For keeping track of the use of sophisticated mesh mode physical frame, we use an individual component for maintaining physical frame operating states and a variety of sequence numbers (i.e., frame counters).

Fig 4.2 shows the IEEE 802.16 mesh mode frame structure defined in [5]. K is the number of schedule control subframes between two network control subframes. Each network control subframe consists of one network entry and N_{NCFG} network configuration transmission opportunities for MSH-NENT and MSH-NCFG messages sending, respectively. In the same fashion, N_{DSCH} distributed scheduling transmission opportunities are used for sending MSH-DSCH messages. Following the control subframe, the data subframe is divided into mini-slots for data transmission.

Four sequence numbers are maintained in this component:

FRAMSN

Frame sequence number, increased by one for every frame.

NENTSN

Network entry transmission opportunity sequence number, increased by one for every network control subframe.

NCFGSN

Network configuration transmission opportunity sequence number, increased by N_{NCFG} for every network control subframe.

DSCHSN

Distributed scheduling transmission opportunity sequence number, increased by N_{DSCH} for every schedule control subframe.

The MAC-layer module uses these sequence numbers to determine which type of control messages or data should be sent in the current frame.

Network Entry Process Manager

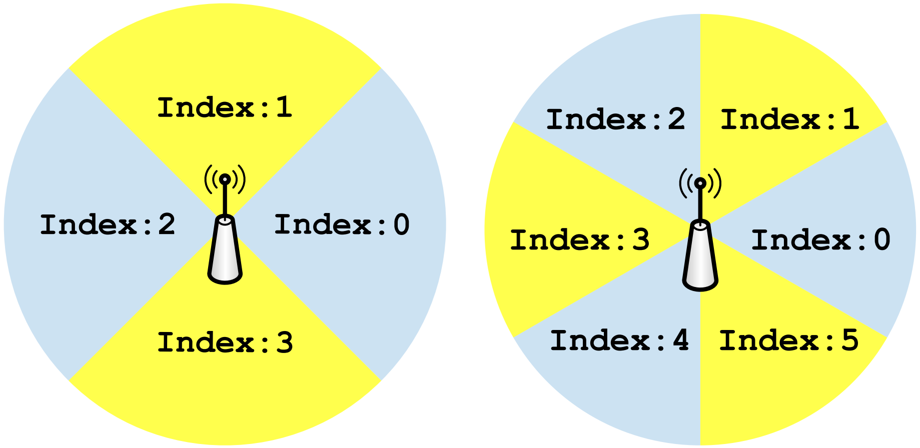
The network entry process manager performs a network-attaching procedures when a new node is attaching itself to the network. Besides, for a functional node its network entry process manager will perform sponsoring procedures to help new nodes attach themselves to the network.

Control Message Schedulers

NCFG and DSCH schedulers are used for scheduling transmissions of MSH-NCFG and MSH-DSCH messages, respectively. A control message schedule determines the next transmission opportunity of the control messages using the mesh election algorithm explained in Section 3.1.3. To this end, it maintains the latest next transmission opportunity and holdoff exponent value of neighboring nodes. When receiving a MSH-NCFG or MSH-DSCH message from a neighboring functional node, the control message scheduler updates the above information which will be used by the mesh election algorithm.

Data Scheduler

The data scheduler manages mini-slot allocation in the data-plane. It maintains the status of each mini-slot allocation, which is defined as a range of mini-slots spanning a certain number of frames. The status of a mini-slot allocation indicates if an allocation is ready to transmit/receive data packets. The data scheduler thus



(a) Antenna beam width $\frac{\pi}{2}$.

(b) Antenna beam width $\frac{\pi}{3}$.

Figure 4.3: Antenna domain definition.

can determine whether a request to a mini-slot allocation can be accepted using the maintained allocation statuses. The scheduler will try to find an available range of mini-slots for the MAC-layer module when it has data to send. Besides, the data scheduler has to record mini-slot allocations used by neighboring nodes to avoid conflicting the schedules of neighboring nodes.

4.3 Directional-antenna Related Terminologies

We define an *antenna domain* as an area covered by a sector antenna. Each domain is given a unique number, called "*domain index*". Fig 4.3 illustrates a node's antenna domains from the geometric view. The rule for indexing such domains, which use antennas with a beam width of radian B, is as follows. A domain i covers angles between $B \cdot \left(i \pm \frac{1}{2}\right) \bmod 2\pi \ \forall\ 0 \leq i \leq \frac{2\pi}{B}$. As Fig 4.3 (b) shows, the four domains are $B \cdot \left(i \pm \frac{1}{2}\right) \bmod 2\pi \ \forall\ 0 \leq i \leq 3$

4.4 Modified Network Entry Process

4.4.1 Issues involved in Using Directional-antenna

In an omni-directional-antenna network, during the initialization stage a new node learns the existence of its neighboring functional nodes by monitoring their MSH-NCFG messages. In a directional-antenna network, however, two undesired issues may arise. One is that a new node cannot start the network entry procedure if it cannot detect any neighboring functional nodes. In a directional-antenna network, a new node cannot predict when and in which direction its neighboring nodes may transmit their MSH-NCFG messages before successfully attaching to this network.

The other issue is that even if a new node has completed the synchronization and selected a proper sponsoring node, it cannot determine when to send its MSH-NENT message because it cannot know when its sponsoring node is ready to receive this message (i.e., point its antenna to cover this new node). Similarly, a functional node cannot predict when or from which direction it can receive a new node's MSH-NENT message. In the following, we explain how to solve these two problems.

4.4.2 Node Selection for Synchronization and Network Entry

As mentioned previously, a new node cannot reliably receive MSH-NCFG messages in a directional antenna network. To solve this problem, a functional node and a new node should determine when and where their antennas must point to each other. To solve this problem, we define the following hash function:

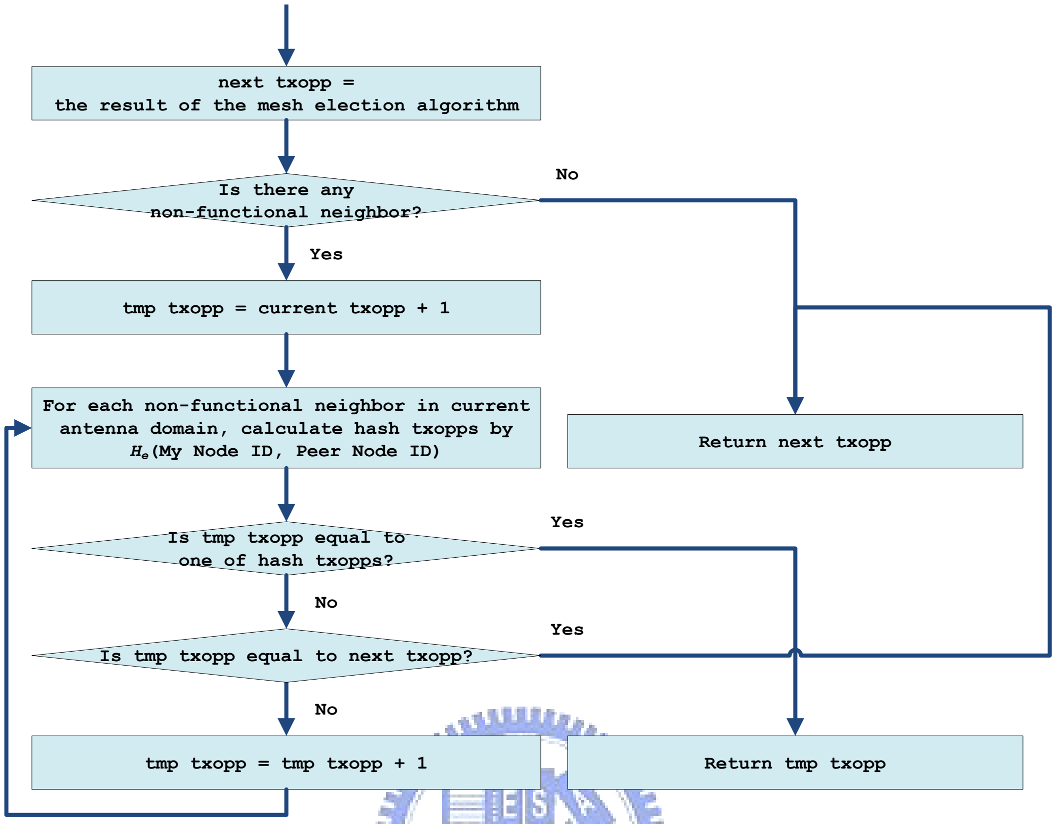


Figure 4.4: The refined mesh election algorithm.

$$
\begin{aligned}
&H_e(n_{Tx}, n_{Rx}) = ((n_{Tx}\ \ \&\ \ N_m) \ll N_{bit}) \mid (n_{Rx}\ \ \&\ \ N_m),\\
&\qquad\qquad \text{where } n_{Tx} \text{ is transmitting node ID}\\
&\qquad\qquad\qquad n_{Rx} \text{ is receiving node ID}\\
&\qquad\qquad\qquad N_m \text{ is a mask value that may be adjusted under different networks.}\\
&\qquad\qquad\qquad N_{bit} \text{ is the number of bits of } N_m
\end{aligned}
\tag{4.1}
$$

The resulted hash value is the **NCFGSN** (defined in Section 4.2) for a functional node to transmit its MSH-NCFG message. The value of N_m may limit the scalability of network. We fix the value of N_m to be ‘0x1f’ in our simulations.

We then refine the original mesh election algorithm with Equation (4.1), which is shown in Fig 4.4. Each functional node uses this refined mesh election algorithm to determine its next transmission opportunity.

Similarly, a new node can use the hash function to know when its neighboring function node will transmit MSH-NCFG messages to itself. Different from the functional node, the new node just uses the hash function to predict the transmission timing of its neighboring functional nodes' control messages, instead of deriving its control message transmission timing.

4.4.3 Antenna Orientation for MSH-NENT message Transmission

In a directional-antenna network, antenna orientation is key to the success of network operation. For a pair of a sending and receiving nodes, they should point their antennas to each other at the same time to correctly transmit/receive their control messages. Moreover, a sponsoring node and a new node should know the transmission timing of their control messages. Otherwise, the new node cannot proceed its network entry process. To achieve this, we design two hash functions, one of which is for sponsoring nodes and the other is for new nodes.

$$H_f(t) = t \bmod N, \text{where } N \text{ is the number of domains} \tag{4.2}$$

$$\text{where } t \text{ is the current } \mathbf{NENTSN} \text{ of a functional node}$$

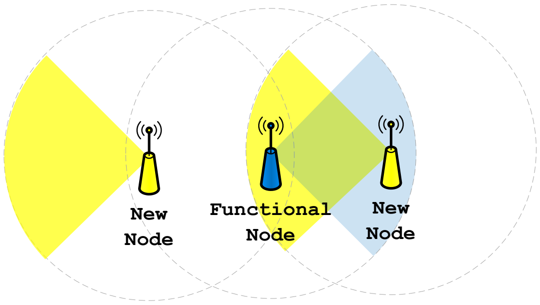
$$H_n(t) = \begin{cases} B_H + \pi & 0 \le B_H < \pi \\ B_H - \pi & \pi \le B_H < 2\pi \end{cases} \tag{4.3}$$

$$\text{where } B_H = B \cdot H_f(t)$$

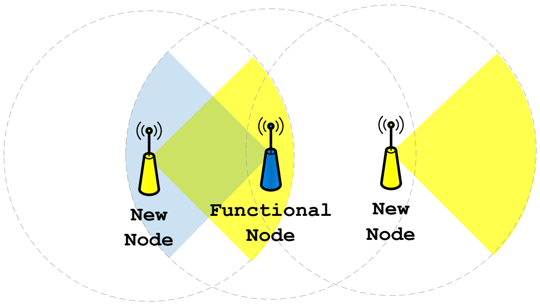
$$B \text{ is the antenna beam width}$$

$$t \text{ is the current } \mathbf{NENTSN} \text{ of a new node}$$

After a new node synchronizes with a neighboring functional node, the **NENTSN** will be consistent with the network. (i.e., the **NENTSN** of the new node will be the same as all functional nodes in this network) In the beginning, all functional



(a) Case $N = 4, t = kN$



(b) Case $N = 4, t = kN + 2$

Figure 4.5: Antennae orientation for MSH-NENT transmission.

nodes use Equation (4.2) to derive the MSH-NENT message transmission timing of new nodes. Similarly, new nodes use Equation (4.3) to know the orientation of their antennas at any time.

With such a design, each new node can exchange control messages with its sponsor node every N MSH-NENT transmission opportunities and thus proceed its network entry process. Fig 4.5 (a) shows a cases with $N = 4, t = kN$ and Fig 4.5 (b) shows a case with $kN + 2$ where $k \in \mathbb{N}$.

4.5 Modified Contention Resolution for Control Messages

4.5.1 Issues of using Directional-antenna

Functional nodes in an IEEE 802.16 mesh network requires periodically transmitting MSH-NCFG and MSH-DSCH messages to exchange their collected local information for network maintenance. For example, these two messages contain the holdoff time exponent values and the next transmission opportunities of nodes adjacent to the transmitting node. On receiving such a message, the receiving node should use the received information to update its local neighborhood list. As a functional node is going to transmit a MSH-NCFG or a MSH-DSCH message, it will perform the mesh election algorithm with this updated local neighborhood list as input to determine its next transmission opportunity.

In a network employing directional antennas, however, exchanges of MSH-NCFG and MSH-DSCH messages are possible only when two neighboring nodes' antenna beams can cover each other. In such a condition, updating a node's local neighborhood list is more challenging and difficult. For example, in Fig 4.6 only node B can successfully receive the message transmitted by the sending node. In such a condition, nodes A and C cannot receive the latest next transmission opportunity and holdoff time exponent value of the sending node. This is very likely to result in failed synchronization between the sending node and these two nodes. Even worse, several nodes in the sending node's extended neighborhood (defined in Section 3.1.1) may not obtain the latest scheduling information of the sending node if they update the sending node's scheduling information based on only nodes A and C's control messages.

4.5.2 Antenna Orientation for MSH-NCFG and MSH-DSCH messages Transmission

Consider node C in Fig 4.6. If node C is able to know when the sending node will send its control message, node C can point its antenna to the sending node in time. To achieve this, the sending node has to notify other nodes of its next transmission opportunity precisely.

However, in [5], instead of a precise number, a node's next transmission opportunity is represented by an interval of length 2^{exp} (explained in Section 3.1.3). Therefore, a node cannot know its neighboring nodes' next transmission opportunities accurately. Besides, more than one nodes may transmit their control messages

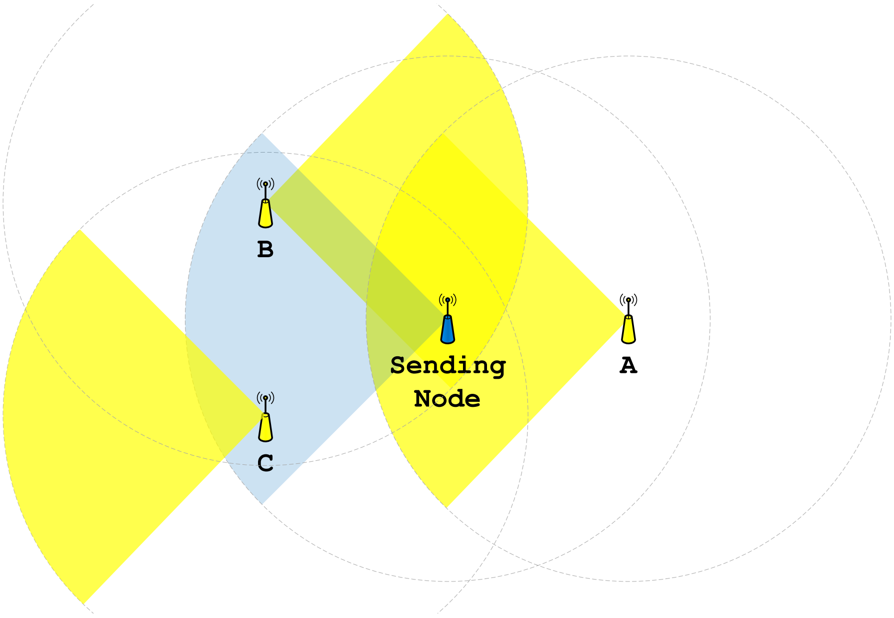


Figure 4.6: Receiving control messages from the sending node is more difficult in directional-antenna networks.

during the same interval. In such a condition, the receiving node should point its antenna to only one of these nodes during the interval and thus will miss control messages transmitted by the other neighboring nodes.

Due to the limit of the current standard, it is impossible to describe the accurate transmission opportunity of a network node using the currently-defined control message format. To solve this problem, we extend the use of the formats of MSH-NCFG and MSH-DSCH messages to carry additional offset information for each node's next transmission interval. Using such a design, a receiving node can obtain the starting transmission opportunity of a transmitting node's next transmission interval and an offset value. As shown in Fig 4.7, the receiving node can then derive the accurate next transmission opportunity of the transmitting node by adding the starting transmission opportunity to the offset value.

