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submitted by

Jackline Alphonse Guama Shulle

for the fulfilment of the requirements for the degree of

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Date

Signature : ____________________

Main Supervisor : Dr. Mohamad Naufal Mohamad Saad

Date : ____________________

Co-Supervisor : ____________________

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Improving the Performance of Medium Access Control Protocols for Mobile Ad-hoc Network with Smart Antennas

By

Jackline Alphonse Guama Shulle

A THESIS

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DEGREE OF MASTERS OF SCIENCE IN ELECTRICAL AND ELECTRONICS ENGINEERING

Electrical and Electronics Engineering

BANDAR SERI ISKANDAR,

PERAK

JUNE, 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Name : Jackline Alphonse Guma Shulle

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ABSTRACT

Requirements for high quality links and great demand for high throughput in Wireless LAN especially Mobile Ad-hoc Network has motivated new enhancements and work in Wireless communications such as Smart Antenna Systems. Smart (adaptive) Antennas enable spatial reuse, increase throughput and they increase the communication range because of the increase directivity of the antenna array. These enhancements quantified for the physical layer may not be efficiently utilized, unless the Media Access Control (MAC) layer is designed accordingly.

This thesis implements the behaviours of two MAC protocols, ANMAC and MMAC protocols in OPNET simulator. This method is known as the Physical-MAC layer simulation model. The entire physical layer is written in MATLAB, and MATLAB is integrated into OPNET to perform the necessary stochastic physical layer simulations. The aim is to investigate the performance improvement in throughput and delay of the selected MAC Protocols when using Smart Antennas in a mobile environment. Analytical methods were used to analyze the average throughput and delay performance of the selected MAC Protocols with Adaptive Antenna Arrays in MANET when using spatial diversity. Comparison study has been done between the MAC protocols when using Switched beam antenna and when using the proposed scheme.

It has been concluded that the throughput and delay performance of the selected protocols have been improved by the use of Adaptive Antenna Arrays. The throughput and delay performance of ANMAC-SW and ANMAC-AA protocols was evaluated in details against regular Omni 802.11 stations. Our results promise significantly enhancement over Omni 802.11, with a throughput of 25% for ANMAC-SW and 90% for ANMC-AA. ANMAC-AA outperforms ANMAC-SW protocol by 60%. Simulation experiments indicate that by using the proposed scheme with 4 Adaptive Antenna Array per a node, the average throughput in the network can be improved up to 2 to 2.5 times over that obtained by using Switched beam Antennas. The proposed scheme improves the performances of both ANMAC and MMAC protocols but ANMAC outperforms MMAC by 30%.

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ABBREVIATIONS AND SYMBOLS

WLAN	Wireless Local Area Network
MAC	Medium Access Control
SINR	Signal to Interference and Noise Ratio
SDMA	Space Division Multiple Access
MANET	Mobile Ad-hoc Network
IEEE	Institute of Electrical and Electronics Engineering
DS	Distribution System
BS	Basic Service Set
DCF	Distributed Coordination Function
PCF	Point Coordination Function
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DIFS	Distributed Inter Frame Space
CRC	Cyclic Redundancy Check
ACK	ACKnowledgement
SIFS	Short Inter Frame Spacing
RTS	Request To Send
CTS	Clear To Send
NAV	Network Allocation Vector
BER	Bit Error Rate
PIFS	PCF Interframe Space
EIFS	Extended Interframe Space
FHSS	Frequency Hopping Spread Spectrum
DSSS	Direct Sequence Spread Spectrum
OFDM	Orthogonal Frequency Division Multiplexing
DSP	Digital Signal Processing
RF	Radio Frequency
OPNET	Optimized Network Evaluation Tool

