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**The Improvements in Ad Hoc Routing and Network
Performance with Directional Antennas**

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<p>The ad hoc network has typically been applied in military and emergency environments. In the past decade, a tremendous amount of MAC protocols and routing protocols have been developed, but most of these protocols are designed for networks where devices equipped with omni-directional antennas. With fast development of the antenna technology, directional antennas have been proposed to improve routing and network performance in ad hoc networks. However, several challenges and design issues (like new hidden terminal problem, deafness problem, neighbor discovery problem and routing overhead problem) arise when applying directional antennas to ad hoc networks, consequently a great number of directional MAC and routing protocols have been proposed.</p> <p>In this thesis the implementation of directional antennas in ad hoc networks is studied from technical point of view. This thesis discusses the problems of utilizing directional antenna in ad hoc networks and reviews several recent proposed MAC algorithms and routing algorithms. The improvement of ad hoc routing and network performance with directional antennas compared with omni-directional antennas are evaluated based on simulations which are done with the QualNet simulator.</p> <p>The main finding of this study is that directional antennas always outperform omni-directional antennas in both static and mobility scenarios, and the advantage of directional antennas is more obvious when channel condition becomes worse or mobility level is larger.</p> <p>This thesis provides a survey of directional MAC and routing protocols in ad hoc networks. The result and principles obtained in this thesis are quite valuable for researchers working in this field. They can use it as reference for further researches. The theory parts of smart antenna technology and IEEE 802.11 MAC protocol can be considered as a technical introduction for beginners.</p>		
Keywords: ad hoc network, AODV, directional antennas, MAC, OLSR, performance, routing		

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Abbreviations

3G	3 rd Generation
ADC	Analog-to-Digital Converter
AOA	Angle of Arrival
AODV	Ad Hoc On-Demand Distance Vector
B3G	Beyond 3 rd generation communication system
BER	Bit Error Rate
BFN	BeamFormer Network
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
C-DRTS	Circular DRTS Scheme
CMA	Constant Modulus
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	contention window
DCF	Distributed coordinate function
DCTS	Directional CTS
DD	Direction-Direction
DMAC	Directional MAC Scheme
DNAV	Directional NAV
DO	Direction-Omni
DOA	Directional of Arrival
DRTS	Directional RTS
DSP	Digital Signal Processing
DSR	Dynamic Source Routing
DSSS	Direct-Sequence Spread-Spectrum
DVCS	Directional Virtual Carrier Sensing
E-R/CTS	Extended RTC/CTS Scheme
FDMA	Frequency Division Multiple Access
FTP	File Transfer Protocol
GloMoSim	Global Mobile Information System Simulator
GUI	Graphical User Interface
HSLs	Hazy Sighted Link-State
IAPP	Inter-Access Point Protocol
ISM	Industrial, Science and Medical
LAR	Location-Aided Routing
LMS	Least Mean Square

MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
MMAC	Multi-hop RTS MAC
MPR	Multipoint Relay mechanism
MRC	Maximum Ratio Combining
NAV	Network Allocation Vector
N-BF	Non BeamForming
OFDM	Orthogonal Frequency Division Multicarrier
OLSR	Optimized Link State Routing
PARSEC	Parallel Simulation Environment for Complex Systems
PCF	Point Coordination Function
PHY	Physical
QoS	Quality of Service
OSPFv2	Open Shortest Path First Version 2
RERR	Route Error
RF	Radio Frequency
RFZ	Receiver Forbidden Zones
RIPv2	Routing Information Protocol Version 2
RLS	Recursive Least Square
RREP	Route Reply
RREP-ACK	Route Reply Acknowledgement
RREQ	Route Request
RTS	Request to Send
SATCOM	Satellite Communication
SDMA	Spatial Division Multiple Access
SINR	Signal to Interference and Noise Ratio
SMI	Sample Matrix Inversion
T-BF	Transmitter-BeamForming
TC	Topology Control
TDMA	Time Division Multiple Access
TFZ	Transmitter Forbidden Zones
TR-BF	Transmitter and Receiver-BeamForming
UWB	Ultrawideband
VCS	Virtual Carrier Sensing
VoIP	Voice over Internet Protocol
WLAN	Wireless Local Area Network
WTS	Wait to Send
ZRP	Zone Routing Protocol

List of Symbols

ψ	array phase
D	element spacing
B	constant phase delay
A_m	element amplitude
f	frequency
θ	elevation angle
M	number of element
λ	Wavelength
P_R	Power level at receiver
$P_{R,\min}$	Minimum receiving power
P_T	Power level at transmitter
G_T	Transmitter antenna gain
G_R	Receiver antenna gain
h_T	Transmitter antenna height
h_R	Receiver antenna height
D_{\max}	Maximum transmission range
G_d	Directional antenna gain
G_o	Omni-directional antenna gain

D_{do}	Maximum transmission range between DO link
D_{dd}	Maximum transmission range between DD link

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CHAPTER 1

INTRODUCTION

1.1 Basic principles of ad hoc networks

The ad hoc is a Latin phrase which means “for this (purpose)”. [1_1] According to the Cambridge Dictionary, the definition for ad hoc is “made or happening only for a particular purpose or need, not planned in advance [1_2]”. The definition point to the main merit of the ad hoc network: the network can be deployed immediately on demand by surrounding nodes without any fixed infrastructure supporting. Because the ad hoc network is based on peer-to-peer communication, each node in the network is not only a host taking charge of sending and receiving packets but also a router with responsibility for relaying packets for other nodes. The mobile nodes could join and leave the network with freedom, which causes frequent link breaks. This requires the ad hoc network to have high capability of self-organization and maintenance which is fulfilled by utilizing intelligent routing protocol and efficient resource management in a distributed manner. [1_3]

The nature of ad hoc networks makes it highly suitable for many applications. The self-maintenance and self-configuring is highly suitable for low cost commercial communication systems and temporary communication systems. The following scenarios indicate that there is a huge demand for ad hoc networks. In military environment, ad hoc networks could support reliable, efficient and secure communication between foot soldiers or among high speed mobile military objects such as airplane, warships or tanks. In an emergency situation, especially where the infrastructures are severely destroyed by disasters, ad hoc networks can be deployed quickly and with flexibility to coordinate and organize different rescue groups to work efficiently. In the wireless sensor field, ad hoc networks are applied to offer a wireless communication infrastructure among the sensor devices in different application domains such as environment monitoring and border intrusion detection. Ad hoc networks could form a wireless mesh network which provides an alternative economical data transfer path with the freedom of mobility in residential zones, highways, business zones, important civilian regions or university campus. In short, ad hoc networks provide an easy-deployment and self-organizing independent wireless and mobile communication system for various applications which could support many new services. [1_3][1_4]

1.2 Research problem and scope of the study

Traditional wireless communication systems utilize omni-directional antennas which waste channel resource by radiating radio frequency energy in all directions. The current Medium Access Control (MAC) protocols and routing protocols in ad hoc network naturally work well with omni-directional antennas. With the fast development of directional antenna technology, the size of a directional antenna becomes smaller and the cost of it reduces also. The nature of radiating radio energy only towards a certain direction makes directional antennas save more power, increase transmission range and reduce neighborhood interference compared with omni-directional antennas. However, the challenges are always coming together with the opportunities. In ad hoc networks, directional antennas introduce new hidden terminal problem and deafness problem when working with traditional MAC protocols and bring in new neighbor discovery problem and routing overhead problem when working with conventional routing protocols. It motivates many research groups to commit to this field and to propose several modified MAC protocols and routing protocols.

The goals of this thesis can be concluded from the following four aspects:

1. It presents the overview of smart antennas technology starting from very basic elements and gives a general operating principle of switched beam antennas and adaptive antennas from signal processing point of view.
2. It illustrates the current ad hoc MAC protocols (IEEE 802.11 family protocols) and three categories of ad hoc routing protocols (reactive, proactive and hybrid routing protocols) in detail. It only presents the three popular routing protocols for each category and ignored others. The three routing protocols are Ad Hoc On-Demand Distance Vector (AODV), Optimized Link State Routing (OLSR) and Zone Routing Protocol (ZRP).
3. It analyzes the problems in the MAC layer and the routing layer when utilizing directional antenna and reviews several proposed MAC algorithms and routing algorithms developed by other research groups. They are modifications of IEEE 802.11 MAC protocols and AODV protocols. There is a comparison of these proposals from technical point of views.
4. It evaluates the improvement in ad hoc routing and network performance with directional antennas using proposed MAC and routing protocols compared with omni-directional antennas for static and mobility scenarios through case study which is done with the QualNet simulator.

1.3 Methods and approaches

The method of working throughout this thesis includes studying available literature and other relevant material of this subject. The most important source is the standardized technical specification. The approach used in case study is simulations which are done with the QualNet simulator to present the improvement in ad hoc routing and network performance of directional antennas compared with omni-directional antennas. There are also many discussions with researcher working on ad hoc network studies.

1.4 Thesis structure

In Chapter 2, the basic of smart antennas from technical point of view are introduced. Chapter 3 covers the conventional MAC layer protocol used in ad hoc networks with omni-directional antennas. Chapter 4 presents the MAC layer problem with directional antennas and reveals five proposals in detail. In Chapter 5, current ad hoc routing protocols (AODV, OLSR and ZRP) are presented. This chapter focuses on AODV and OLSR since they are commonly used in ad hoc networks. Chapter 6 discusses two directional routing problems: directional neighbor discovery problem and routing overhead problems. Then it reveals two routing algorithms for solving the first problem and three routing methods for mitigating the second problem. Chapter 7 presents the case studies for comparing the ad hoc network and routing performance between directional antennas and omni-directional antennas in different scenarios. Chapter 8 presents conclusions and further research work.

CHAPTER 2

TECHNICAL FUNDAMENTAL OF SMART ANTENNAS

This chapter presents an overview of smart antennas and discusses the technical basis of two basic categories, switched beam antennas and adaptive array antennas. Since smart antennas are consisted of multiple antenna elements, antenna array essentials are reviewed in order to help comprehend smart antenna technology. In addition, groups of merits of smart antenna system from technical and economical point of view are presented in the beginning of this chapter. Last but not least, the switched beam antenna model used in the QualNet simulator is demonstrated at the end of this chapter.

With the fast development of mobile communication technology, capacity has become one critical issue. In current 3rd generation (3G) mobile communication system, lower price of service rate together with bundling market strategy lead to tremendous increase of number of subscribers and more attracting new mobile services cause to higher bit rate demand. Both of them make an enormous increase of traffic which put a demand to provide sufficient capacity in the network. From the technical point of view, the bottleneck of capacity is basically due to multi-path and co-channel interference. Multi-path is a situation when multiple copies of desired signal arrive at the receiver antenna from different directions due to reflection and diffraction from various obstacles in the propagation environment. The phase difference when combing these multiple signals would cause serious degradation of signal quality at the receiver side. The co-channel interference occurs when signals operate at the same frequency interfere with each other. [2_1] [2_2]

Smart antenna technology could effectively mitigate multi-path and co-channel interference in mobile communication system to dramatically increase capacity by adjusting antenna radiation pattern only towards the desired receiver based on traffic condition and propagation environment.

2.1 Overview of smart antennas

Antenna is a kind of port through which Radio Frequency (RF) energy (electromagnetic energy) is radiated from the transmitter to outside space and finally is propagated to the receiver. The method of distributing signal energy from sender and gathering signal energy from surrounding area at receiver determines how efficient the frequency resource is utilized and how good the quality of service this network could provide. Actually the antenna is not smart but the antenna system could be controlled in an

intelligent way to maximize the combined antenna array performance based on digital signal processors. [2_3]

The smart antenna consists of multiple antenna elements arranged in a special configuration and connected through complex weights. The pattern of this antenna array is determined by the weights with signal processing capability to obtain maximum SINR of target signal. The smart antenna could be also considered as pattern controllable antennas. [2_4]

The smart antenna technology born in 1960's is quite new in the mobile communication field. Smart antennas are developed and deployed in military communication system in the early stage. The feature of narrow beam with high gain towards desired receiver and null towards other directions could tremendously reduce interference due to noise and other signal and increase security level, since it is extremely difficult to detect the directions of active communication pair. This unique feature can be also used to solve the mobile operators' headache problem, the capacity issue. Recently more and more companies and institutes are working on applying smart antenna technology to current and future personal communication system to accommodate more users enjoying high data rate mobile service and improve emergency communication system.

2.1.1 Motivation of smart antennas

There are many motivations to deploy smart antenna in communication system. They are presented separately in two groups as follows: from comparing with conventional omni-directional and sectorization antennas point of view and from feature and benefits of smart antenna point of view.

The conventional omni-directional antenna is a simple dipole antenna which radiates and receives equally in all directions. This radiating manner causes large waste of signal energy because only a small part is transmitted to desired receiver. Another big problem is that this omni-directional broadcast scheme causes serious interference to neighbor base stations and terminals. In poor propagation environment, omni-directional antenna has to increase power level of the broadcast to overcome this bad channel condition. This will also distribute the negative impact farther to interfere with larger neighborhood area. The direct consequences are poorer spectrum efficiency, limited frequency reuse, both leads to low capacity.

The sectorization scheme could reduce the interference level by dividing one cell into several sectors and using directional antenna to radiate/receive radio frequency power in certain sectors. Compared with omni-directional antennas, sectorization scheme support more capacity due to sectorization gain. However, one drawback of

conventional sectorization is that signal cannot be separated in the spatial domain which could not carry out spatial interference cancellation or reduction. Another problem is that sectorization could not adjust antenna orientation or beamwidth according to changing traffic condition and propagation environment, which lead to wasting of capacity in sparse traffic sector and blocking traffic in dense traffic sector. [2_1]

To deal with the above problems, one method is an antenna array with the capability of spatial signal separation. It could radiate radio frequency energy towards a desired receiver with narrow beamwidth and null towards an interfering terminal to reduce the negative impact of multipath and co-channel interference. The features and benefits of smart antennas which control the antenna array intelligently based on signal processing are presented next.

To make effective use of limited spectrum resource, several multiple access techniques have deployed in current mobile communication system. The 1st generation cellular network applied analog Frequency Division Multiple Access (FDMA) method, which enables different users to communicate simultaneously by using different frequencies. The 2nd generation digital cellular network applied Time Division Multiple Access (TDMA) method, which enables different users use same frequency in different time slots. Current 3rd generation digital cellular network applied Code Division Multiple Access (CDMA) method, which enables individual users communicate simultaneously on the same frequency base on unique user spreading code. Smart antenna adds a new mechanism named Spatial Division Multiple Access (SDMA), which enables multiple separated spatially users to communicate simultaneously with the same frequency and same spreading code. Such a kind of intra-cell frequency reuse mechanism with spatial separation achieves a high increase of system capacity.

The multipath signal of one user is combined in smart antenna system to maximize the Signal to Interference and Noise Ratio (SINR). By using narrow beam towards the desired receiver, smart antennas could increase the base station range and coverage. Higher directional gain could reduce the transmit power to save battery power. With a few of adaptive mechanisms, smart antennas could generate null precisely towards interfering terminals, which helps to achieve more effective frequency reuse to increase system capacity. Composite spatial information from the array is used to alleviate negative impact of fading and multipath propagation. This multipath rejection feature could reduce the effective delay spread of channel, which leads to less loss of received signal power and supports higher bit rates service and improves QoS. The spatial information could also be used to locate target user in emergency scenario. Last but not least, smart antennas make it more difficult to tap a connection. The intruder has to be in the same direction as the active user from the other user point of view in order to successfully tap a connection. [2_3] [2_4] [2_5]

2.1.2 Classification of smart antennas

Regarding different transmitting strategies, smart antenna could be classified by two major categories: switched beam antenna and adaptive array antenna.

The switched beam antenna is the simplest smart antenna. It explores a number of fixed beams in predetermined directions at the antenna site. Base station selects the beam that supports the maximum SINR. As the mobile terminal moves, base station would switch among several beams that provide the best performance according to changing propagation conditions. Switched beam antenna could achieve an array gain of M due to M beams and a diversity gain. Figure 2.1 presents an example of predefined antenna pattern of switched beam antenna.

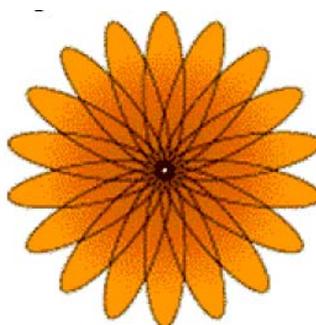


Figure 2.1: Switched beam antenna pattern

From the above antenna pattern we could see one drawback is that the predefined main beams could only focus on certain prefixed directions. If user is accidentally positioned between two main beams, it could not get any directional gain from switched beam antenna system. This problem could be mitigated by increasing number of beams.

Adaptive array antenna is an advanced smart antenna which could solve the above problem completely. It uses a complex signal processing algorithm to continuously detect among desired signal, multi-path and interference and dynamically adjust main beam smoothly towards desired receiver and null towards interference according to changing traffic condition and propagation environment. Figure 2.2 shows the antenna pattern of adaptive array antenna. The adaptation is obtained by multiplying input signal with complex weights, then summing them together to generate the desired antenna pattern. These complex weights are adjusted by different algorithms using information derived from antenna array output to dynamically adapt to the changing propagation environment.

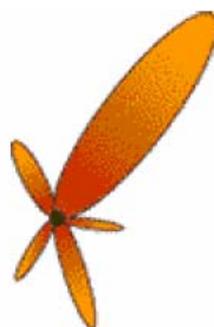


Figure 2.2: Adaptive array antenna pattern

If choosing the Maximum Ratio Combining (MRC) algorithm with M antenna elements, this adaptive array antenna system could achieve an array gain of M and an M -fold diversity gain. That shows that the adaptive array antenna could reach higher gain than the switched beam antenna based on complex calculation of weight in signal processing. [2_3] [2_5]

2.1.3 Usage of smart antennas

A smart antenna system could apply to all current major wireless protocol and industrial standards to achieve higher system capacity, larger network coverage and higher data rate. These applicable standards include FDMA used in AMPS, TACS and NMT; TDMA used in GSM and IS-136; CDMA used in IS-95, WCDMA and TD-SCDMA; FDD and TDD. [2_3]

TD-SCDMA is one of 3rd generation communication system applying smart antenna system at the early deployment phases. Smart antenna has defined as one key feature of Beyond 3rd generation communication system (B3G). With cost reducing of the smart antenna, it will become widely used in different communication system like Wi-Fi, RFID, Ultrawideband (UWB), WiMax, mobile satellite TV and etc. [2_5]

2.2 Antenna array fundamentals

The antenna array is a group of antennas with a given radiation pattern (Array Element Pattern) arranged in a form (line, circle, planar, etc) to generate a new radiation pattern (Array Pattern).

In this part, we assume a linear array with M multiple antenna elements allocated along Z axis, the distance between each element is d . The constant phase delay between elements is β and the equal antenna element amplitude is A_m . The array could generate a given radiation pattern by controlling element excitation phasing. This kind of array can be called phased array whose main beam could be controlled towards the desired

direction without physical antenna moving. [2_6] The array model from two side views is presented in Figure 2.3.

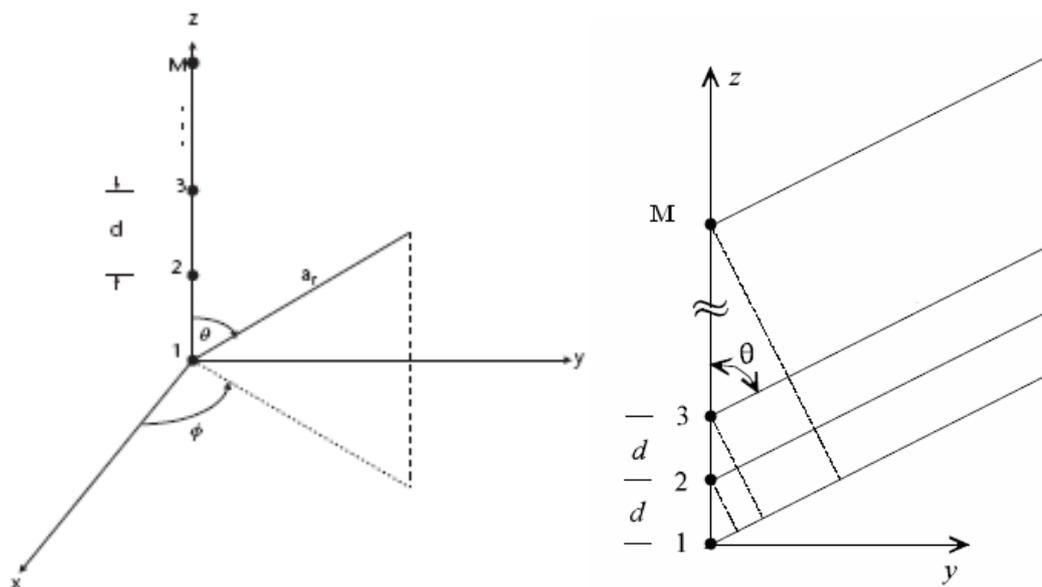


Figure 2.3: Coordinate system for uniform linear antenna arrays [2_1]

2.2.1 Antenna array pattern

The total radiation pattern of an antenna array in the far field is represented by a product between two factors, the element factor and array factor. The element factor depends on physical dimensions and electromagnetic characteristics of the radiating element, whereas the array factor depends on the amplitude, phase, and position of each of the elements in the antenna array. [2_1] This radiation pattern theorem is described as follow from the mathematic point of view.

$$E(\theta, \varphi) = AF(\theta, \varphi) \times EF(\theta, \varphi)$$

Assume the equal element amplitude A_m is 1 and the mutual coupling between elements placed in an array is ignored, the normalized array factor of uniformly excited, equally spaced linear array is

$$AF = \frac{1}{M} \cdot \frac{\sin\left(\frac{M}{2} \cdot \Psi\right)}{\sin\left(\frac{\Psi}{2}\right)}$$

The array phase function ψ is a function of element spacing d , constant phase delay β , frequency f and elevation angle θ which is between array axis and the vector from the origin to the observation point. The formula of array phase function is as follow.

$$\psi = kd \cos \theta + \beta, \text{ while } k = 2\pi/\lambda = 2\pi c/f$$

From the above discussion, we could draw a conclusion that AF depends on:

- The number of antenna elements
- The geometrical allocation of antenna array
- The relative excitation magnitudes
- The relative phase delay between antenna elements

In fact, these parameters could also impact the antenna array radiation pattern and system performance. We take the number of element M and the element spacing d for example to illustrate this relationship.

Increasing number of element could generate narrower main beam, higher gain and more and deeper null, which would lead to better interference cancellation and better system performance due to higher gain and more degree of freedom of radiation pattern. However, at the same time, it also produces more sidelobes and larger array which would lead to more complexity and higher cost.

Increasing element spacing could also produce higher gain and larger antenna pattern with narrower main beam. But the grating lobes would come together and have a negative impact on interference nulling and power saving. The grating lobe is the replicas of main lobe coming in an undesired direction. So in practice, we choose $\lambda/2$ as optimum element spacing.

2.2.2 Beamforming scheme

From the array factor formula, it is evident that the maximum AF is coming with $\psi=0$.

$$\psi = kd \cos \theta + \beta = 0 \Rightarrow \beta = -kd \cos \theta$$

Where θ is the direction of the maximum radiation, which is the direction of main lobe. When $\theta=90^\circ$, the main lobe direction is 90° and phase delay $\beta=0$, that means all antenna elements would be driven with the same phase. The maximum of the radiation pattern is always directed to the array axis. This array with main lobe at $\theta=90^\circ$ is called Broadside Array. So normalized AF of broadside array function can be simply reduced to

$$AF = \frac{1}{M} \cdot \frac{\sin\left(\frac{Mkd}{2} \cdot \cos \theta\right)}{\sin\left(\frac{kd}{2} \cdot \cos \theta\right)}$$

While $\theta=0^\circ$ or $\theta=180^\circ$, the phase delay could be calculated as $\beta=\pm kd$. This array with

main lobe at $\theta=0^\circ$ or 180° is called End-fire Array. So normalized AF of end-fire array function can be simply reduced to

$$AF = \frac{1}{M} \cdot \frac{\sin\left(\frac{Mkd}{2} \cdot (\cos\theta \mp 1)\right)}{\sin\left(\frac{kd}{2} \cdot (\cos\theta \mp 1)\right)}$$

As we know from above discussion, a broadside array comes with $\theta=90^\circ$ and $\beta=0^\circ$. If we need the array main beam to towards other directions, we could get

$$\psi = kd \cos\theta + \beta = \frac{2\pi}{\lambda} \cdot \frac{\lambda}{2} \cos\theta + \beta = \pi \cos\theta + \beta \Rightarrow \beta = -\pi \cos\theta$$

The linear antenna array is connected to a signal generator or a receiver. To generate main beam towards desired direction and null at other directions, the antenna array needs to feed with multiple signal generators or receivers through a feed network called beamformer. The following 4x4 beamformer with hybrid coupler in Figure 2.4 is called Butler Matrix.

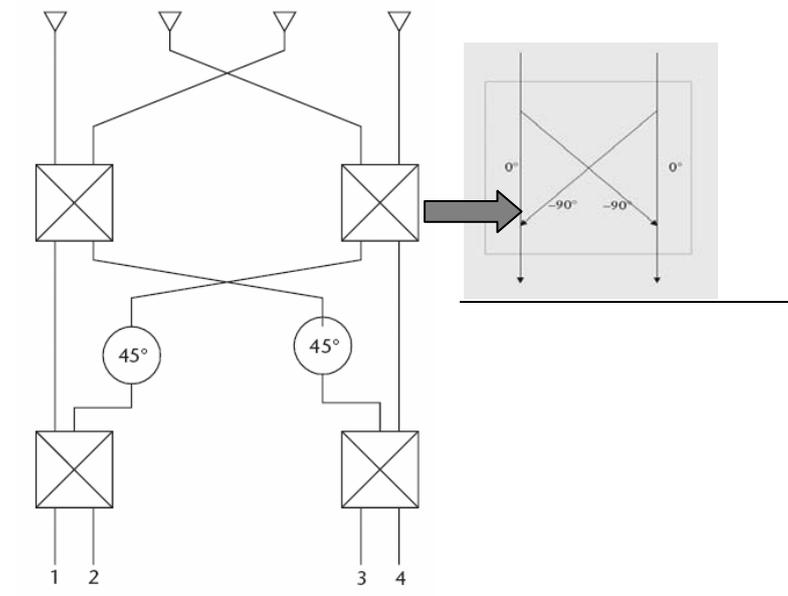


Figure 2.4: 4x4 Butler matrix beamformer [2_1]

In the above fixed beamformer network, the four input ports are connected to four antenna elements and output ports with number are linked to signal generators or receivers. The four 90° hybrid couplers and two phase shifters leads to a phase shift between adjacent input ports and array elements, which results in an array antenna pattern with main beam and nulls in required directions.

2.2.3 Butler matrix

The Butler Matrix is the most popular beamformer network to produce M beams, where M is any integral power of 2. The 90° hybrid power dividers and fixed phase shifters are combined to generate total required phase shift for each array element in order to form simultaneous multiple beams for desired directions. The relationship of element phasing, beam direction, inter-phase shift is presented in Table 2.1.