While the neighbors' next transmission opportunities are announced exactly, what the receiving node has to do is to turn its antenna to the node using the current transmission opportunity for control message sending.

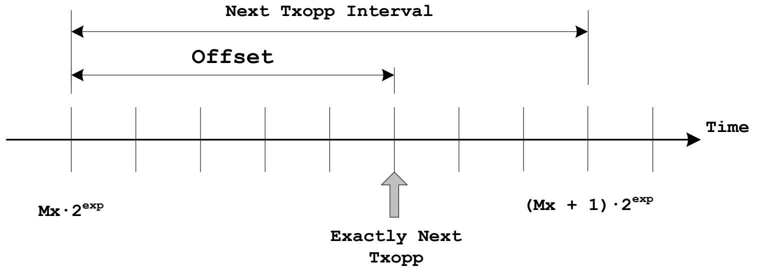


Figure 4.7: The offset used for expressing the transmission opportunity exactly.

4.5.3 Modifications of Control Message Scheduler

To realize the design described in the previous section, some modifications are applied to the control message scheduler in the following sections.

Multiple Next Transmission Opportunities (MNTO) Maintenance

Due to the nature of the directional antenna, it is impossible for a node to broadcast its next transmission opportunity to the nodes in all antenna domains in a transmission opportunity. Nevertheless, the node can tell all nodes in just one antenna domain its next transmission opportunity when its antenna beam covers the whole targeted domain.

For each antenna domain of the transmission node, we maintain an individual next transmission opportunity in the control message scheduler. In other words, the scheduler should maintain N different next transmission opportunities simultaneously in its internal data structure, where N denotes the number of antenna domains of the node.

Directional-antenna version Mesh Election Algorithm (DMEA)

In MNTO scheme, all antenna domains' next transmission opportunities must be pairwisely different. If the control message scheduler uses the original version mesh election algorithm, it may get a next transmission opportunity which was chosen for another antenna domain. Since the mesh election algorithm is a deterministic algorithm, the same result would be yielded if the input of the algorithm is not

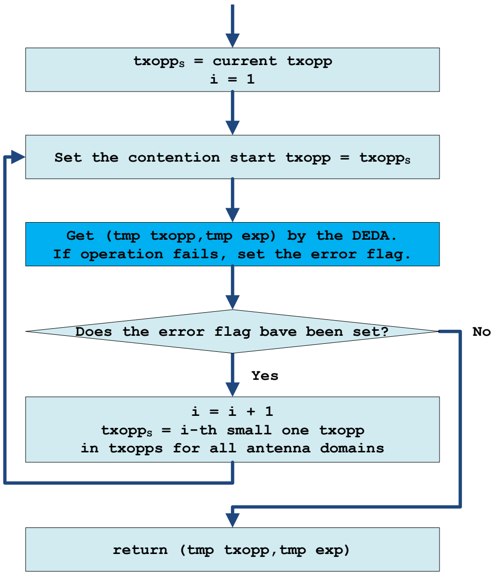


Figure 4.8: Directional-antenna version Mesh Election Algorithm.

changed. To coordinate with the MNTO, we refine the mesh election algorithm as shown in Fig 4.8. We will explain this algorithm more elaborately in the following paragraphs.

Recall in Section 3.1.3, the algorithm by default uses the current transmission opportunity plus holdoff time as the first contending transmission opportunity, which is illustrated in Fig 3.1. If the control message scheduler finds the resultant next transmission opportunity is used by another antenna domain, it changes the first contending transmission opportunity to the second smallest transmission opportunity in all antenna domains. If a duplicated transmission opportunity is obtained, it pushes the first contending point to the third smallest one. In any case, a distinct transmission opportunity will be chosen when using the largest transmission opportunity as the first contending point. Fig 4.9 is helpful to understand this idea.

After the first contending transmission opportunity is settled, we use DEDA to get the next transmission opportunity and holdoff time exponent value. (DEDA will soon be explained in Section 4.5.3) This information are told to the nodes in the current antenna domain. Hence, these nodes can determine when they should turn their antennas back to the sending node again.

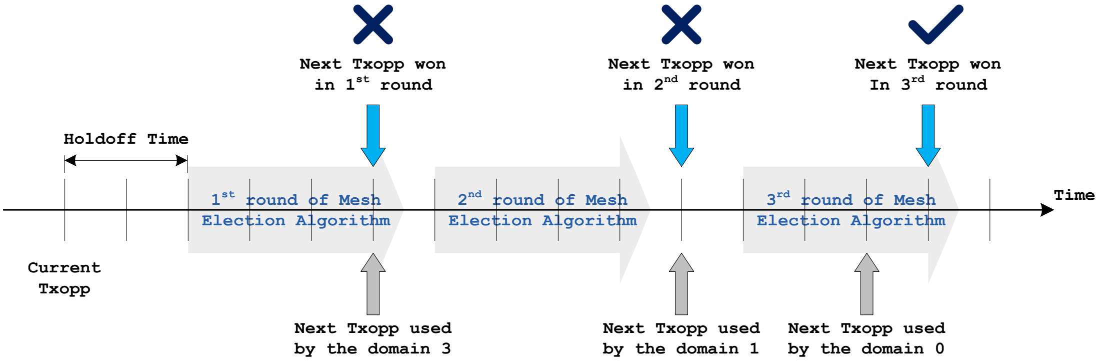


Figure 4.9: Determine the next transmission opportunity for the antenna domain with index 2

In summary, DMEA is used by the control message scheduler before sending a message to one of its antenna domains. The schedule uses DMEA to determine the next transmission opportunity and holdoff time exponent value for the domain in the current antenna direction. This information will be carried to all the receiving node in the domain by embedding it into the control message. Besides, it will be used for updating the next transmission opportunity of this domain in the scheduler's internal data structure.

Dynamic Holdoff Time Exponent Determination Algorithm

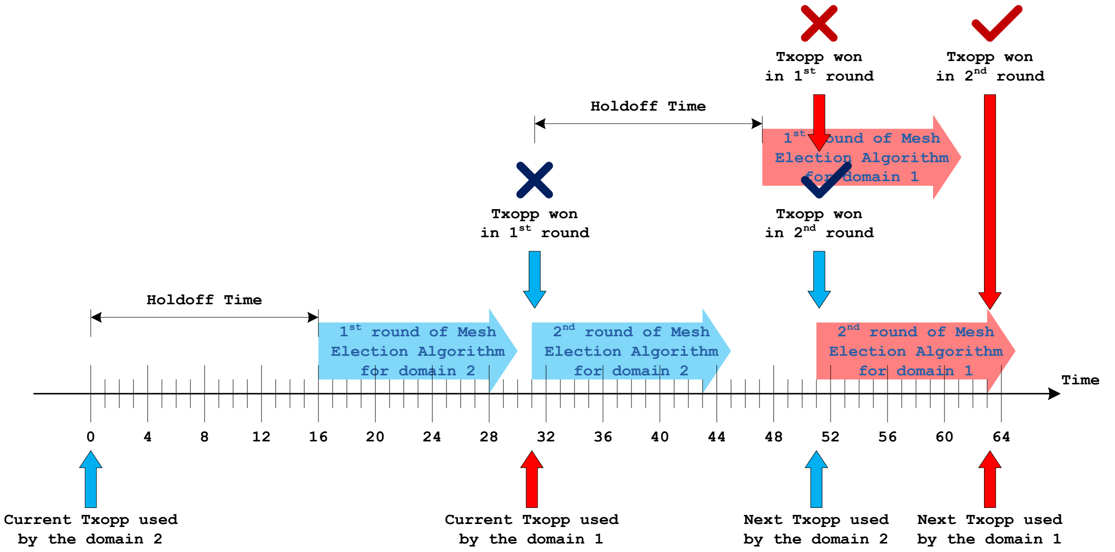
For the sake of the network performance, the directional-antenna network operating is based on the static holdoff time assignment version mentioned in the Section 3.2.2. In such a version, each network node is assigned a fixed holdoff time exponent value individually depending on its neighborhood size. Thus, a network node uses this holdoff time value in DMEA to obtain different next transmission opportunities for all antenna domains.

So far, the directional-antenna based mesh network works well but will not work efficiently under the present design. Compared with the omni-directional-antenna network, a node has to use roundly N times control messages for notifying nodes in all the antenna domain to update the next transmission opportunity of the node (N is the number of antenna domains). The transmitting interval between two control messages for each neighboring node is extended about N times since the control messages are sent to each antenna domain in a round-robin like fashion. This phenomenon increases the delay of three-way handshake using MSH-DSCH messages.

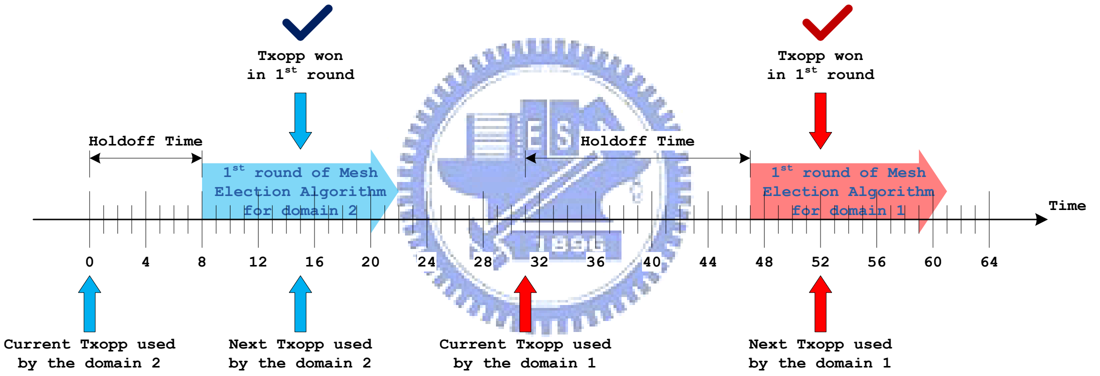
The reason for a lower frequency of sending control message is that a consistent holdoff time is used for all antenna domains of a node. When the holdoff time used in DMEA for determining the current antenna domain's next transmission opportunity is the same as that used for the previous one, it is very likely to obtain the same transmission opportunity by using DMEA with unchanged holdoff time value. Especially, if the neighborhood list has not been updated before determining the next transmission opportunity of another antenna domain, the same transmission opportunity would be always obtained. This is because the neighborhood list is the primary input to the mesh election algorithm (Recall Section 3.1.3).

Fig 4.10 (a) explains this problem more clearly if a static holdoff time value is used in DMEA. A node first tries to get the next transmission opportunity for the antenna domain with index 2. The first round of DMEA fails because it chooses a transmission opportunity used by the antenna domain with index 1. Fortunately, a free transmission opportunity is generated in the second round of DMEA. Sequentially, the node uses two iterations of DMEA to determine the next transmission opportunity for the antenna domain with index 1 since the first chosen transmission opportunity just meets the one which is determined previously for the antenna domain with index 2. In this case, we only consider two antenna domains for simplicity. Actually, it would be worse when more antenna domains exist.

To decrease the probability of resulting the same transmission opportunity using DMEA for different antenna domains, we introduce a dynamic holdoff time scheme. In each DMEA round, instead of using only the preassigned holdoff time exponent value, DMEA changes the holdoff time exponent value if it cannot find a free transmission opportunity by using the previous one. Fig 4.10 (b) shows this idea more clearly. When DMEA detects that a free transmission opportunity cannot be found by using a holdoff time of 16, it changes the holdoff time to 8



(a) Two antenna domains contend the next transmission opportunity using static holdoff time in DMEA



(b) Two antenna domains contend the next transmission opportunity using dynamic holdoff time in DMEA

Figure 4.10: Using different holdoff time values for different antenna domains.

and runs the mesh election algorithm again. In this case, a valid transmission opportunity for the antenna domain with index 2 is found in the first round of DMEA. Moreover, the transmission opportunity is found in the first round of DMEA without changing of the holdoff time.

The algorithm how DMEA changes the holdoff time is called DEDA, which is presented in Fig 4.11. Some details of DEDA are explained below.

First, we define two constants as follows:

$\boldsymbol{\alpha}$ The maximum amount of decreased exponent.

$\boldsymbol{\beta}$ The maximum amount of increased exponent.

The constant α is used for restricting the number of exponent that can be decreased while β is used for restricting the number of exponent that can be increased in DEDA. In other word, if DEDA starts with exponent e, the exponent used by DEDA will not excess $e+\beta$ or less than $e-\alpha$. These two constants should be consistent for all network nodes using DEDA.

Initially, DEDA uses the preassigned holdoff time exponent value explained in Section 3.2.2 as the exponent value when it turns from a new node into a functional node. Subsequently, it uses the previous adopted exponent value of the current antenna domain as the initial exponent value. When sending regular control message, DEDA first adjusts the exponent value increasingly until the exponent value exceeds the defined threshold. If DEDA cannot find an appropriate exponent by increasing the exponent value, it resets the exponent value and adjusts the value decreasingly. DEDA may fail if it is unable to get an proper exponent value which can help the mesh election algorithm to get a transmission opportunity free from overlapping others antenna domains' transmission opportunities. In such a condition, the control message scheduler will resort to DMEA to start the next round.

Exploiting the Information of Three-way Handshake Procedure

Recall that the three-way handshake procedure used for establishing a data schedule requires transmitting three MSH-DSCH messages (Section 4.2). Without considering the dynamic bandwidth needs of nodes, DEDA may choose a large exponent for a node when determining the next transmission opportunity of MSH-DSCH regardless whether the node has data to send. Thus, the delay between two consecutive MSH-DSCH messages for the three-way handshake procedure can be large. This will result in decreased per-hop (as well as end-to-end) data transmission delays and increased per-hop (as well as end-to-end) data transmission throughputs.

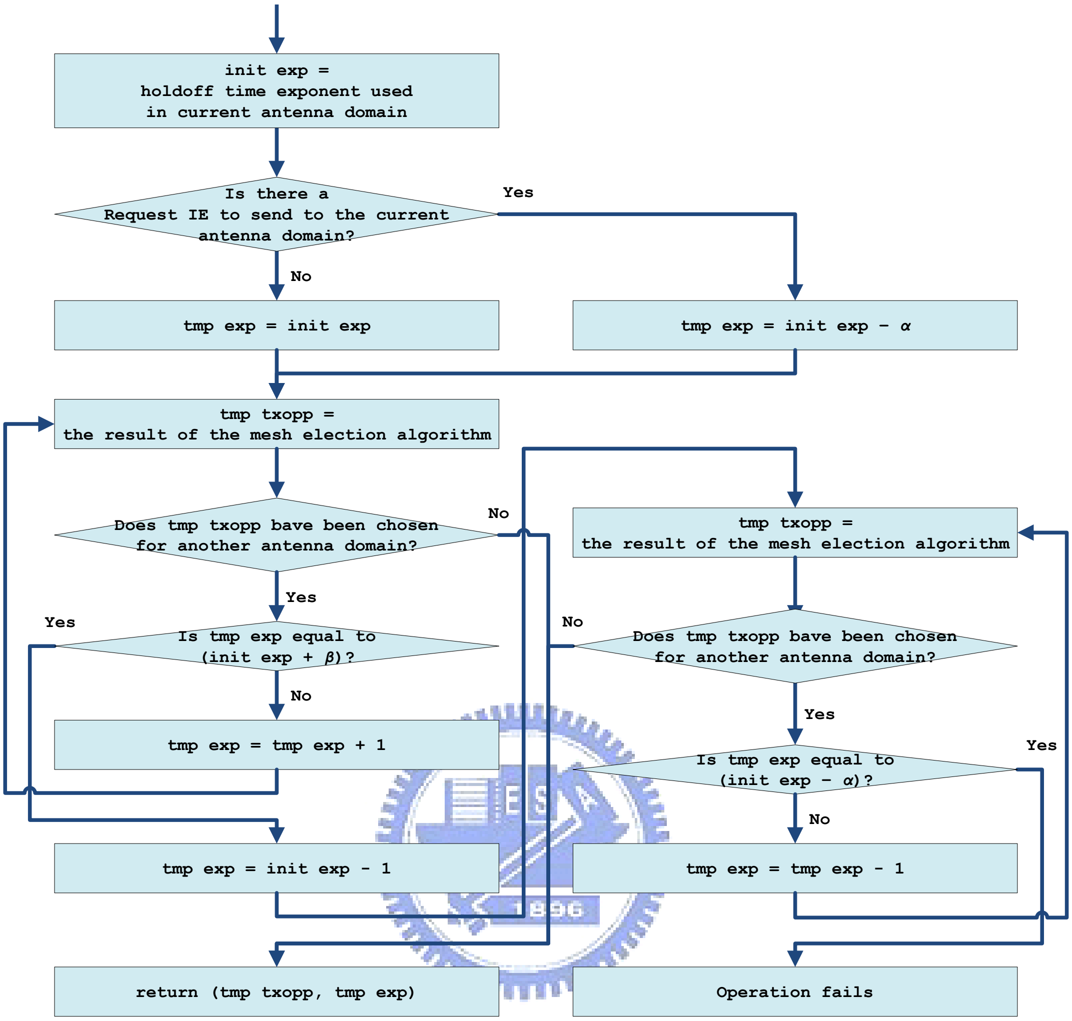
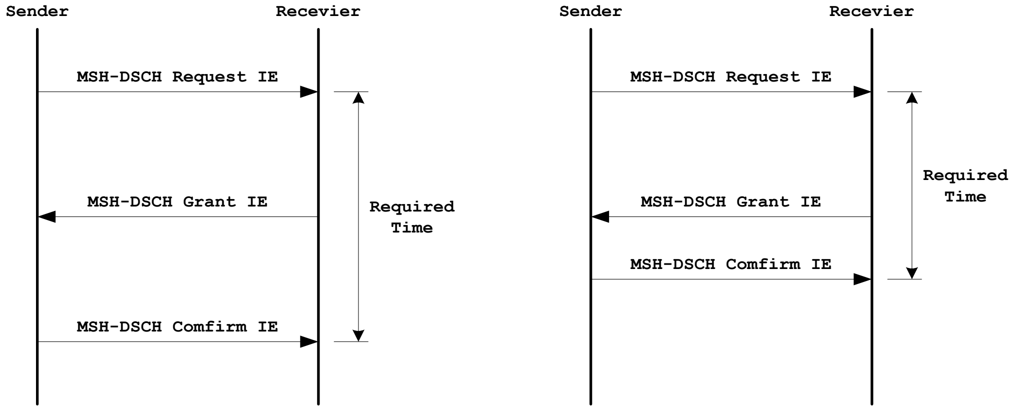


Figure 4.11: Dynamic Holdoff Time Exponent Determination Algorithm



(a) The native version.