ESPRIT	Estimation of Signal Parameters via Rotational Invariance Technique
ANMAC	Angular MAC
MMAC	Multihop-RTS MAC
PHY-MAC	Physical and MAC
CCI	Co-Channel Interference
ANMAC-LS	ANMAC with Location Scheduling
DVCS	Directional Virtual Carrier Sensing
DNAV	Directional NAV
AOA	Angle Of Arrival
UDP	User Datagram Protocol
ROMA	Receiver-Oriented Multiple Access
QoS	Quality of Service
DO	Direction-Omni
DD	Direction-Direction
AN-RTS	Angular-RTS
AN-CTS	Angular-CTS
DOA	Direction Of Arrival
MUSIC	Multiple Signal Classification
LMS	Least Mean Square
NLMS	Normalized Least Mean Square
RLS	Recursive Least Square
SIR	Signal-To-Interference Ratio
MSE	Mean Square Error
CDMA	Code Division Multiple Access
I	Initial state
S	Stationary state
R	Right-move state
L	Left-move state

EAPS	Enhanced Antenna Positioning System
FSM	Finite State Machine
KP	Kernel Procedures
HTTP	Hyper Text Transfer Protocol
ANMAC-SW	Angular-MAC with Switched-beam Antenna
ANMAC-AA	Angular-MAC with Adaptive Antenna Array
BPSK	Binary Phase Shift Keying
PL	Path Loss
R_{zz}	Covariance matrix of Z array
E_x	Signal subspace for X array
E_y	Signal subspace for Y array
E	Ensemble expectation operator
θ_i	Angle of Arrival
k	Sample index
d	Element spacing between adjacent antenna elements
λ	Waveform length
N	Number of antenna elements
$S_i(t)$	Signal arriving at the different antenna elements
$X_i(t)$	The received signal
$Y(t)$	Output sent to the receiver
f_c	Carrier frequency
$n(t)$	Noise
$r(t), d(t)$	Reference signal
$S(k)$	Desired signal
$i_n(t)$	Interfering signals
α	Interelement phase Shift
ϕ_o	Desired beam direction
$N(t)$	Additive White Gaussian Noise
β	Phase propagation
A	Arbitrary gain constant
w_i	Weight

$\tau_k(\theta_i)$	Delay
$\varepsilon(t)$	Error signal
μ	Step size parameter of LMS algorithm
$(.)^H$	Complex conjugate transposition
$(.)^T$	Transposition
$a(\theta)$	Array propagation vector or steering vector for a particular value of θ
$a(\theta_i)$	The array propagation vector of the i^{th} interfering signal
$w^H(t)$	Hermitian transpose of the antenna weight
$d(t)$	Desired symbol or reference signal
∇w	The gradient of the performance surface
$\nabla(J)$	Gradient vector
$\frac{\partial}{\partial \underline{w}^*}$	Conjugate derivative with respect to vector
$\varepsilon(n)$	Cost function
$\nabla(J(n))$	Instantaneous estimate of the gradient vector
$\lambda_{\max}$	The largest eigenvalue
ϕ	Azimuth angle
θ	Elevation angle
$\overline{pd}$	Pointing Direction Vector
$\overline{tx}$	Geocentric Transmission Object vector
$-\overline{tx}$	Opposite of transmitter vector
$\overline{rx}$	Geocentric Receiver Object vector
$\overline{d}$	Difference vector
n_d	Normal Vector to plane containing $\overline{pd}$ and $\overline{d}$
n_neg_tx	Normal vector to plane containing $\overline{pd}$ and $-\overline{tx}$
v	Speed
t	Time
p	Probabilities
M	Total number of nodes
l	Number of packets

n_t	Total number of packets transmissions
n_r	Number of new transmissions
n_n	Number of retransmission
l	The number of packets
X_k	The state at slot k
p_n	The probability with which an unblocked terminal transmits a packet
p_r	The probability with which a blocked terminal retransmits its backlogged packet
k	The number of slots
a	Total number of transmissions
i, j	States
$S(j)$	Conditional throughput
ϕ_k	The phase of symbol k
$p_s(l,E)$	The probability of a successful packet reception given l total transmissions and that the node can form E nulls
$\overline{B}$	Average number of blocked terminals
S_{in}	Average throughput
$\overline{D}$	Delay
$b(t)$	Symbol
b_k	The original baseband symbol
$p(t)$	Square pulse
$G(\theta,\varphi)$	Antenna response beam pattern
U_{ave}	The average power density
$U(\theta,\phi)$	The power density in direction
η	The efficient of the antenna