Table 2.1: Element phasing, beam direction, inter-phase shift for 4x4 butler matrix

	In Port 1	In Port 2	In Port 3	In Port 4	Inter-Phase Shift β	Beam Direction θ
Out Port 1	0°	-45°	-90°	-135°	-45°	104.5°
Out Port 2	-90°	45°	-180°	-45°	135°	41.4°
Out Port 3	-45°	-180°	45°	-90°	-135°	138.6°
Out Port 4	-135°	-90°	-45°	0°	45°	75.6°

The result of radiation pattern is showed in Figure 2.5. It is evident that each output port main beam is corresponding to other output port null, which is called perfect orthogonal. That special characteristic is useful for switched beam system and adaptive array system discussed later. [2_1] [2_7] [2_6]

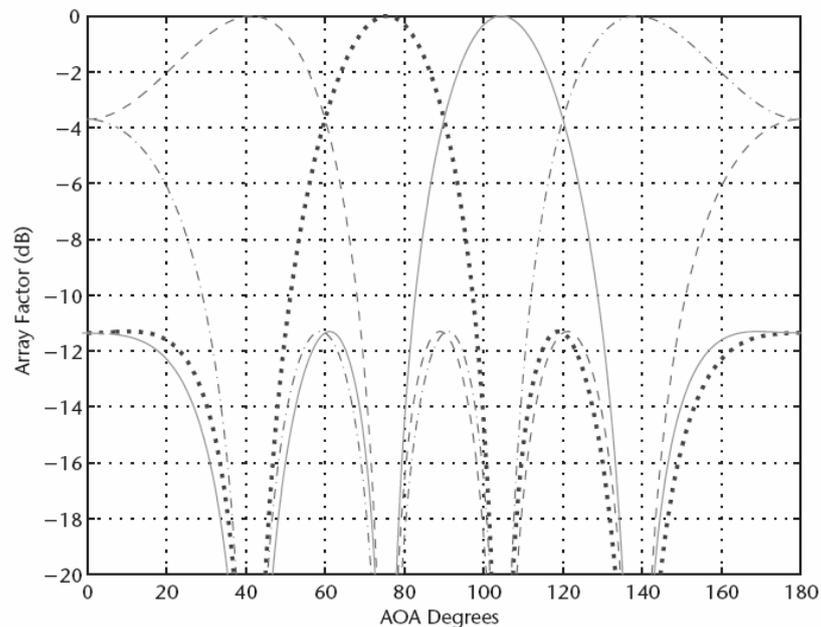


Figure 2.5: Antenna radiation pattern of 4x4 butler matrix beamformer [2_1]

2.2 Switched beam antennas

The switched beam antenna produce a group of overlapped fixed directional beams together result in omni-directional coverage. The principle switching function is to select among separate antenna elements in receiving mode or predefined array beams in transmission mode. The block diagram of switched beam antenna in Figure 2.6 consists of a fixed BeamFormer Network (BFN), RF switch unit for actuating the right beam and control logic unit for beam selecting. [2_1]

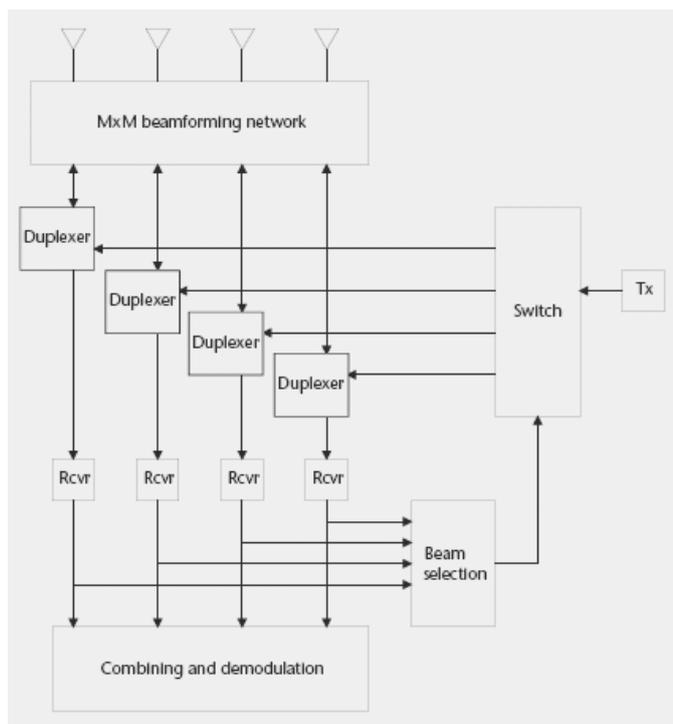


Figure 2.6: Block diagram of switched beam antennas

The basic operation of switched beam antenna is presented as follow. An array of M antennas is combined using a Butler matrix beamformer network which sums up input signal from every antenna ports and produce M separate beams. The switch unit then generates a path from beamformer network output port to the desired radio channel which is connected to multiple receivers. The beam selection unit will work by monitoring all the beams and radio frequency channels. It would choose the optimum beam for each frequency channel and send the result binding information to switch unit. Normally the beam with the highest SNR would be selected. The switch unit finally would produce a radio frequency path from the selected beam to the receiver. [2_1]

This smart antenna technique is quite simple in operation and cheap in cost. It works well in low interference environment but poorly in high interference environment due to its natural characteristic, predefined fixed beams.

2.3 Adaptive array antennas

With advanced signal processing functionality, the adaptive antenna system could steer the main beam dynamically towards the target terminal even a mobile terminal and introduce null towards interference arising from other terminals. The operation principle of adaptive antenna is presented next.

Based on the received signal from output of antenna array, Directional of Arrival (DOA) algorithms are utilized to compute and estimate the direction of arrival of multipath signals and interfering signals. Then the estimated angle information is fed to beamforming network.

Once receiving the result of DOA, beamforming network works to compute the complex weight including amplitude and phase information used for beam steer. The desired terminal signal would be identified in the end. When this terminal is moving, beamforming network will update the complex weight accordingly.

Based on the desired terminal direction of arrival information, the radiation pattern of antenna array is formed and the main beam will continuously steer in the direction of desired terminal and null will also constantly towards to interfering terminals. Like switched beam antenna system, the direction of main beam is determined by the inter-element phase shift, so adaptive antenna system could steer the main beam to the desired terminal continuously by adjusting this phase shift β .

In fact, the Digital Signal Processing (DSP) is the core technology of adaptive antenna system, because most of dynamic adjusting functionality is done by DSP. The basic process is as follow. The received signal is required to down-convert to baseband or intermediate frequency and then converted to digital format by Analog-to-Digital Converter (ADC) in order to further be processed by DSP. Then the signal processor will begin to work after receiving these signals. It will interpret these incoming data and compute the complex weight and finally multiply these weights to each element output to generate the radiation pattern.

There are several optimization criterions to achieve maximum beam gain at the desired direction and minimize noise and interference in other directions. These adaptive algorithms could update and compute the optimum complex weight due to changing propagation environment. The adaptive algorithms can be classified by different approaches and summarized in Table 2.2. [2_1][2_7]

Table 2.2: Category of adaptation algorithms

Category	Criteria Description	Algorithms
Based on Adaptation		
Continuous Adaptation	The weights are adjusted by the updating incoming data in order to converge to the optimal solution.	Least Mean Square (LMS); Recursive Least Square (RLS)
Block Adaptation	The weights are adjusted by estimating from a temporal block of data periodically.	Sample Matrix Inversion (SMI)
Based on Information Required		
Reference Signal Based	The mean square error between received signal and reference signal which has high correlation with desired signal is to be minimized.	Least Mean Square (LMS); Recursive Least Square (RLS); Sample Matrix Inversion (SMI)
Blind Adaptive Based	The required reference signal is not received but is generated from the received signal by the algorithms itself.	Constant Modulus (CMA); Cyclostationary; Decision-Directed

2.4 Directional antenna model used in QualNet simulator

QualNet is network simulation software developed by Scalable Network Technologies. In the QualNet, the directional antenna radiation pattern is defined in the default.antenna-azimuth file. The antenna array consists of eight antenna elements arranged in the circular form, with each element having an omni-directional pattern. The element space is 0.4λ . This array radiation pattern presented in Figure 2.7 is produced by phase shift algorithm. The radiation pattern portrays the eight different predefined directional beams with beamwidth of 45° to cover all the directions.

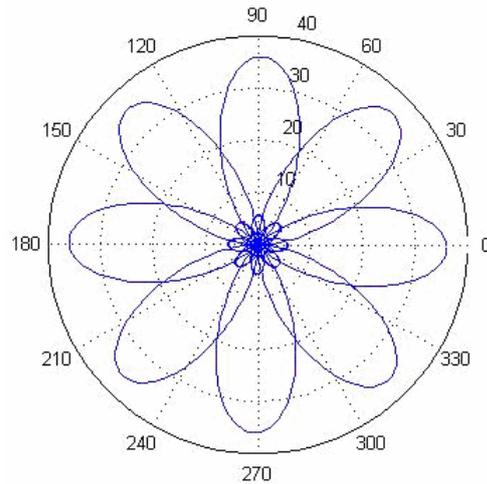


Figure 2.7: Antenna radiation pattern used in QualNet

Figure 2.8 shows the eight element pattern together in one orthogonal coordinate, it is obvious that each main beam is coming with null in all other element patterns and the different maximum gain between each main beam is less than 3dB.

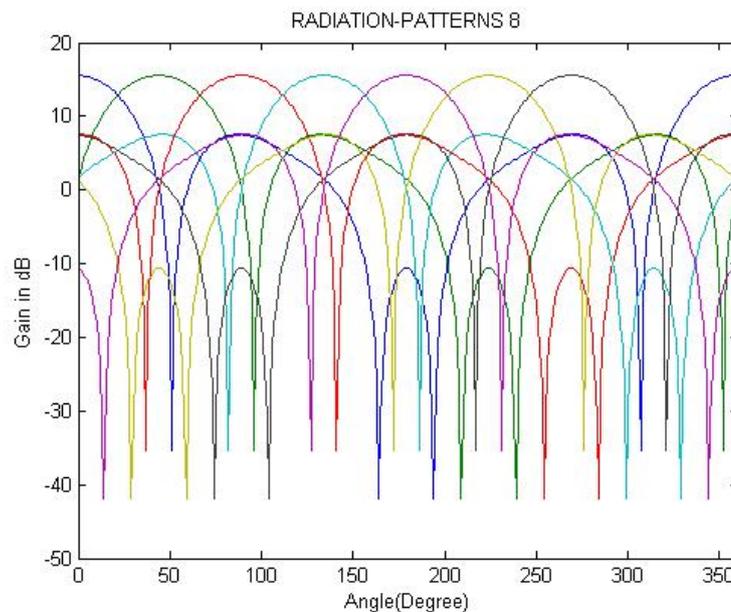


Figure 2.8: 8 Element antenna pattern used in QualNet

Working in the MAC layer, the switched beam antenna is assumed to transmit RTS frame directionally or omni-directionally depending on whether the location of desired receiver node is known or not and send CTS and data frame in the direction of the source node. The beam pattern will be locked while the communication is going on and unlocked after the ACK frame is successfully exchanged. [2_8]

2.5 Comments and summary

In this chapter, basic concepts of smart antenna technology are reviewed. Beamforming, the core technique of antenna array, is discussed in detail from the mathematics point of view. Different algorithms to generate the radiation pattern in both switched beam and adaptive array antennas are summarized.

In fact, switched beam and adaptive array antenna are two main kinds of smart antenna. Both of them have their own merits and drawbacks. Let's make a comparison of them from the following points of view.

- **Cost/Incorporation**
Building a switched beam system is much cheaper than adaptive array system due to complex signal processing technologies needed in adaptive array antennas. Switched beam antennas are commonly implemented as add-on technology due to its simple structure, while Adaptive array antenna requires more new hardware when deploying with a fully integrated approach.
- **Range/Coverage**
The switched beam antenna could increase range from 20 to 200 percent over traditional sector cells depending on environment and hardware/software used. With more advanced signal processing functionality, adaptive array could cover a larger and more uniform area with same transmitting power as switched beam antenna.
- **Interference Rejection**
The switched beam antenna could reduce the interference from other directions away from main beam. However, the predefined fixed beam could not support continuously tracking the desired moving terminal due to the fact that it cannot distinguish between a desired signal and interference, the interference would enhance significantly provided that the interfering terminal is accidentally in the direction of the current main beam. While adaptive array antenna could generate a narrower main beam and could dynamically focus to desire terminal, so it could support more comprehensive interference rejection.

The coverage comparison in Figure 2.9 suggests that switched beam antennas outperform conventional antennas and the switched beam antennas perform better in less interference environment but work poorer in higher interference environment. In any environments, adaptive array antennas always have advantage.

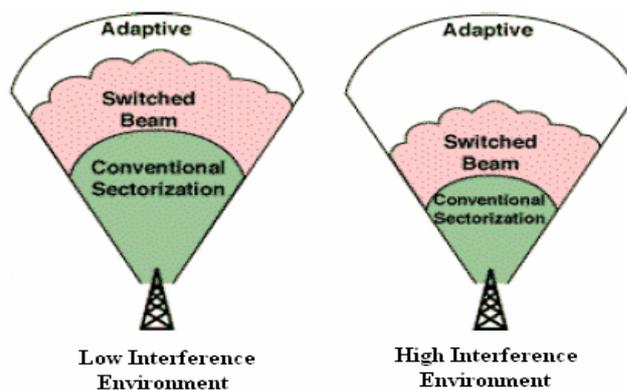


Figure 2.9: Coverage pattern for switched beam and adaptive array antennas

- SDMA
The adaptive array system employs advanced processing technology to achieve more efficient frequency reuse due to higher level of interference rejections and more efficiently steering desired terminal continuous than switched beam antenna. [2_3]

CHAPTER 3

BASICS OF IEEE 802.11 MAC LAYER OPERATIONS

This chapter first present the IEEE 802.11 network structure including Physical (PHY) and MAC layer and protocol family in briefly. Then it focuses on the distributed MAC protocol and discusses the motivation and basic operation of CSMA/CA, VCS and fragmentation in detail.

Nowadays, the lifestyle of people has become more and more mobile, and they would like to check email on the subway, call friends on walking and surf internet with personal digital devices in public area. Wireless connectivity makes people do anything anytime and anyplace without worrying about the restriction of fixed cable. As a result, the traditional computer network can not satisfy the challenges posed by people new demand. It is motivated to launch a new network technology which could support people using broadband network services regardless of location. IEEE 802.11 is such a kind of wireless network specification which is popularly utilized in Wireless Local Area Network (WLAN).

3.1 Overview of IEEE 802.11 networks

IEEE 802.11 family includes a set of protocols which mainly define both PHY and MAC layers of the OSI model for wireless network. The PHY layer describes how to transmit and receive with RF technology and the MAC layer specifies how different frames of different users compete for limited medium to forward packets. The operating frequencies of IEEE 802.11 standard include two Industrial, Science and Medical (ISM) frequency band, 2.4GHz and 5.8GHz. The 802.11 network topology is either infrastructure based which needs a fixed access point or base station to centralize or infrastructure-less based which enable flexible peer-to-peer communication. Original IEEE 802.11 standard was frozen in 1999, however there are still some 802.11 standard amendments going on, such as 802.11f for Inter-Access Point Protocol (IAPP), 802.11e for Quality of Service (QoS), 802.11i for security, 802.11h for transmit power control/dynamic frequency selection and 802.11d for scanning schemes. Figure 3.1 illustrates the relationship of various components in the 802.11 family. [3_1] [3_2]

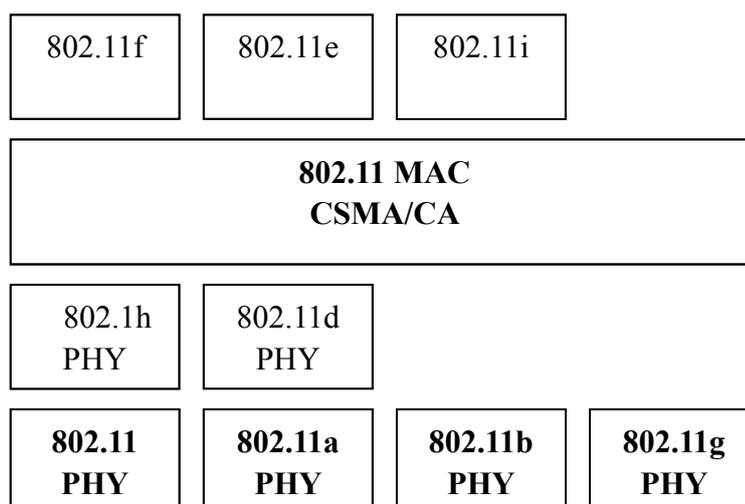


Figure 3.1: IEEE 802.11 family tree

IEEE 802.11a uses the unlicensed 5 GHz frequency band and could support transmission data rate up to 54Mbps, which applied Orthogonal Frequency Division Multicarrier (OFDM) in the Physical Layer as transmission scheme.

IEEE 802.11b is operated on another unlicensed 2.4GHz frequency band based on Direct-Sequence Spread-Spectrum (DSSS) link layer protocol but has lower maximum transmission data rate (11 Mbps) compared to IEEE 802.11a due to channel conditions and protocol overhead.

IEEE 802.11g is operated on the same frequency band as 802.11b (2.4GHz) and applied the same physical layer protocol as 802.11a (OFDM) which enables the maximum transmission data rate of 54Mbps.

Due to using same frequency band, the inter-working between 802.11b and 802.11g becomes possible. There are two options in 802.11g header of signal structure. The DSSS header option also named DSSS-OFDM enable an 802.11g terminal to use CSMA/CA mechanism when competing for accessing medium with 802.11b terminal. The OFDM header option also named as ERP-OFDM use RTS/CTS mechanism to compete for accessing channel with 802.11b, because 802.11b can not decode the OFDM header information which makes the CSMA/CA mechanism could not work properly here[3_1] [3_3].

3.2 Distributed coordinate function (DCF)

IEEE 802.11 was originally designed for infrastructure-based wireless local area networks. Point Coordination Function (PCF) is used to support communications in the network via access points or base stations. To satisfy the dramatically increasing demand for mobile communications, IEEE 802.11 DCF is developed to provide communications between multiple independent mobile node pairs without using access

point or base station. [3_4] IEEE 802.11 DCF belongs to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) family which defines various kinds of inter-frame spacing used when a source node intending to access the channel in order to prevent collision happening in the channel. IEEE 802.11 DCF also defines a Virtual Carrier Sensing (VCS) channel reservation mechanism in MAC layer to solve the well known hidden terminal problem.

3.2.1 Carrier sense multiple access with collision avoidance

CSMA is a kind of efficient Time Division Multiple Access (TDMA) mechanism. It enables multiple independent mobile nodes to compete for accessing same medium for communicating with each others at different time to avoid collision happening in the channel. CSMA can also be seen as Space Division Multiple Access (SDMA) mechanism when several mobile node pairs equipped with directional antennas are communicating with each other in the same time slots without interfering each other.

In traditional wired LAN (Ethernet), CSMA/CD is used to detect collisions in MAC layer, if source node could stop transmission immediately when noticing collision happened in wired channel and retransmitting after a backoff period. While owing to source node could not detect channel collision in wireless medium, a new MAC method, CSMA/CA is developed aiming to reduce the probability of collision happen in the channel. CSMA/CA involves various inter-frame spacing which is defined a little bit different in different 802.11 standards and Contention Window (CW) which is used to determine the random back-off time. It forces source nodes wait for above mentioned period before starting transmission to prevent them to access radio channel at the same time. The CSMA/CA mechanism is illustrated in Figure 3.2 and is explained in the next paragraph.

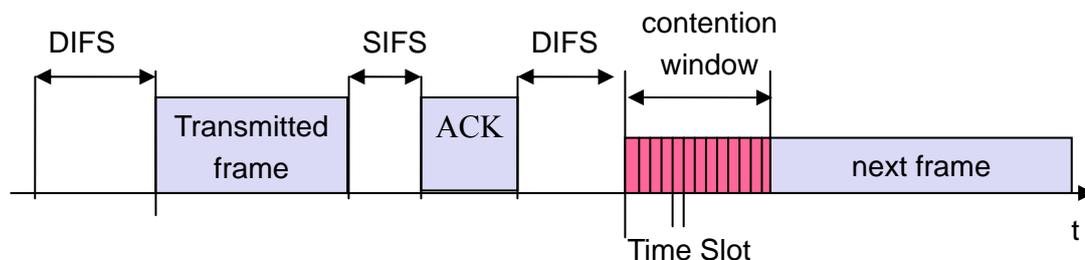


Figure 3.2: Basic operation of CSMA/CA

When a source node intends to send a packet, it first senses the medium. Once the source node detects the medium idle for a longer duration than DIFS, it could transmit the data frame immediately, like the first transmitted frame in Figure 3.2. The destination node would response with an ACK frame after a SIFS when no bit errors are detected, which is based on applying Cyclic Redundancy Check (CRC). The channel is reserved for the whole data transmission and error check process. The following frame can be transmitted at least one DIFS after the reserved duration. The different

inter-frame spacing in μs could be found in Table 3.1. It is obvious that SIFS has more priority than DIFS, which is the reason for using SIFS before CTS, data frame and ACK.

Table 3.1: Inter-frame value in IEEE 802.11

	802.11a	802.11b	802.11g
SIFS	16	10	16
DIFS	34	50	34

To avoid two or more waiting frames to transmit simultaneously immediately after previous transmission data frame releasing the channel, CSMA/CA also adds a random backoff time to every waiting frames after one DIFS. The backoff time slot is chosen randomly from 0 to contention window, failure transmission could cause CW to increase exponentially up to a maximum window size. The time slot varies in different 802.11 standards, eg $9\mu\text{s}$ in 802.11a and $20\mu\text{s}$ in 802.11b. Figure 3.3 shows the dramatically increasing of CW which alleviates collision happens.

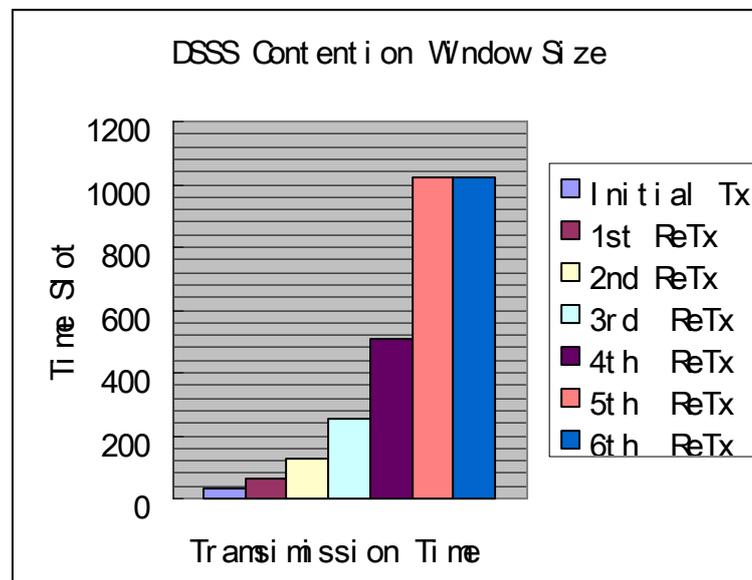


Figure 3.3: DSSS contention window size

When source node senses the medium to be busy, it will wait until the medium to become idle then continue to keep sensing the medium for a DIFS and an additional random back-off. The source node could start to transmit packets after that period only if it senses the medium is always idle within the sensing duration. If the source node senses the medium to become busy during waiting period, it will stop downcounting backoff and defer until the medium is idle again, then it will begin to transmit after waiting for a new DIFS together with the remaining back-off time during which period the medium should keep idle constantly. The CW value can be updated due to bad channel condition. Each time source node fails to transmit, the CW value of this node will increase accordingly up to a maximum CW value 1023 time slots defined by IEEE

802.11a. We could find the larger the CW value, the high probability of bigger random back-off time, the less probability of repeated collisions, and of course the more delay for transmission. After each successful transmission, the source node will generate a post-back-off time interval. [3_1] [3_2] [3_3]

3.2.2 Virtual carrier sense

Carrier sensing is the most important method for alleviating collisions in channel. IEEE 802.11 has defined two kinds of carrier sensing mechanism: PCS and VCS. PCS is operated in physical layer by measuring the signal strength to detect collision. PCS is an effective method in high mobility scenario. Nodes around active communication links could still sense channel even they fail to receive medium control packets. However, PCS hardware for RF-based media is expensive to build. Another big problem is that PCS can not solve the well known hidden terminal problem which is illustrated in detail in the following paragraph. VCS operated in MAC layer could perfectly solve the above problems by introducing Network Allocation Vector (NAV) and Request to Send (RTS)/Clear to Send (CTS) mechanism. NAV is kind of timer which indicated the time duration the channel is reserved for transmitting data frames and all necessary control frames. Each node with a NAV timer can not transmit until this time downcount to 0 which means the channel is idle. [3_1] Figure 3.4 shows the basic operation of VCS which is explained as follow.