(b) The version considers the dynamic bandwidth needs.

Figure 4.12: A comparison between the time required for establishing a data schedule with and without considering dynamic bandwidth needs

Fig 4.12 (a) shows the ordinary three-way handshake procedure. To reduce the required time between transmitting a request IE and transmitting a confirm IE, DEDA uses a larger exponent value for regular control messages sent by the transmitting node to prevent nodes with a lower initial holdoff time exponent value from monopolizing transmission opportunities. On the other hand, DEDA uses $e-\alpha$ as the initial exponent value instead of the previously adopted exponent value if it detects that the node is ready to send a request IE to the nodes in the current antenna domain. With such a detection, a requesting node will mostly transmit a confirm IE as soon as possible after receiving a grant IE as shown in Fig 4.12 (b). DEDA with the capability of exploiting the information of three-way handshake procedure is called DEDA-ITHP in the following sections.

4.5.4 Modified Determination of Eligible Nodes within a Node's Extended Neighborhood

For a specific transmission opportunity, each network node should determine the nodes that are eligible to contend for this transmission opportunity within its extended neighborhood (defined in Section 3.1.1). The eligibility of a contending node is discussed in the following subsections.

Eligibility of One-hop Neighbors

Since the MNTO scheme is used, care should be taken when determining the eligibility of a one-hop neighbor. Consider Fig 4.13, when node A sends a control message to node B, only the next transmission opportunity for the antenna domain containing node B would be told, 5 in this case. As time for node B to choose its next transmission opportunity for node A, while contending for transmission opportunity 5, node B will consider node A as an eligible node. But in the case of 8, node A will not contending with node B since it cannot knows that node B uses this opportunity for another antenna domain. If node A wins transmission opportunity 8 without contending with node B, as the transmission opportunity 8

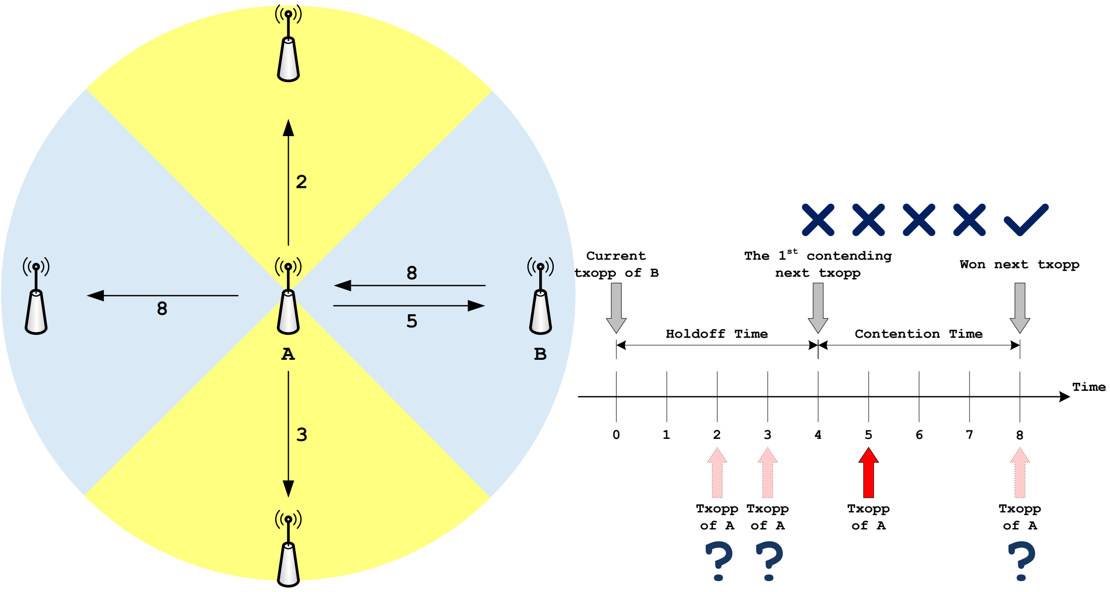


Figure 4.13: Issue in determining the eligibility of a one-hop neighbor.

comes, node B will be confused, since it has no idea of to which antenna domain it should direct its antenna.

To solve this problem, a directional-antenna based network node would always considers that its one-hop neighbors are eligible to contend for its next transmission opportunity. In the case of Fig 4.13, node B has to consider node A as eligible when it contends for transmission opportunities from 4 to 8.

Such a method will slightly affect the utilization of the total transmission opportunities since a node may lose when contending for a transmission opportunity even if there is, actually, no other nodes contending for it. We will propose an advanced solution for this problem in the next section.

Improved One-hop Neighbors Eligibility Determination

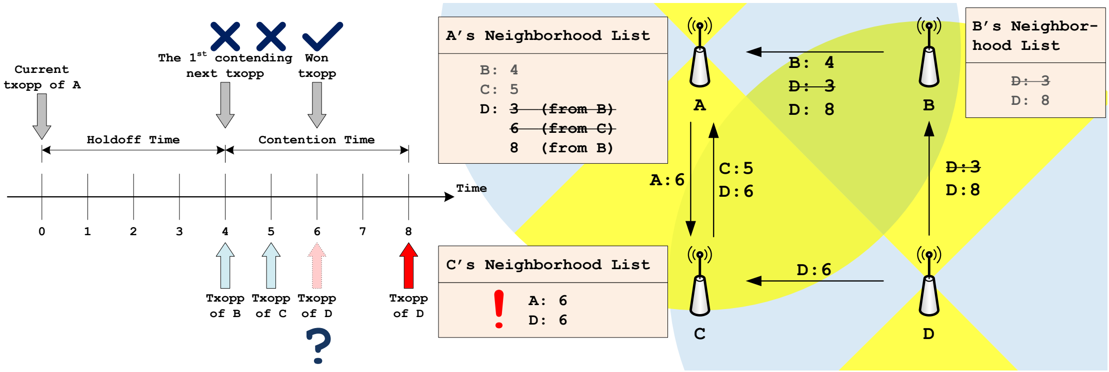
To prevent unnecessary transmission opportunity contentions in the MNTO scheme, we propose an improved eligibility determination for one-hop neighbors. A node has to consider all one-hop neighbors as eligible since it only knows the next transmission opportunity on which its one-hop neighbors transmit to the node. In the improved eligibility determination, each node in the network shall nofigy its one-hop neighbors of its next transmission opportunities for all antenna domains. Using additional information about neighbors' next transmission opportunities, a node can determine whether a one-hop neighbor will contend with it for a certain transmission opportunity. A node thus does not have to contend with all its one-hop neighbors for each transmission opportunity in which it is interested.

In the case of Fig 4.13, node A shall tell node B about all its next transmission opportunities, i.e., 5, 2, 8 and 3, when using the improved eligibility determination for one-hop neighbors. Therefore, node B will consider node A as eligible only when it contends transmission opportunities 5, 2, 8 and 3.

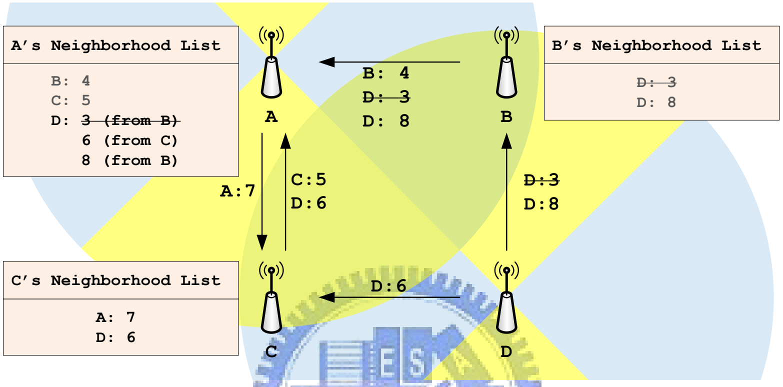
Extended Neighborhood List Maintenance for Two-hop neighbors

The standard[5] requests each node in IEEE 802.16 mesh network to maintain a local physical neighborhood list via receiving the control messages from its one-hop neighbors (More detail described in Section 3.1.1). The next transmission opportunity of each neighbor is stored in this list and updated in time. This information are used for determining eligible nodes in the mesh election algorithm.

Different from the network using omni-directional-antennas, the MNTO scheme is required for all node in the directional-antenna network. Hence, a network node cannot maintain only one next transmission opportunity of each two-hop neighbor. Single next transmission opportunity maintaining is insufficient in selecting correct eligible nodes list from two-hop neighbors. Fig 4.14 (a) shows this insufficiency. In this case, node A wins the transmission opportunity without considering node D eligible because the information told by node C (node D will send messages to me at transmission opportunity 6) is covered by the later received message sent from node B. Node C will be confused if it is told that the transmission opportunity 6 is won by node A while it has thought that node D will send at that transmission opportunity. In the next paragraph, we will show how a node maintains multiple next transmission opportunities of each two-hop neighbor in the directional-antenna network. (The node can still maintain a single next transmission opportunity for each one-hop neighbor. This was discussed in the previous



(a) Without maintaining multiple next transmission opportunities.



(b) With maintaining multiple next transmission opportunities.

Figure 4.14: Multiple next transmission opportunities of the two-hop neighbors.

section)

Consider the scenario shown in Fig 4.14 (b). From node A's perspective, node B and node C are one-hop neighbors and node D is a two-hop neighbor respectively. Over control messages exchanging, under the MNTO scheme, node D tells node B that its next transmission opportunity is 3 while telling node C that it is 6. (Note that, in the omni-directional-antenna network, next transmission opportunity told to node B and node C would be identical.) Owing to the standard requirement, node B and node C would tell node A about their next transmission opportunities (also different when using omni-directional-antenna) and the next transmission opportunities of their one-hop neighbors. (Only node D in this case) When node A receives a control messages from one of its neighbors, it saves the carried next transmission opportunity and records by which neighbor the messages was sent. (3 from node B and 6 from node C) In a while, node A will be notified by node B that the next transmission opportunity of node D is changed from 3 to 8, then node A will update only the entry about node D, which was told by node B, instead of replacing all entries about node D in the neighborhood list.

Under the MNTO scheme, a node has to consider all transmission opportunities of a two-hop neighbor while performing eligibility determination on it. Thus, the collision free property of transmitting control messages can be guaranteed in the directional-antenna-network.

4.6 Modified Data Transmission Time Scheduling

4.6.1 Validity of Allocation in the Omni-direction-antenna Network

Recall from Section 4.2 a mini-slot allocation is defined as a periodical using of mini-slots in the data subframe. A node can use the mini-slot allocation to transmit data to or receive data from a certain neighboring node. This neighboring node will be recorded with the mini-slot allocation in the internal data structure of the data scheduler. To achieve collision free data transmission among the neighborhood, each mini-slot allocation will be carefully judged by the data scheduler before the mini-slot allocation is allowed to use.

The data scheduler manages mini-slot allocations by mapping these mini-slot allocations into four kind of status as follows:

XMIT

The mini-slot allocation is use by the local node to transmit data.

RECV

The mini-slot allocation is use by the local node to receive data.

NBRXMIT

The mini-slot allocation is use by a neighboring node to transmit data to a certain node excluding the local node itself.

NBRRECV

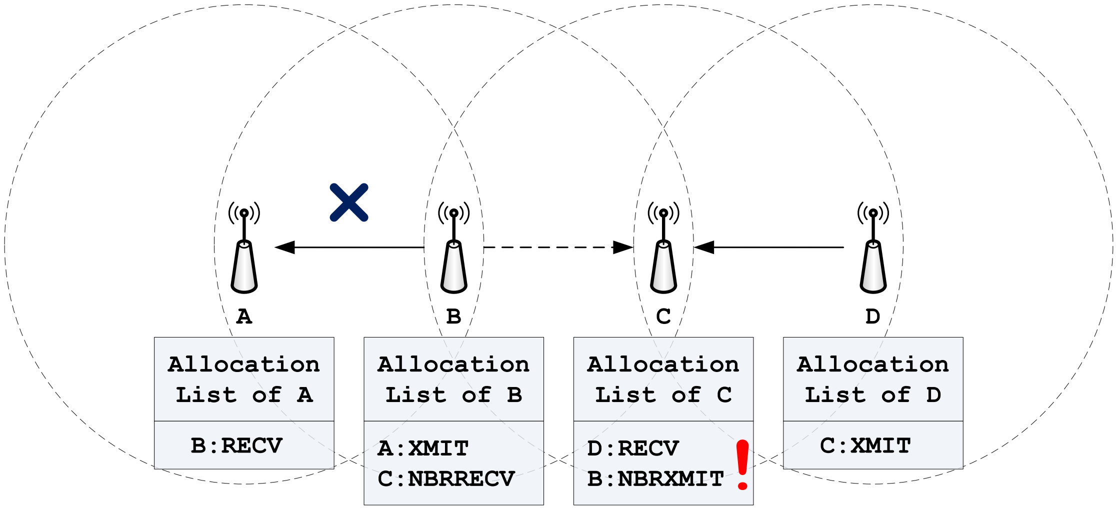
The mini-slot allocation is use by a neighboring node to receive data from a certain node excluding the local node itself.

For a network node, the data scheduler will record a mini-slot allocation with status XMIT or RECV in its mini-slot allocation list if the node use the mini-slot allocation to send or received data. On the other hand, from the received MSH-DSCH messages sent by a neighbor, a node can learn the neighbor's transmitting time or receiving time. If the node is not performing three-way handshake with the neighbor that sent the MSH-DSCH message, the data scheduler of the node will record a mini-slot allocation with status NBRXMIT or NBRRECV. In the following, we present how the data scheduler judges the validity of a mini-slot allocation for transmitting or receiving data.

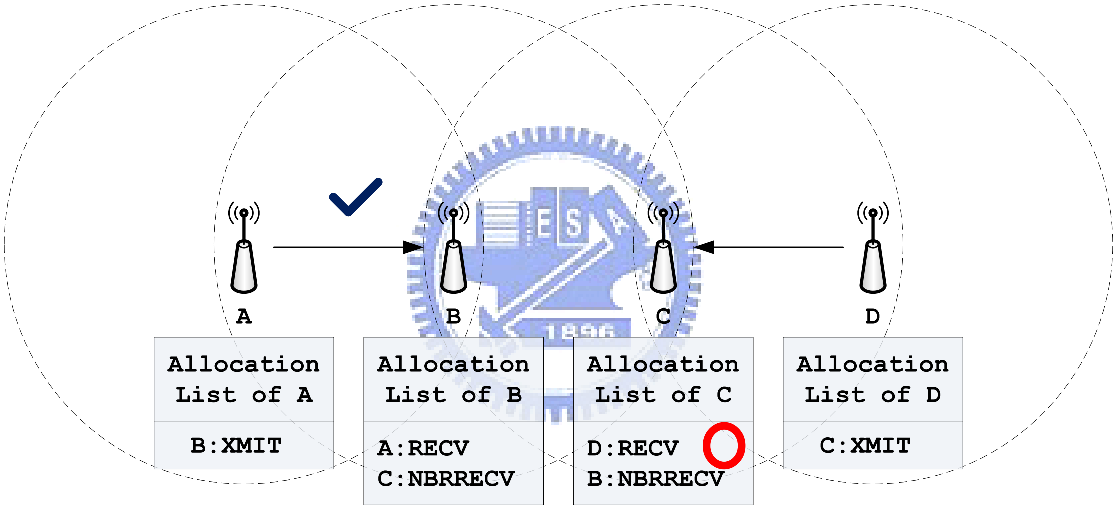
To determine the validity of a mini-slot allocation for transmitting data, the data scheduler has to ensure that the mini-slot allocation does not cover the range of all recorded mini-slot allocations with any status in the mini-slot allocation list. Differently, when determining the validity of a mini-slot allocation for receiving data, the data schedule will not consider recorded mini-slot allocations with status NBRRECV. Therefore, simultaneous data transmissions can be allowed in the extended neighborhood under a specific case. We use Fig 4.15 to explain the determination more clearly in the next paragraph.