CHAPTER 1

INTRODUCTION

1.1 Background

The need for high quality links and great demand for high throughput in Wireless LAN especially Mobile Ad-hoc Network has motivated new enhancements and work in Wireless communications such as Smart Antenna Systems. Smart Antennas enable spatial reuse and they increase the communication range because of the increase directivity of the antenna array. If the Media Access Control (MAC) layer is not designed accordingly these enhancements quantified for the physical layer may not be efficiently utilized. The goal of using Smart Antennas is to maximize the performance of the WLANs by increasing throughput, range and Signal-to-Interference-Plus-Noise Ratio (SINR). Smart Antennas also provide an increase in radiated power because of focusing the transmitter power in one direction. This improves the range of the transmitter. The antennas operate reciprocally, and for this reason, the received power at the receiver is also increased. The directivity of the antenna also allows the node to cancel interfering signals arriving at the receiver from other directions.

The ability to achieve Spatial Division Multiple Access (SDMA) is the key advantage of using Smart Antennas. At the same time and same frequency in SDMA, simultaneous transmissions can occur; this is because stations are separated by their locations, and by the use of proper MAC. The accessible algorithms proposed for SDMA, assume contention free and reservation based medium access. The important issues to be addressed in realistic scenarios in both schemes are synchronization and initialization. On the other hand, SDMA with random access is challenging in realistic scenarios, especially when packet destinations are not known. Stations have to determine which stations and which sectors are idle in order to avoid collisions and retries since the medium is shared. If a packet at the head of the sender’s queue is destined to a busy node or towards a busy sector queuing delays can grow unboundedly, giving rise to in low throughput. Other benefits include greater coverage, meaning fewer base stations are needed to cover the same area compared to those using conventional antennas. For these reasons, Smart Antennas have gained greater interest in recent years [1-3].

1.1.1 Overview of Mobile Ad-hoc Network

Mobile Ad-hoc NETwork (MANET) is a system of wireless mobile nodes that can freely and dynamically self-organize in arbitrary and temporary network topologies without the need of a centralized administration as shown in Figure 1-1 [4]. MANET comprise of mobile devices (e.g. laptop, palmtop, internet mobile phone etc.) that use wireless transmission for communication. Nodes in an ad-hoc network may serve as hosts (end points of communication) or as routers forwarding packets to other hosts. Traditionally, ad-hoc networks have been known to use Omni-directional antennas for transmission as well as reception. The use of Omni-directional antennas may result in lower power efficiency due to interference caused by the transmission of packets in undesired directions. Use of Smart Antennas in Ad-hoc Networks is envisioned to take advantage of Space Division Multiple Accesses (SDMA) to increase network efficiency by directing the transmitted power in the desired direction [5-6]. This thesis explores the effect of using Smart Antennas in Mobile Ad-hoc Wireless Networks. Since Ad-hoc Networks use a broadcast medium for packet transmission, it is important to observe the effect of Smart Antennas on Medium Access Control schemes. The main MAC protocol for MANET is IEEE 802.11.