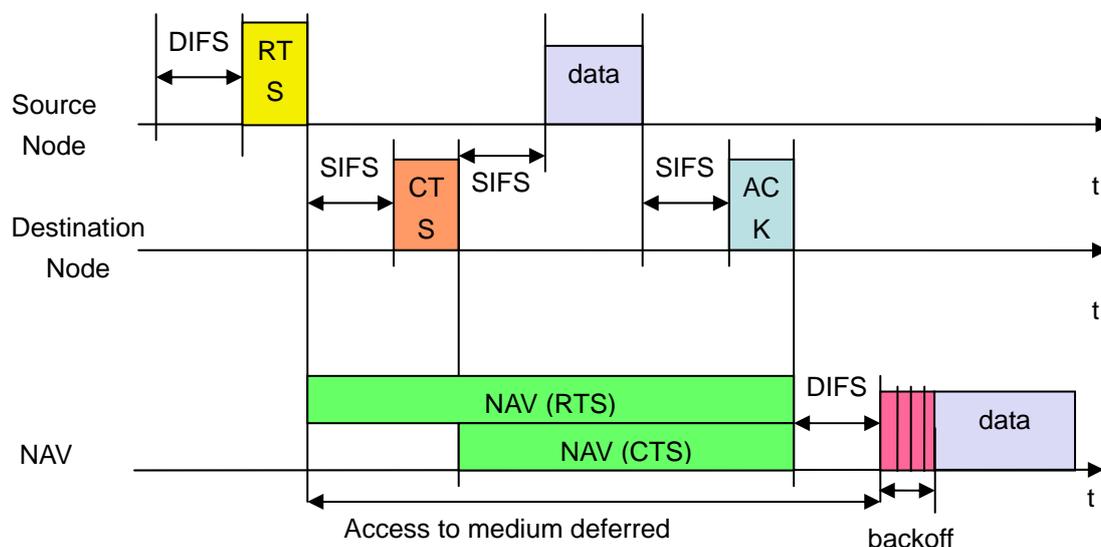


Figure 3.4: Virtual carrier sense

A source node which is intending to transmit first broadcast a RTS packet, after detecting the medium is idle for a DIFS time, to its neighbor nodes to ask whether the medium is free before transmitting data packets. After detecting the medium is free, the receivers will generate a CTS after a SIFS time, then the transmission can start after an

delay of a SIFS time. The surrounding nodes which overhear these messages will be controlled by NAV in order to prevent interference. The NAV duration is announced within RTS/CTS frame for the region covered by the transmission range of the source and destination node. The region is reserved for the required data transmission, other nodes within this area region will keep silence, and that is the reason to call it as silenced region. After the destination node successfully received the data packet, it will send an ACK back to the source node after a SIFS time. The following node intending to send data could begin to sense the channel and downcount backoff timer after a DIFS and prepare to transmit. The RTS/CTS could absent when their frame size is comparable with data frame size, which is controlled by a threshold parameter `dot11RTSThreshold`. That means that data frame shorter than this value is transmitted without RTS/CTS exchange. [3_1] [3_5]

The RTS/CTS mechanism is also a good solution for the hidden terminal problem whose scenario is shown in Figure 3.5. The hidden terminal problem is introduced briefly as follow. It will happen when two source nodes send packets to the same destination node at the same time due to unawareness of the existences of each other. In the flowing scenario source node A is transmitting packets to B. Another source node C also wants to transmit packets to B because C is out of transmission range of A and can not physical carrier sense the on going transmission of A. A is “hidden” for C, which could lead to channel collision and hence reduce the throughput significantly. [3_6]

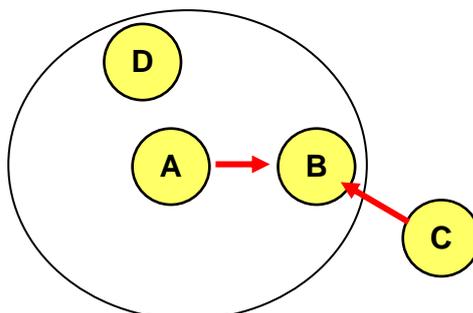


Figure 3.5: Hidden terminal problem

The solution provided by VCS is explained together with Figure 3.6 which shows the same scenario as above. Using VCS mechanism source node A first generate a RTS and broadcast it to its neighbor B and D. Destination node B then answers a CTS to A and also send it to its neighbor node C. Although node C is out of transmission range of A, it can still receive the CTS message from B to update its NAV. It will make sure there are not inferences during data transmission. [3_6]

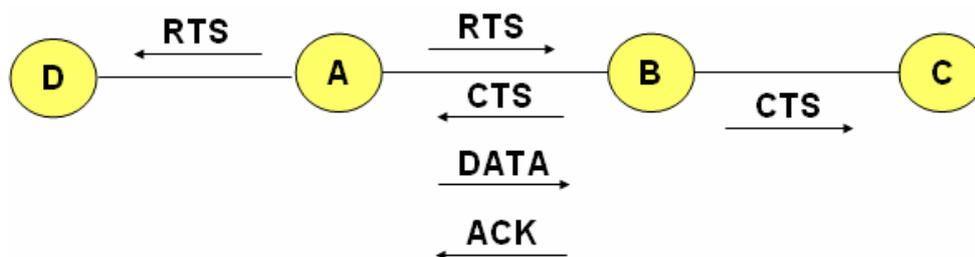


Figure 3.6: Solution for hidden terminal

3.2.3 Fragmentation

Often a source node needs to send more than one frame, there will be lots of RTS/CTS transmission and backoff time wastes in the channel using traditional VCS mechanism. In order to save channel capacity and avoid collisions, we could use fragmentation to send a long frame. After channel sensing and initial RTS/CTS exchange, source node will transmit data frame by frame followed by an ACK for each. The inter-frame spacing between frame and ACK is SIFS. The process could be described like RTS+CTS+Frag0+ACK0+Frag1+ACK1+ Frag2+ACK2+... [3_2] Another reason to use Fragmentation is that there is a higher Bit Error Rate (BER) of 10^{-4} in wireless channel compared with BER of 10^{-9} in fiber optics. Obviously short frame size could lead to less transmission error, and the time for retransmission is much shorter than before even when error occurs. [3_7]

3.3 Summary

In this chapter, an overview of IEEE 802.11 wireless LAN standards is presented and the principle operation of DCF is investigated. From the discussion, it is evident that the conventional 802.11 MAC protocol could solve hidden terminal problem with RTS/CTS mechanism and support wireless communication perfectly when terminals in the network equipped with traditional omni-directional antennas.

CHAPTER 4

AD HOC MAC WITH DIRECTIONAL ANTENNAS

This chapter investigates several distributed MAC protocols with directional antennas. A number of challenges introduced by directional antenna using conversational MAC protocol are presented first. The problems motivate the development of new MAC protocols based on traditional IEEE 802.11 DCF. We will review five modified MAC protocols with directional antennas and compare them from various points of views. The basic idea of these new MAC schemes is that they define different transmit and receive strategies for different MAC control frames in order to completely exploit directional antennas to obtain better performance.

Using directional antenna in ad hoc networks could bring many advantages over omni-directional antenna. The main reason is that directional antenna enable signal energy accurately focuses on the desired direction for transmitting or receiving. With the same energy as omni-directional antenna, directional antenna has more antenna gain by increasing the transmission and reception range and reducing signal interference significantly. That means more simultaneous transmission and fewer hops could be possible. All above could lead to increase system throughput, coverage and capacity. [4_1]

Exposed terminal problem, one critical problem in omni-directional antennas is solved by directional antenna by increasing simultaneous transmission. Exposed terminal problem could be described as the nodes within the range of the transmission node but out of the range of receiver node are forbidden to transmit [4_2]. This node is not allowed to transmit in omni-directional antennas, while directional antennas enable it to transmit in a way without interfering the on-going session.

Traditional Ad hoc research is mainly based on omni-directional antennas. This chapter will introduce several new mechanisms at the medium access control layer for exploiting directional antennas. Each node mentioned in this chapter is assumed to have only one radio transceiver which is equipped with several directional antennas.

4.1 Medium access problem with directional antennas

Conventional IEEE 802.11 MAC protocol could not offer substantial network improvements with directional antennas. In fact, sometimes network performance even deteriorates due to several specific problems produced by directional antennas. Some major issues are summarized below and several new MAC mechanisms to mitigate them are reviewed in next several subchapters.

4.1.1 Neighbor location information and main lobe direction

To transmit data with a directional antenna, the source node must first know the direction of the destination node and neighbor nodes which could cause interferences in order to decide the main lobe of antenna gain pattern for transmitting. The receiver node also takes the same procedure to decide the main lobe of antenna gain pattern for receiving.

In traditional way, medium control frame is transmitted omni-directionally. The idle node is assumed to listen to the channel on all its antennas. After it received the RTS transmitted omni-directionally by source node, it response with CTS omni-directionally and records the direction from which they receiving the RTS with the maximum power to identify the source node direction. The source node receives the CTS in the same fashion to identify the receiver node direction. [4_2]

In order to save channel resources by alleviating redundancy of the control frames, two methods are involved to identify the angular position of neighbor nodes in order to transmit RTS/CTS directionally in an efficient manner. One method is that each node use GPS information to compute the neighbor nodes directions. The other method is to estimate DOA using complex algorithms. [4_3]

4.1.2 Extended transmission range

Increasing transmission range is one merit of direction antenna, which could reduces number of hops and even achieves connecting between far network clusters. The other side of the coin is that longer transmission range could lead to interference to far nodes. Since conventional medium control frames transmit omni-directionally, directional forwarding data could reach beyond the reserved area due to higher antenna gain. [4_3] To solve these problems, some new MAC protocols assume that directional antennas have the same transmission range as omni-directional antenna.

4.1.3 New hidden terminal problem

The hidden terminal problem could be described as the nodes out of the range of transmission node but within the range of the receiver node which could interfere with this receiver node in an unawareness way. [4_2] Traditional hidden terminal problem is solved by the RTS/CTS mechanism of IEEE 802.11 MAC protocol, but there are new problems when using directional antennas basically due to two reasons: unheard RTS/CTS and asymmetric antenna gain between omni and directional antennas.

- New hidden terminal problem due to unheard RTS/CTS

The new hidden terminal problem due to unheard RTS/CTS is caused by the directional antenna pattern which has a larger gain in the desired direction and a lower gain in other directions.

This situation could be depicted as in Figure 4.1. Assume that the communication between A and B is going on. C intends to send packet to D, and then it initiates Directional RTS (DRTS) to D. Although A is in the transmission range of DCTS initialed by D, A could not hear it due to beamforming to B. When communication between C and D is on process, A finishes its communication with B and wants to send packet to D. It is very likely that the DRTS initialed by A would interfere with data send by C, which leads to collision at D. [4_5]

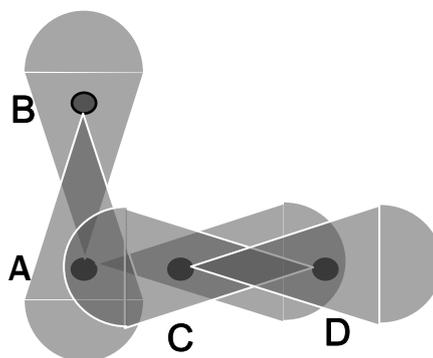


Figure 4.1: New hidden terminal problem due to unheard RTS/CTS

- New hidden terminal problem due to asymmetric gain

The new hidden terminal problem due to asymmetric gain is caused by the fact that directional antennas have much larger gain than omni-directional antennas.

The problem could be depicted as in Figure 4.2. Assume that A and B have established a communication link with directional antennas. That means A and B are beamforming towards each other. Node C which is far from node A is sensing channel omni-directionally and it could not detect that the channel is busy, because the gain of the omni-directional antennas is much lower than directional antennas. Once C intends

to communicate with A using directional antenna, it is very likely that the RTS initiated by C would interfere with data send by A, which could leads to collision at B. [4_5]

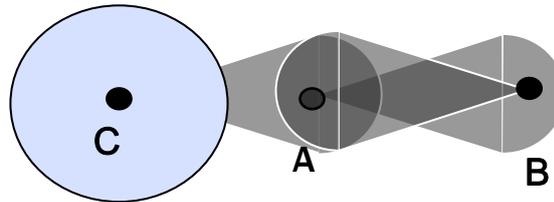


Figure 4.2: New hidden terminal problem due to asymmetric gain

This problem could also be illustrated in the view of mathematics. The two-ray model is chosen as path loss model in wireless ad hoc network, all the parameters in the following formulas use absolute value.

$$P_R = P_T \cdot G_T \cdot G_R \frac{h_T^2 \cdot h_R^2}{D^4}, \text{ where}$$

P_R is the power level at receiver,

sometimes $P_{R,\min}$ is used to represent the minimum receiving power level

P_T is the power level at transmitter

G_T is the transmitter antenna gain

G_R is the receiver antenna gain

h_T / h_R is the transmitter/receiver antenna height

D is the distance between transmitter and receiver

We could rearrange the above equation to obtain maximum transmission range as below

$$D_{\max} = \sqrt[4]{\frac{P_T}{P_{R,\min}} \cdot h_T^2 h_R^2} \cdot \sqrt[4]{G_T \cdot G_R} = K \cdot \sqrt[4]{G_T \cdot G_R}$$

Where K a constant value can be used to simplify the above equation

$$K = \sqrt[4]{\left(\frac{P_T}{P_{R,\min}}\right) \cdot h_T^2 h_R^2}$$

It is obvious that directional antenna gain G_d is much larger than omni-directional antenna gain G_o . The directional RTS/CTS transmission range when the potential interfering nodes is in omni mode is

$$D_{do} = K \cdot \sqrt[4]{G_d \cdot G_o}$$

When the communication is on process, although the potential interfering nodes are out of transmission range of RTS/CTS and cannot receive RTS/CTS in omni-directional mode, it is very likely that they interfere with this on-going communication when transferring data frame with directional antennas. The maximum interfering range between current communication node and interfering nodes is

$$D_{dd} = K \cdot \sqrt[4]{G_d \cdot G_d}$$

Due to the asymmetric gain, we could see there is a neglect ring area between DO link and DD link which is depicted in Figure 4.3. The grey area is the interfering ring where neighbor nodes unheard RTS/CTS packet could cause interferences to the active communication. That is the new hidden problem due to asymmetric gain.

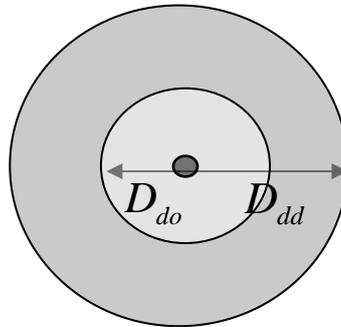


Figure 4.3: Interfering ring

4.1.4 Deafness problem

The deafness problem is caused when a source node fails to communicate with desired receiver which is beamforming to another direction for an on-going communication.

This problem is depicted as in Figure 4.4. Assume that C intends to communicate with B using relay node A. After receiving packet from C, node A beamforms in the direction of B to forward this packet. Because C is out of range of control frame exchange between A and B, it could not sense the channel is busy, then C send new packet to B via A. If node A happens to send a packet to B by beamforming in that direction, it could not receive the packet initiated by C. The deafness of A would lead multiple retransmissions initiated by C, which causes serious wastage of channel resources. [4_4]

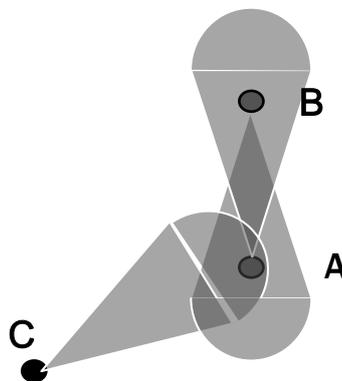


Figure 4.4: Deafness Problem

4.2 Directional MAC (DMAC) scheme

Two MAC scheme extensions of IEEE 802.11 DCF using directional antenna are proposed in [4_6]. The main modifications are directional transmission of RTS, DATA and ACK and alternative omni-directional transmission of RTS if none of antenna pattern of transmitter is blocked. Actually they are per-antenna basis IEEE 802.11 DCF protocol. A node would not transmit in the direction by which it receiving directional RTS or CTS until the on-going communication completes, but it can transmit in other directions simultaneously.

4.2.1 Network model

Each node equipped with one transceiver and multiple directional antennas is assumed to know about the location of all neighbor nodes and own location using GPS device. A node could not transmit two packets simultaneously via different antennas due to one transceiver. The transmission range of a directional antenna is assumed to be the same as omni-directional antenna.

4.2.2 DMAC scheme 1

DMAC scheme 1 allows a source node to transmit RTS packets directionally point to destination node and destination node to transmit CTS packet omni-directionally after successfully obtaining RTS packet. Figure 4.5 depicts the basic operation of DMAC 1. Node A intends to send data to B and also assumes that there is no active communication within A neighborhood area. Node A sends a DRTS packet to B and node B then reply a CTS packet omni-directionally to all its neighbor nodes. After RTS/CTS exchange successfully, Node A would send data packet directionally towards B and receives directional ACK from Node B in the end to ensure errorless transmission.

The pro of DMAC 1 is obviously efficient utilization of bandwidth and higher spatial reuse than conventional IEEE 802.11 DCF. One example is that traditional IEEE 802.11 DCF prevents node C from transmitting when communication between A and B is on process. While DMAC 1 enables C to transmit in the opposite direction of current communication session of A and B, so Node C could send data packets to D simultaneously.

The con of DMAC 1 is possible increasing collision probability of control packets due

to the use of directional RTS packet. For example node E in Figure 4.5 could not overhear DRTS packets send by A and it assumes the channel is idle as matter of course. When node E intends to communicate with A, the DRTS packet initiated from node E could be collided with CTS, data or ACK send from node B at the node A, which motivates to develop DMAC 2 to solve this problem.

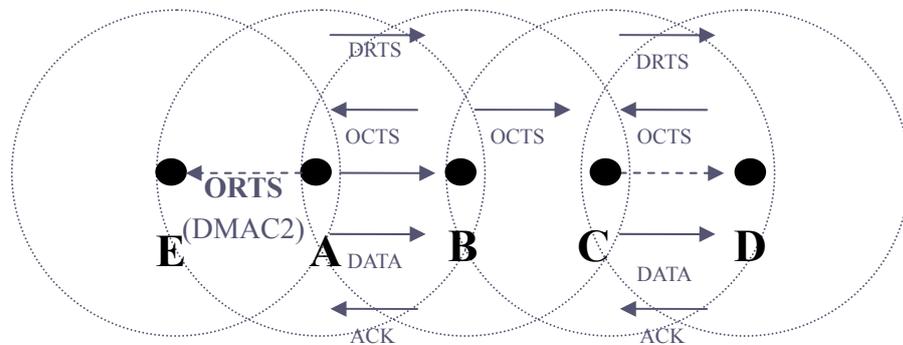


Figure 4.5: DMAC scheme 1&2

4.2.3 DMAC scheme 2

The difference between DMAC 2 and DMAC 1 is in setting a condition in DMAC 2 before the source node transmits RTS packet. The condition as follow:

- If none of the directional antennas of source node are blocked by other on-going communications, then source node would send an omni-directional RTS packet.
- Otherwise, it would send a directional RTS packet via the directional antennas which are not blocked.

In the above scenario, when source node A finds that all its directional antennas are not blocked, it will transmit RTS omni-directionally. Node E of course will receive one copy of RTS and defer its transmission during the on-going communication of A and B.

One potential problem of the above scenario is presented in Figure 4.6. Assume that D far away from current on-going communication between A and B intends to send data to packet to C and transmit directional RTS packet point to C first. Node C, which is within range of B's OCTS packet, could not reply an OCTS packet to D in order to interfere with B. Due to unhearing OCTS packet, D will retransmit DRTS continuously based on backoff mechanism in IEEE 802.11.

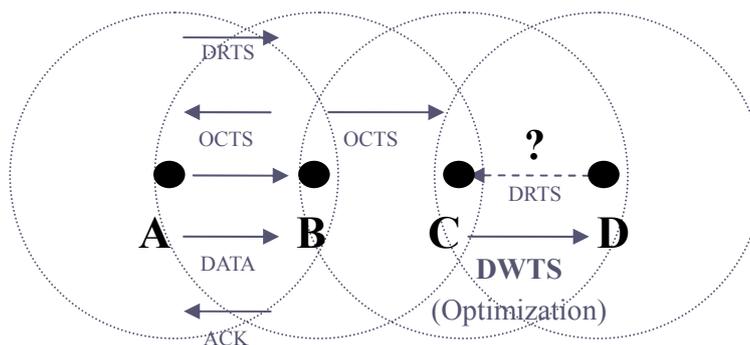


Figure 4.6: DMAC optimization

4.2.4 Directional wait to send

When the above scenario occurs, C would send a directional Wait to Send (WTS) packet to D without interfering with B instead of keeping silence passively. This DWTS reports the desired receiver antenna is blocked by other on-going communications and how long this communication will take. Then the source node D when receiving DWTS will defer its retransmission accordingly. [4_6]

4.3 Multi-hop RTS MAC (MMAC) scheme

The multi-hop RTS MAC scheme exploits the higher transmission gain of directional antennas to compensate for negative impact of new hidden terminal problem and deafness problem by reducing route length (number of hops).

4.3.1 Network model

MMAC enables directional reception together with directional transmission. Each node is equipped with an omni-directional antenna and an adaptive antenna which have higher gain than the omni-directional antenna. So the neighbor nodes could be divided into two groups based on utilizing different antennas.

- Direction-Omni (DO) Neighbor is the neighbor node which could receive a directional transmission packet even it senses a channel using omni-directional antennas
- Direction-Direction (DD) Neighbor is the neighbor node which is able to receive the directional transmission packet only when its directional antenna beamforms the current sender node for reception.

Obviously DD-neighbor route is much longer than DO-neighbor route, which could save number of hops. [4_5]

4.3.2 The detailed protocol

The basic operation of MMAC could be described as follow based on Figure 4.7. Assume that node A intends to send data packet to F. Using the above new classification method, the neighbor nodes can be sorted as DD neighbor A-F and DO neighbor A-B-C-F. Node A first send DRTS packet towards F. Then the neighbor nodes between A and F like D and G would defer for transmission along this direction during A-F communication is going on. If F happens to beamform its directional antenna to A, the DD link would be established immediately. Otherwise DD link will need DO neighbor nodes to establish directional communication. Node A will send forwarding-RTS packet to DO neighbor Node B, and B will forward it through C to F. The intermediate nodes send the forwarding-RTS without any backoff and will not update its DNAV tables, which speeds up the forwarding time. In the meantime, A beamforms in the direction of F and waits for directional CTS. When destination node F receives the forwarding-RTS and then replies with a CTS packet in the direction of A. Finally after A receiving the CTS from A via DD route, the DD link will be established and communication could start. [4_5]

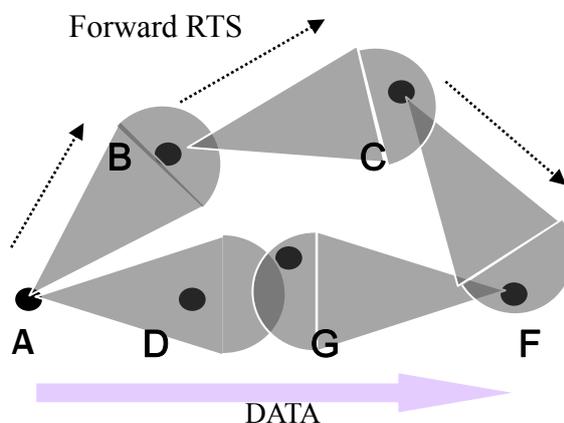


Figure 4.7: Multi-hop RTS MAC scheme

4.4 Directional Virtual Carrier Sensing (DVCS) scheme

DVCS is a new carrier sensing mechanism for wireless communication using directional antenna and also supports interoperability of directional and omni-directional antenna. DVCS selectively disables particular directions in which the node would interfere with on-going communications, and allows the node to transmit

via other directions, which increases network capacity greatly.

4.4.1 Network model

DVCS not only allows directional transmission but also enables directional reception. The transmission range of directional antenna is assumed to be the same as the omni-directional antenna. To locate each node on demand, DVCS only requires minimum information from physical device like Angle of Arrival (AOA) and antenna gain for each signal instead of any additional hardware like GPS device.

4.4.2 The detailed protocol

DVCS is still based on IEEE 802.11 DCF MAC protocol with AOA, beam locking/unlocking and Directional NAV (DNAV) setting. The only three significant differences between DVCS and IEEE 802.11 VCS are as follows:

- AOA caching

Every node estimates and caches the angle of arrival of any signals received from its neighbors all the time. The node intending to transmit packets will send RTS packet directionally towards the receiver if the cache held the AOA information for the desired node and it will retransmit up to 4 times when failing to get any CTS packets; otherwise it will resend omni-directional RTS packet up to 3 times.

- Beam locking/unlocking

When the destination node receives the RTS or the DRTS, it will adjust its main lobe towards the direction of the source node and lock the pattern for further sending CTS and ACK frame. After receiving the DCTS send by destination node, the source node would also lock the main lobe towards the destination node and lock the pattern for transmitting data. Both of these patterns will be unlocked after that the source node receives an ACK packet successfully.

- DNAV setting

DNAV is directional version of NAV which only prevents a small amount of interference nodes from transmitting in certain directions in order to increase spatial reuse. Each DNAV includes a direction and a width to define which angle range of the directional antennas of that node should be disabled, together with a timer to define how long this situation lasts. So when an intermediate node overhears a packet not meant for itself, it will calculate the AOA of this signal and set the DNAV according to the result of AOA.

DVCS could increase network capacity significantly which could be depicted with the following scenario in Figure 4.8. Assume that A intends to send packets to B. Node C

along the active communication link will receive the DRTS from A and DCTS (Directional CTS) from B and update its DNAVs based on the AOA of A and B together with the defined width of DNAV. The two light grey areas in the directional antenna pattern of C is prevented from transmission during communication between A and B is in process. However C could still send packets to the other directions such as in the direction of D. Two nearby communication sessions could be running simultaneously without interfering each other, whose phenomenon is impossible by utilizing omni-directional antennas but directional antennas with DVCS. [4_7] Using DVCS, the nodes along active communication link have free space for transmission, which could also reduce the negative impact of new hidden terminal problem due to unheard RTS/CTS.

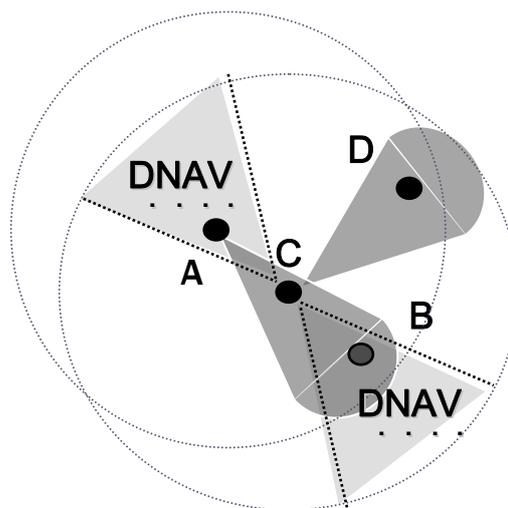


Figure 4.8: DVCS scheme

4.5 Circular DRTS (C-DRTS) scheme

The C-DRTS scheme needs neither any additional location identifying hardware like a GPS device nor any neighbor location estimation algorithms. Without any predetermined neighbor location information, the source node uses all directional antennas circularly scanning the whole neighbor area to inform the neighbors for the intended communication. It also enables all control packets directional transmissions in order to reduce the negative impact of new hidden terminal problem and deafness problem.

4.5.1 Network model

Due to the use of the scanning scheme, each directional antenna needs to be numbered with the same rule beforehand. Suppose that each node is equipped with M directional antennas, which construct M beams without overlapping. We could number these beams from 1 to M clockwise beginning with the beam located just right of the 3'o

clock position. The coverage area formed by successive sequential scanning of directional antennas is much larger than omni-directional antenna due to higher gain in directional antennas.

4.5.2 The detailed protocol

Each node also needs to maintain a location table for recording information of neighbor nodes. The table contains identification of neighbor node and own, the beam number from which the neighbor node could receive the neighbor node packet and the beam number through which it sends packet to. The location table would be updated dynamically once receiving any packets from neighbor nodes to avoid out of date information.

The source node would first transmit a DRTS packet consecutively in a circular way. The destination node when receiving this control packet will transmit CTS directionally towards the direction of the source node after the source node finishing RTS scanning in a whole circle. Once the source node receiving the DCTS in omni-directional reception mode, the communication starts. Because every control packet header contains the beam pair which the source node and destination node will use to transmit and receive packet. The intermediate node that receives RTS or CTS packets will examine its location table to find the neighbor node (source or destination node) through which beam to send the control packet to itself. If the beam number is the same as the beam pair inside the control packet header, which means the source or destination node not only use the same beam to transmit control packets to this intermediate node but also intend to maintain the active commutation link. So this intermediate node should defer transmission using its beam corresponding to the collided neighbor beams during the DNAV time.