In Fig 4.15 (a), on node B's perspective, if the data scheduler allows a mini-slot allocation for data transmission to node A without considering the mini-slot allocation with status 'C:NBRRECV', a collision will happen on node C when receiving the wireless signal from both node B and node D. In such a case, there can be only one data transmission in the extended neighborhood.

In Fig 4.15 (b), if node B requires a mini-slot allocation for receiving, the data scheduler of node B does not consider the mini-slot allocation with status



(a) Collision occurs in a careless scheduling.



(b) Collision free in a fine scheduling.

Figure 4.15: Data scheduling in the omni-directional-antenna network.

'C:NBRRECV'. Since node A's wireless signal will not influence node C while node D's wireless signal will not influence node B, these two data transmissions can take place simultaneously.

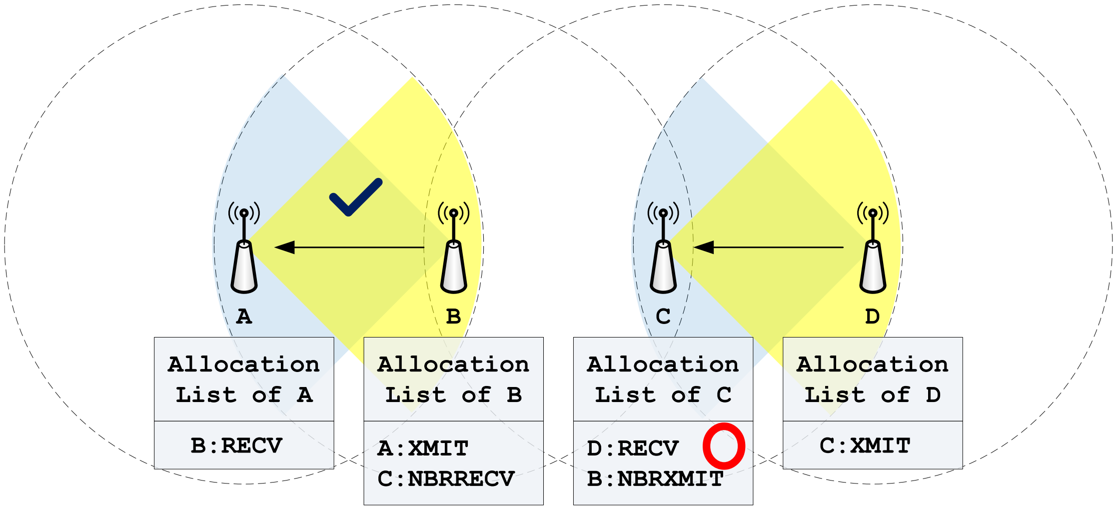
4.6.2 Validity of Allocation in the Directional-antenna Network

In the directional-antenna network, we make some modifications to the mini-slot allocation validity determination of the data scheduler. Using our modifications, the data scheduler can increase the concurrency of data transmission in the directional-antenna network.

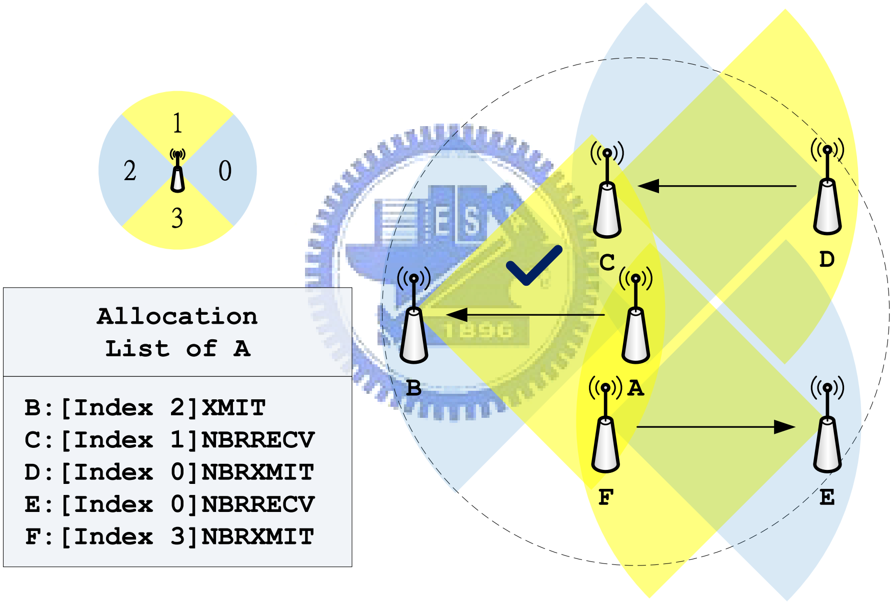
Compare the case in Fig 4.16 (a) with the case in Fig 4.15 (a), in the latter one, node B is allowed to transmit data even if the mini-slot allocation with status ‘C:NBRRECV’ exists in the mini-slot allocation list. The collision will not occur on node C since node C will not in the antenna coverage of the node B at the transmission time. This case demonstrates the simplest simultaneous data transmission which is not allowed in the omni-directional-antenna network.

In the directional-antenna network, the data scheduler uses the antenna domain index, defined in Section 4.3, in the mini-slot allocation validity determination. Thus, each mini-slot allocation is marked with an additional identifier which is the index of the antenna domain containing the neighbor relative to the mini-slot allocation. When the scheduler determines the validity of a mini-slot allocation with status NBRXMIT or NBRRECV, it will only consider the mini-slot allocation with an identifier that is the same as the index of the antenna domain containing the negotiating neighbor.

We explain the above idea by a more sophisticated case shown in Fig 4.16 (b). When node A tries to transmit data to node B, it has to get a mini-slot allocation from the data scheduler. The validity of this mini-slot allocation will be determined by the scheduler before the mini-slot allocation is allowed for the data transmission. The data scheduler first ensures that the mini-slot allocation does not cover the range of each mini-slot allocation with status XMIT or RECV in its mini-slot allocation list. Then, the data scheduler will take care of each mini-slot allocation with status NBRXMIT or NBRRECV. Since node B is in the antenna domain with index 2, only the mini-slot allocation with identifier 2 will be considered by the data scheduler. Such mini-slot allocation does not exist in this case, so the mini-slot allocation will be allowed by the data scheduler to node A to transmitting data to node B. Additionally, we can find that three simultaneous data transmissions are allowed in an extended neighborhood. In the same manner, more simultaneous data transmissions can exist in a more dense



(a) Comparing with using omni-directional-antenna.



(b) More complex case.

Figure 4.16: Data scheduler in the directional-antenna network.

directional-antenna network.

Chapter 5

Performance Evaluation

In this chapter, we use the NCTUns network simulator[17] to evaluate the performances of our proposed design, comparing those of the static version proposed in [16]. The performances of these different networks are evaluated in terms of application throughputs and several MAC-layer performance metrics.

5.1 Simulation Parameters

Holdoff Time Exponent Downward Range Coefficient (α)

Recall the DEDA presented in Section 4.5.3, we use different α values varying from 1 to 6 in simulations to investigate the effects of the α value on performances of directional-antenna networks. When the α value is set to zero, the holdoff time exponent value will be fixed to a static value and will not be adjusted dynamically by DEDA.

Eligible Nodes Determination for One-hop Neighbors

In Section 4.5.4 we propose an improved eligibility determination for a node's one-hop neighboring nodes. A node shall carry the next transmission opportunities of all its antenna domains in MSH-NCFG and MSH-DSCH messages when adopting this improved mechanism. The performance gain of this mechanism is evaluated in the following sections.

DEDA and DEDA-ITHP

Compared with DEDA, DEDA-ITHP can lower holdoff exponent value when nodes establish data schedules. The detailed comparison between DEDA and DEDA-ITHP is discussed in the following sections.

Antenna Beam Coverage

To evaluate the effect of the number of antenna domains, we adopt antennas with beam width $\frac{\pi}{2}$ and beam width $\frac{\pi}{3}$, shown in Fig 4.3.

5.2 MAC-layer Performance

5.2.1 Performance Metrics

The Average Transmission Opportunity Utilization of Nodes (ATOUN)

The utilization of a node's control-plane bandwidth is an important metric used to evaluate the efficiency of DEDA. A node's transmission opportunity utilization is defined as the aggregate transmission opportunity use within a node's extended neighborhood. It indicates how well its extended neighborhood utilize the network's transmission opportunities. The ATOUN metric is the average across all node's transmission opportunity utilization in a network case. The detailed definition of the ATOUN metric is given in [16].

The Average Three-way-Handshake Procedure Time (ATHPT)

The three-way handshake procedure time shows the efficiency of data schedule establishment. The average three-way handshake procedure time metric is defined as the average time required by the three-way handshake procedure to establish a data schedule across all network nodes in a network case. The detailed definition of the ATHPT metric is given in [16].

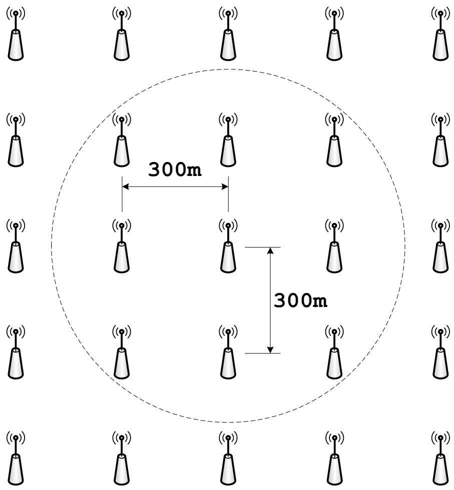


Figure 5.1: The simulation network topology.

The Average Number of Established Data Schedules (ANEDS)

The number of established data schedules (NEDS) of a node, defined by Equation (5.1), is used to measure the achieved spatial reuse degree of a node. We then use Equation (5.2) to compute a network case's ANEDS value, which is the average of all network nodes' NEDS values. ANEDS is important to evaluate the overall spatial reuse degree of a directional-antenna network.

$$NEDS(i) = \sum_{j \in NBR_{1i}} n_{ij} \tag{5.1}$$

where n_{ij} is the number of data schedules established from $Node_i$ to $Node_j$

NBR_{1i} is the set of $Node_i$'s one-hop neighbors

$$ANEDS = \frac{\sum_{i=1}^{N} NEDS(i)}{N} \tag{5.2}$$

where N is the number of nodes in a network case.

5.2.2 Simulation Environment

We use a 5x5 grid network comprising 25 nodes for simulation. As shown in Fig 5.1, each node is spaced 300 meters apart from its vertical and horizontal neighbors.

All nodes except boundary ones have 8 surrounding one-hop neighbors.

To shed light on the performances of our proposed design, we first conduct simulations with all combinations of the parameters listed in Section 5.1, including the α value, antenna beam width, ... As a result, in total 56 different cases are generated using the 5x5 grid network topology. The β value discussed in Section 4.5.3 is fixed to be 7 in all simulation cases. Each simulation case is run five times, each time using a different random number seed.

The simulated time for each run is set to 310 seconds. During simulation, each node starts a MAC-layer pseudo data scheduler at the 150th second to periodically establish data schedules with its neighboring nodes in a round-robin manner. The frequency is chosen to be one data schedule every 100 milliseconds. With this frequency setting, the pseudo data scheduler can generate a heavy traffic load which approaches the maximum control-plane utilization.

5.2.3 Simulation Results

As shown in Table 5.1 and Table 5.2, the ATOUN results show that the directional-antenna network has higher transmission opportunity utilization than the omni-direction-antenna network, if DEDA-ITHP is adopted. The directional-antenna network, however, has larger ATHPT values than omni-direction-antenna networks. There are two reasons for explaining this phenomenon.

First, since our design employs only a steerable directional antenna for a network node, each node is allowed to transmit control messages to one of its antenna domains at a time (i.e., it cannot transmit control messages to multiple beams simultaneously.). As such, one node transmits control messages to all of its antenna domains in a rough round-robin manner. To complete a three-way handshake procedure, a requesting node should transmit two MSH-DSCH messages, one of which carries the request IE and the other carries the confirm IE. Thus, a requesting node typically requires two rounds (a round can be roughly defined as the minimum of the required time for a node to transmit its control messages to all of its antenna domains.) to complete a three-way handshake procedure. In contrast,

Table 5.1: MAC-layer results using antenna with beam width $\frac{\pi}{2}$

(a) With DEDA.

		ATOUN		ATHPT (ms)		ANEDS	
		Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		0.575	0.000	35.275	0.304	366.872	5.873
Using next txopp of the covered beam only	$\alpha = 0$	0.301	0.000	263.967	3.643	521.472	21.429
	$\alpha = 1$	0.376	0.000	219.514	4.338	602.416	22.813
	$\alpha = 2$	0.391	0.000	211.961	3.197	615.024	20.303
	$\alpha = 3$	0.397	0.000	210.843	3.598	613.504	20.669
	$\alpha = 4$	0.400	0.000	210.043	3.323	621.624	17.666
	$\alpha = 5$	0.401	0.000	209.860	3.572	624.568	15.375
	$\alpha = 6$	0.401	0.000	209.119	3.377	624.992	16.423
Using next txopps of all beams	$\alpha = 0$	0.323	0.000	260.384	1.282	551.664	17.337
	$\alpha = 1$	0.377	0.000	219.946	4.113	603.984	19.772
	$\alpha = 2$	0.391	0.000	213.957	0.709	625.656	2.583
	$\alpha = 3$	0.397	0.000	212.887	0.765	631.208	1.978
	$\alpha = 4$	0.400	0.000	212.045	0.918	634.392	10.288
	$\alpha = 5$	0.401	0.000	211.184	0.756	630.384	7.284
	$\alpha = 6$	0.402	0.000	212.229	1.057	629.864	5.150

(b) With DEDA-ITHP.

		ATOUN		ATHPT (ms)		ANEDS	
		Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		0.575	0.000	35.275	0.304	366.872	5.873
Using next txopp of the covered beam only	$\alpha = 0$	0.301	0.000	263.967	3.643	521.472	21.429
	$\alpha = 1$	0.552	0.000	155.311	1.193	744.680	3.436
	$\alpha = 2$	0.617	0.000	142.506	1.120	785.776	1.942
	$\alpha = 3$	0.652	0.001	138.470	0.494	793.312	3.640
	$\alpha = 4$	0.681	0.001	138.712	0.720	807.200	5.448
	$\alpha = 5$	0.701	0.000	136.008	4.477	795.888	38.682
	$\alpha = 6$	0.709	0.001	135.385	6.179	790.096	62.781
Using next txopps of all beams	$\alpha = 0$	0.323	0.000	260.384	1.282	551.664	17.337
	$\alpha = 1$	0.557	0.001	152.286	3.354	730.048	23.838
	$\alpha = 2$	0.621	0.001	141.695	0.895	781.752	6.596
	$\alpha = 3$	0.657	0.000	138.123	0.688	800.464	7.798
	$\alpha = 4$	0.686	0.001	138.187	0.626	802.224	8.980
	$\alpha = 5$	0.705	0.000	137.351	0.927	805.744	9.814
	$\alpha = 6$	0.714	0.001	137.369	0.356	812.912	7.712

Table 5.2: MAC-layer results using antenna with beam width $\frac{\pi}{3}$

(a) With DEDA.

		ATOUN		ATHPT (ms)		ANEDS	
		Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		0.575	0.000	35.275	0.304	366.872	5.873
Using next txopp of the covered beam only	$\alpha = 0$	0.301	0.000	397.102	21.905	384.376	32.487
	$\alpha = 1$	0.512	0.000	243.006	1.004	607.936	5.622
	$\alpha = 2$	0.540	0.000	231.830	0.478	631.560	9.062
	$\alpha = 3$	0.555	0.000	227.656	1.067	630.704	8.988
	$\alpha = 4$	0.567	0.000	225.551	1.210	640.576	5.898
	$\alpha = 5$	0.574	0.000	224.659	1.032	633.312	10.199
	$\alpha = 6$	0.578	0.000	223.063	1.069	635.560	6.080
Using next txopps of all beams	$\alpha = 0$	0.317	0.000	410.736	1.903	409.744	8.867
	$\alpha = 1$	0.513	0.000	242.636	1.212	609.888	9.287
	$\alpha = 2$	0.541	0.000	232.718	1.103	638.120	10.549
	$\alpha = 3$	0.556	0.000	226.700	1.344	629.320	10.470
	$\alpha = 4$	0.568	0.000	225.115	0.568	639.352	3.796
	$\alpha = 5$	0.575	0.000	223.731	0.935	635.200	8.699
	$\alpha = 6$	0.579	0.000	222.394	1.068	632.944	9.892

(b) With DEDA-ITHP.