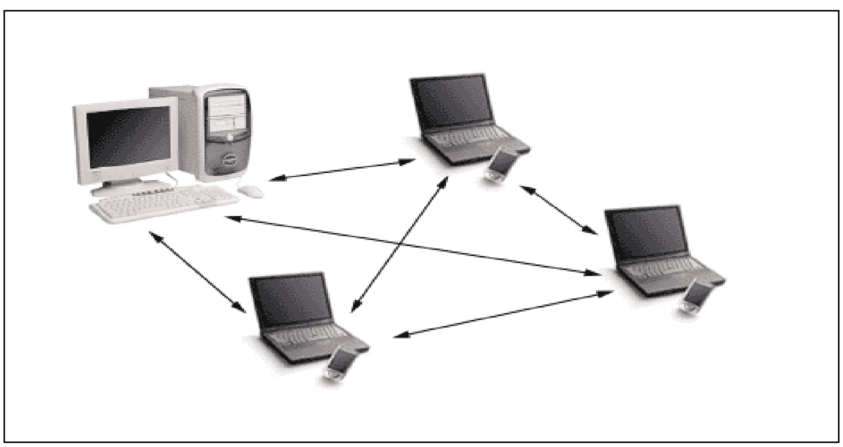


Figure 1-1: Mobile Ad-hoc Network [4]

1.1.2 IEEE 802.11 Wireless LAN Standard

This section provides the overview of the 802.11 standard. It is set to understand the fundamental concepts, the principle of operations and the reason behind some of the features and/or also components of the standard.

a) IEEE 802.11Architecture

IEEE 802.11 is a popular protocol that defines the functionality of MAC and physical layer of a Wireless Ad Hoc Network. 802.11 WLAN is based on cellular architecture where the system is divided into cells. Each cell is called Basic Service Set (BSS). On the other hand, the cells can be formed by stations without an infrastructure (more specifically without any Access Point), which is called the Ad-Hoc Mode. The Access Points are connected through some kind of backbone (called Distribution System or DS), typically Ethernet, and in some cases wireless itself.

As mentioned above, the 802.11 protocol covers MAC and Physical Layers. Beyond the functionality usually performed by the MAC layer, there are other functions performed by the 802.11 MAC that are typically related to upper layer protocols, such as Fragmentation, Packet Retransmissions, and Acknowledgements. The MAC layer defines two different access methods, these are; the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) [7]. The access mechanism, called DCF, is basically a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism.

In CSMA, a station desiring to transmit senses the medium, if the medium is busy (i.e. some other station is transmitting) then the station will defer its transmission to a later time [14]. If the medium is sensed free then the station is allowed to transmit. These kinds of protocols are very effective when the medium is not heavily loaded, since it allows stations to transmit with minimum delay, but there is always a chance of stations transmitting at the same time (collision), caused by the fact that multiple stations may sense the medium free and decide to transmit at once. The MAC layer can coordinate the retransmission of the packet in case of a collision, which will cause significant delay [1-8].

Carrier sensing alone does not prevent collisions, since in some cases, stations may not hear each other. The 802.11 standard defines a Virtual Carrier Sense mechanism in order to reduce the probability of collision of two stations. Under the basic access method, a station willing to transmit a packet first senses the channel status. If the channel receiver status is found to be idle for at least a duration determined by the DIFS parameter, the station chooses a random number for the back off timer. The random number specifies the number of time slots the transmitter must sense the channel as idle before transmitting the packet. The back-off timer continues to decrement while the channel is idle and is stopped if the channel becomes busy some time during the back off period. When the back off timer reaches zero, the data frame is transmitted. This helps in arbitration if numerous nodes attempt to obtain the channel at the same time, because the back off time is selected randomly for all nodes. After transmitting a data frame, the transmitter waits for an ACK frame from the receiver for a period determined by the parameter Short Inter Frame Spacing (SIFS). If the ACK frame is not received within the specified period of time, a binary exponential back off procedure is invoked.

In the Request To Send (RTS) / Clear To Send (CTS) control information exchange, which includes the source, destination addresses, and the duration of the following transaction, after the back off duration the transmitter sends a RTS to the receiver node. The destination node, upon receiving the RTS message, sends a CTS frame after a duration dictated by the SIFS. The CTS effectively reserves the channel for the sender, implicitly notifying all neighboring stations of the upcoming transmission. After the exchange of RTS/CTS control frames the sender begins the transmission of data frames to the destination node after a duration determined by the SIFS.