From Figure 4.9 it can be seen how C-DRTS scheme works to mitigate the new hidden terminal problem due to asymmetric gain. The left part of this figure depicts the traditional MAC protocol with directional antenna that could not avoid the new hidden terminal problem. Assume that A sends packet to B, the traditional directional RTS and omni-directional CTS exchange could not inform every potential interfering node like C always using omni-directional antennas for receiving in idle mode. Once C intends to send a packet to A or B directionally, it obviously would destroy the active communication dramatically. However, the C-DRTS scheme in the right part of this figure could solve this problem by sending DRTS packets in a circular way, C could receive this control packet even in idle mode and update its DNAV after checking its location table. [4_8]

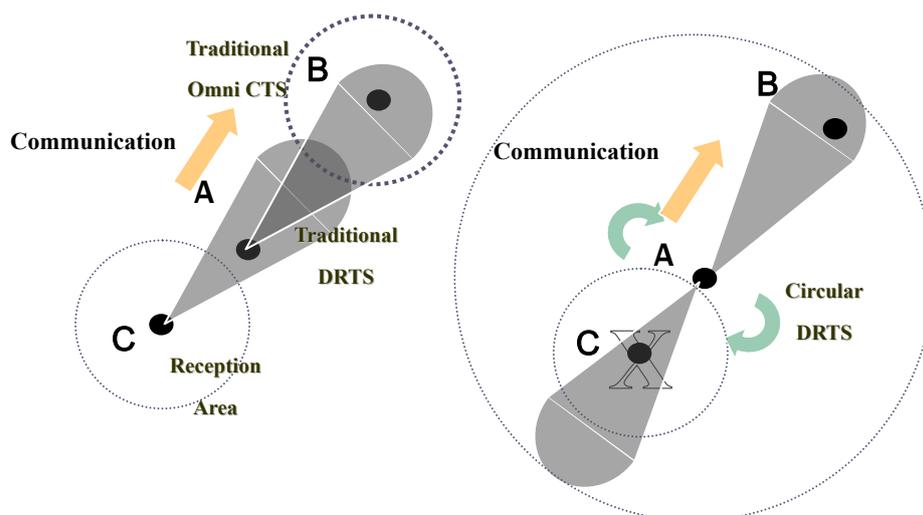


Figure 4.9: Improvement of Circular RTS scheme

4.6 Extended RTC/CTS (E-R/CTS) scheme

The motivation to develop the E-R/CTS scheme is to mitigate the new hidden terminal problems introduced by directional antennas. The hidden terminal node due to asymmetric gain is quite difficult to detect and inform about using traditional MAC protocols with directional antennas, but in fact these nodes could interfere with active communication seriously with DD link, which should be given more attention.

4.6.1 Network model

The E-R/CTS scheme is based on predetermined neighbor node location. There are three main modifications compared with traditional MAC protocols with directional antenna. First, an antenna pattern with two lobes is used to transmit DATA differently from normal one lobe to transmit RTS/CTS/ACK; Second, higher transmitting gain is used to transit RTS/CTS differently from normal directional antenna gain to transmit DATA/ACK; Third, two different NAV timer transmitting NAV and receiving NAV are used to prevent nearby nodes to transmit when receiving RTS and CTS packets.

4.6.2 The detailed protocol

From the first section of this chapter, it is known that the existence of an interfering ring leads to a new hidden terminal problem. This scheme tries to deal with interfering ring to overcome this problem. The term of Forbidden Zones is introduced to help identifying which nodes are potential interfering nodes. It is known from previous deduce in section 4.1.3, the interfering ring is the ring between beyond the radius of DO

link and within the radius of DD link. The interfering ring of the receiver is called Receiver Forbidden Zones (RFZ), and the interfering ring of the transmitter is called Transmitter Forbidden Zones (TFZ).

In the following we separately explain the operation of three modifications to deal with nodes in RFZ and TFZ in detail.

- Two lobe antenna pattern for DATA transmission

Instead of one lobe for transmission of data, the source node would use one extra lobe for transmitting a tone signal in the opposite direction of the active communication link to prevent nodes in that forbidden zone from transmitting packets. In Figure 4.10, A is sending packets to B, the potential interfering C is covered by A added lobe, C senses the channel busy by physical carrier sensing and will keep silence.

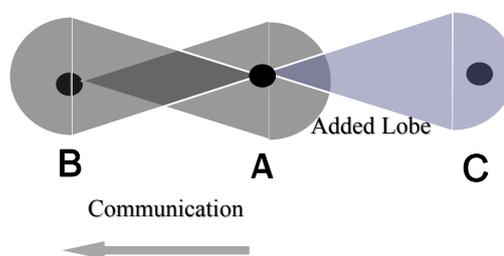


Figure 4.10: Two lobes antenna pattern

- Higher gain for RTS/CTS transmission

It is known that the hidden terminal problem due to asymmetrical gain is caused by the neglected ring between the radius of DO link for channel reservation and the radius of DD link for packets transmission. To overcome this problem, we increase the transmission range of sending RTS/CTS packet to cover an extra area caused by the DD link. Since the nodes in the forbidden zone are listening to the channel in omni-directional mode, the RTS/CTS transmission gain needs to be much larger than G_d . The minimum gain for sending RTS/CTS could be calculated as follow.

$$D_{RTS/CTS} = K \cdot \sqrt[4]{G_{RTS/CTS} \cdot G_o} = K \cdot \sqrt[4]{G_d \cdot G_d} = D_{dd},$$

$$\text{where } K = \sqrt[4]{(P_T/P_{R,\min}) \cdot h_T^2 \cdot h_R^2},$$

So we choose $G_{RTS/CTS} = G_d^2 / G_o$.

From the left part of Figure 4.11, it can be seen that the hidden terminal nodes C and D in the RFZ are covered by extended CTS and will keep silence in the direction of Receiver node B. The same situation in the right part of Figure 4.11, the hidden terminal nodes E and F in the TFZ are covered by extended RTS and will keep

silence in the direction of Sender node A.

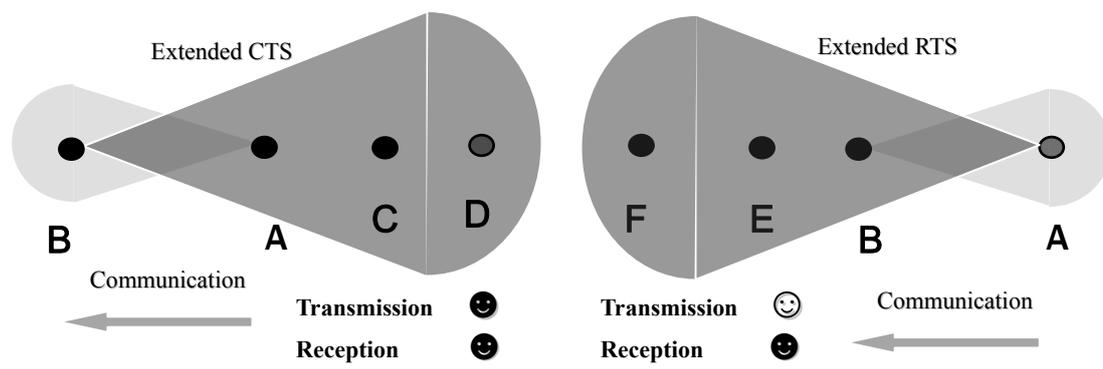


Figure 4.11: Limitation of RFZ/TFZ nodes

- Transmission NAV and Receiving NAV

In Figure 4.11, the nodes in both RFZ and TFZ could not receive any packet in the direction of receiver or transmitter nodes when active communication is going on. However, nodes in TFZ, like E and F could transmit packets in the direction of transmitter without adding any interference due to receiver antenna is beamforming towards the transmitter. So the NAV timer should be divided into two groups: transmission NAV and reception NAV. [4_9]

4.7 Comments and summary

In this chapter, five recent proposed contention based MAC protocols based on IEEE 802.11 DCF using directional antennas are reviewed. All these protocols are trying to exploit the benefits of directional antennas in the challenging mobile ad hoc network scenario where every node could move and initiate communication with other nodes. This challenging scenario together with the character of directional antennas leads to multiple problems, and the major problems illustrated in section 4.1.3 are new problem due to unheard RTS/CTS or due to asymmetric gain and deafness problem, which are dealt with in these new MAC proposals.

Most of these proposals need predetermined receiver node location information: DMAC1/2 is simply based on an additional GPS device to locate receiver node; MMAC, DVCS and E-R/CTS runs different DOA algorithms to estimate receiver node location. Only C-DRTS sends directional RTS packet in the manner using circular antenna scanning without requiring the receiver location. In fact C-DRTS consumes more time and power to scan receiver nodes with RTS packets and maintenance of location tables may not be suitable for a high mobility scenario. The location table could help to identify the interfering nodes more precisely to increase spatial reuse.

Another main difference of the above MAC proposals is in using different antenna pattern and different antenna gain when sending RTS/CTS/DATA/ACK separately. The

main reason to use different antenna strategies to send control packets and data packets is to mitigate the new MAC problem with directional antennas. It is noticed that C-DRTS and E-R/CTS are such kinds of schemes, which could compensate more negative impact of above mentioned problems than the other three schemes. The comparison among different MAC schemes is shown in Table 4.1, which indicate which antenna pattern and gain are used for sending packets: Omni-directional (o); Directional (d); circular directional antenna pattern (cir); Extend directional antenna pattern (ex) and two lobes directional antenna pattern (2lob).

Table 4.1: Comparison of directional MAC schemes

	RTS		CTS		DATA		ACK	
	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx
802.11	o	o	o	o	o	o	o	o
DMAC1	d	o	o	o	d	o	d	o
DMAC2	d/o	o	o	o	d	o	d	o
MMAC	d	o	d	d	d	d	d	d
DVCS	d/o	d	d	d	d	d	d	d
C-DRTS	cir	o	d	o	d	d	d	d
E-R/CTS	ex	o	ex	o	2lob	d	d	d

Most of the MAC proposals use one lobe to transmit DATA, except of E-R/CTS. With two lobe antenna pattern could absolutely make sure interference-free in the direction of receiver node ever and again. However, it will consume more power for the extra lobe. The same situation also happens in transmitting RTS/CTS with additional gain to cover more potential interfering nodes according to E-R/CTS. It is also a tradeoff between reduction of interference and power-consumption.

Compared with simulation result of DMAC1 and DMAC2, it is found that in low density network topology, scheme 2 has more throughputs due to less probability of control packet collision, the fact that in a high density network topology; scheme 2 has fewer throughputs due to its ORTS packets reduce number of concurrent communications. So the conclusion is that each scheme is a tradeoff between probability of collision and throughput depending on the scenario and traffic flows.

CHAPTER 5

BASICS OF AD HOC ROUTING PROTOCOL

In this chapter, three kinds of ad hoc routing protocols which try to solve the routing problem in ad hoc network are discussed. The reactive routing approach discovers routes only on demand by flooding discovery packets in the network. The AODV routing protocol defined in RFC 3561 is one example which could reduce the control traffic overhead by initializing and maintaining route at the cost of the delay for finding a new route. The proactive routing approach shares the latest network topology knowledge with all the nodes by periodically exchanging control messages. The OLSR protocol defined in RFC3626 is one example which could provide the required route immediately at the cost of channel resource used for exchanging periodic updated topology knowledge. The hybrid routing approach combines the advantages of reactive protocol and proactive protocol. ZRP is one example which has not been standardized yet.

5.1 Reactive routing protocol- AODV

The AODV routing protocol are discussed from the basic elements: routing table and message format. The strategies for new route finding and old route maintaining are reviewed then. In mobile ad hoc networks, nodes communicate with each other directly or relayed by other intermediate nodes using multi-hop wireless links. The routing protocol must meet drastic network topology change according to high node mobility and also bring less routing packets. AODV is such a kind of reactive routing algorithm which is based on demanded use.

5.1.1 Introduction to AODV routing algorithm

The AODV like any traditional distance vector routing algorithm uses a routing table to route packets. However, AODV only maintains the best path towards any destination as the active route in the routing table for a valid period. The route finding action only plays when there are two nodes which need to communicate with each other and there is not any fresh route information in the route table. The node does not maintain any route which is not used in active communication. AODV involves a destination sequence number to keep the routing information fresh and a drop out of date route which could lead to a routing loop. AODV also support quick convergence when network topology

changes to avoid the Bellman-Ford “counting to infinity” problem [5_1].

5.1.2 Route table

The AODV provides only one route for one destination in the route table, this route could forward packets fast and reliably, sometimes it might not be the shortest-hop path, because some other factors like congestion plays an important role especially in a high density situation. A mobile node maintains an active route table entry for each destination. Each route table entry consists of the following information [5_2]:

<Destination, Next Hop, Number of hops (metric), Destination sequence number, Active neighbors for this route, Expiration time for this route table entry>

5.1.3 Message formats

The AODV messages help a source node to discover a route to the destination and also help to maintain recent active route. All AODV messages are sent to the network port number 654 using UDP [5_1]. In the following RREQ, RREP, RERR and RREP-ACK messages are introduced briefly and the HELLO message is ignored since it is optional to perform local connectivity maintenance and the current MAC protocol can take this responsibility already.

- Route Request (RREQ) Message Format

A node intends to communicate with an “unknown” node which have not route packets before or whose previous route information has been out of date already. This node needs to initiates path discovery which will be discussed in detail later by sending a RREQ message to the network to find one best effort path. The RREQ packets are dealt as broadcast packets in the MAC layer [5_3]. RREQ contains the following fields: <Source address, Source sequence number, Broadcast id, Destination address, Destination sequence number, Hop count>

The unique pair <Source address, Broadcast id> is used to distinguish RREQ clearly. The broadcast id will increase by one once the source node sends a new RREQ. The destination node creates the destination sequence number which is included along with any route information towards the requesting node. This number increases before the destination node sends out any type of message [5_4] which helps the source node to choose the fresh route (largest sequence number) to avoid a routing loop. Hop Count indicates the number of hops from the source node to the current node which is holding the request message.

- Route Reply (RREP) Message Format

An intermediate node which knows a fresh route to the target destination or the

destination node could send a RREP message back to the requesting node. RREP packets are treated as unicast packets with a specified neighbor along the return route to the source node in the MAC layer [5_3]. A RREP contains the following information: <Source address, Destination Address, Destination sequence number, Hop count, Lifetime>

The Hop Count has different meanings from the one in RREQ message. It indicates the numbers of hops from the RREQ requesting node to the destination node or the number of hops to the multicast tree member sending this RREP in multicast route request situation. Lifetime records the time in milliseconds during which the route can be considered as valid for nodes receiving this RREP. [5_1]

- **Route Error (RERR) Message Format**

A node will send RERR to its neighbor when finding a link break which could cause previous destination to be unreachable, such as a neighbor node moving away could cause a link break. RERR packets are considered to be broadcast packets in MAC layer [5_3]. A RERR contains the following information:

<Destination count, Unreachable destination address, Unreachable destination sequence number>

- **Route Reply Acknowledgement (RREP-ACK) Message Format**

Some RREP message with 'A' bit set to ask for acknowledgement in order to complete a route discovery cycle under a danger of unidirectional links. In that case, nodes which successfully receive a RREP message need send a RREP-ACK message in response to that RREP.

The details of RREQ, RREP, RERR and RREP-ACK format table can be found in appendix1 [5_1].

5.1.4 Path discovery procedure

Path discovery only takes place when a source node wants to communicate with another node for which the source node does not have any fresh route information in the route table. The source node begins path discovery by broadcasting a RREQ packet to the neighbor nodes within the transmission range. Intermediate nodes which does not have any fresh route information for the target destination node forward the RREQ to its neighbor when it have not received the RREQ message with the same unique pair of broadcast ID and source address, otherwise it will drop the redundant RREQ and ignore to rebroadcast it [5_2]. These intermediate nodes need to record the following information for implementing reverse path setup and forward path setup together with the final RREP:

<Destination IP address, Source IP address, Broadcast ID, Expiration time for reverse path route entry, Source node sequence number>

- Reverse path setup

In order to make source node and destination node communicate with each other, a reverse path from the destination to source is demanded. To fulfill it, each intermediate node keeps track of address of the neighbor through which it received the first copy of RREQ. The expiration time for this reverse path route entry which was mentioned above is long enough for RREQ message to trace the whole network to find a best effort path and send a RREP to the source node [5_2]. Each RREQ has a TTL value to limit how many hops the request message can forward to its neighbor and subsequent neighbors. If the source node does not receive RREP in a predefined period (NET_TRAVERASAL_TIME) in milliseconds, it may try re-broadcast another new RREQ up to a maximum of RREQ_RETRIES times. For each attempt, the TTL value will increase with some predefined step and the waiting time for RREP will double [5_1].

- Forward path setup

The intermediate node which knew a fresh route to the destination node will check whether the current route is still valid or not. If the destination sequence number in its own route table entry is larger or equal to the one in the receiving RREQ message, it means this route is fresh enough for routing packets. The forward path setup will take place immediately. The current intermediate node firstly unicasts a RREP back to its neighbor from which it received the RREQ. The RREP will be forwarded one by one back towards the source node with the help of each intermediate node records. The time when a broadcast packet arriving at the intermediate node, that could provide a valid route to the destination node, indicates the reverse path to the source of the RREQ message has been created successfully. Each intermediate node along the current active path creates a pointer to the node from which RREP send and updates its timeout for this pair of source and destination and also update latest destination sequence number in the forwarding process of RREP message. Nodes not along the active route are notified by RREP forwarding will timeout and delete the reverse pointers, which can be seen clearly from the Figure 5.1. [5_2]

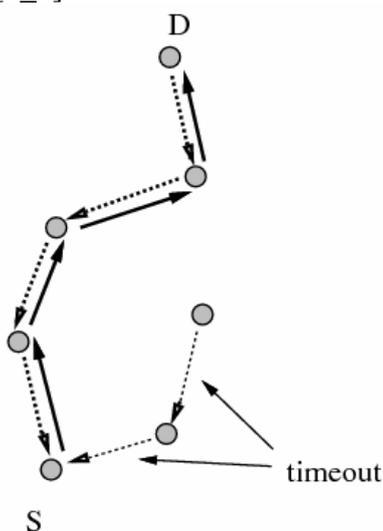


Figure 5.1: Forward Path Formation [5_2]

In some cases, intermediate node could receive multiple RREPs from neighbor nodes, this node will forward the first arrived RREP to the source node according to protocol. It is very likely that some RREP with better route information comes later, so the intermediate node will also make a comparison of the sequence number and hop number between the new route and the current route about, and when finding a larger destination sequence number or smaller hop number, it will store this new route and forward this RREP to the source node, otherwise it just drops the later arrived RREP messages.[5_5] The source node may start data transmission once it is received the first arrived RREP and can choose a better route for data forwarding later when a new RREP arrives.

- Path maintenance

Movement of the destination node or intermediate node along an active path could lead to link break. When the data link layer detects a fatal transmission error, such that the time for retransmission is beyond the maximum number of retransmission number, a RERR packet will be sent back to the source node of current active route. Then the source node may initiate a new route discovery procedure to find a new path for data forwarding. [5_2]

5.2 Proactive routing protocol-OLSR

OLSR is a proactive table-driven link state routing protocol. It maintains and updates network topology knowledge for each node by exchanging periodical messages. In classical link state approach, the topology information is flooding through the entire network. The OLSR is an optimized link state protocol due Multipoint Relay mechanism (MPR) which enables control messages to efficiently flood. Basically, OLSR contains three mechanisms to achieve this optimization: It performs neighbor discovery based on periodic exchange of HELLO messages within one-hop neighbors; It utilizes an efficient mechanism named MPR algorithm for flooding control messages in the whole network to avoid duplicate retransmission; It computes the optimal route to each destination in the network for every node based on sufficient topology information which is provided by exchanging control messages. [1_3] [5_6][5_7]

5.2.1 Multipoint relays

The core mechanism in OLSR is the MPR which is intended to minimize the number of flooding packets in the same region of network by reducing the duplicate retransmissions. Not every node in the network is allowed to forward the broadcast message after receiving it from its neighbor node like in classical link state protocols. In OLSR, each node selects a set of MPR nodes which are permitted to relay the flooding message; while other nodes would keep silence after receiving the same flooding messages. Each node also records a set of neighbor nodes named MPR selectors which

choose this node as their MPR node. It means that this node only retransmit the flooding messages which is received from their MPR selector nodes. The difference between the simple flooding algorithm and the OLSR algorithm based on MPR mechanism can be observed from Figure 5.2. The flooding message which is initiated by the center node would be received by every one-hop neighbor node and only be forwarded by the MPR nodes (black nodes) to all the two-hop neighbor nodes in the right OLSR scenario. It is obvious that OLSR scheme saves more bandwidth for full coverage of the same region than the simple flooding scheme by reducing a large amount of duplication retransmissions. [5_8]

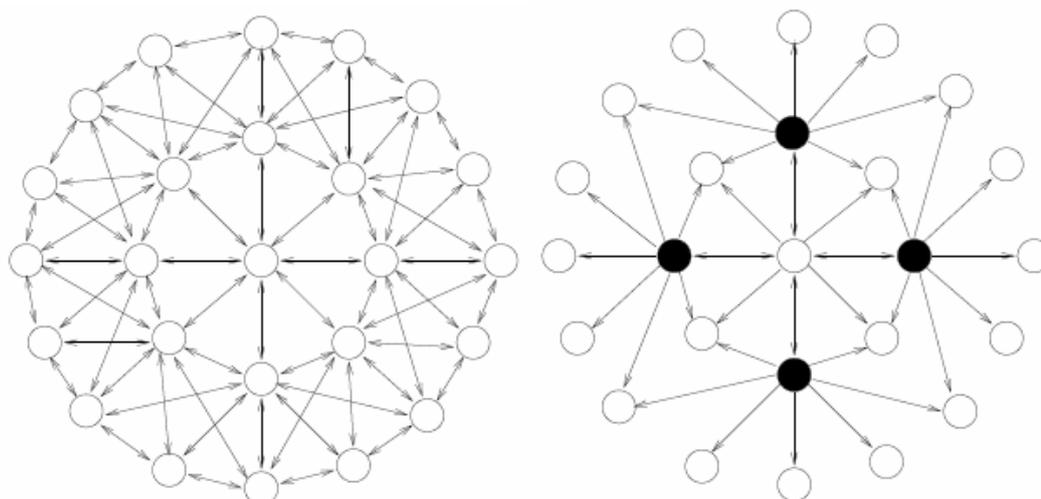


Figure 5.2: Simple flooding approach Vs OLSR flooding approach [5_7]

It is evident that the way to choose MPR nodes for each node determines whether the flooding scheme is efficient or not. Each node chooses its MPR nodes from its one hop neighbor independently. The set of MPR nodes must be symmetrical neighbor nodes which could cover all the two neighbor nodes of this node in the network. The symmetrical neighbor means that the link between the node and this neighbor node is bi-directional. According to this rule, each node could broadcast messages to every node in the network only via the MPR nodes. Actually the smaller the MPR set, the more optimal is the routing protocol. Each node could also declare them to be a MPR node for its neighbor by setting a willingness parameter range from 1 to 8 in the HELLO message. So the MPR selection procedure would consider this willingness parameter when choosing MPR nodes for each node. [5_7][5_8]

5.2.2 Neighbor discovery

OLSR performs neighbor discovery by exchanging a HELLO message whose format can be found in Appendix 2. Each node periodically broadcasts the HELLO message containing the information about its one-hop neighbor nodes and the link status. This

HELLO message is received by all of the one-hop neighbors but not relayed to any further nodes. Figure 5.3 presents the procedure of link status determination. Node A first sends an empty HELLO message to B. Node B then registers A as an asymmetric neighbor after receiving its HELLO message since B can not find its information in this message. Next Node B sends a new HELLO message for declaring Node A as its asymmetric neighbor. Node A would find its own information in this HELLO message and would set B as a symmetric neighbor and send a new HELLO message to declare this. Node B would also set A as a symmetric neighbor upon receiving this message. [5_7]

Through exchanging the HELLO message, each node recognizes all its neighbor nodes including one-hop and two-hops'. Based on this neighborhood knowledge with a sequence number recorded in the neighbor table, each node would perform MPR sensing. The result of selected MPR nodes is finally indicated in the HELLO message with the link status MPR. Each node would also perform MPR selector sensing upon receiving these HELLO messages and record this information in its MPR selector table. [5_6]

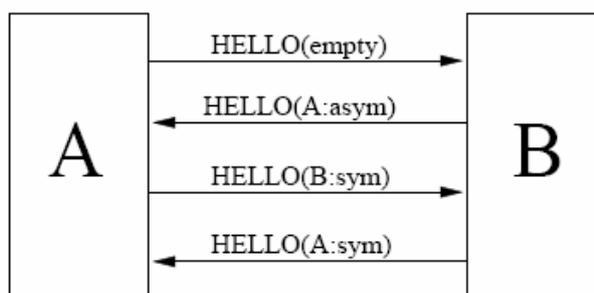


Figure 5.3: Neighbor discover procedure with HELLO message [5_7]

5.2.3 Multipoint relay selection

The rule for selecting MPR nodes is as follows: The MPR nodes must forward the broadcasting message to all the two-hop neighbor nodes of the given node. The two-hop neighbor node information can be tracked from HELLO message and would be stored in the neighbor table. The selected MRP nodes of the given node are declared in the new HELLO message broadcasted by this node. With this information, each node could construct its MPR selector table. The MRP set needs to be reselected when a change occurs in the neighbor nodes within two hops. [5_6]

5.2.4 Topology information diffusion

To construct a route table for each node, an amount of sufficient network topology information diffused by other nodes is needed. In OLSR, each node with a MPR

selector set periodically broadcast a Topology Control (TC) message whose format can be found in Appendix 2. A TC message consists of the address of the originated node of this message named last hop node and the address of all the MPR selectors of this node is called destination node. The TC message utilizes the same MPR flooding mechanism which is used for diffusing HELLO messages, but the TC message needs to flood in the entire network. The node receiving this TC message can reach the destination node through the last hop node from which it received this TC message. The interval between transmissions of two TC messages will be reduced when a change occurs in the MPR selector set. This information diffused in the network by TC messages will help each node to build its topology table step by step. The entry in the topology table consists of the address of potential destination (an MPR selector of originator of TC message), the address of corresponding last hop node and MPR set sequence number. The topology table update by incoming TC messages are based on the freshness of the sequence number. [5_6][5_8]

5.2.5 Route calculation

In OLSR, only an MRP node can be selected as relay node for routing packets. The route calculation is based on the information contained in the topology table and the neighbor table of each node. In order to route a packet in the entire network, each node need to calculate the route for any potential destination in the network. Since each node distributes its TC message in the whole network and at the same time receives the TC messages from all the other nodes, so each node could build the route table by extracting the information from TC messages which consist of the entry of last hop and destination. The route calculation procedure is to search the [last hop, destination] entry in the TC table in order to obtain a complete and connected route from current origin node to any potential destination node. The finding process begins with the TC entry of the given destination node, and continues to look for the TC entry of last hop node in a descending order, and so forth until the TC entry of the origin node is obtained. Although the route discovery process is from the destination node to the current origin node, the resulting route is also suitable for the reverse direction since each MPR link is bi-directional. The minimum path will be added to the route table which contains destination node address, next hop node address and estimated distance to the destination node. If any changes occur in the topology table or neighbor table, the routing table needs to be recalculated to update the route information for each node in the network. [5_6]

5.3 Hybrid routing protocol-ZRP

The hybrid means combining the strength of the two above discussed routing protocol. The ZRP is such a kind of hybrid routing protocol which has not been accepted as

experimental RFCs by the IETF yet. ZRP is based on the concept of zones. Each node in the network has a zone which is defined by a zone radius in a given hop count number. In Figure 5.4, the zone radius of node S is 2 hops. The four peripheral nodes of S also belong to other neighbor nodes to help bridging of different zones, that means Node I is not only belonging to the zone of Node S but also inside the zone of Node K. [1_3]

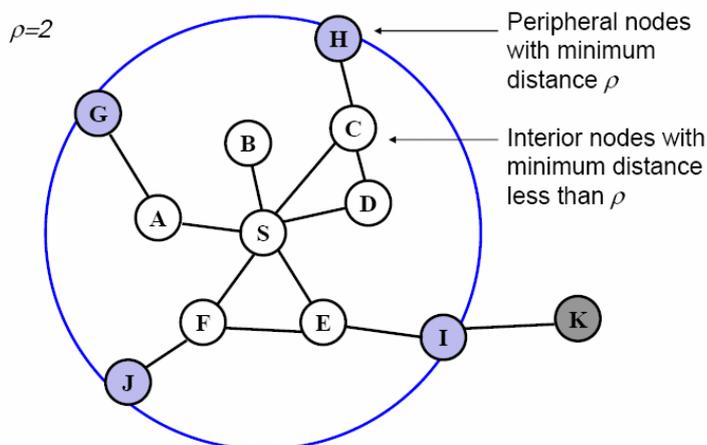


Figure 5.4: Zone concept in ZRP [5_9]

The key of ZRP is that different routing protocols are used separately outside and inside of the zone in order to combine the advantages of these protocols. Because a great amount of packets will be routed to nearby destinations, so the proactive routing protocol is used within the zone to reduce the topology maintenance costs in a limited zone. In addition, there is no initial delay when the source and destination node are within the same zone. While the reactive routing protocol is utilized outside the zone when sometimes there is packet to be routed to the remote destination outside the zone. [1_3]

5.4 Summary

In this chapter, three basic routing protocols were discussed together with three typical corresponding algorithms, AODV, OLSR and ZRP. Each of them has advantages and specific appropriate applications. The AODV reduces the route maintenance cost by discovering a route on demand and could find the latest route, and it performs better in a network with low mobility, less frequent link breaks. The OLSR reduces routing overhead and the number of broadcast packets and also minimizes initial communication establish time, it performs better in network with sporadic traffic. ZRP reduces the control overhead compared to the RREQ flooding scheme used in reactive protocols and the periodic routing information flooding used in proactive protocols. [1_3] [5_7]

CHAPTER 6

AD HOC ROUTING WITH DIRECTIONAL ANTENNAS

In this chapter, two routing problems (directional route discovery and routing overhead) using directional antennas based on current routing protocols are investigated, since the conventional routing protocol is designed for omni-directional antennas. Because the directional antennas could increase the directional range of the signal to reach a larger distance than omni-directional antennas, the big difference between directional routing and omni-directional routing occurs in the route discovery procedure and packet forwarding procedure. Since the success of the directional packet forwarding is based on the appropriate route chosen in the directional route discovery procedure, several proposed ad hoc routing schemes for route finding process with directional antennas are reviewed in this chapter.