		ATOUN		ATHPT (ms)		ANEDS	
		Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		0.575	0.000	35.275	0.304	366.872	5.873
Using next txopp of the covered beam only	$\alpha = 0$	0.301	0.000	397.102	21.905	384.376	32.487
	$\alpha = 1$	0.581	0.000	213.000	0.843	633.416	5.135
	$\alpha = 2$	0.635	0.000	199.284	1.111	666.336	5.626
	$\alpha = 3$	0.661	0.001	196.341	0.806	676.680	14.175
	$\alpha = 4$	0.684	0.000	194.016	0.156	685.992	11.105
	$\alpha = 5$	0.703	0.001	193.432	0.672	701.952	6.773
	$\alpha = 6$	0.716	0.000	192.495	1.327	720.144	4.936
Using next txopps of all beams	$\alpha = 0$	0.317	0.000	410.736	1.903	409.744	8.867
	$\alpha = 1$	0.582	0.001	212.646	0.926	625.512	7.455
	$\alpha = 2$	0.638	0.000	198.638	1.170	658.808	8.489
	$\alpha = 3$	0.664	0.001	195.994	1.258	677.928	8.368
	$\alpha = 4$	0.687	0.000	193.061	0.341	695.096	6.481
	$\alpha = 5$	0.707	0.001	192.608	0.875	703.224	14.102
	$\alpha = 6$	0.720	0.000	191.917	1.023	699.608	19.719

in an omni-directional antenna network, a network node can transmit information elements for different nodes using the same MSH-DSCH message due to the broadcast nature and thus reduce the required time of the three-way handshake procedure.

Second, our proposed DEDA may choose a larger holdoff time exponent for an antenna domain for maintaining network operation (avoid collisions of antenna coverage with neighboring nodes). To address this problem, we also propose the DEDA-ITHP design, extended from DEDA, to improve the efficiency of establishing data schedules. The ATHPT results show that DEDA-ITHP shortens ATHPT by a factor of 1.5, when compared with DEDA. Regarding ANEDS, the directional-antenna network can complete more three-way handshake procedures within the same simulated time by factors from 1.05 to 2.216 (at least 1.642 if the holdoff time exponent value is not fixed), when compared with the omni-direction-antenna network. In addition, DEDA-ITHP can on average outperform DEDA in ANEDS by a factor of 1.25.

Fig 5.2 shows that the ATOUN value on average is increased as the α value or the number of antenna domains is increased. Besides, we can see that DEDA-ITHP efficiently increases the ATOUN value. Lastly, the ATOUN value is slightly increased by the improved one-hop neighbors eligibility determination.

Fig 5.3 shows that the ATHPT value is decreased as the α value is increased. Besides, the results show that DEDA-ITHP can further shorten ATHPT. Also note that if the number of antenna domains decreases, ATHPT can be decreased because in such a condition the required time for a round of control message dissemination can be reduced.

Fig 5.4 shows that the ANEDS value increases as the α value increases. As we can see in this figure, DEDA-ITHP greatly increases ANEDS in all cases. However, increasing the number of antenna domains does not increase the ANEDS value. The reason for this unexpected result is that for a grid network, using 4 or 6 antenna domains does result in much different spatial reuse degree because for each node, the density of neighboring nodes is quite regular. The effect of the

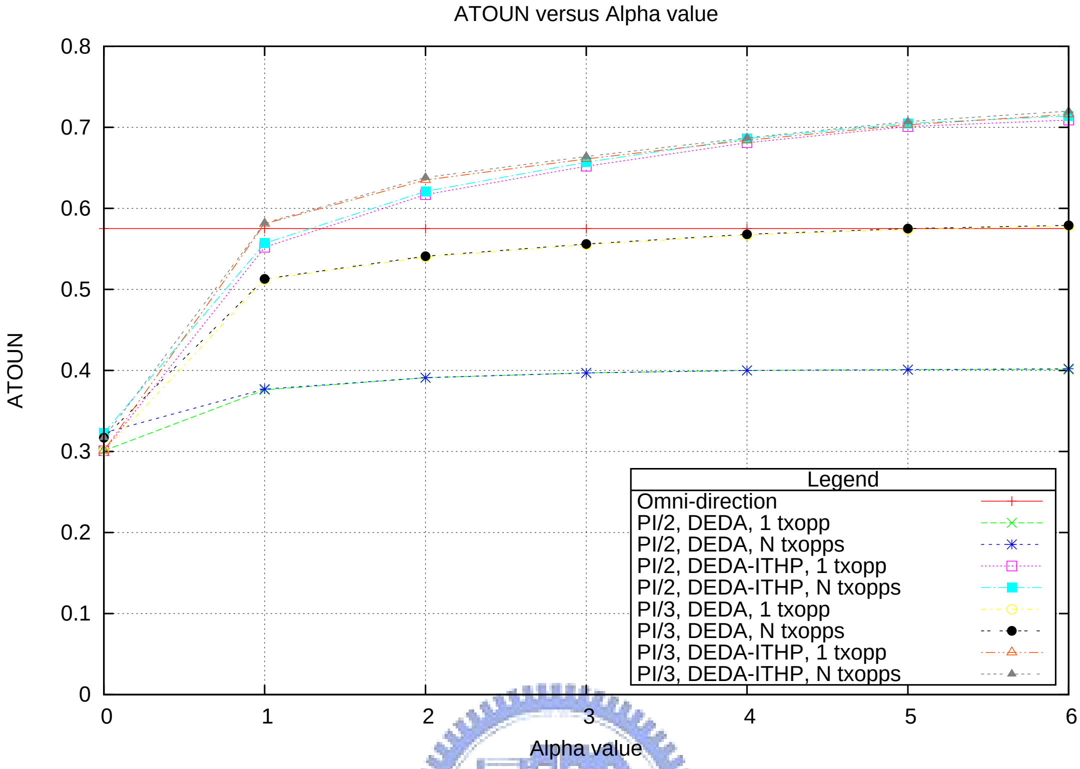


Figure 5.2: ATOUN versus α value.

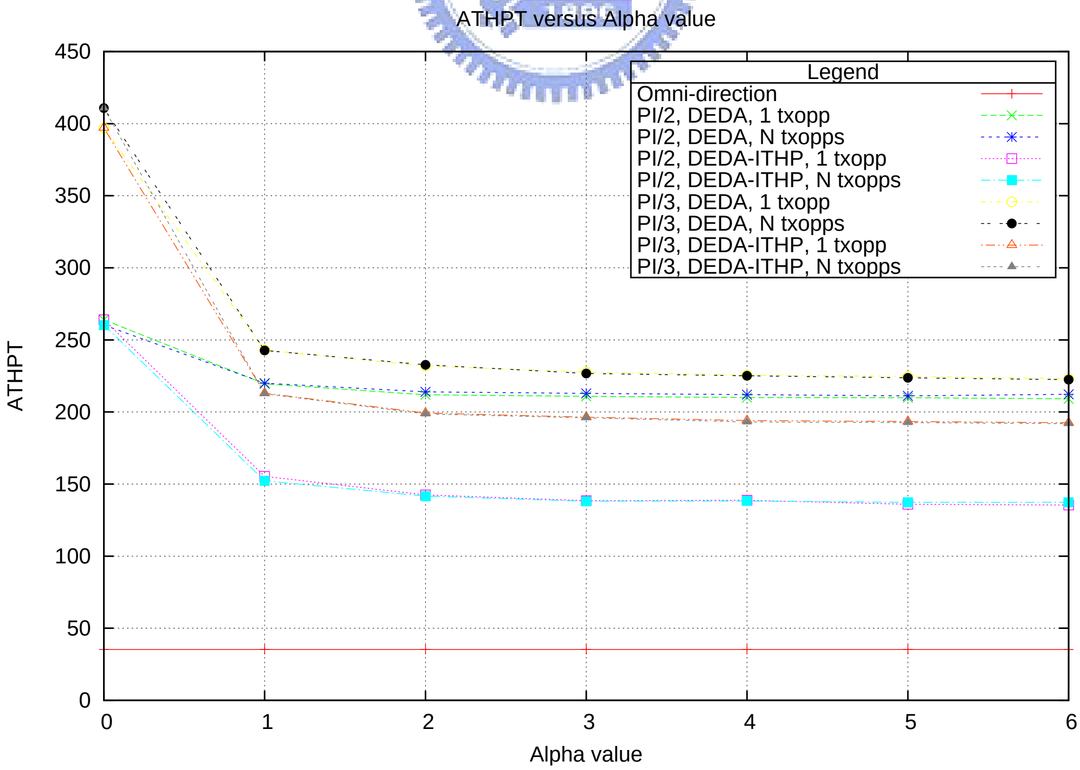


Figure 5.3: ATHPT versus α value.

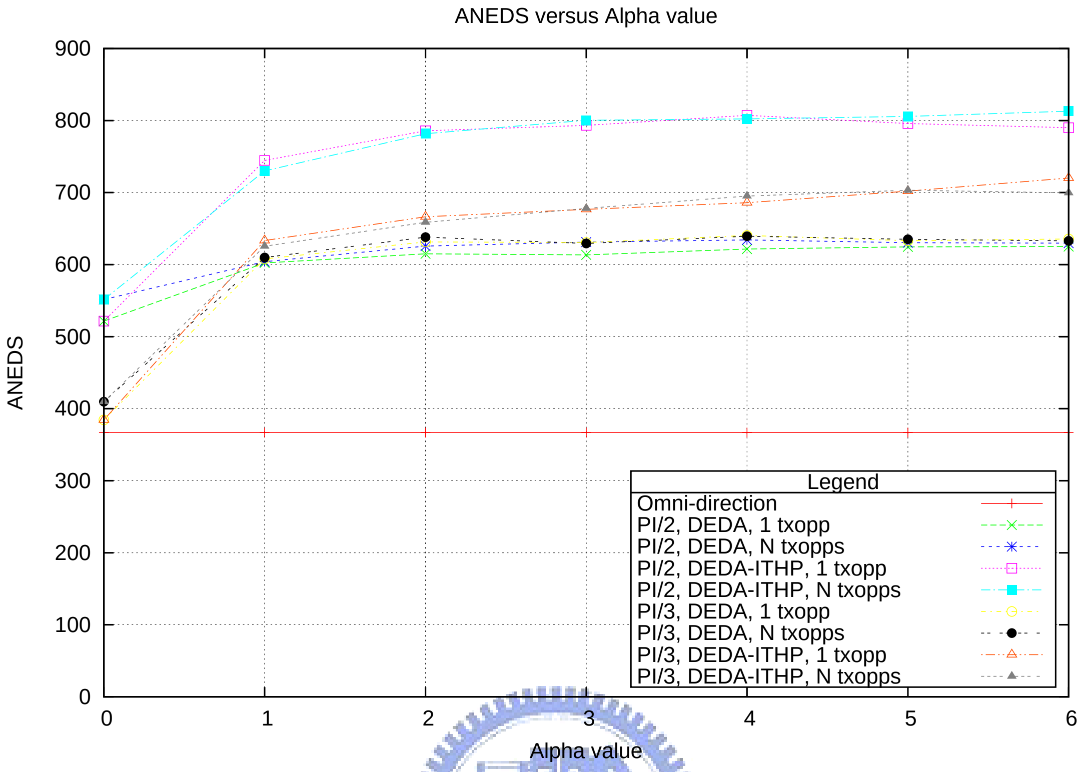


Figure 5.4: ANEDS versus α value.

number of antenna domains can further studied using random network topologies in the future.

In summary, these simulation results show the following observations. First, a directional-antenna network utilizes the control-plane bandwidth more efficiently than an omni-direction-antenna network. Second, DEDA is essential to the directional-antenna network since it provides a higher control-plain utilization, a shorter three-way handshake procedure time, and a larger number of established data schedules, as compared with the static holdoff time exponent setting. Then, DEDA-ITHP provides better performances than DEDA does. Fourth, the improved one-hop neighbors eligibility determination slightly increases the control-plane utilization. Finally, a larger number of antenna domains slightly increases the control-plane utilization but lengthens the procedure time of three-way handshake.

5.3 Application Throughputs

5.3.1 Performance Metrics

Aggregate Traffic Flow Throughput (ATFT)

We use the aggregate throughputs of all traffic flows (TCP or UDP) to show how much bandwidth a network node can obtain in a simulation run. The aggregate traffic flow throughput (ATFT) for a network node is defined by Equation (5.3).

$$ATFT(i) = \sum_{j \in NBR_{1i}} t_{ij} \tag{5.3}$$

where t_{ij} is the average throughput of the flow set up from $Node_i$ to $Node_j$

NBR_{1i} is the set of $Node_i$'s one-hop neighbors

The Average of Aggregate Traffic Flow Throughput(AATFT)

We use the average of ATFT to show the average throughputs of all traffic flows in a simulation case, which is defined by Equation (5.4).

$$AATFT = \frac{\sum_{i=1}^{N} ATFT(i)}{N} \tag{5.4}$$

where N is the number of nodes in a simulation case.

5.3.2 Simulation Environment

We use the same simulation setting and topology listed in Section 5.2.2 to evaluate throughputs obtained by TCP and UDP, respectively. In the network topology, each node sets up a traffic flow (TCP or UDP) to each one-hop neighbor at the 150th second. All traffic flows last for 150 seconds in simulations. For the network with 25 nodes, more than 100 traffic flows will exist at the same time for evaluating the concurrency of the network.

5.3.3 Simulation Results

Table 5.1 and Table 5.2 show the AATFT values of TCP and UDP flows averaged across all simulations with different random seeds. The AATFT values show that TCP flows in directional-antenna network obtain much higher throughputs by factors from 2.854 to 7.506 (at least 5.582 if the holdoff time exponent value is not fixed) when compared with TCP flows in omni-directional-antenna network. On the other hand, UDP flows also obtain higher throughputs by factors from 1.644 to 2.436 (at least 2.111 if holdoff time exponent value is not fixed) in directional-antenna network. In addition, DEDA-ITHP can outperform DEDA in AATFT.

Fig 5.5 and Fig 5.6 show the TCP ATFT value of each node in a directional-antenna network are greatly larger than the TCP ATFT value of each node in a omni-directional-antenna network. Fig 5.7 and Fig 5.8 show DEDA-ITHP increase the TCP ATFT value of each node in the directional-antenna network when compared to results generated with DEDA in Fig 5.5 and Fig 5.6.

Fig 5.9, Fig 5.10, Fig 5.11, and Fig 5.12 show the UDP ATFT value of each node in a directional-antenna network are also larger than the UDP ATFT value of each node in a omni-directional-antenna network and DEDA-ITHP provides larger ATFT values when compared with DEDA.

TCP is a protocol which adjusts its data transmission rate according to the network condition. From results of the TCP and UDP flows, we can observe that AATFT values of TCP traffic flows are great improvements over AATFT values of UDP traffic flows. Therefore, a directional-antenna network also provide a better network condition when compared with a omni-directional-antenna network.

Table 5.3: Application throughputs using antenna with beam width $\frac{\pi}{2}$

(a) With DEDA.

		TCP (KB/sec)		UDP (KB/sec)	
		Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		7.953	32.801	122.353	203.340
Using next txopp of the covered beam only	$\alpha = 0$	36.374	68.214	246.902	209.813
	$\alpha = 1$	44.390	80.238	258.255	209.879
	$\alpha = 2$	51.538	86.487	262.446	209.478
	$\alpha = 3$	45.994	82.045	264.558	209.797
	$\alpha = 4$	46.357	82.587	267.394	209.802
	$\alpha = 5$	46.069	81.848	267.078	209.532
	$\alpha = 6$	45.811	81.488	267.363	209.583
Using next txopps of all beams	$\alpha = 0$	36.415	68.872	251.785	209.803
	$\alpha = 1$	44.961	80.338	257.891	209.600
	$\alpha = 2$	45.973	81.135	264.171	209.580
	$\alpha = 3$	45.794	81.465	265.991	209.279
	$\alpha = 4$	46.113	81.713	264.611	209.237
	$\alpha = 5$	47.075	82.862	267.617	209.378
	$\alpha = 6$	45.333	81.226	265.836	209.470

(b) With DEDA-ITHP.