The destination node acknowledges successful data frame transmission by sending an ACK to the source node. For data transmissions involving data packets greater than the maximum allowed data frame size, the source node may continue to transmit packet fragments at intervals of SIFS duration after receiving the ACK. This can continue until the packet is completely transmitted or the node uses the channel for time duration equal to the dwell time boundary [8].

Figure 1-2 [10] shows a transaction between two stations, and the Network Allocation Vector (NAV) setting of their neighbors. This mechanism reduces the probability of a collision on receiver area by a station that is hidden from the transmitter, since that station will hear the CTS and reserve the medium as busy until the end of the transaction. The duration information on the RTS also protects the transmitter area from collisions on the ACK packet. It should also be noted that RTS and CTS exchange also reduces the overhead of collisions. Since RTS and CTS are short frames, collisions are recognized and recorded faster. This is true for data packets significantly bigger than the RTS/CTS. The standard allows for short packets to be transmitted without the RTS/CTS transaction, and this is controlled per station by a parameter called RTS Threshold [9].

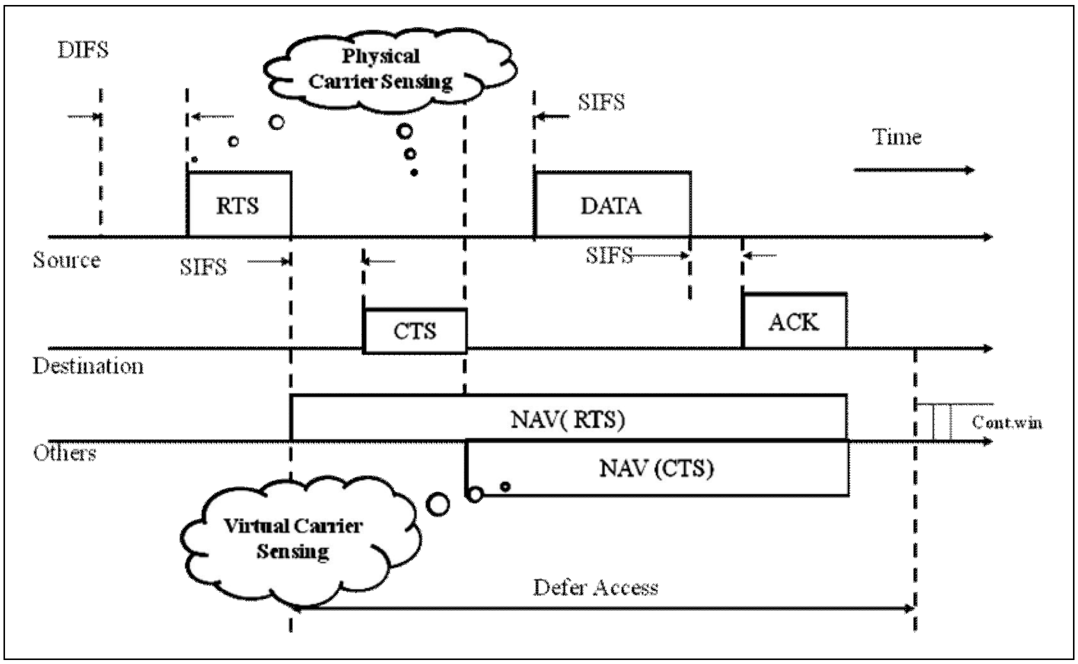


Figure 1-2: IEEE 802.11 DCF (CSMA/CA) with RTS/CTS Mechanism [10]