6.1 Routing problem with directional antennas

For the same transmission power, directional antennas could focus on the desired direction to lead to a larger transmitting range than omni-directional antennas. The increase of transmission range of directional antennas could result in discovering a route with fewer hops than omni-directional antennas. However, there are several problems when applying traditional routing protocols to directional antennas in ad hoc networks. The two main directional route finding problems are presented next.

6.1.1 Directional route discovery problem

Current route discovery algorithms are carried out using an omni-directional broadcast scheme. A RREQ packet is broadcast throughout the network until it reaches the destination or intermediate node which could send back a RREP packet to the source node. This approach is quite inefficient when employing directional antennas. Because an omni-directional route finding scheme could not discover a neighbor node (DO and DD neighbor nodes) with the directional antenna transmission range, so the neighbor nodes which could be reached by directional antennas are ignored. The consequence is that the number of hops will not be reduced even using directional antennas, because the limited omni-directional broadcast transmission range could not achieve to discover shorter hop routes. We need new route discovering algorithms to make DO even DD neighbor nodes to be available for efficient packet forwarding with directional antennas. [6_1]

6.1.2 Routing overhead problem

One reason to cause large routing overhead in the route discovery procedure is that the RREQ packet is broadcasted omni-directionally. Only a small part of broadcast packets reach the target neighbor nodes to set up routing information. This route finding approach causes not only power waste but also inefficient channel usage which could also result in channel collision.

Another reason is that some directional routing scheme produces many routing redundant packets in the route discovery procedure, like the sweeping scheme which will be discussed in following section. Although this approach could achieve to find all DO neighbors with directional antennas, sweeping the beam sequential across all directions would result in much more routing overhead than a conventional route finding algorithm.

6.2 Sweeping scheme

The sweeping scheme is working on a reactive routing protocol using directional antennas. In [6_2] [6_3], the performance of a reactive routing protocol for different scenarios with directional antennas is evaluated. Through sequentially sweeping the antenna beam in omni-directions, DO neighbors are easily detected in the route discovery procedure. The directional antennas with these DO neighbors could achieve route with least hops and better performance than omni-directional antennas.

6.2.1 Antenna model

The switched beam antenna with six prefixed non-overlapping beams is used in [6_2] [6_3]. The elements numbered from 1 to 6 and radiation pattern with beamwidth of 60 degree are illustrated in Figure 6.1. The antenna system could offer omni-directional mode and directional mode. The antenna of an idle node is in omni-directional mode, it will change to directional mode when a signal is detected and will focus the main beam on that direction the received signal power is at maximum. Since the directional antennas have a higher gain than the omni-directional antennas, this scheme could find DO neighbor by directional transmitting signal to an idle neighbor which is always in omni-directional reception mode. [6_3]

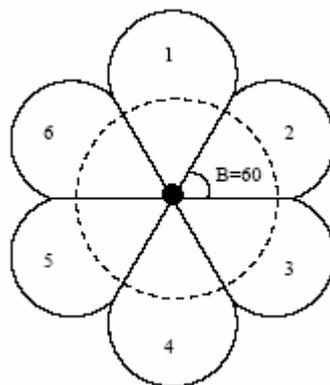


Figure 6.1: Antenna model in sweeping scheme

6.2.2 The detailed protocol

In a reactive routing protocol, the route discovery procedure begins with broadcasting RREQ to all neighbor nodes. Using a directional MAC protocol, RREQ broadcast is achieved with the sweeping scheme. The RREQ packet is sequentially send over all six beams. That means the same packet is transmitted 6 times in order to reach all surrounding DO neighbor nodes.

The sweeping scheme is performed without any backoff mechanism. After sensing that the channel is idle, the antenna element would transmit the RREQ packet immediately. Otherwise the antenna elements, which sense that the channel is busy, are marked and the following elements would work continuously. In the next round, the RREQ packet would only be send via those marked antenna elements. If some elements still sense the channel is busy, then the RREQ packet would be dropped.

The sweeping scheme help a node to recognize of utilizing which antenna element to reach surrounding DO neighbors. Once a node receives a packet, it will update its neighbor nodes information. This information is cached in a look-up table which consists of source node identity and the antenna element used to receive the packet. To keep this information fresh, a scanning mechanism forces each node to broadcast Hello packet with the sweeping scheme. The receiving node would correct its neighbor information when finding the look-up table becomes out of date. [6_3]

6.2.3 Comments

Due to higher gain of directional antennas, the sweeping scheme could discover neighbors away from a larger distance (which leads to shorter hop route) than omni-directional antennas. Since all the idle nodes in the omni-directional mode receive packet reactively, so only DO neighbor nodes could be detected. Sweeping

scheme could not deal with DD neighbor nodes.

Sweeping the same packet N times leads to $N-1$ times more delay than in omni-directional broadcasting scheme. However, without using backoff mechanism, the sweeping scheme could save extra waiting time for transmitting RREQ packets and reduce the delay a little bit. The tradeoff is that the probability of collision would increase a little bit without backoff mechanism. In addition, transmitting the same packet N times could increase the routing overhead significantly.

6.3 Heartbeat scheme

The heartbeat scheme is used in the first complete system Ad Hoc network [6_4]. The Hazy Sighted Link-State (HSLS) routing protocol utilizes heartbeat information to discover not only DO neighbors but also DD neighbors. In fact, the difficulty in discovering the DD neighbors is to choose the right antenna element and right time for sending a heartbeat packet. The DD neighbor could be found only if both sender and receiver point towards each other at the same time a heartbeat packet is sent. There are two proposed method for this problem, informed discovery and blind discovery. The antenna model, like the switched beam antenna used in sweeping scheme also includes omni-directional mode and directional mode. [6_4]

6.3.1 Heartbeat packet

The heartbeat scheme is based on periodical broadcast and scoring of the heartbeat packet. The heartbeat control packet consists of source node identifier, the band, the mode and “up” indicator. The mode is to describe the antenna model and can be classified by Non BeamForming (N-BF), Transmitter-BeamForming (T-BF) and Transmitter and Receiver-BeamForming (TR-BF). It is obvious that N-BF could find OO neighbor nodes, T-BF could discover DO neighbor nodes and TR-BF could obtain DD neighbor nodes. [6_4]

6.3.2 Informed discovery

The informed discovery is used when a node has some form of information about its neighbor nodes. The source node first performs simple blind OO neighbor discovery by broadcasting heartbeat packets with mode N-BF using the omni-directional antenna. The heartbeat packets which are received from neighbor nodes are scoring. A Node X considers a Node Y to be “up” if the scoring number of heartbeats packet received from Y is above a threshold. Finally each node has its one-hop OO neighbor information. Then routing updates which is triggered by links declared as being “up”

are distributed. The result of exchanging routing update information is that a Node X may know about the existence and position of a Node Y which is out of N-BF range. Node X could perform informed T-BF discovery by sending a directional heartbeat packet with T-BF mode and position of X to Node Y. The Node Y in idle mode could receive the heartbeat packet and send another directional heartbeat packet. If enough score on the heartbeats are reached at Node X and Node Y, a DO link is established between them. [6_4]

6.3.3 Blind discovery

The blind discovery is used when a node is not aware of the existence of other nodes. The difficulty is to force two nodes without any information of each other beforehand to beamform towards each other simultaneously. All nodes need to be synchronized with a common clock with a GPS device to make them work all together. The periodical TR-BF discovery scheme is illustrated in Figure 6.2. All nodes performs discovery by a common direction which is chosen depending on the time. Each node alternates randomly between sending heartbeat packet in that direction and listening in the opposite direction for heartbeat packet. In Figure 6.2, two nodes detect each other in that direction successfully and a DD links between them would be established after enough score of the heartbeats packets are exchanged. It is obvious that after at least one heartbeat packet is exchanged in each direction, each node could detect the position of its DD neighbor nodes to help further establishment of a DD link. [6_4]

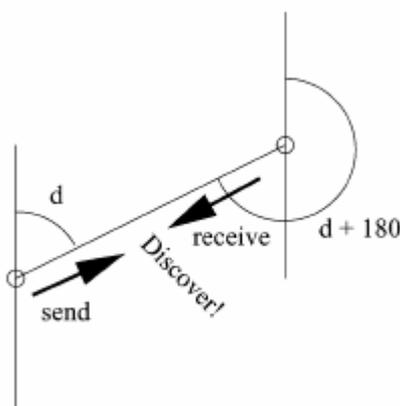


Figure 6.2: Blind TR-BF discovery [6_4]

6.3.4 Comments

We found that the blind discovery algorithm is more efficient and less complex than the simple scanning discovery algorithm. Only one cycle TR-BF discovery could detect all DD neighbor nodes, which could reduce the hop number. The tradeoff is that

each node needs to have the exact common time, since synchronization is the key factor to determine whether the DD neighbor nodes will be discovered or not.

6.4 Routing overhead mitigation scheme

Since the reactive routing protocol performs route discovery by broadcasting RREQ packet via flooding, it would generate an excessive amount of redundant traffic in the medium and produce a large amount of interference among neighbor nodes. This route discovery procedure leads to less efficient utilization of the channel and higher probability of collision in the shared medium than the packet forwarding procedure. This situation would be worse with directional antennas than with omni-directional antennas for route discovery. The higher transmission range of directional antennas would lead to larger impacted area by flooding. The utilization of the simple sweeping scheme discussed in section 6.2 also produces large routing overhead due to the fact that the same RREQ packet is transmitted sequentially by every antenna element. [6_2] The problem of redundant transmission of RREQ packets is referred to broadcast storm problem.

Both probabilistic approaches and deterministic approaches have been proposed for efficient broadcast with directional antennas. In the probabilistic approach, a node forwards RREQ packets with probability p and takes no action with probability $1-p$. The probabilistic algorithm could be combined with a counter-based scheme, location-based scheme, distance-based scheme and cluster-based scheme to maintain an acceptable delivery ratio of the RREQ packet. [6_6] In the deterministic approach, only a few nodes are chosen to forward RREQ packets in the network like MPR in OLSR protocol. Most of the deterministic approaches use a localized algorithm to select the forwarding nodes based on their N hops neighbors information.[6_7] In this section we investigate three probabilistic flooding schemes for overcoming the routing overhead problem.

6.4.1 Selective forwarding scheme

The main idea of the selective forwarding scheme is to prevent the same RREQ packet from transmitting back to the node from which the RREQ packet is received. In Figure 6.3, Node X receives a RREQ packet from Node S, the same RREQ packet is not necessary to transmit back from Node X back to Node S.

The antenna elements of the switched-beam antenna used in [6_2] are numbered from 1 to 6 in Figure 6.3. The node initiating the RREQ packets will transmit in all omni-directions. The intermediate nodes receiving this control packet will continue to forward it using half of its antenna elements in the opposite direction of incoming

AOA after a uniformly distributed random delay. Node X receiving the RREQ packet with antenna Element 5 from Node S will forward it using antenna Elements 1, 2 and 3 in the opposite direction of the receiving antenna Element 5. The active/passive mode of each antenna element is controlled by the MAC layer based on the AOA information [6_5]. It is obvious that a great amount of flooding RREQ packets will be saved using this selective forwarding scheme if there are multi-hop between the source node and destination node like the scenario in Figure.3. [6_2]

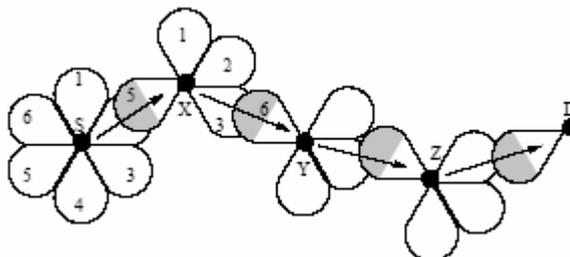


Figure 6.3: Selective forwarding scheme [6_2]

6.4.2 Relay-node-based scheme

The difference between it and previous broadcast scheme is that not every node receiving the RREQ packet can forward this packet in this scheme. The Relay-node-based scheme innovates a way to decide the relay node which could forward the RREQ packets efficiently. This scheme can be considered as a distance-based probabilistic approach. The principle of a distance-based scheme is to choose a relay node far away from the sender from which the RREQ packet is received. This optimized flooding scheme could select the relay node which has the largest additional coverage. The additional area is the region away from the common neighbor area and within the relay node transmission range [6_8]. There is only one relay node in each antenna element direction to forward the RREQ packet. The node which is the farthest from the RREQ packet sending node will be selected as relay node. Actually the signal strength of a RREQ packet sent from that relay node is the weakest among all the neighbor nodes in that direction. [6_5]

Each node in the network sends Hello messages periodically to all surrounding neighbor nodes and performs relay nodes discovery by comparing all the signal strengths from all neighbor nodes. Each node will reselect and store its relay nodes in every antenna element direction once a refresher timer. This node will also attach its relay nodes information in the header of each RREQ packets. After this the node broadcasts the RREQ packet in other directions other than that in which the packet arrives, only the selected relay nodes will perform forwarding a RREQ packet after a random delay in the same way until the RREQ packet reaches the destination node. If the same RREQ packet arrives in this node before the delay expiring, this relay node

will drop that packet. If no relay node information in the RREQ packet header due to failure of discovery the relay nodes, all the receiving nodes will forward this packet. The node which is not selected as relay node by the first RREQ packet will not perform forwarding even if it receives the same packet from other nodes which consider it as a relay node. [6_5]

6.4.3 Location-based scheme

With the Relay-node-based scheme, it is found that even the relay node is the farthest neighbor node of the source node, but the additional coverage area might not be at maximum. In fact, the total additional coverage area consists of the additional coverage areas of each antenna element. If the additional coverage area of a relay node which is the largest one in a certain direction has more overlap with that of the adjacent direction, this node should not be selected as a relay node. Also the Relay-node-based scheme does not consider the relative orientation of two nodes. This motivates to the development of a more accurate algorithm to calculate additional coverage area for each direction of each node. This information will determine whether the direction of this node can be used to relay a RREQ packet controlled by the forwarding delay. The location-based scheme is such a kind of approach which is assisted by a GPS device to decide which direction of the receiving node can be used to forward RREQ packets. [6_5]

The difference between it and the selective forwarding scheme is that the node receiving the RREQ packet for the first time will forward this packet using the antenna elements in the directions other than the incoming AOA in this scheme. However, whether this packet can be forwarded with those directions is determined by the forwarding delay. The node must wait for the forwarding delay before forwarding the RREQ packet. If the same RREQ packet arrives before the delay timer expires, the node will not forward packets in the incoming direction. The delay for each direction is inversely proportional to the additional coverage ratio which is calculated as the additional coverage area over a quarter of the circle area. Figure 6.4 presents the relationship between the forwarding delay and the additional coverage ratio. The larger the additional coverage ratio, the smaller the forwarding delay, the less is the probability that the same packet arrives in the certain direction and the larger is the probability that the node forwards a RREQ packet in that direction. [6_5]

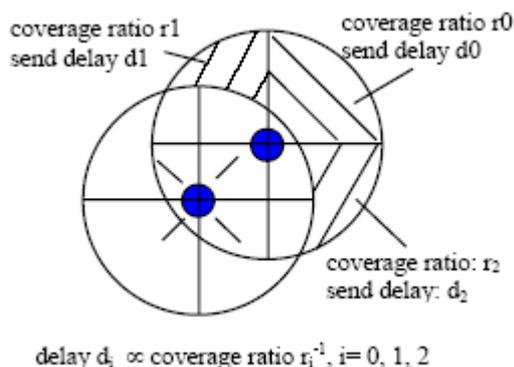


Figure 6.4: Location-based scheme [6_5]

Each node in the network obtains its current location from a GPS device and attaches it in the header of any transmitted RREQ packet. The receiving nodes will calculate the additional coverage ratio based on the relative position of the source node of current received control packets and determine the forwarding delay for each direction. It is obvious that the location based scheme could cover a larger additional broadcast coverage than the relay-node-based scheme and the location based scheme does not need hello message exchange.

6.4.4 Comments

Three probabilistic approaches for mitigating routing overhead problem with directional antennas were presented in this section. The selective forwarding scheme is simple to implement by switching off half of the antenna element of intermediate nodes when forwarding a RREQ packet. The relay-node-based scheme is more efficient than the selective forwarding scheme due to the fact that only the selected nodes determined by the distance-based scheme can forward the RREQ packet. The location-based scheme has a better performance based on its maximum additional coverage area aided by location information.

6.5 Summary

In this chapter, the directional neighbor discovery problem and routing overhead problem were investigated and several approaches to solve these problems were reviewed separately.

In the directional neighbor discovery procedure, the sweeping scheme performing directional broadcasts could discover a good quality route. However, the multiple sequential transmissions by each node cause large route overhead and delay in finding the route. Moreover, the sweeping scheme could only discover routes with DO links.

The heartbeat scheme utilizes the heartbeat control packet with both omni-directional antenna and directional antenna to discover route both with DO and DD link. The tradeoff is that each node need the exact synchronization with a GPS device in order to find their DD neighbor nodes.

In the routing overhead mitigating procedure, the three probabilistic approaches could reduce a great amount of the overhead packets and the delay during route discovery procedure. However, some route might miss due to probabilistic selecting forwarding algorithms.

CHAPTER 7

CASE STUDIES

Because the ad hoc technology has not yet massively deployed, the researches in this field mostly rely on simulation. The objective of the case studies of this thesis focuses on evaluating the improvement of network and routing performance in ad hoc networks when terminals are equipped with directional antennas. The previously discussed IEEE 802.11 with DVCS MAC protocols, AODV and OLSR routing protocols are utilized in the simulations. The case studies will compare several performance metrics between omni-directional antennas and directional antennas for static and mobility scenarios.

7.1 Introduction to simulator

The simulator used in this thesis is QualNet 3.9, which is developed by Scalable Network Technologies. QualNet is a discrete event simulator of scalable network technologies. The simulation is running based on an event scheduler. That means the simulation is not performed in a constant time flow, but at specific points of time when events occur. [7_1] QualNet is a predictive high-fidelity modeling tool for wireless and wired networks of tens of thousands of nodes. It makes good use of computational resources and models large-scale networks with heavy traffic load and mobility in reasonable simulation times [7_2].

7.1.1 QualNet history

QualNet is a commercial product which is derived from Global Mobile Information System Simulator (GloMoSim). GloMoSim is a scalable simulation library produced at the UCLA Computing Laboratory to simulate large-scale network using parallel and/or distributed execution on a diverse set of parallel computers. It is originally designed for both wired and wireless networks systems, but it now only supports pure wireless networks. GloMoSim is built using C-based Parallel Simulation Environment for Complex Systems (PARSEC) simulation environment which is designed at the UCLA Parallel Computing Laboratory. Although GloMoSim can be obtained without fee for education, research or non-profit organizations, it lacks of good documentation and sets of tools to monitor the systems behavior, to analyze the simulation results. The commercial version of GloMoSim QualNet adds many additional features to

alleviate the GloMoSim drawback. The advanced capabilities of QualNet include the power Graphical User Interface (GUI) for custom code development and report option, the fast simulation results, the scalability up to tens of thousand of nodes and multi platforms support. [7_3] [7_4]

7.1.2 QualNet protocols

QualNet has an OSI layer architecture. A simulation is a collection of network nodes which are with their own protocol stack parameters and statistics. Each layer is an object with its own variables and structures. The message is a unit defining an interaction between protocols and between nodes. There are two types of messages: packets which are used for communication between nodes and timers which allow protocols to schedule events in a future time. The packet life cycle is displayed in Figure 7.1. [7_5]

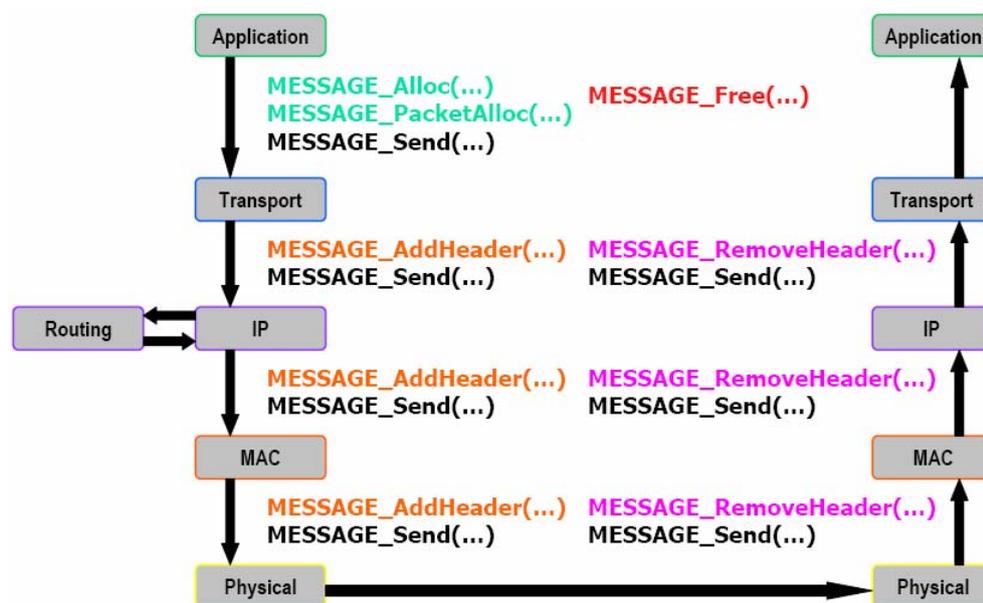


Figure 7.1: Packet life cycle [7_5]

The QualNet is working based on an event scheduler. The overview of a typical protocol is displayed in Figure 7.2. Every protocol begins with an initialization function which reads the external input and configures the protocol. Then the event dispatcher takes charge of handling. If an event for that layer occurs, QualNet will determine the specific event protocol and hands it to the dispatcher of that protocol. The event dispatcher then checks the type of event and calls the appropriate event handler to process it. In the end, every protocol will call a finalization function to print out the collected statistics. At the end of the simulation, the event to bring the simulator into finalize state is generated automatically. [7_1]

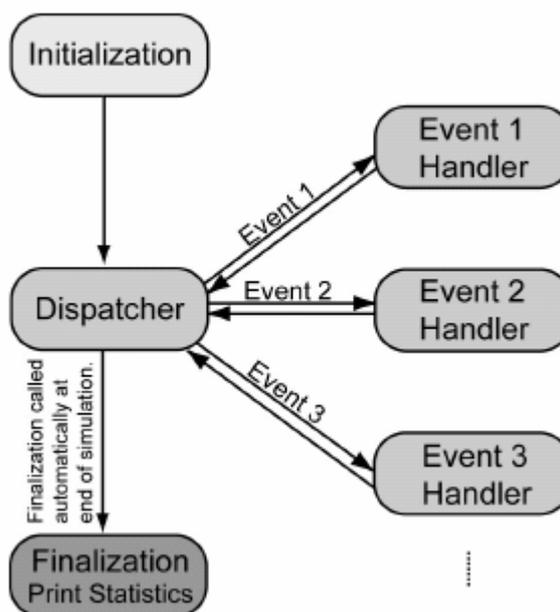


Figure 7.2: QualNet event handling [7_1]

The QualNet library is the basis for the QualNet Developer software suit which contains a collection of five different tools to simulate and analysis network performance: [7_1] [7_4]

- The QualNet Simulator: The simulator itself. It is designed to accommodate high-fidelity models of networks of tens of thousands nodes with heavy traffic and high mobility.
- QualNet Animator: A graphical user interface for intuitive experiment setup and animation tool. It can be used to watch the traffic flows and specific network performance metrics and replay the simulation.
- QualNet Designer: A finite state machine tool for custom protocol modeling. It is a state-based visual tool defines the events and processes of a new protocol model.
- QualNet Analyzer: A statistical graphing tools for reporting the custom network performance metrics.
- QualNet Tracer: A packet level visualization tool for watching the packets going up and down the protocol stack.

7.1.3 QualNet models

The QualNet simulation experiment life cycle which can be divided into three stages is displayed in Figure 7.3. In the startup stage, the simulator reads input files, initializes wireless environment and create nodes. There are three vital input files to define the simulation experiment: the config file which consists of main configuration parameter settings for the simulator; the application file which define the traffic flows during the entire simulation time and the node placement file which specifies the coordinate of each node. In the execution stage, the simulator checks for external inputs and executes all the events. In the shut down stage, the simulator finalizes nodes and produces the output files.