		TCP (KB/sec)		UDP (KB/sec)	
		Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		7.953	32.801	122.353	203.340
Using next txopp of the covered beam only	$\alpha = 0$	35.662	66.645	246.902	209.813
	$\alpha = 1$	55.467	94.766	286.516	210.536
	$\alpha = 2$	57.615	96.555	293.124	211.115
	$\alpha = 3$	58.195	97.525	292.697	211.351
	$\alpha = 4$	58.235	97.871	289.229	211.885
	$\alpha = 5$	59.990	99.241	296.581	210.952
	$\alpha = 6$	58.603	98.385	294.736	211.205
Using next txopps of all beams	$\alpha = 0$	36.671	68.744	251.785	209.803
	$\alpha = 1$	54.487	93.561	286.645	210.799
	$\alpha = 2$	56.558	95.342	288.736	211.996
	$\alpha = 3$	58.693	98.587	295.406	210.692
	$\alpha = 4$	59.167	98.975	295.498	210.751
	$\alpha = 5$	59.693	98.826	298.028	210.259
	$\alpha = 6$	59.196	98.663	296.151	210.784

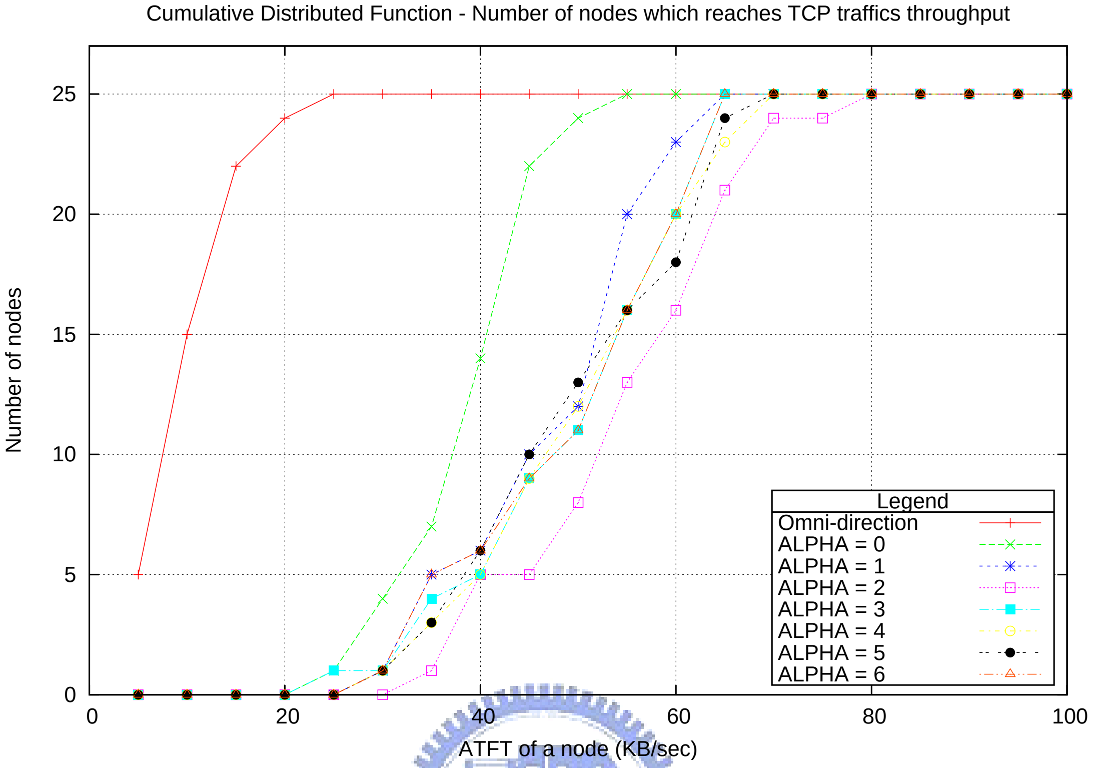
Table 5.4: Application throughputs using antenna with beam width $\frac{\pi}{3}$

(a) With DEDA.

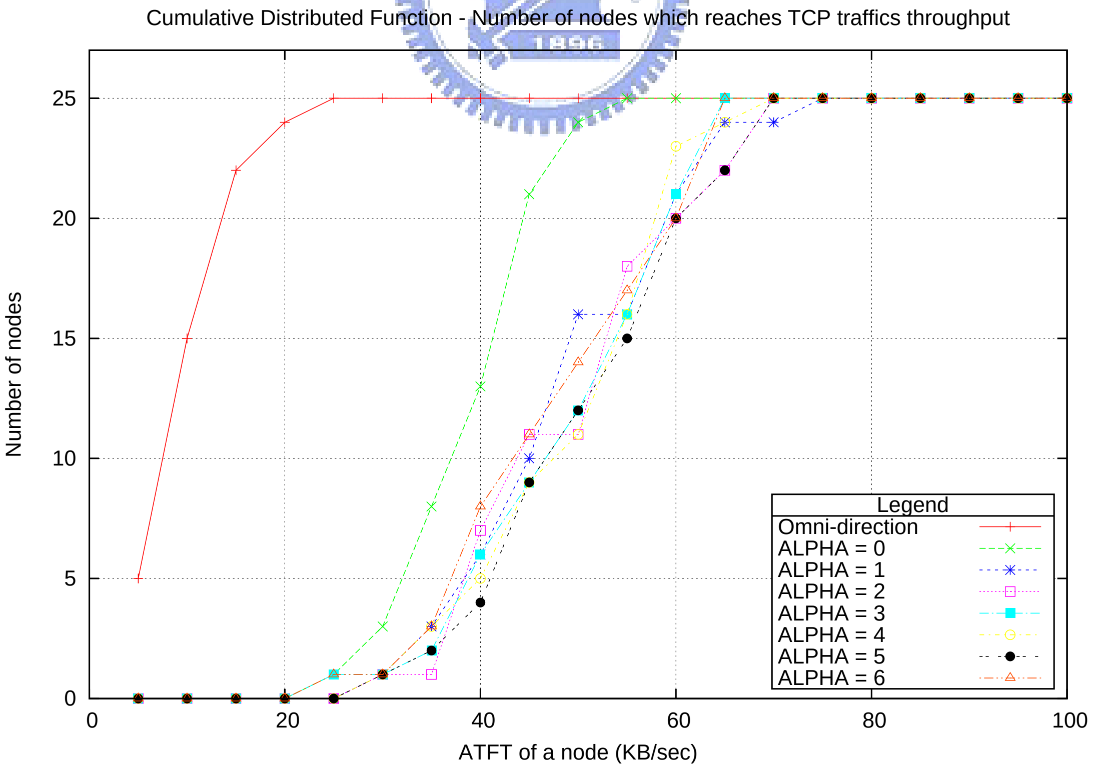
		TCP (KB/sec)		UDP (KB/sec)	
		Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		7.953	32.801	122.353	203.340
Using next txopp of the covered beam only	$\alpha = 0$	22.698	49.987	201.181	203.216
	$\alpha = 1$	48.912	81.913	269.606	204.233
	$\alpha = 2$	49.407	83.411	271.787	204.498
	$\alpha = 3$	50.458	83.798	274.183	204.793
	$\alpha = 4$	50.781	84.553	276.492	204.500
	$\alpha = 5$	49.893	82.799	273.031	204.697
	$\alpha = 6$	51.230	84.677	277.310	204.342
Using next txopps of all beams	$\alpha = 0$	23.683	50.406	206.228	204.403
	$\alpha = 1$	48.600	81.660	270.494	204.217
	$\alpha = 2$	50.306	83.283	270.966	204.807
	$\alpha = 3$	50.763	84.535	273.254	205.112
	$\alpha = 4$	50.772	83.917	274.503	204.381
	$\alpha = 5$	50.825	85.130	274.891	204.577
	$\alpha = 6$	52.749	86.682	278.131	204.140

(b) With DEDA-ITHP.

		TCP (KB/sec)		UDP (KB/sec)	
		Avg.	Std. dev.	Avg.	Std. dev.
Omni-direction-antenna		7.953	32.801	122.353	203.340
Using next txopp of the covered beam only	$\alpha = 0$	23.091	50.997	201.181	203.216
	$\alpha = 1$	54.458	89.465	282.213	205.023
	$\alpha = 2$	57.471	92.877	288.112	205.288
	$\alpha = 3$	60.271	95.860	292.095	204.706
	$\alpha = 4$	58.725	93.467	294.233	205.026
	$\alpha = 5$	59.057	94.656	293.269	205.038
	$\alpha = 6$	58.400	93.325	292.903	204.826
Using next txopps of all beams	$\alpha = 0$	23.214	50.438	206.228	204.403
	$\alpha = 1$	44.209	83.059	283.846	204.927
	$\alpha = 2$	57.973	92.690	292.049	204.978
	$\alpha = 3$	57.534	92.469	292.961	204.431
	$\alpha = 4$	57.722	92.687	290.623	205.777
	$\alpha = 5$	58.571	93.239	291.795	205.559
	$\alpha = 6$	59.454	95.531	294.820	205.045

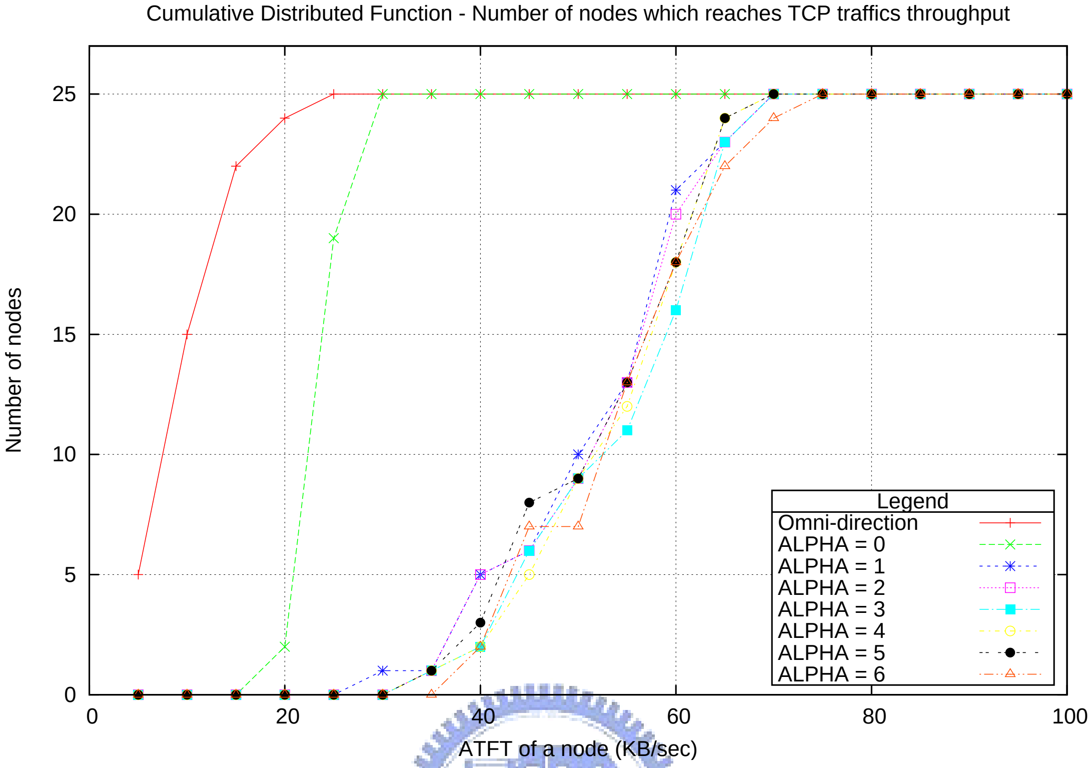


(a) Using next txopp of the covered beam only.

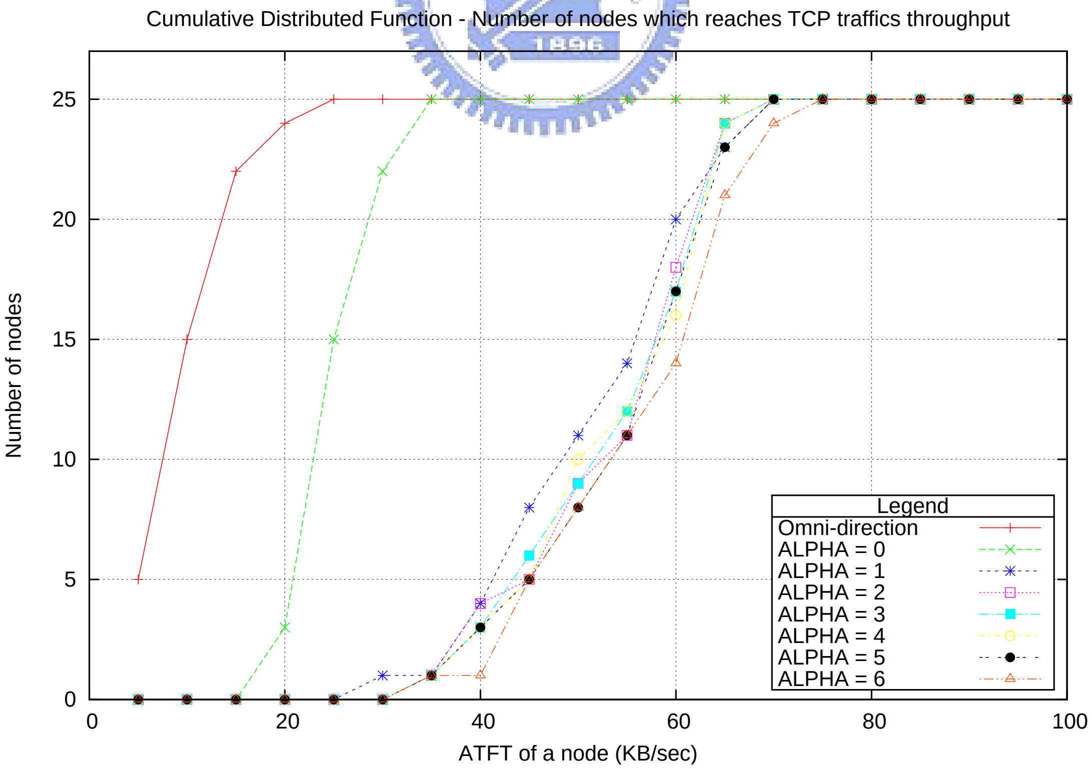


(b) Using next txopps of all beams.

Figure 5.5: TCP throughput using antenna with beam width $\frac{\pi}{2}$ with DEDA.

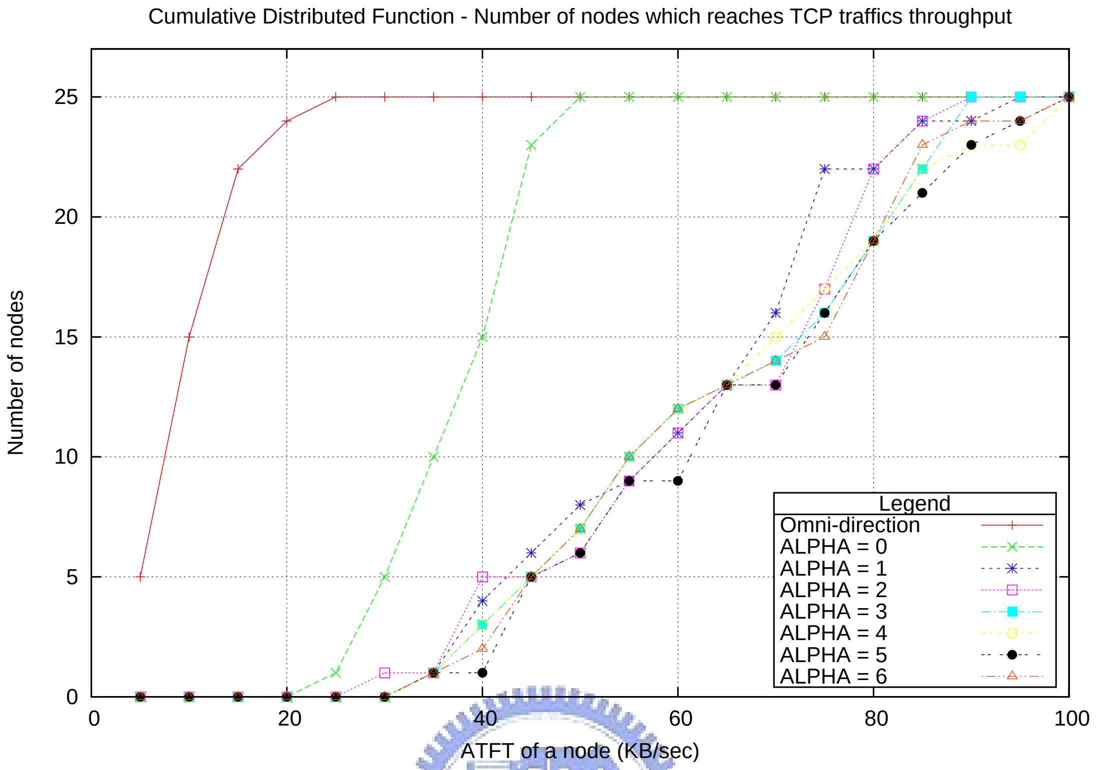


(a) Using next txopp of the covered beam only.