b) Physical Standard

The IEEE 802.11 Wireless LAN standard defines the specifications for the physical channel to be used by Wireless Networks. The specification mainly comprises channel characteristics such as type of modulation, frequency of operation, channel bandwidth and transmission power. The original standard supported the use of Direct Sequence Spread Spectrum (DSSS) which has been used in this study. Since the development of the original standards, the specifications have been expanded to allow for higher data rates and the use of a different frequency band. The 802.11b standard was the first to be held by industry and it allows the use of frequencies in the range 2.400-2.4835 GHz, which corresponds to the frequency of operation of home appliances such as microwave ovens. This allows the operation of the network at data rates of 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. The standard offers organizations an affordable, fast and easy to integrate wireless LAN solution. The 802.11b 11 Mbps modes is now widely used by organizations to support their applications such as email messaging, file sharing and Internet access. IEEE 802.11b uses CSMA/CA for MAC. The standard can support 11 channels in the available 83.5 MHz band, although typically only three of the non overlapping channels are effectively used. In a typical indoor environment, 802.11b can provide coverage up to 400 feet; however, the effective bandwidth available fluctuates as the distance between the wireless nodes increases. The IEEE 802.11a standard was introduced to supply increase in bandwidth. IEEE 802.11a can support data rates up to 54 Mbps and operates at 5 GHz. The gain in bandwidth is obtained by using Orthogonal Frequency Division Multiplexing (OFDM) modulation. The two standards, 802.11a and 802.11b are not compatible with each other [2].

1.1.3 Smart Antennas System

Smart Antennas are basically an extension of sectoring, in which multiple beams replace the coverage of sectors. Smart Antenna uses a predetermined set of antenna elements in an array. The signals from these antenna elements are combined to form a changeable beam pattern that can be steered, using either Digital Signal Processing (DSP) or Radio Frequency (RF) hardware, to a desired direction that follow mobile units as they move. Smart antennas allow efficient use of the radio signal-processing algorithm to continuously distinguish between desired signals, multipath, and interfering signals as well as to calculate the direction of arrival. There are basically two types of Smart Antennas: Switched-beam or fixed beam antennas and Adaptive array antennas [11-12].This will be discussed in more details in chapter 2.

1.2 Problem Statement

Adaptive Antenna Arrays can be used to increase spatial reuse of wireless channels and communication range in Multi-hop ad-hoc networks. However**,** it is difficult to find ways to set and control the direction of such antenna at each node in order to achieve the expected performance improvement in a Multi-hop communication environment of Mobile Ad-hoc Networks. This difficulty is mainly due to mobility and lack of centralized control. This may lead to hidden terminal problems, deafness and problem of determination of neighbor's location, resulting into an expected collision, decrease the system capacity (gain), causes more delay and further the network throughput may decrease significantly; especially when the network load becomes heavy. Hidden terminal problem usually arises when two sender nodes, which are out of range of each other or unaware of each other's transmission, transmit packets at the same time to the same receiver, resulting in collisions at the receiver. Since sender nodes are out of each other's range, they do not detect carrier even though the other node is sending data, and if their data packets reach the destination at the same time, these packets are dropped due to collision at the receiver. Deafness problem occurs when communicating nodes are unaware of the communication of the nodes with directional transmission.

Therefore this thesis proposes to develop a suitable MAC protocol in Mobile Ad-hoc Network to exploit the advantages of Smart Antennas to overcome some of the mentioned problems. Various Medium Access Control Protocols have been proposed under the assumption that antennas are directional [13-22] but these MAC Protocols do not overcome all the above mentioned problems.

The most important aspect of Mobile Ad-hoc Networks is their dynamic behavior. Mounting of an antenna on a mobile node can result in complex antenna movement. This decreases the system gain, causes more delay and further the network throughput may decrease. In such a case the layers are designed to operate under these conditions by allowing nodes to adapt to the changing circumstances. Wireless communication in OPNET simulator makes use of antenna models for gain calculation. Since an antenna on a mobile node can result in complex antenna movement, in this work, an enhanced Adaptive Antenna Positioning System was developed to help improve the performance gain.