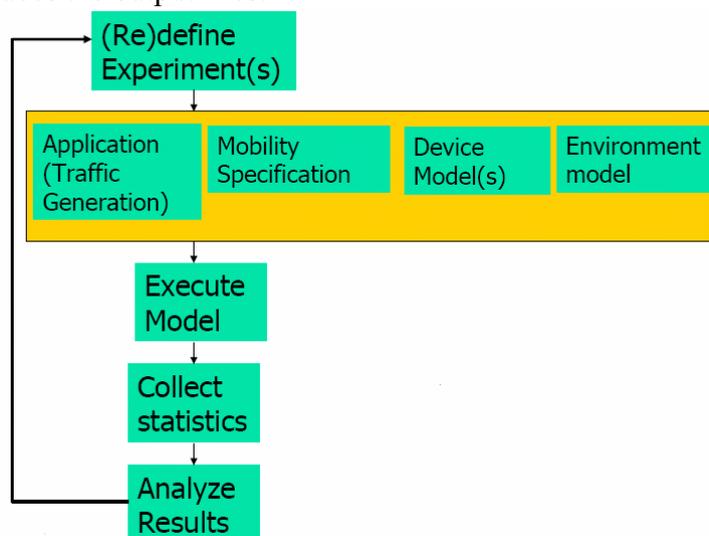


Figure 7.3: Simulation study life cycle for network models

QualNet supports four ways to allocate nodes in the defined physical terrain: grid, random, uniform and file. The grid node placement starts at coordinate (0, 0) and the nodes are placed in a grid format with each node a grid unit away from its neighbor. The random node placement allocates nodes randomly within the physical terrain based on the seed specified in the config file. The uniform node placement divides the physical terrain into a number of cells and allocates every node randomly in each cell. The file node placement enables the user to define each node position.

QualNet mobility model includes four mobility options: none, random waypoint, group and file. The none option fixes all nodes in place for the whole simulation period. The random waypoint option specifies three parameters (mobility-wp-min-speed, mobility-wp-max-speed and mobility-wp-pause). Each node randomly selects a destination within the physical terrain, and then it moves in that direction in a speed uniformly chosen between mobility-wp-min-speed and mobility-wp-max-speed. After it reaches its destination, the node stay there for

mobility-wp-pause time period. The group option divides the nodes into different mobility group within which every node follows the same random waypoint model. The file option enables user to define a time order trace file to specify every node position.

QualNet provides different traffic generator models to produce data flows across a network. This paragraph only introduces several traffic generators supported by Qualnet. The Constant Bit Rate (CBR) is generally used to simulate multimedia traffic or to fill in background traffic to affect the performance of other application being analyzed. The File Transfer Protocol (FTP) is used to simulate exchanging files between server and client. The Voice over Internet Protocol (VoIP) is used to simulate the routing of voice conversations over the internet or through any other IP based network. The traffic generator is used to simulate a random distribution based traffic flows.

In PHY layer, QualNet supports three propagation pathloss models: free space, two ray and irregular terrain models. It offers two fading models: Rayleigh and Ricean model. QualNet provides three antenna models: omni-directional antenna, switched-beam antenna and steerable antenna.

In MAC layer, QualNet supports CSMA, Multiple Access Collision Avoidance (MACA), MAC802.11, TDMA, MAC802.3/switched-ethernet and Satellite Communication (SATCOM) which is used for satellite network.

In Network layer, QualNet offers three kinds of routing protocols. The proactive protocols include Bellman-Ford algorithm, Routing Information Protocol (RIPv2), Open Shortest Path First (OSPFv2) and OLSR. The reactive protocols consist of AODV, Dynamic Source Routing (DSR) and Location-Aided Routing (LAR1). The static routing needs input routing file which specify by user. [7_5] [7_6]

7.2 Performance Metric

There are several quantitative parameters that are used to weight and analyze the simulation results in order to evaluate the network and routing performance with different scenarios. This section will present all the quantitative parameters which are measured and analyzed in the case studies.

7.2.1 Packet delivery ratio

The packet delivery ratio is the ratio between the number of data packets correctly delivered to the destinations and the number of data packets generated by the sources.

The case studies only consider average packet delivery ratio, which is the mean value of the packet delivery ratios of all the traffic flows in the network. The higher packet delivery ratio means the less data loss at the receivers of all the destinations and the better network performance.

7.2.2 Throughput

The throughput is the amount of data that can be successfully transferred through the channel in a given time period. In fact it is a related metric to packet delivery ratio but the throughput is weighted by bits not number of data packets. Typically it is measured in kbps, Mbps and Gbps. The average throughput measured in the case studies is the mean value of the throughput of all the traffic flows in the network.

7.2.3 End to end delay

The end to end delay is the time used to deliver a data packet from the application layer of the source to the corresponding layer of the destination. It consists of all possible delay caused by buffering during route discovery latency, queuing at the interface queue, retransmission delays in MAC layer, propagation and transfer times. The mean value of the end to end delays of all the traffic flows in the network is measured in the case studies.

7.2.4 Path length

The path length is the number of hops that a data packet needs in the delivery from the source to the destination. In a mobility scenario, the connection link often breaks due to any moving objects or any shadowing blocks. So the path length is measured as that the total number of hops for all routes divided by the number of all selected routes. The mean value of path length of all the traffic flows in the network is evaluated in the case studies. The less path length means the less relay nodes are needed for forwarding data packets, the less probability of data loss and the better routing performance.

7.3 Simulation setup

This section will describe how the case studies were done. There are four case studies in this thesis:

- Communication distance simulation (Case 1): In this simulation the distance between the source and destination nodes is varied to see how it affects the different metrics.

- Physical data rate simulation (Case 2): In this simulation the physical data rate (channel bandwidth) is varied to see how different routing protocols behave with and without directional antennas.
- Mobility pause time simulation (Case 3): In this simulation the pause time, the time period of the node being still after moving, is varied to see how the mobility pause time influences the network performance.
- Mobility speed simulation (Case 4): In this simulation the speed value is varied to see how it affects the network performance.

The general simulation parameters are presented in Table 7.1. All the simulations use IEEE 802.11a PHY protocol and IEEE 802.11a with DVCS MAC protocol. In Case 1 and Case 2, the directional antenna gain is 15 dBi. Although directional antennas have much higher gain compared with corresponding omni-directional antennas in real life. In Case 3 and Case 4, the directional antenna gain is set as 0 dBi in order to see how omni-directional antenna and directional antennas behave with the same transmission range.

Table 7.1: The general simulation environment parameter

Parameter	Value
Propagation channel frequency	5 GHz
Path loss model	Two Ray
Directional antenna model	Switched beam
Directional antenna gain	15 dBi / 0 dBi
MAC protocol	IEEE 802.11 with DVCS
Directional NAV delta Angel	37 degree
AOA cache expiration time	2 s

The Case 1 and Case 2 compare the network and routing performance of AODV and OLSR separated with omni-directional antennas and directional antennas. The mobility simulations Case 3 and Case 4 only utilize AODV as routing protocol and show how the two mentioned antenna models behave in the network. The AODV parameters setting are shown in Table 7.2.

Table 7.2: The AODV parameter setting

Parameter	Value
Active route timeout	10 s
RREQ packet retry	2
Hello message	No
Search best route	Yes
Local repair	No
TTL initial value	1
TTL increment value	2
TTL threshold	7
Maximum hops between two nodes	35

In mobility simulations, the node coordinates, mobility pattern, CBR senders and receivers are generated randomly. To avoid the evaluating results of a single simulation that been characterized by a peculiar happening, not representative of the general situation, each simulation is executed 5 times with different random generator seeds. Although 5 times is not sufficient to obtain the precise value, the result approaches to the real situation. All the data in the figures and tables are the average value of all the 5 times repeated simulation experiments. In each case, the random simulation settings are the same for omni-directional antennas and directional antennas in order to compare the network and routing performance fairly under the same simulation environment.

7.4 Case 1: Communication distance simulation

The Case 1 evaluates network and routing performance for different communication distance with different combinations of antenna models and routing protocols.

7.4.1 Case description

The QualNet simulator constructs a static network topology which is shown in Figure 7.4. Node 22 is always chosen as source node and the Nodes 23, 24, 25, 26, 27 and 28 are selected as destination nodes separately. The distance between neighbor nodes is 200 m.

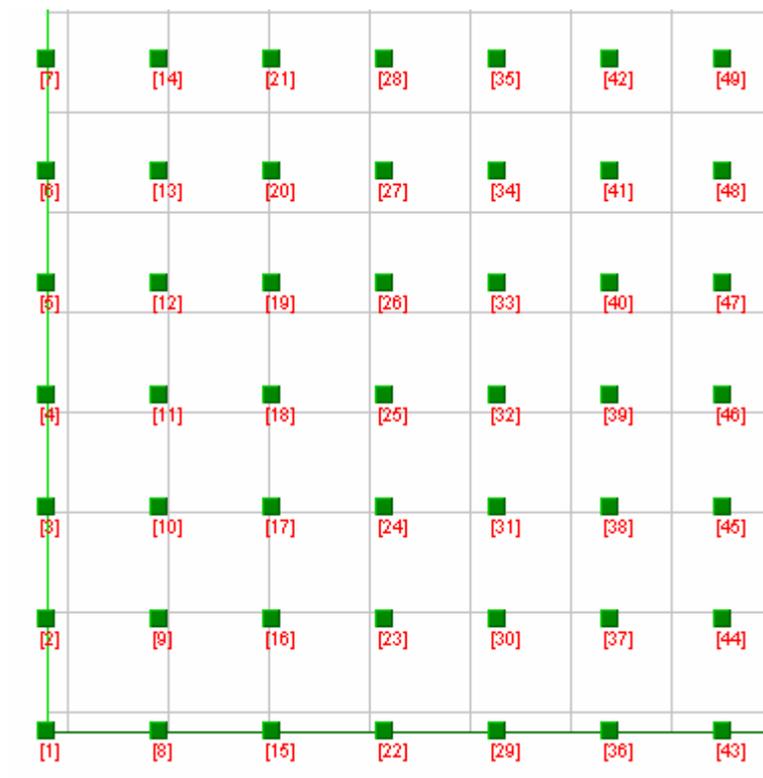


Figure 7.4: Grid node topology

The detailed simulation parameters are presented in Table 7.3. There is only one CBR traffic flow during the simulation time and the packet size and packet rate are fixed for all the communication distance cases. The initial time is 200 s which is sufficient for the OLSR routing protocol to build up its routing table. The presimulation time is also needed for the system to become steady.

Table 7.3: The simulation environment of Case 1

Parameter	Value
Number of nodes	49
Node placement	Grid
Grid size	200 m
Terrain size	2000x2000 m
Simulation time	600 s
Bandwidth	24 Mbps
Transmission power	18 dBm
Receiver sensitivity	-83 dBm
Mobility model	None
Traffic type	Constant Bit Rate
Packet rate	8 packets/s
Packet size	512 byte
Number of flows	1

7.4.2 Simulation results

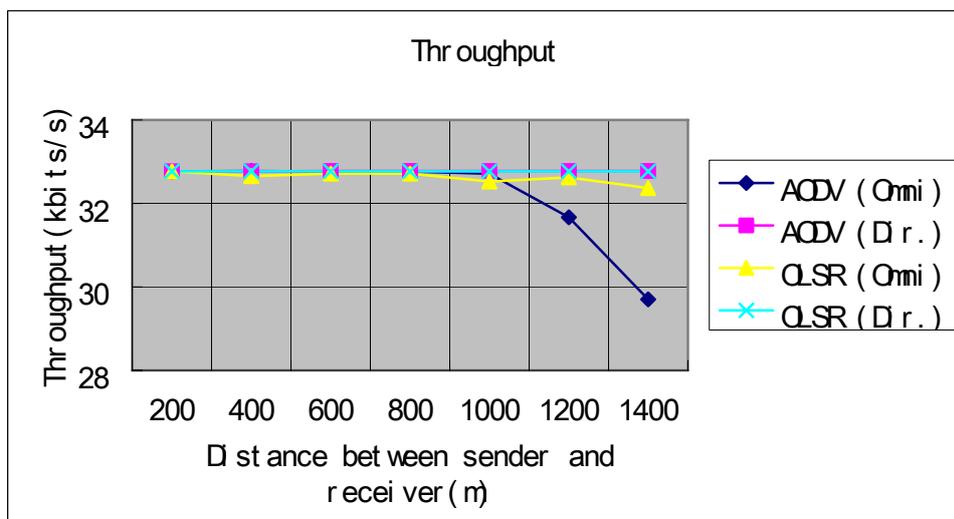


Figure 7.5: The average throughput of Case 1

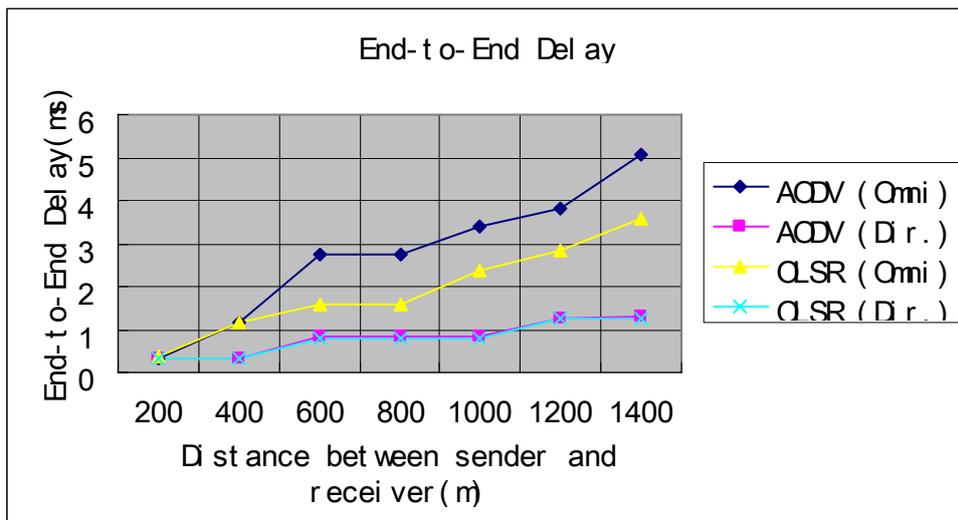


Figure 7.6: The end-to-end delay of Case 1

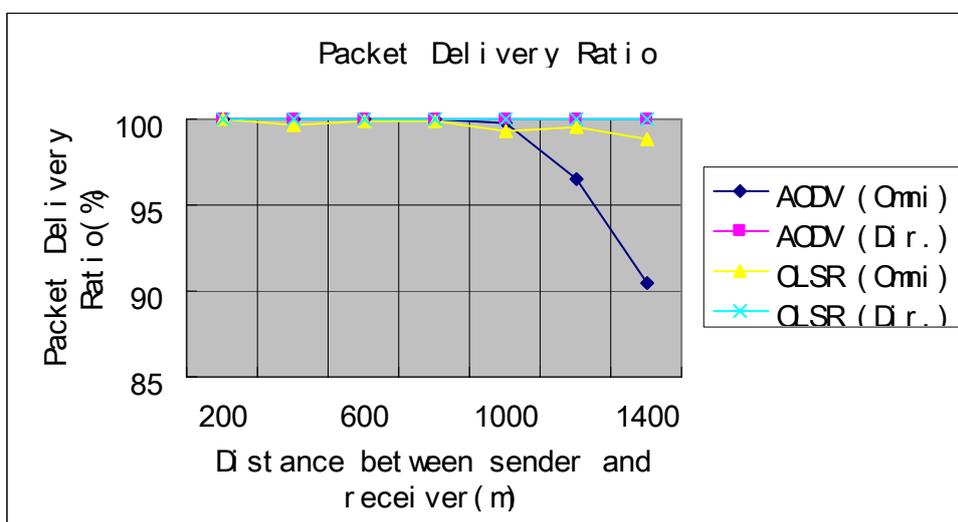


Figure 7.7: The packet delivery ratio of Case 1

Table 7.4: The path length of Case 1

Distance (m)	200	400	600	800	1000	1200	1400
AODV (Omni)	1	2	3	3	4	5	6
AODV (Dir)	1	1	2	2	2	3	3
OLSR (Omni)	1	2	3	3	4	5	6
OLSR (Dir)	1	2	2	2	2	3	3

7.4.3 Analysis

The throughput of single CBR is shown in Figure 7.5. In the short communication range (distance between source and destination is less than 800 m), the throughputs of AODV and OLSR routing protocol with omni-directional antennas and directional antennas have no significant difference. With the communication distance increasing, the throughput of AODV with omni-directional antennas decreases severely, the throughput of OLSR with omni-directional antennas decreases slightly. The throughput of AODV with omni-directional antennas decreases significantly when the communication distance increases to 1400 m. It is obvious that the throughputs of AODV and OLSR with directional antennas were not affected by increasing the communication distance.

The end to end delay is presented in Figure 7.6. When observing together with the Table 7.4, it is obvious that the end to end delay depends mostly on the number of hops for each path. One example is the end to end delays for 600 m, 800 m and 1000 m of the OLSR routing protocol with directional antennas are similar since they have the same number of hops. When the number of hops increases, the end to end delay rises significantly. The end to end delays of two directional cases outperform the ones of two omni-directional cases. The directional antennas with AODV and OLSR routing protocols behave similarly, while the omni-directional antennas with OLSR perform better than the one with AODV when the distance more than 600 m. With the same number of hops except 1 hop, the end to end delays of directional antennas are much less than the ones of omni-directional antennas.

The packet delivery ratio is shown in Figure 7.7. The performance of packet delivery ratio is similar to the ones of throughput. The directional antennas outperform omni-directional antennas. The worst performance of packet delivery ratio occurs in AODV routing protocol with omni-directional antennas when distance between source and destination is more than 1000 m. It reduces around 10% when the communication distance is 1400 m.

7.5 Case 2: Physical data rate simulation

Case 2 evaluates network and routing performance for different physical data rates with different combinations of antennas models and routing protocols.

7.5.1 Case description

The QualNet simulator constructs the static network topology which can be found in

Figure 6.4. The differences of network topology between this case and Case 1 are that the distance between neighbor nodes is 60 m and network area is 1500x1500 m in Case 2. There are three constant traffic flows (15->21, 22->28 and 29->35) running during the whole simulation period. All the quantitative results are the average value of the three CBR flows. The detailed simulation parameters are presented in Table 7.5 and Table 7.6.

Table 7.5: The simulation environment of Case 2

Parameter	Value
Number of nodes	49
Node placement	Grid
Grid size	60m
Terrain size	1500x1500 m
Simulation time	300 s
Mobility model	None
Traffic type	Constant Bit Rate
Packet rate	2 packets/s
Packet size	1024 byte
Number of flows	3

Table 7.6: The power settings of Case 2

Bandwidth (Mbps)	9	18	24	36	48	54
Transmission power (dBm)	20	19	18	18	16	16
Receiver sensitivity (dBm)	-85	-83	-78	-78	-69	-69

The values of transmission power and receiver sensitivity are default values of QualNet which comes from industry standards.

7.5.2 Simulation results

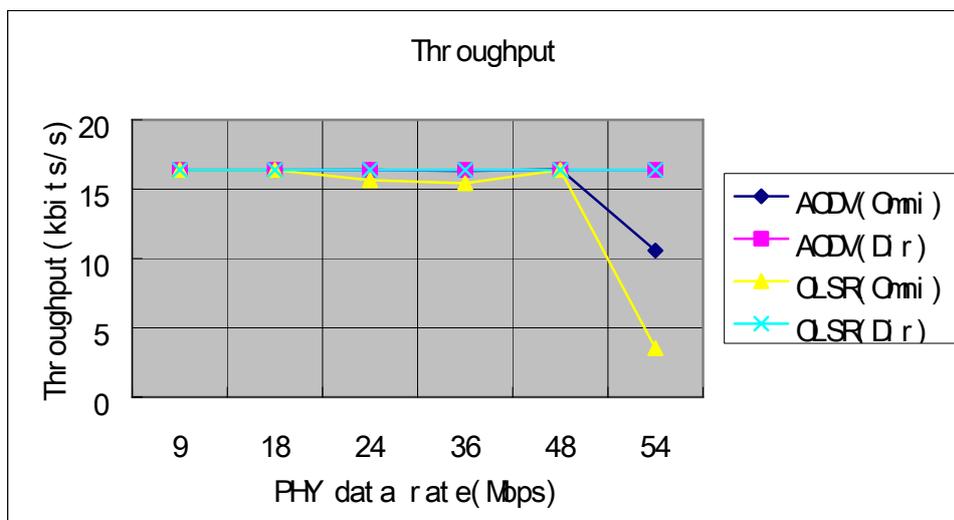


Figure 7.8: The average throughput of Case 2

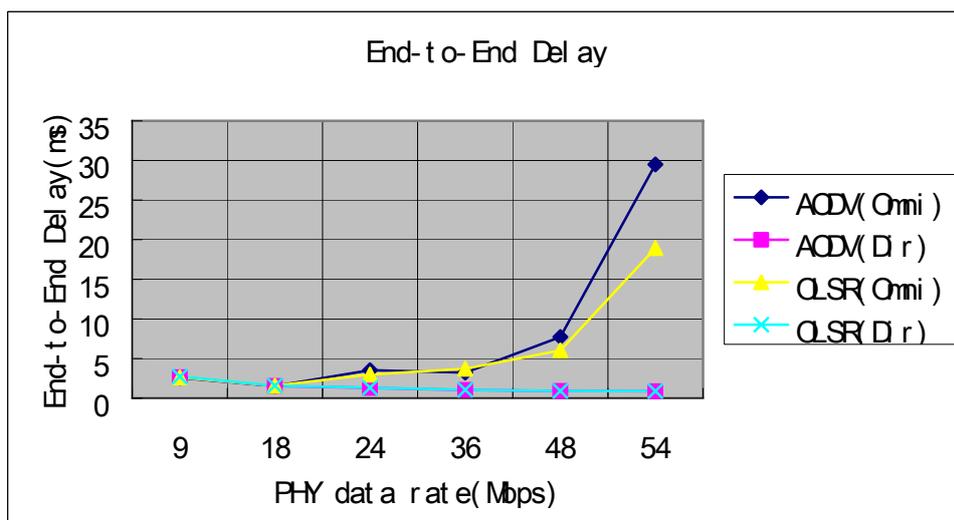


Figure 7.9: The end-to-end delay of Case 2

Table 7.7: The average path length of Case 2

Bandwidth (Mbps)	9	18	24	36	48	54
AODV(Omni)	1	1	2	2	6	6
AODV(Dir)	1	1	1	1	1	1

7.5.3 Analysis

The average throughput of three CBR flows is presented in Figure 7.8. The throughputs of two directional antennas cases were not affected by increasing the PHY data rate from 9 Mbps to 54 Mbps. The throughput of AODV with omni-directional antennas were not influenced by increasing the PHY data rate when it is less than 48 Mbps, but it reduces 15% when the PHY data rate is 54 Mbps. The throughput of OLSR with omni-directional antennas decrease slightly with increasing the PHY data rate when it is less than 48 Mbps, but it reduces around 78% when the PHY data rate is 54 Mbps due to severe data packet loss.

The average end to end delay of three traffic flows is shown in Figure 7.9. The end to end delays of two directional antennas cases were influenced a little by increasing the PHY data rate from 9 Mbps to 54 Mbps. The end to end delays of two omni-directional antennas cases increase in accord with PHY data rate and have a significant increase from 48 Mbps to 54 Mbps. The end to end delay of OLSR with omni-directional antenna increase three times and the one of AODV with omni-directional antennas rises more than 4 times. One reason of the notable increase of end to end delay of AODV is that the considerable increase of path length from 48 Mbps to 54 Mbps, which can be found from Table 7.7.

7.6 Case 3: Mobility pause time simulation

The Case 3 evaluates network performance for different mobility pause time with two antennas models for AODV routing protocol.

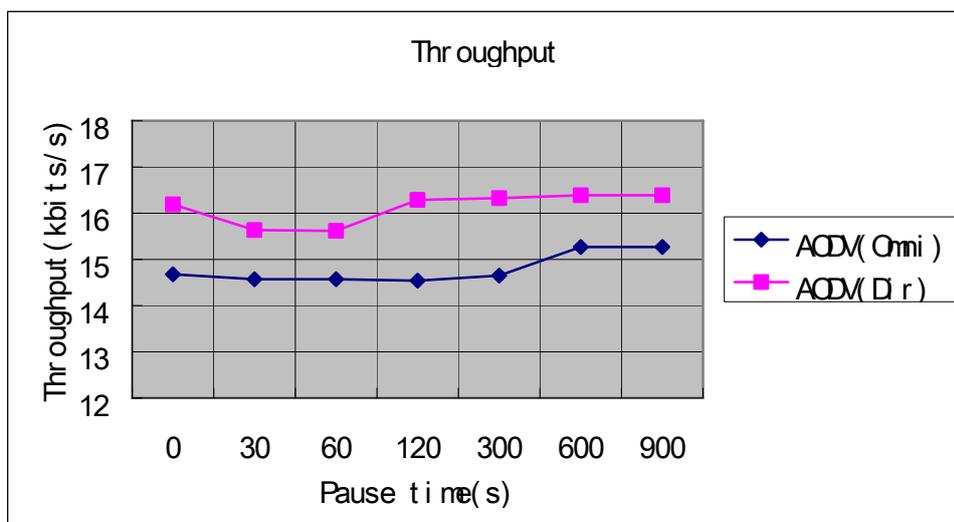
7.6.1 Case description

The pause time is the period during which a node stands still before randomly choosing a new destination location and a speed, within the minimum speed and the maximum speed, which will be used to reach that location. Case 3 chooses 0 s, 30 s, 60 s, 120 s, 300 s, 600 s and 900 s separately as pause time. There are three traffic patterns (10 CBR, 20 CBR and 30 CBR) are used for the simulations. In the network layer, only AODV routing protocol is used in the experiments. The detailed simulation parameters are given in Table 7.8.