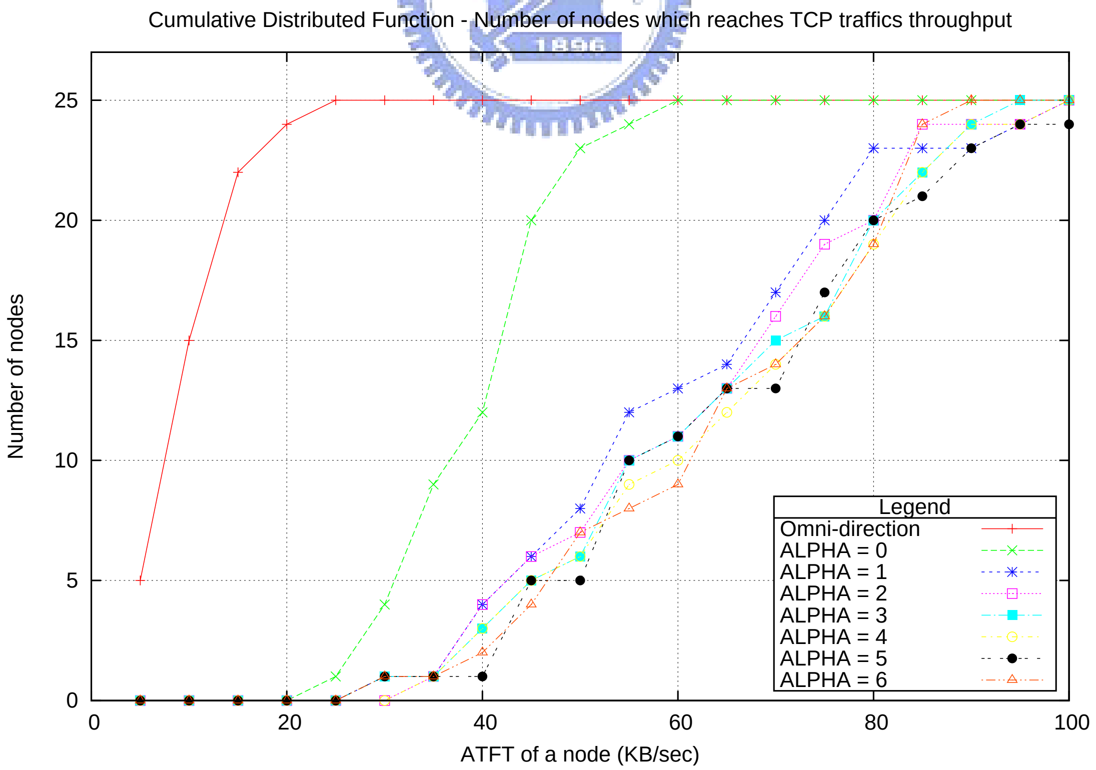


(b) Using next txopps of all beams.

Figure 5.6: TCP throughput using antenna with beam width $\frac{\pi}{3}$ with DEDA.

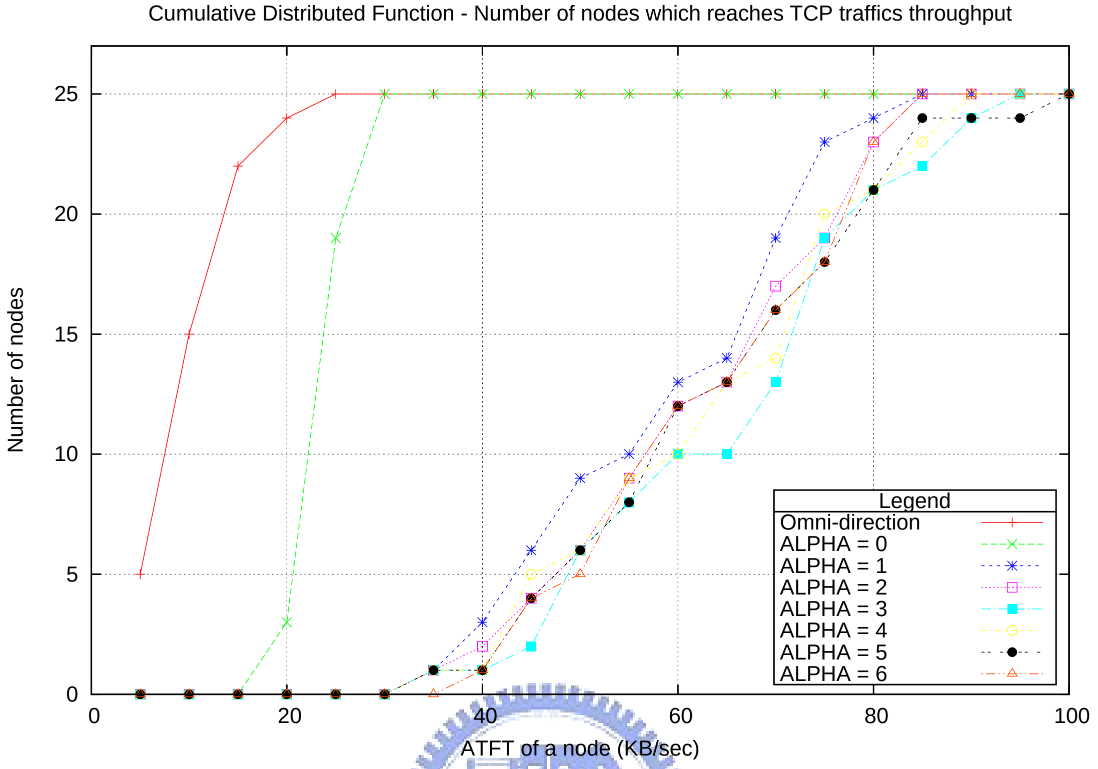


(a) Using next txopp of the covered beam only.

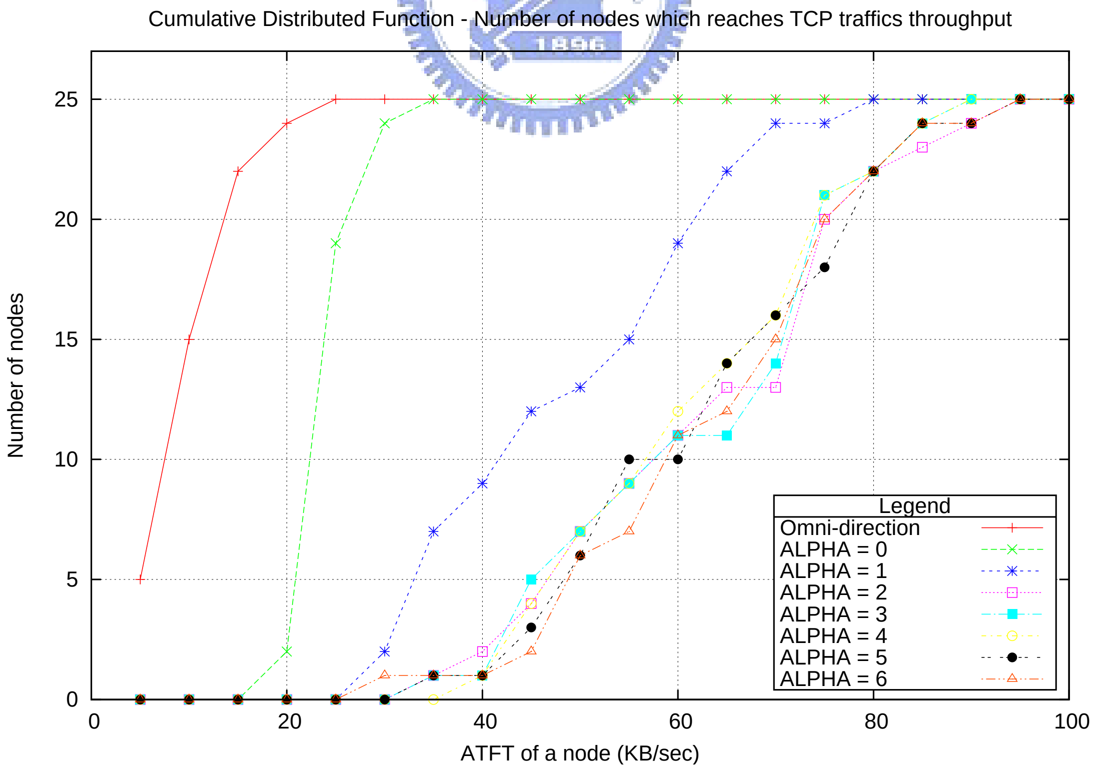


(b) Using next txopps of all beams.

Figure 5.7: TCP throughput using antenna with beam width $\frac{\pi}{2}$ with DEDA-ITHP.

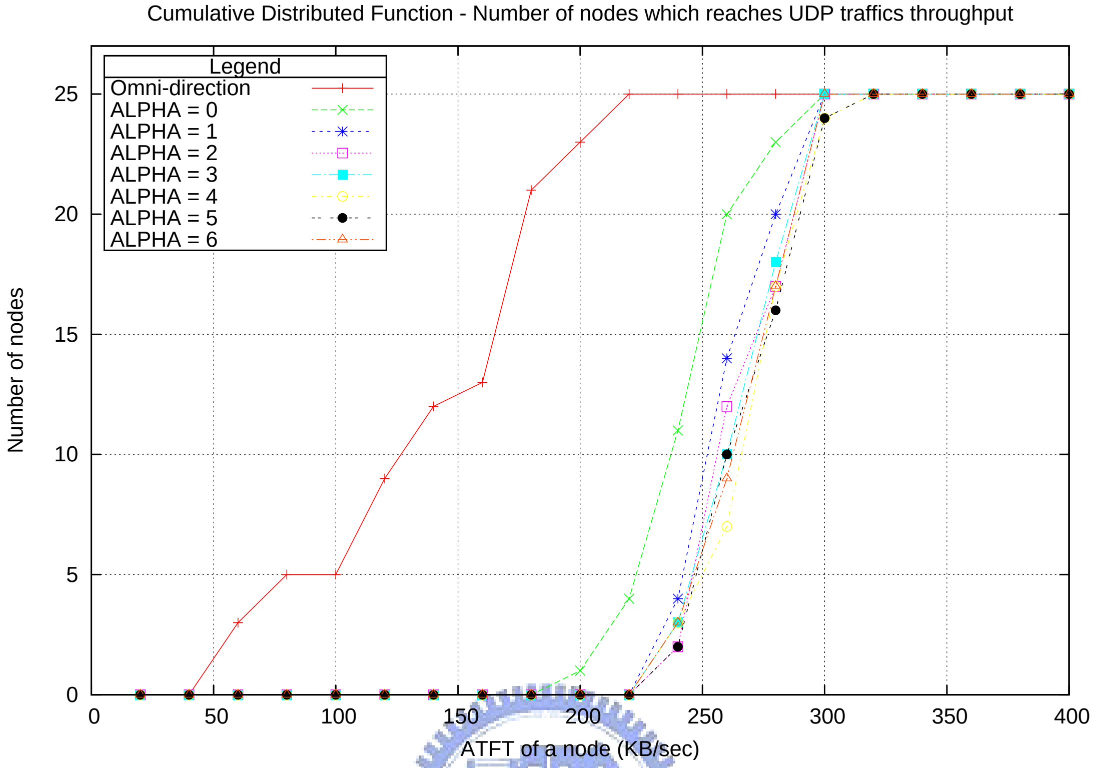


(a) Using next txopp of the covered beam only.

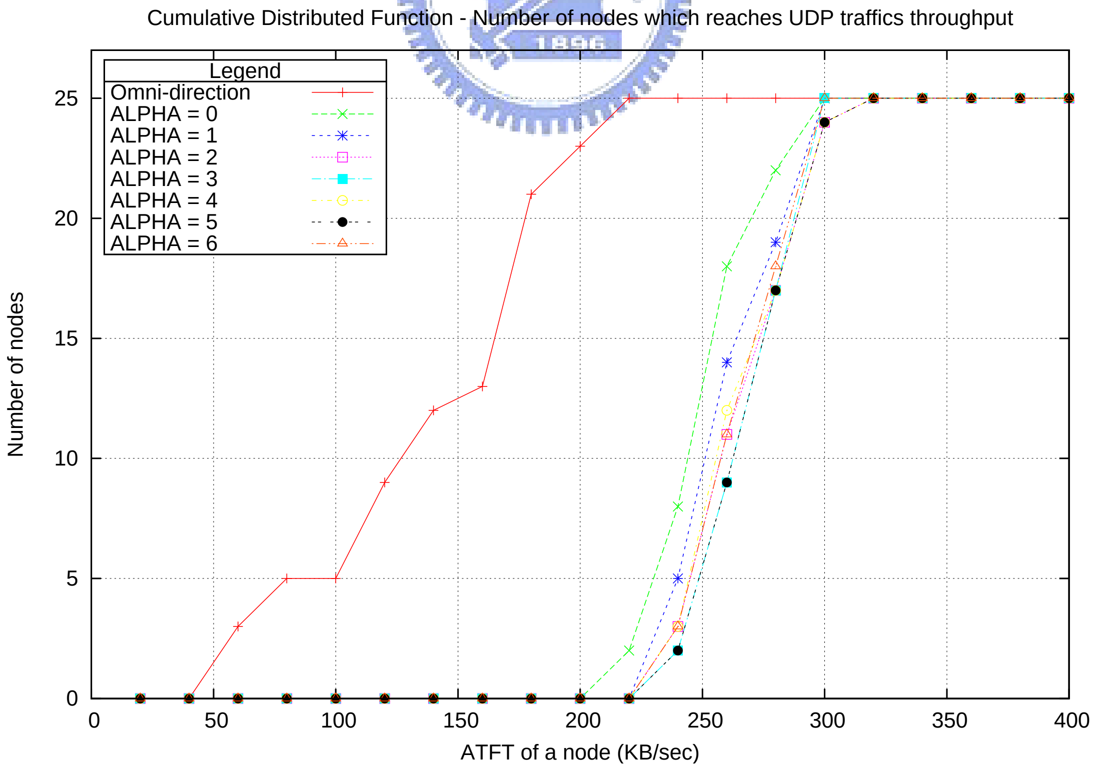


(b) Using next txopps of all beams.

Figure 5.8: TCP throughput using antenna with beam width $\frac{\pi}{3}$ with DEDA-ITHP.

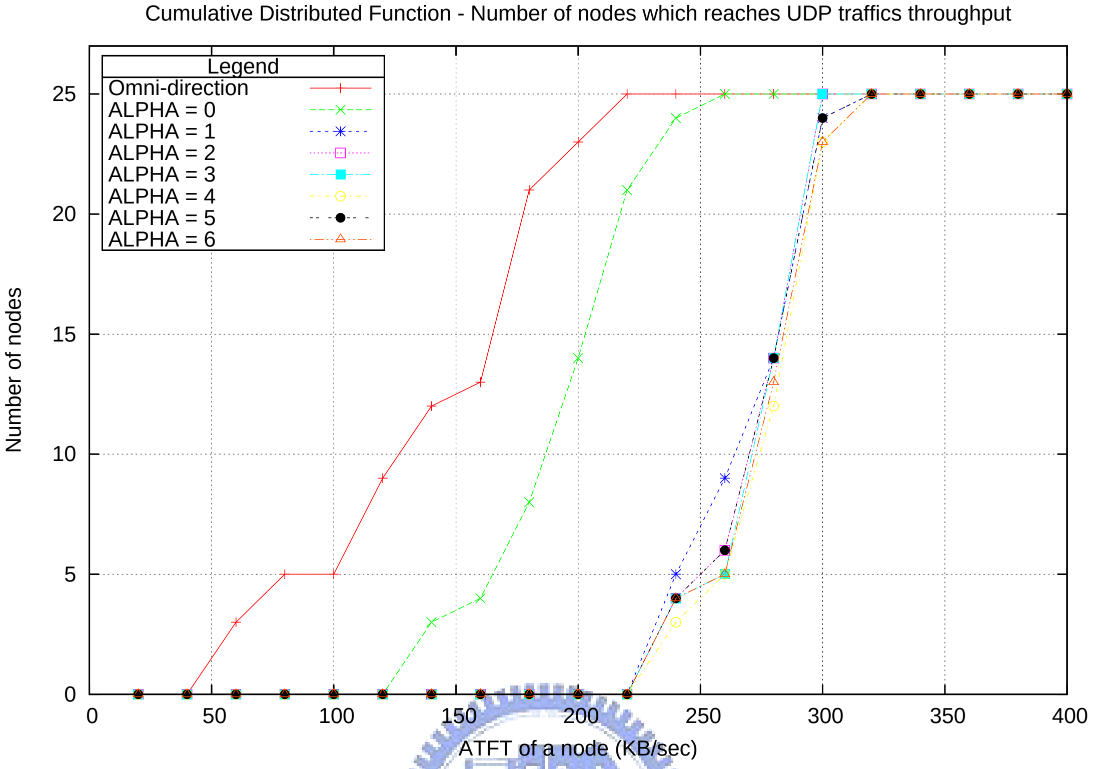


(a) Using next txopp of the covered beam only.