With the development of Smart Antennas, in this research, incorporation of the physical layer aspects directly into the behavior of some of the MAC protocols have been proposed, i.e. explicitly modeling the impact of the physical layer on the dynamic of the MAC protocol. Interest in integrating them has been shown, under the scope of this work, Adaptive Antenna Arrays, into Mobile environment to realize the benefits of Space Division Multiple Accesses. The use of these types of antennas in MANET results not only in an increase in network throughput, but also reduces the overall transmitted power. Further, the use of Enhanced Antenna Positioning System directs the energy towards a desired direction, thus resulting in an increase in range of packet transmission, effectively decreasing the number of hops in a multi-hop route network. These demands need the study of the various links possible and development of a mechanism for establishing those links.

1.3 Objectives

The integration of Smart Antennas especially Adaptive Antenna Arrays into Medium Access Control (MAC) Protocols, for Omni-directional antennas, is a non-trivial problem. To end this, many protocols were designed by using directional antennas. The main focus of this work concentrates on improving the throughput and delay performance of some of these MAC protocols and illustrates typical scenarios using simulations in OPNET. Also analytical methods to evaluate the corresponding throughput and delay performance were used. Another aspect is the development of an Enhanced Antenna Positioning Model and Pipeline Stages to enable antenna positions and orientations in full for gain calculations for Mobile Ad-Hoc Networks.

As mentioned in the section 1.3 above, the main focus of this work is improving the throughput and delay performances of two MAC protocols. To achieve this goal/aim there are several essential tasks;

- Comparison of thirteen existing Directional MAC protocols that use Smart Antennas by contrasting their features.
- Evaluation of Directivity Performance of 3 Dimensions Linear Adaptive Antenna Array pattern when using different parameters.

- Development of a methodology to specify orientation of antenna in three dimensional spaces using an Enhanced Antenna Positioning model.
- Proposal of an Adaptive MAC scheme with Spatial Diversity, based on the RTS/CTS mechanism.
- Use of analytical methods to analyze the average throughput and delay performance of the selected MAC Protocols with Adaptive Antenna Arrays in MANET when using spatial diversity.
- Use of Simulations to compare the performance of the selected Directional MAC Protocols.
- Comparisons of OPNET simulations and the analytical model performances

1.4 Research Methodology

According to the above outlined research objectives, OPNET is utilized for modeling the MAC layer, whereas, the entire physical layer simulator is written in MATLAB. OPNET is an event driven simulation tool. Since physical layer modeling is stochastic in nature, OPNET by itself does not provide a convenient platform for investigation. Thus as part of this work, techniques are explored for integrating physical layer simulation tools, such as MATLAB, into OPNET to perform the necessary stochastic physical layer simulations.

As an initial part of this work, a comparison study of the existing directional MAC protocols that use Smart Antennas is conducted by contrasting their features. It was found that, most of these protocols were applied only in a non-mobile environment and were designed using Switched-beam antennas. In some cases, the above mention problems remained unsolved. This investigation discusses the challenges in improving the throughput and delay performance of some of these Directional Antenna-based MAC protocols and to apply them in a mobile environment. We have selected two protocols in order to improve. These protocols are Angular-MAC (ANMAC) Protocol and Multi-hop MAC (MMAC) Protocol. These protocols were designed using Switched-beam Antennas and were applied only in a non-mobile environment.

As described earlier, Smart Antenna especially Adaptive Antenna Arrays have gained great interest over the recent years as they have promised to increase capacity and performance. These benefits are the results of Smart Antenna System's ability to direct beams in the direction of multipath component and nulls in the direction of interference. To improve the performance of these protocols, Adaptive Antenna Arrays have been proposed.

In the second part of this work, fundamentals of Adaptive Antenna Arrays are given. Directivity performance of 3D Linear Array with varying parameters like, the number of antenna elements, the inter-element spacing, amplitude and phase excitations were made through simulations in MATLAB. Through these investigations, the proposed antenna model was selected and developed.