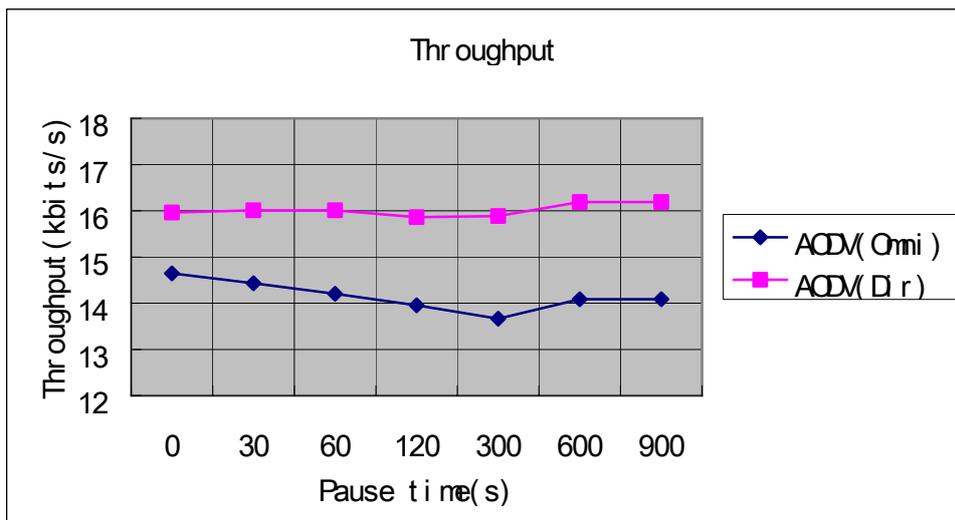
Table 7.8: The simulation environment of Case 3

Parameter	Value
Number of nodes	50
Node placement	Random
Terrain size	1500x300 m
Simulation time	900 s
Initial time	200 s
Bandwidth	24 Mbps
Transmission power	18 dBm
Receiver sensitivity	-83 dBm
Mobility model	Random Waypoint
Minimum speed	0 m/s
Maximum speed	20 m/s
Traffic type	Constant Bit Rate
Packet rate	4 packets/s
Packet size	512 bytes

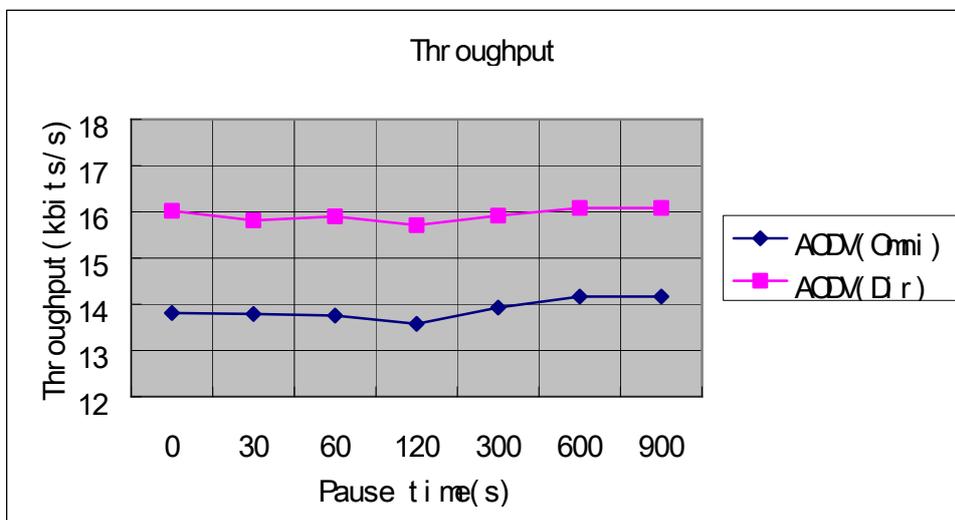
7.6.2 Simulation results



(a) 10 CBR

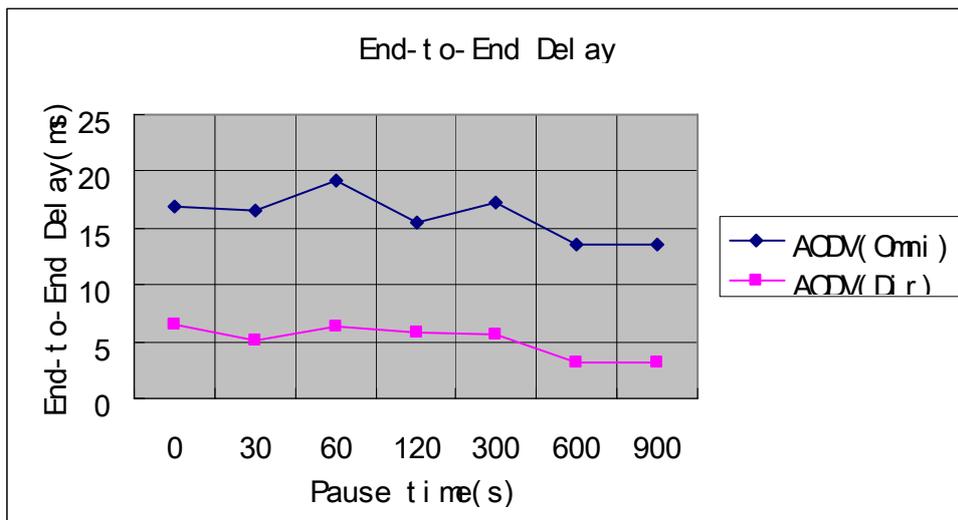


(b) 20 CBR

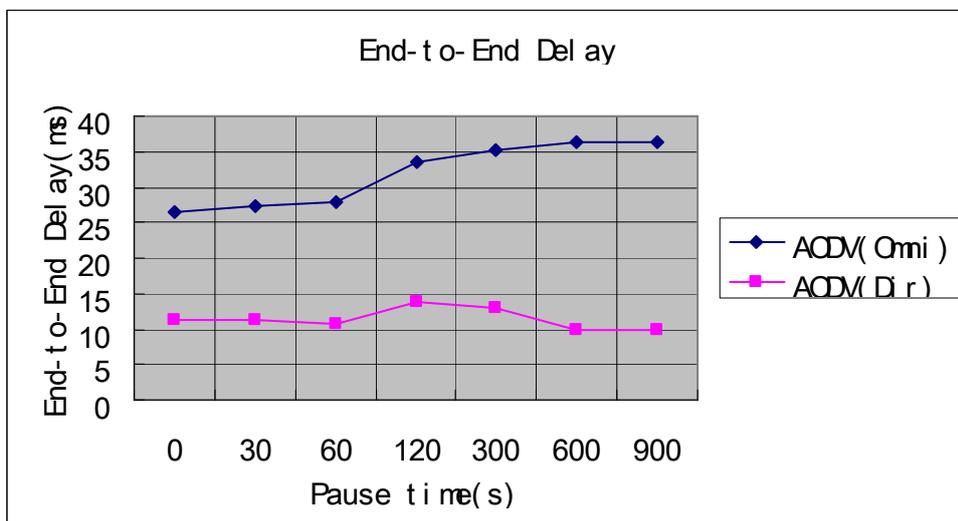


(c) 30 CBR

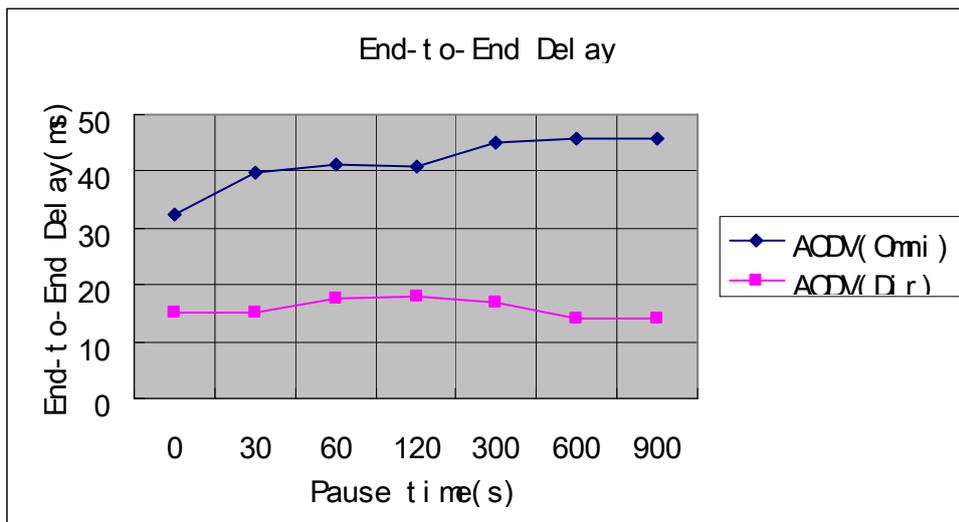
Figure 7.10: The average throughput of Case 3



(a) 10 CBR

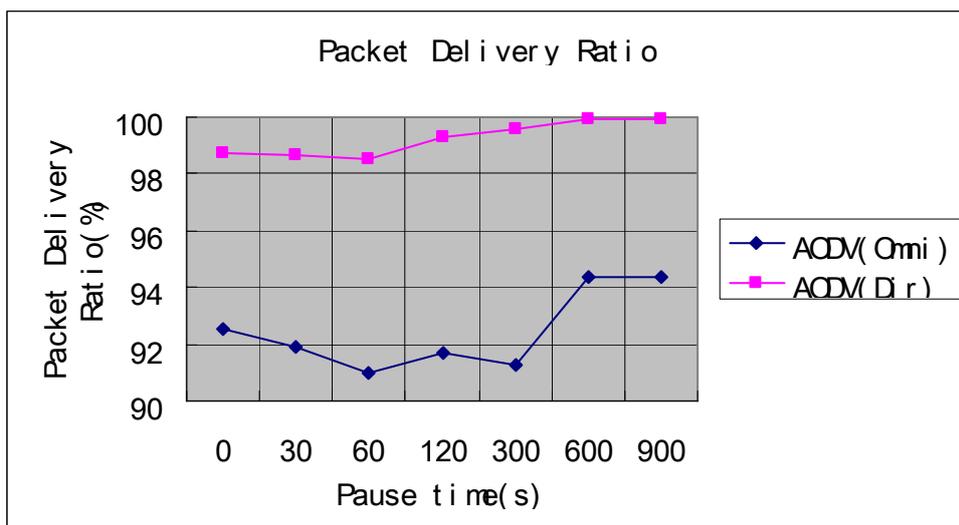


(b) 20 CBR

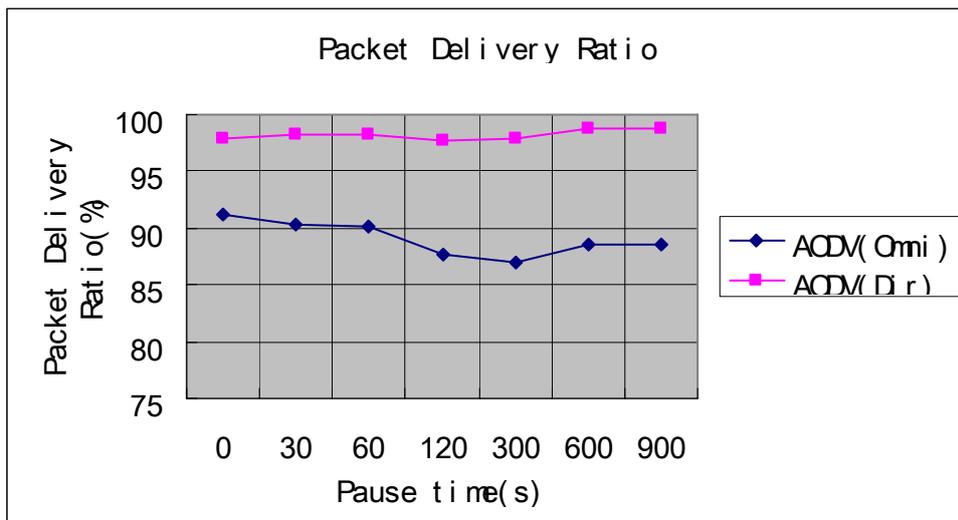


(c) 30 CBR

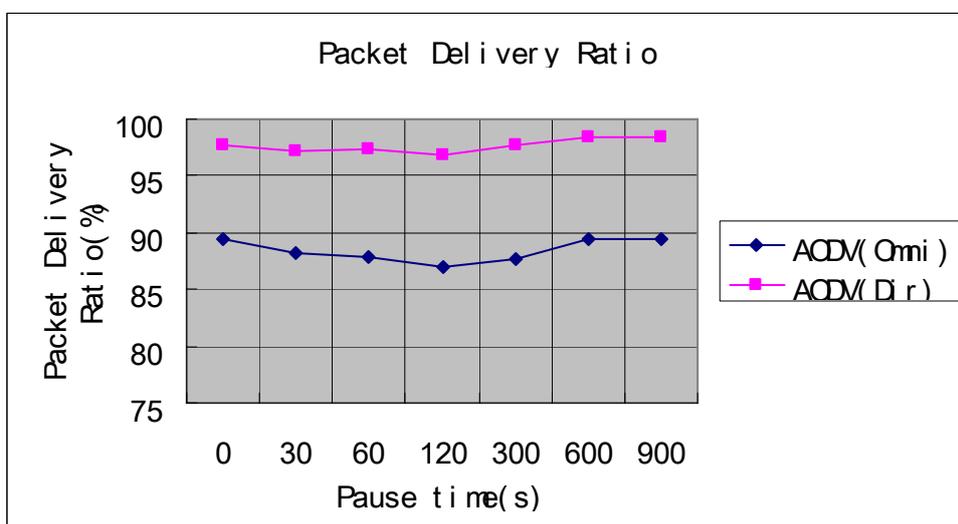
Figure 7.11: The end-to-end delay of Case 3



(a) 10 CBR

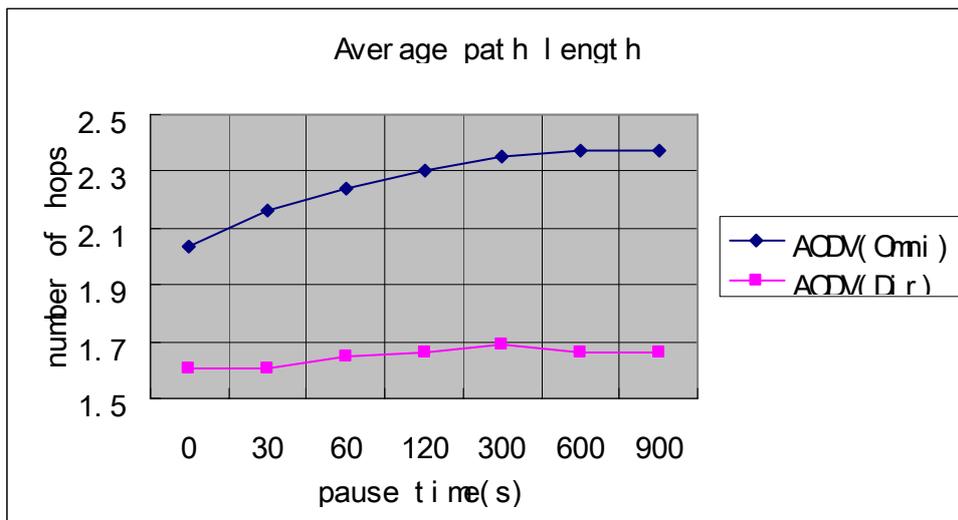


(b) 20 CBR

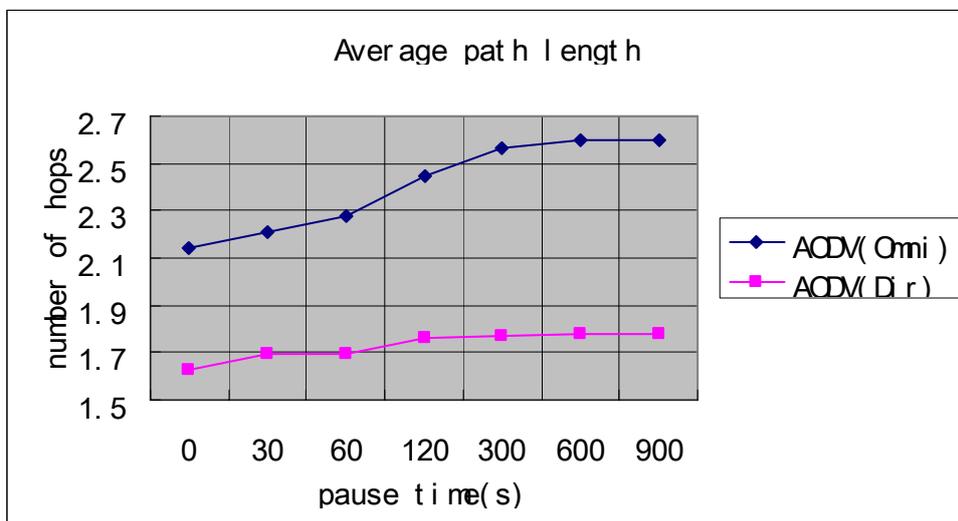


(c) 30 CBR

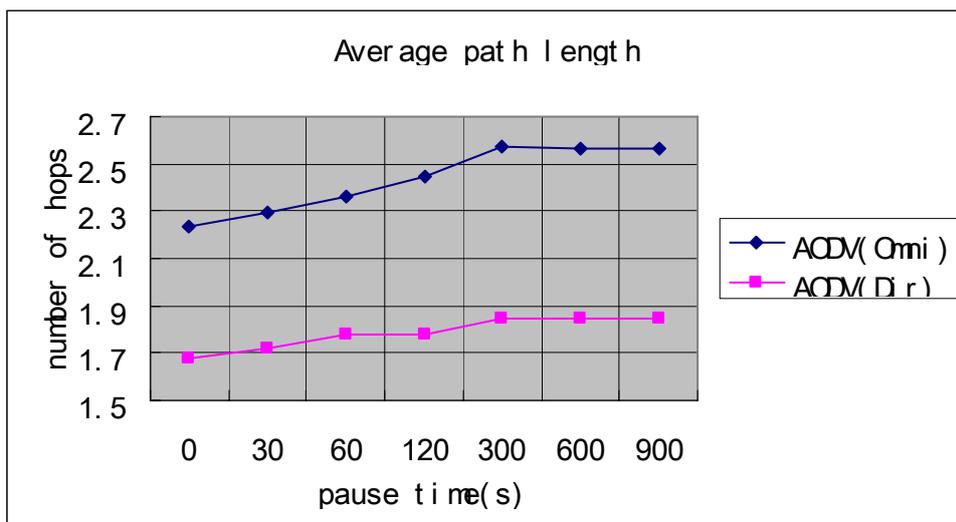
Figure 7.12: The packet delivery ratio of Case 3



(a) 10 CBR



(b) 20 CBR



(c) 30 CBR

Figure 7.13: The path length of Case 3

7.6.3 Analysis

The pause time is the motionless time for each node in the network. The more pause time means the less degree of node mobility from the entire network point of view.

The average throughputs of three traffic patterns are presented in Figure 7.10. With the increase of traffic flows from 10 CBR to 30 CBR, it is visible that the average throughput degrades noticeable for omni-directional antennas and slightly for directional antennas. The throughputs of directional antennas always outperforms the ones of omni-directional antennas, the more traffic flows, the higher node mobility degree, the advantage of directional antennas is more significant. When the node mobility degree decreases, the throughput of directional antennas and omni-directional antennas increase a little bit because the path length also increases especially for omni-directional antennas due to its short transmission range, which are shown in Figure 7.13.

The average end to end delay of three traffic patterns are displayed in Figure 7.11. The more traffic flows in the network, the more end to end delays for both omni-directional antennas and directional antennas. The omni-directional antennas have a poor performance in end to end delays which are always three times of the ones of directional antennas. When the mobility degree decreases, the end to end delay of directional antennas degrades accordingly, but the one of omni-directional antennas rises due to the increase of number of hops for each path.

The average packet delivery ratios of three traffic patterns are depicted in Figure 7.12.

The packet delivery ratio has the same behavior as the throughput. The directional antennas always gain more than 7 % packet delivery ratio compared with omni-directional antennas. With the increase of mobility degree, the advantage of directional antennas becomes more obvious.

7.7 Case 4: Mobility speed simulation

Case 4 evaluates network performance for different mobility level defined by the range of speed with different antennas models.

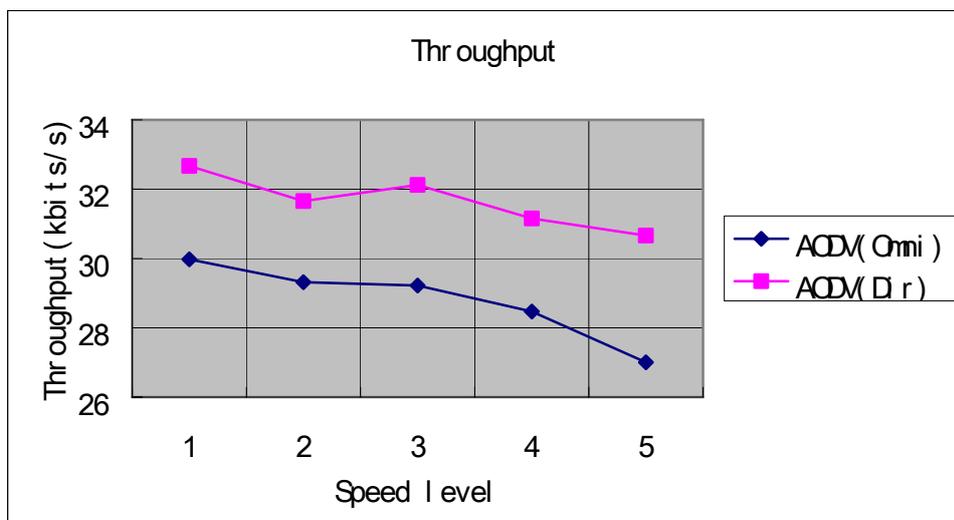
7.7.1 Case description

The detailed simulation parameters setting except of the minimum and maximum speed value, the packet rate (4packets/second) and terrain size (1000 m*1000 m) are the same as Case 3 which are presented in Table 7.8. The node will choose randomly its speed within the minimum and maximum speed value each movement after a pause time which is set as 1s. The Table 7.9 is shown the mobility level which defined by different combination of minimum and maximum speed. The Mobility 1 describes the walker speed, the Mobility 2 shows the jogger speed, the Mobility 3 displays the runner speed, and the Mobility 4, 5 present vehicle speeds.

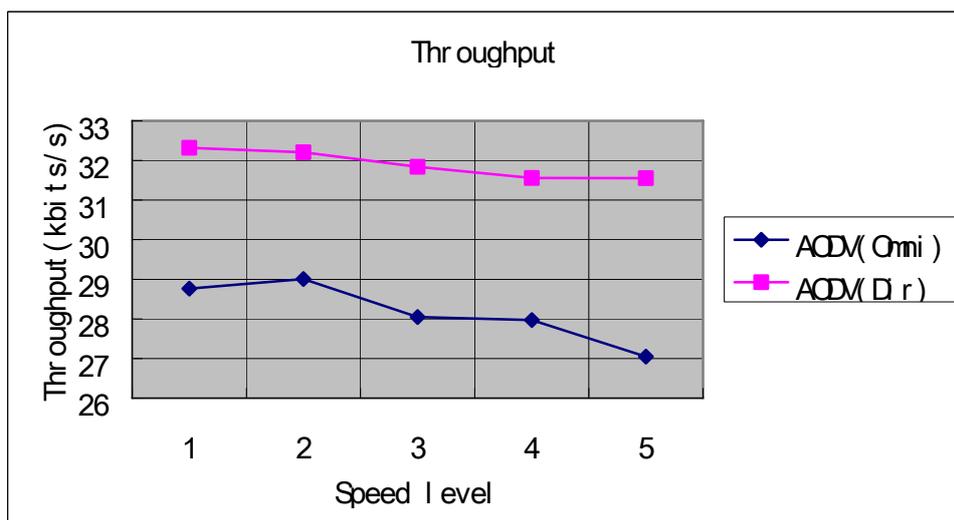
Table 7.9: The mobility level of Case 4

Mobility level	1	2	3	4	5
Minimum speed (m/s)	0	5	10	15	20
Maximum speed (m/s)	5	10	15	20	25

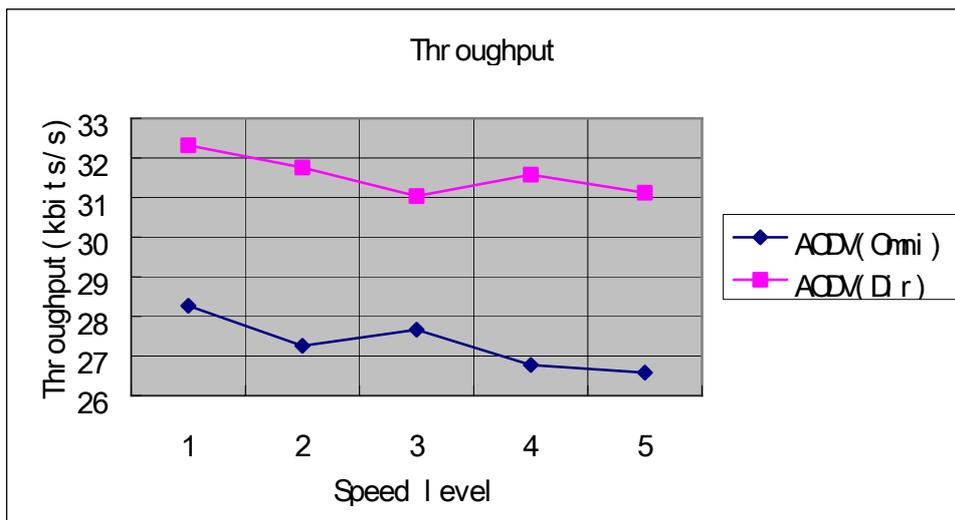
7.7.2 Simulation results



(a) 10 CBR

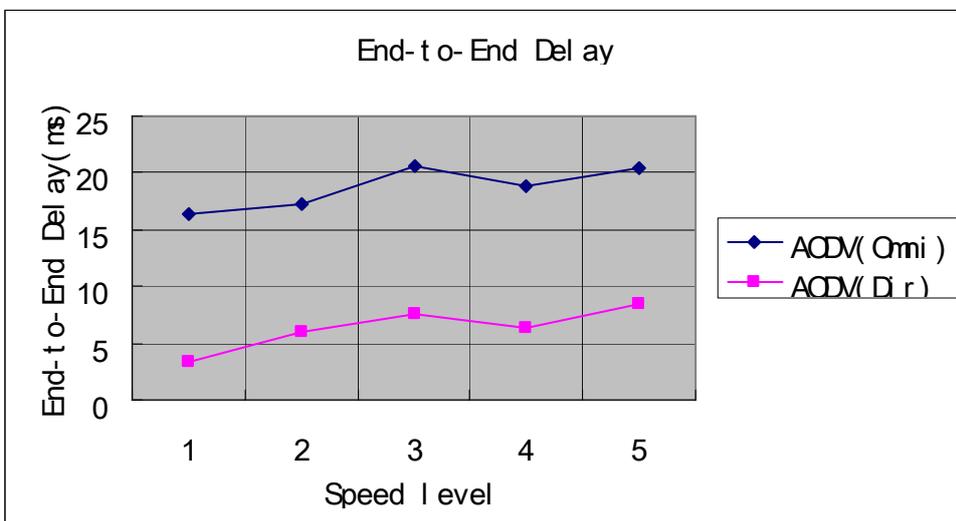


(b) 20 CBR

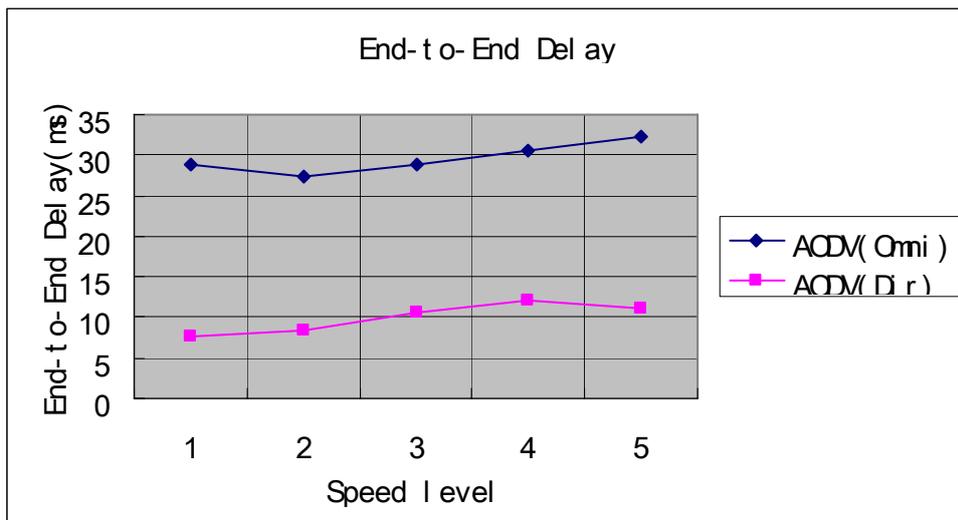


(c) 30 CBR

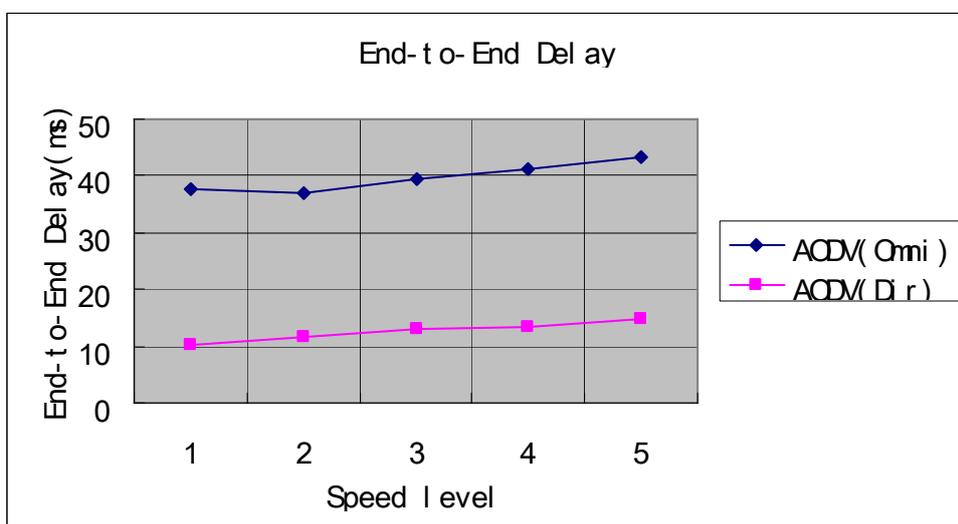
Figure 7.14: The average throughput of Case 4