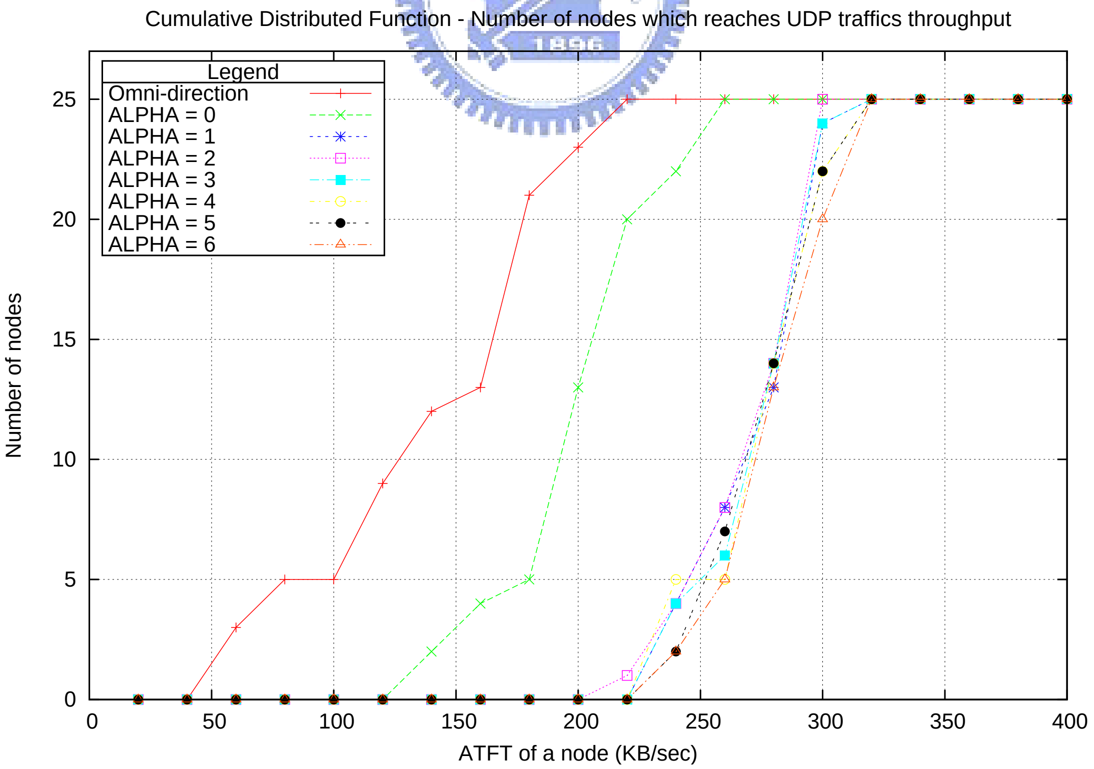


(b) Using next txopps of all beams.

Figure 5.9: UDP throughput using antenna with beam width $\frac{\pi}{2}$ with DEDA.

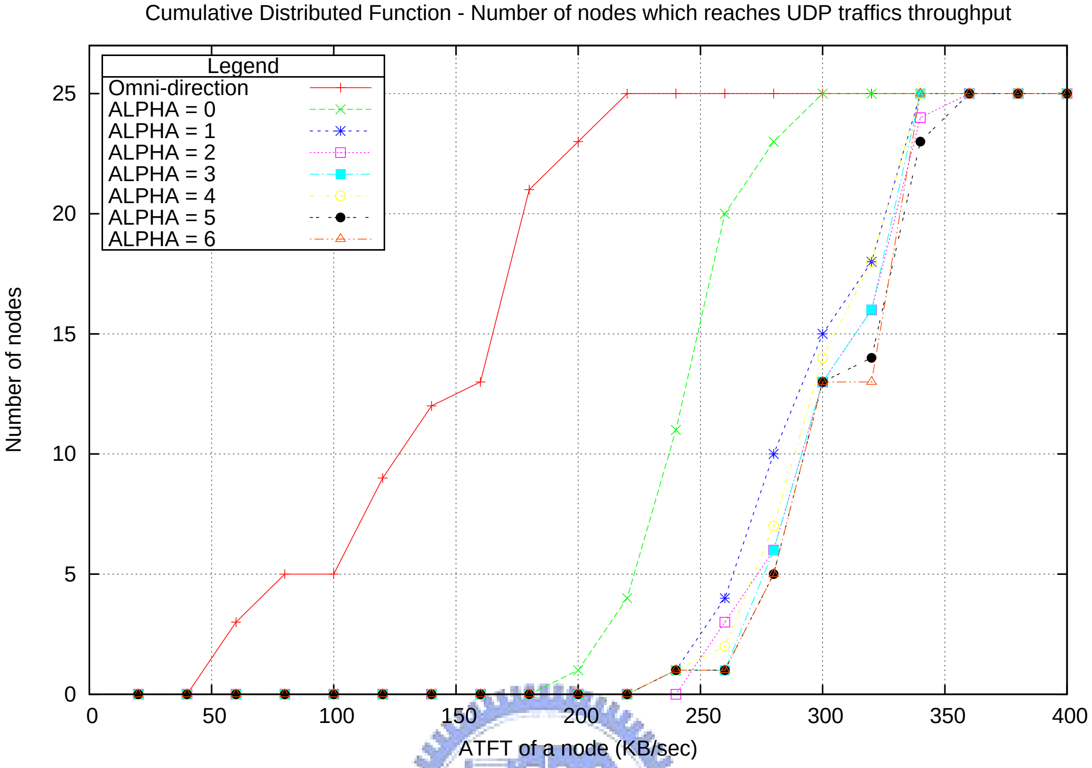


(a) Using next txopp of the covered beam only.

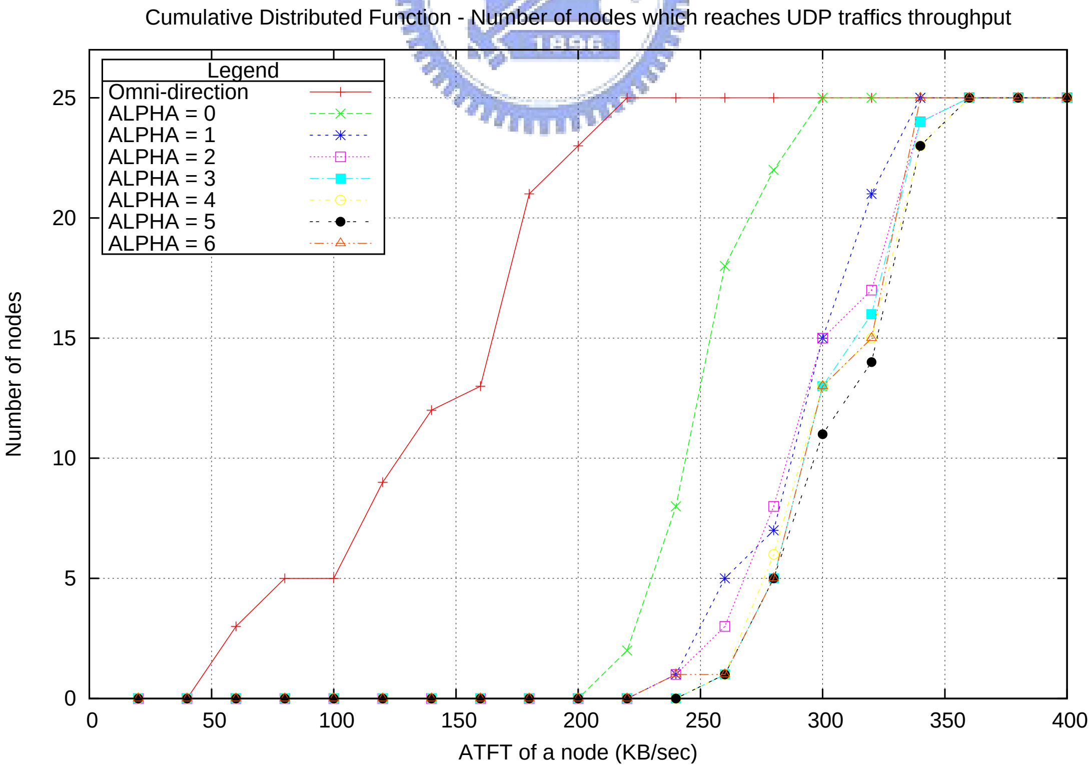


(b) Using next txopps of all beams.

Figure 5.10: UDP throughput using antenna with beam width $\frac{\pi}{3}$ with DEDA.

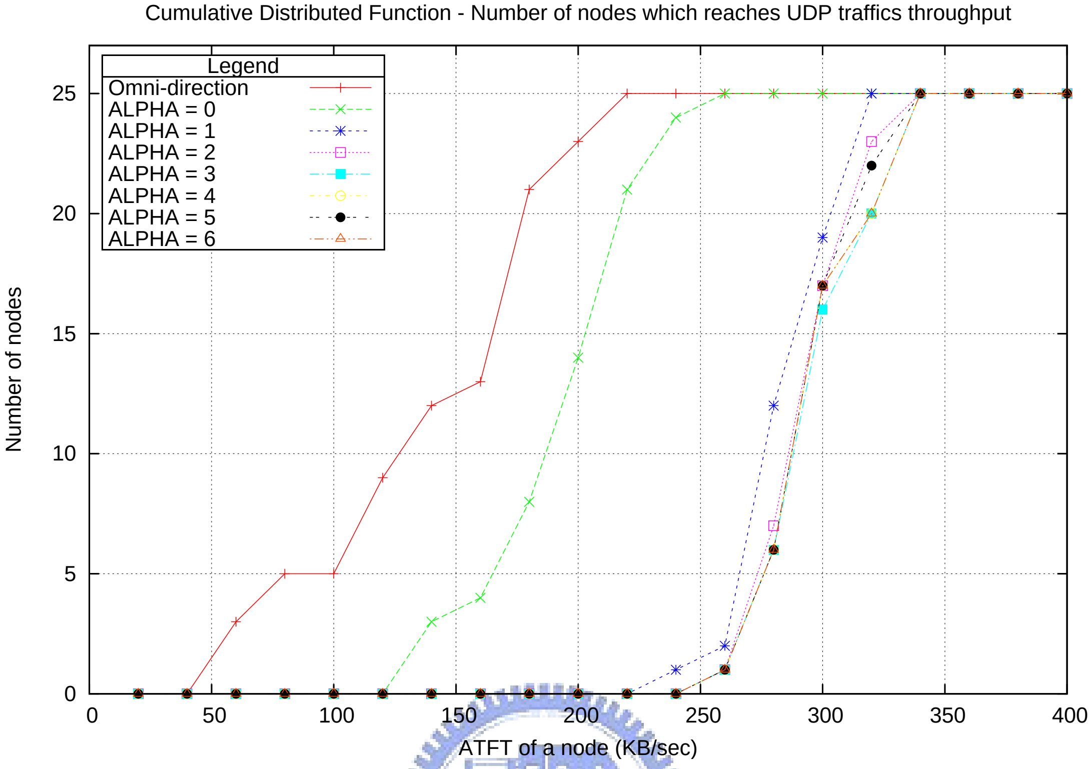


(a) Using next txopp of the covered beam only.

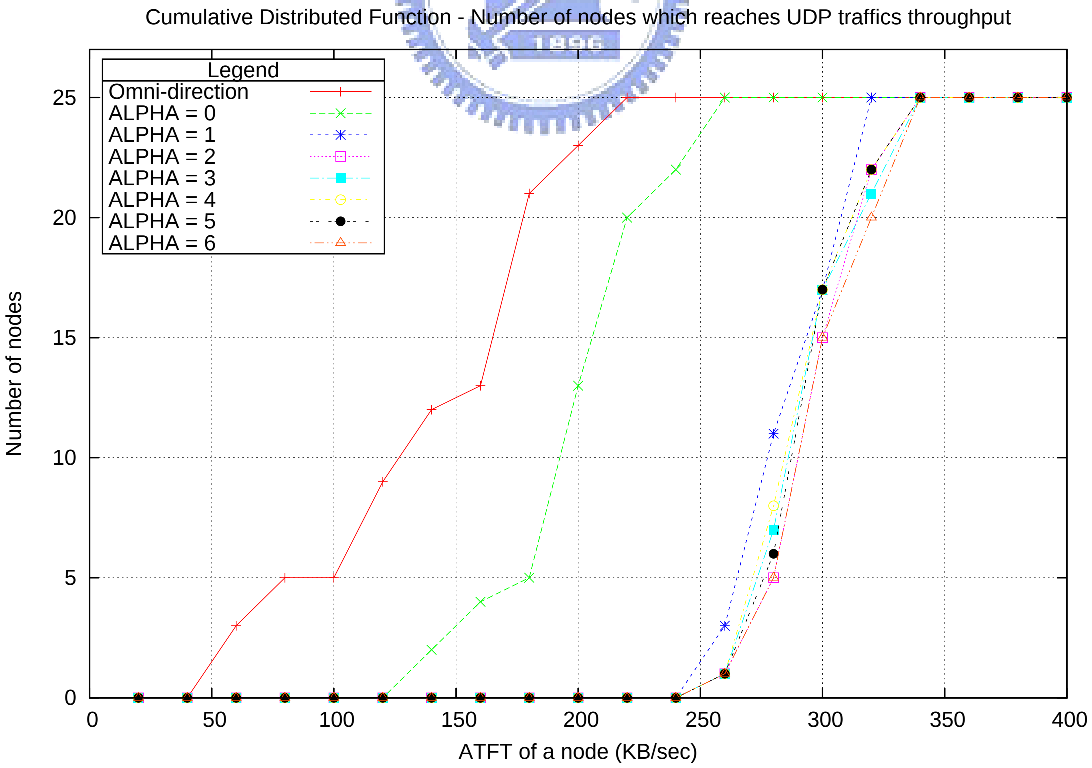


(b) Using next txopps of all beams.

Figure 5.11: UDP throughput using antenna with beam width $\frac{\pi}{2}$ with DEDA-ITHP.



(a) Using next txopp of the covered beam only.



(b) Using next txopps of all beams.

Figure 5.12: UDP throughput using antenna with beam width $\frac{\pi}{3}$ with DEDA-ITHP.

Chapter 6

Future Work

Antenna Domain Based QoS Algorithm

Recall in Section 4.5.3 and Section 4.5.3, a network node uses DMEA and DEDA to choose its next transmission opportunity regardless for which antenna domain the transmission opportunity is used. Thus, traffic flows for all antenna domains will obtain fair bandwidth. However, we can provide a specific QoS requirement for each antenna domains by adding a certain QoS based determination to DMEA and DEDA.

Improving Dynamic Holdoff Time Exponent Determination Algorithm

Recall from Section 4.5.3, the DEDA of our design may choose a larger holdoff time exponent value as an input to the mesh election algorithm, the holdoff time exponent value determination policy in DEDA cannot optimize the utilization of the control-plane bandwidth and efficiently shorten the delay of establishing data schedules. To optimize the efficiency of DEDA, a more complicated algorithm is necessary.

Data Scheduling Using Additional Information

In the current implementation, network nodes use the mini-slot allocation with a constant size in each three-way handshake procedure. However, the size of a mini-slot allocation can be varied dynamically. Hence, a network node can adjust the size of a mini-slot allocation according to the traffic load in the antenna domain for which the requested mini-slot allocation is used.

Using More Steerable Antennas to Improve Network Performances

For the deployment cost consideration, a node in the network is equipped with only one steerable antenna. However, we can extend our design to support more than one steerable antennas to increase network performances by a more sophisticated collocated antennas management algorithm.

Chapter 7

Conclusion

In this thesis, we propose a novel design that employs steerable directional-antenna systems in the IEEE 802.16(d) mesh network. We analyze problems with using steerable directional-antenna systems in IEEE 802.16(d) mesh networks and propose practical solutions to these problems. A directional-antenna version of mesh election algorithm (DMEA) is presented for maintaining network operation. We also propose two versions of holdoff time exponent determination algorithms to enhance the performances of DMEA.

The ATOUN results show that using directional-antennas can increase the control-plane utilization by a factor of 1.252. The ANEDS results show that the number of established data schedules is increased by a factor of 2.216. The TCP results indicate that our design can increase the aggregate TCP throughputs by a factor of 6.633 with DEDA and by a factor of 7.506 with DEDA-ITHP. Regarding UDP traffic, our design can increase the aggregate throughputs by a factor of 2.273 with DEDA and by a factor of 2.436 with DEDA-ITHP. These simulation results show that our design can greatly improve performances of the IEEE 802.16 mesh network as compared with the omni-directional antenna design (including those employing directional antenna arrays to emulate an omni-direction antenna). Besides, since our design employs only a steerable directional antenna for each node, it is more cost-effective than antenna-array-based designs.

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