(a) 10 CBR



(b) 20 CBR

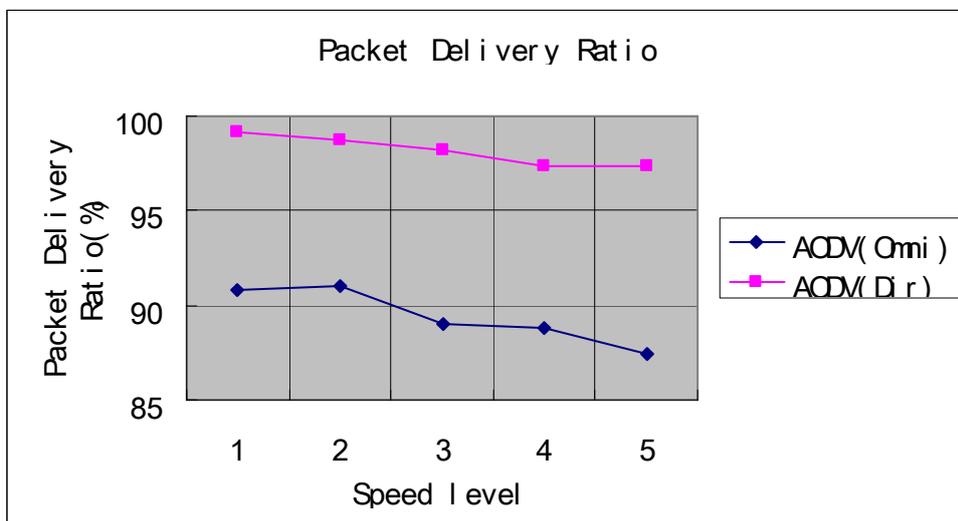


(c) 30 CBR

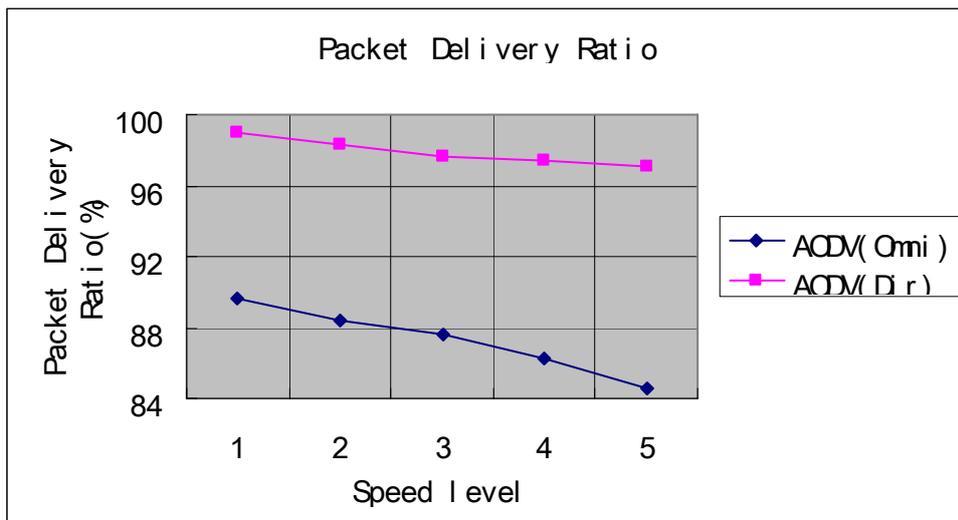
Figure 7.15: The end-to-end delay of Case 4



(a) 10 CBR

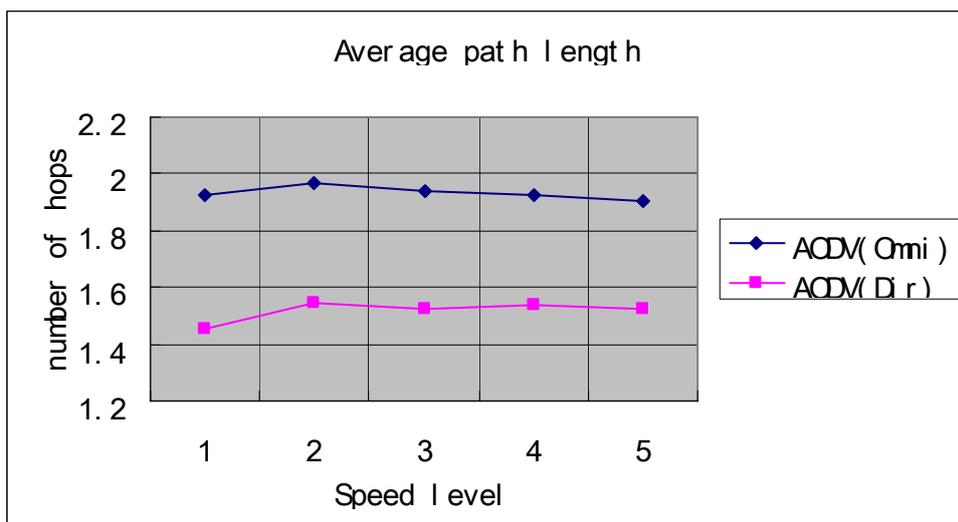


(b) 20 CBR



(c) 30 CBR

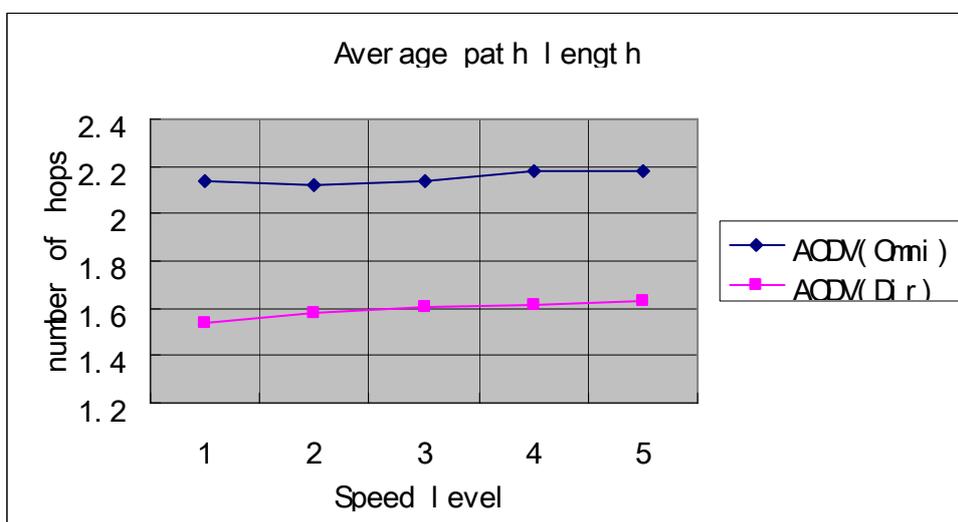
Figure 7.16: The packet delivery ratio of Case 4



(a) 10 CBR



(b) 20 CBR



(c) 30 CBR

Figure 7.17: The path length of Case 4

7.7.3 Analysis

The average throughput is presented in Figure 7.14. The throughputs of both omni-directional antennas and directional antennas decrease with the increase of mobility level. However, the throughput of directional antennas decreases slower than the one of omni-directional antennas. The directional antennas always outperform omni-directional antennas in each scenario. With the increase of the traffic load, the throughput of directional antennas does not have big changes, but the one of omni-directional antennas decreases accordingly.

The average end to end delay is shown in Figure 7.15. When the mobility level increases, the end to end delay rises for both antenna models. In the heavy traffic load scenario, the end to end delay increases slower than in the other two light traffic load scenarios. The more traffic flows in the network, the larger is the end to end delay. The end to end delay of omni-directional antennas is about four times of the one of directional antennas.

The packet delivery ratio is shown in Figure 7.16. The behavior of the packet delivery ratio is almost the same as the one of the throughput. From this figure, it is evident that the directional antennas gain more than 7 % packet delivery ratio when comparing with omni-directional antennas.

The average path length is depicted in Figure 7.7. The path length does have noticeable change when the mobility increases or the traffic flow rises. This suggests that path length slightly depends on the mobility speed level and traffic flows. The directional antennas always save 25 % of the hops when comparing with omni-directional antennas.

7.8 Summary

In a static scenario, on short communication distance, the throughputs of AODV and OLSR with omni-directional antennas and directional antennas behave similarly and they change slightly with the increase of communication distance. On long communication distance, the throughput of AODV with omni-directional antennas decreases dramatically compared with the one of OLSR with same antenna models. The performance of directional antennas does not change in longer distance due to its longer transmission range. The end to end delay of AODV with omni-directional antennas is larger than the one of OLSR with same antenna models, because the route finding is based on demand in AODV protocol which need more time to establish communication links. The end to end delays of directional antennas for both routing protocols perform similarly, because directional antennas could reach far neighbor node to reduce the number of hops. The throughput and end to end delay for both routing protocol with two antenna models does not show significant difference when the PHY data rate below 48 Mbps. In high data rate, the throughput of OLSR with omni-directional antennas has a big negative impact and the end to end delay of AODV with omni-directional antennas has a severe negative influence also. The directional antennas always outperform omni-directional antennas.

In a mobility scenario, it is evident that with the increase of traffic load, the performance of average throughput and average end to end delay becomes worse. The directional

antennas outperform the omni-directional antennas. The heavier traffic load, the higher probability of link breaks since omni-directional antennas send packets in all directions, which leads to serious interference to on-going communications. However, directional antennas could alleviate this problem since they focus the beam on target direction for transmitting packets. With increase of pause time, the average throughput of directional antennas and omni-directional antennas increase slightly, the end to end delay of directional antennas decrease, while the one of omni-directional antennas shows the opposite trend. The reason of the strange behavior of the end to end delay for omni-directional antennas is that the average path length rises when the mobility level decreases. There might be more obstructing nodes between the communication pair in lower mobility level scenario than in high mobility level scenario according to the chosen mobility models used in the simulation. If increasing the number of trials or changing simulation parameters properly, the number of hops might not increase too much with the increase of pause time and the omni-directional antennas might have the same performance trend as directional antennas from the theory point of view. With the increase of speed level, the average throughput decreases, the average end to end delay increases and the average path length keeps constant for both omni-directional antennas and directional antennas. The directional antennas still always have better performance than omni-directional antennas.

There are several limitations of this case study. Due to the limitation of time and computer capability, each experiment is repeated only five times with different random seeds. The results shown in the figure are the average value which might not present the precise routing and network performance. However, the author have repeated several experiments ten times and found the result of ten times does not show big difference from the ones of five times used in the case study. The standard deviation of five trials is analyzed for some simulations. Table 7.10 present one example of deviation analysis for Case 4 of 10 CBR traffic load. In the omni-directional antennas case, the standard deviations are around 1 kbps, the speed level of 3 performs best among all the five trials the largest standard deviation is not more than 1.82 kbps. In the directional antennas case, the standard deviations are quite different, the lowest speed level has the smallest deviation and the largest standard deviation is not more than 1.76 kbps.

Table 7.10: Standard deviation of throughput of 10 CBR for Case 4

Speed Level	1	2	3	4	5
Standard deviation of throughput for omni-directional antennas (kbps)	1.82	1.51	0.86	1.39	1.52
Standard deviation of throughput for directional antennas (kbps)	0.084	1.76	0.13	1.59	1.21

The design of QualNet simulator has several drawbacks which influence the simulation results a little bit. IEEE 802.11 with DVCS MAC protocol is used in MAC layer for

directional antennas. However, the powerful features of directional antennas were not fully utilized only by this MAC protocol, since the longer transmission and reception range of directional antennas was suppressed by the routing layer which discovers the new route with omni-directional antennas. The short path route might be ignored due to short transmission range of omni-directional antennas.

CHAPTER 8

SUMMARY AND CONCLUSIONS

The implementation of directional antennas in ad hoc networks is studied in this thesis. This thesis also presents the challenges and design issues in the MAC layer and the routing layer for equipping ad hoc devices with directional antennas. Several directional MAC proposals aiming to solve the new hidden terminal problem and deafness problems are reviewed in Chapter 4. Some directional routing proposals trying to work out directional route finding and routing overhead problems are discussed in Chapter 6. The improvement of ad hoc routing and network performance with directional antennas compared with current omni-directional antennas are evaluated based on the simulation results in Chapter 7. This thesis can be used as a reference for further research of directional antennas in ad hoc networks. The theoretical parts of smart antenna technology and IEEE 802.11 MAC protocol can be considered as a technical introduction for beginners.

The results show that network performance of directional antennas is not affected by increasing the communication distance in the static scenario. The routing performance of OLSR outperforms AODV when devices equipped with omni-directional antennas in long communication distance. In the mobility scenario, network performance deteriorates with the increase of mobility level, but directional antennas show significant advantage compared with omni-directional antennas even in the network with heavy traffic load.

The significant finding of this study is that the network performance metrics, like throughput, end to end delay, packet delivery ratio, and path length, of directional antennas always outperform omni-directional antennas in both static and mobility scenarios, and the improvement of directional antennas is more obvious when channel condition becomes worse or mobility level is larger.

The theoretical part of this thesis is a literature study of applying smart antenna technology to ad hoc networks. The main contribution is that the author summarizes and compares different recent directional MAC and routing proposals from technical point of view. The case study part is done with the event-based QualNet simulator. One challenge is that the graphical simulation result generated by the QualNet analyzer cannot be used for comparing network performance of different scenarios. The AWK tool is used to extract useful data from simulation result files for further

data analysis.

The limitation of the case study is that the data is the average value of five repeated trials with different random seeds and it might not present the precise routing and network performance. Another limitation of the case study is that the powerful features of directional antennas were not fully utilized only by IEEE 802.11 with DVCS MAC protocol which is used in simulations. The longer transmission and reception range of directional antennas was suppressed by the routing layer which finds the new route only with omni-directional antennas. The drawback of directional routing protocol design leads to a little bit reduction of the performance of directional antennas.

The ad hoc network is a quite hot topic in the communication field. There are many researches going on and many issues that remain to be solved. Due to the limitation of time, the author only focused on studying directional MAC and routing protocols from certain point of views. There are still many issues left for further studies:

- This thesis concentrates on unicast routing protocol. The multicast routing protocol is also an interesting issue that needs to be considered.
- There is a need to implement a new directional route discovery algorithm for directional antennas in the QualNet simulator to replace omni-directional route finding scheme in order to mitigating broadcast storm problem.
- The security is a very important issue in ad hoc networks. Since the ad hoc network does not have any centralized control, the security must be processed in a distributed manner.

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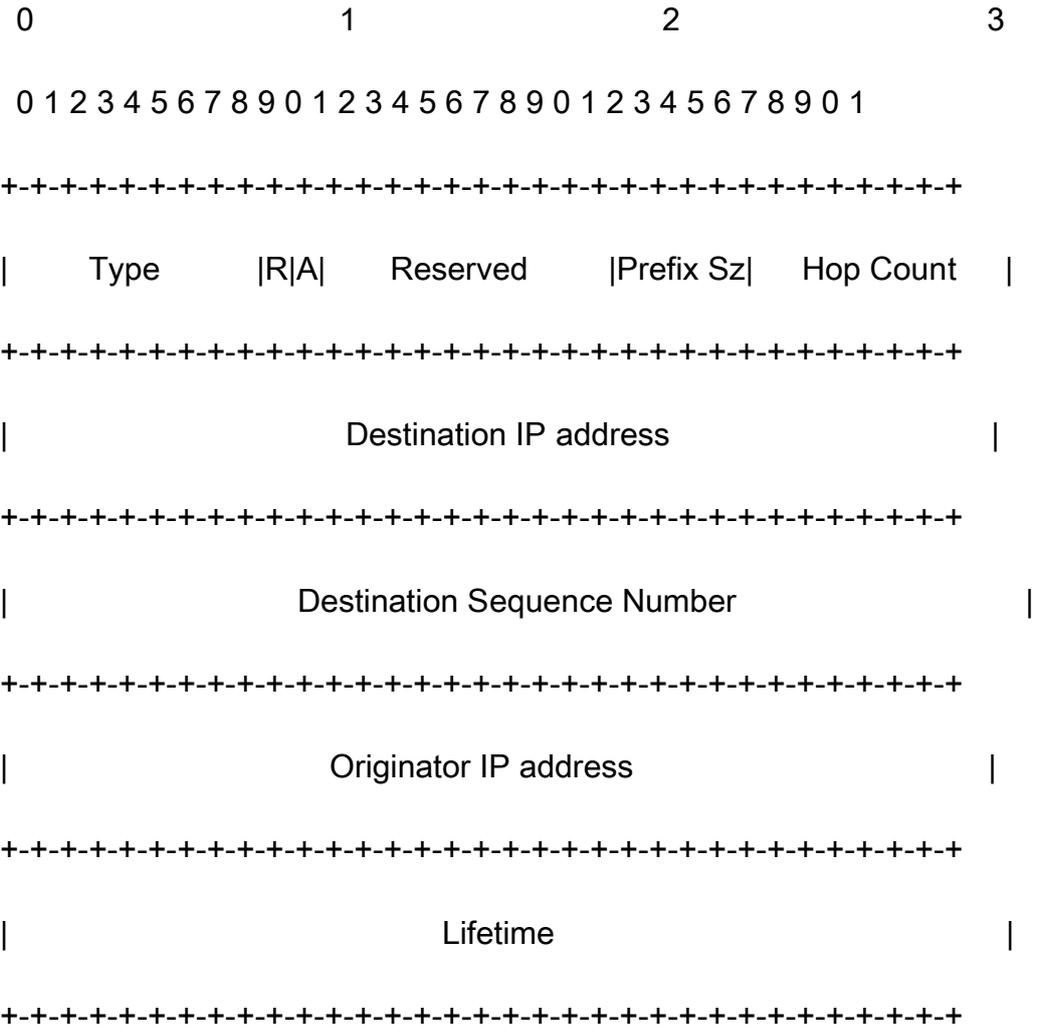
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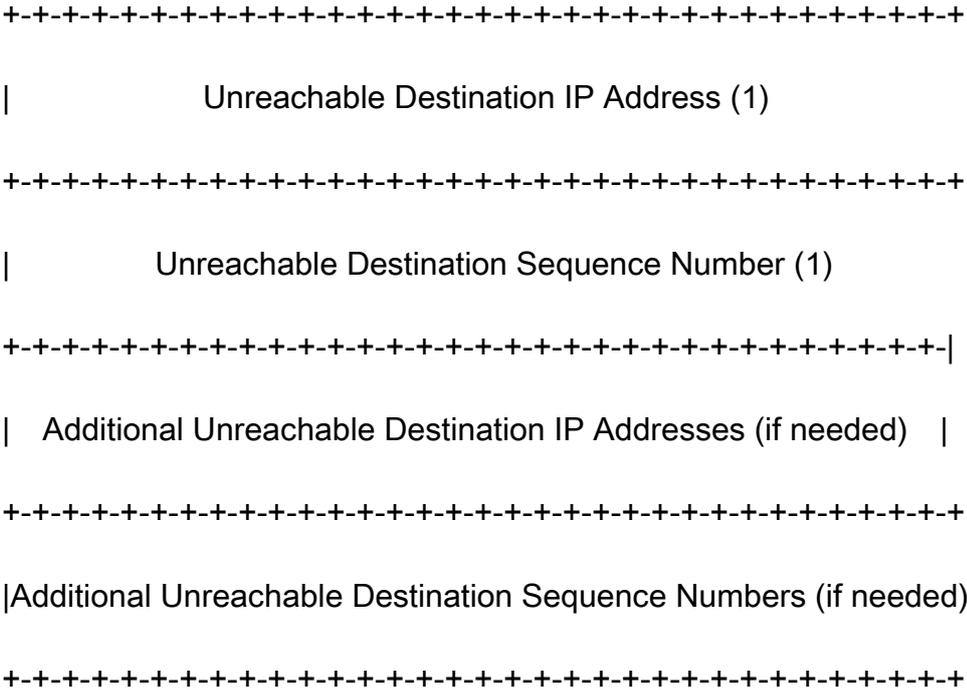
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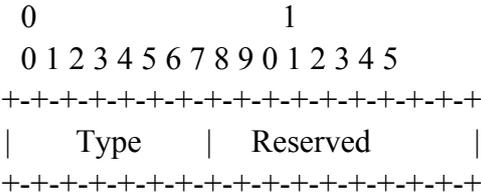


Route Error (RERR) Message Format



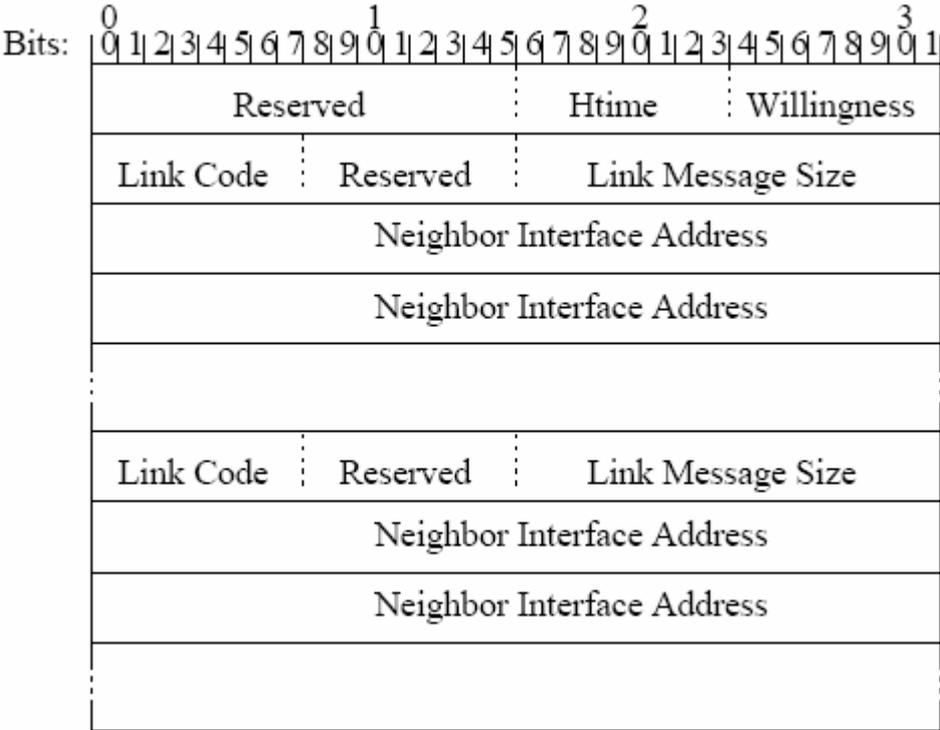


Route Reply Acknowledgment (RREP-ACK) Message Format

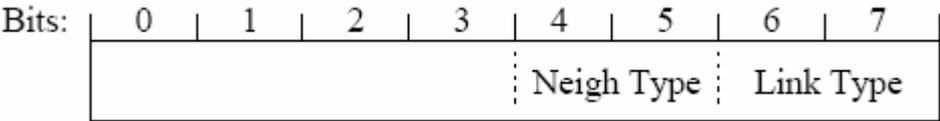


APPENDIX2: Message formats of OLSR

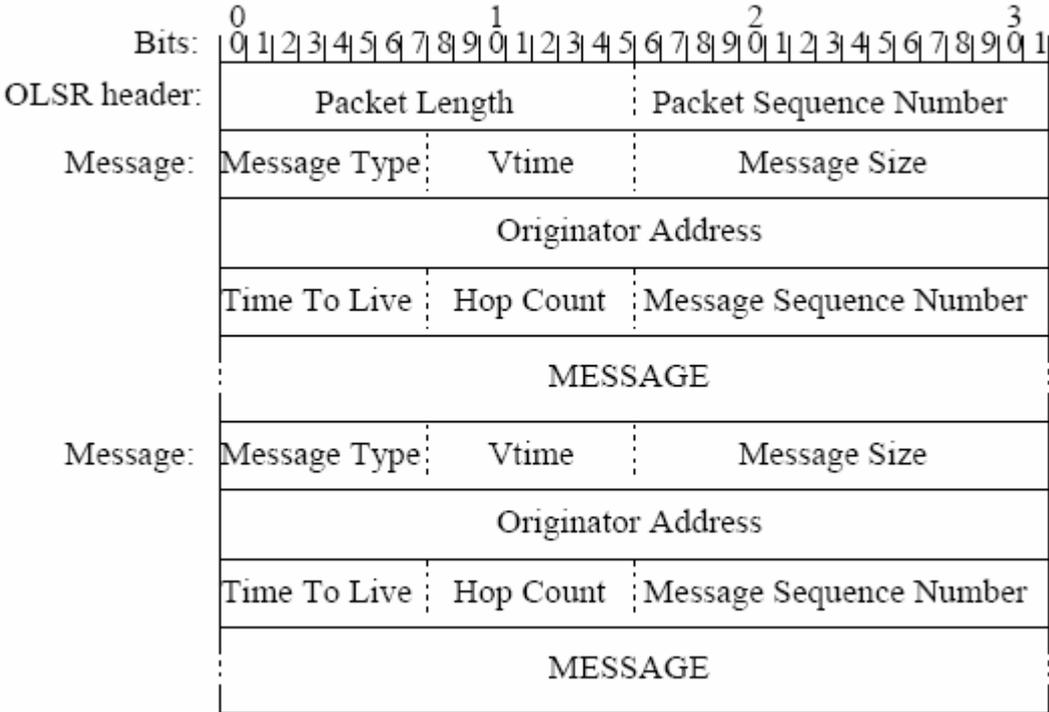
HELLO Message Format



8 bits Link Code Field of HELLO Message



Generic OLSR Packet Format



Topology Control Message Format