The third section of this work is divided into two methods; the first method implements the behavior of these two MAC protocols in OPNET. This method is known as the Physical-MAC layer simulation model. The aim is to investigate the performance in throughput and delay of the selected MAC Protocols when using Adaptive Antenna Arrays in a mobile environment. In mobile ad-hoc network, the data reception based on mobility problem is studied from per node perspective and the following questions are assumed; how does Adaptive Antenna Arrays affect the throughput and delay performance of the selected MAC Protocols and what is the effect of mobility on the performance of the throughput and delay. Analytical methods were used to analyze the average throughput and delay performance of the selected MAC Protocols with Adaptive Antenna Arrays in MANET when using spatial diversity. Lastly, comparisons between the OPNET simulations and the analytical model performances were done.

Wireless communication in OPNET makes use of antenna models for gain calculations. The mounting of an antenna on a mobile object can result in composite antenna movement if a node is mobile. In the second method, which is known as the Baseline Simulation Model, we have developed an Enhanced Antenna Positioning System and Pipeline stages to enable antenna positions and orientations in full details for a Mobile Ad-hoc Network.

1.5 Organization of Thesis

The main aspects of this thesis are structured into six chapters. Chapter one is referred to as the introduction chapter, the need for high quality and high throughput networks and the main reasons for using Smart Antenna System in these networks, types of Smart Antennas and an overview of Mobile Ad-hoc Network are discussed in this chapter. The IEEE 802.11 Standard is also highlighted. The main problem faced by Adaptive Array Antennas in Mobile Ad-hoc Networks; the objectives and scope of study are also outlined. A concise discussion of modeling and simulation methodology used for this research is also given.

Chapter 2 gives the fundamental concepts of Smart Antenna System. The research done to integrate Smart Antennas with Mobile Ad-hoc networks has been summarized. A comprehensive review of literature on the use of Smart Antennas for MANET is first presented. We presented the classifications and the Comparison of thirteen Directional Medium Access Control Protocols. Finally the chapter conclusion is presented.

Chapter 3 introduces the fundamentals of Adaptive Antenna Arrays, which is investigated in this thesis; an introduction to ESPRIT algorithm for Direction Of Arrival estimation and the basics of Adaptive beamforming with arrays is also given. The equations used in the MATLAB simulation are also presented. Investigations on directivity performance of 3D Linear Array with varying parameters like, the number of antenna elements, the inter-element spacing and phase excitations are made. The last section summarizes the chapter.

Chapter 4 presents the antenna models we have used to evaluate the effects of Adaptive Antenna Arrays on the throughput and delay performance of the selected MAC Protocols in a Mobile Ad-hoc Network and the antenna model for Baseline Simulation. Mobility modeling using Random Waypoint Model is also given. Analytical methods using a discrete time Markov-Chain based model to analyze the average throughput and delay performance of the selected MAC Protocols with

Adaptive Antenna Arrays in MANET when using spatial diversity were used. The chapter is concluded in the last section.

Chapter 5 discusses the system model including antenna and network models developed in MATLAB and OPNET 11.5, how they are built and used, and the simulation environment. An overview of components and properties along with a description of the algorithm simulated as part of this research is described. The chapter is summarized in the last section.

Chapter 6 presents the performance evaluation and the simulation results. Comparisons of some selected MAC protocols and analysis of their performance under different scenarios and with different numbers of nodes were presented. Some of the parameters used in implementing the simulation methodologies are given. Baseline simulations are also presented. Lastly a summary of key results for PHY-MAC layer simulations using co-simulations and for the Baseline simulations are given.

Chapter 7 discusses the entire study and summarizes the important findings and contributions and also lays directions for future work in this area.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews some of the work from literature that is relevant to this thesis. The first part introduces the fundamentals of Smart Antenna System. The benefits, types and applications of Smart Antenna System are discussed. Problems facing Smart antennas are also presented. Frameworks and methods demonstrating the difference between the work done and the proposed methods are introduced. The existing methods that have tried to solve the hidden terminal, deafness problems and the problems of determination of neighbor's location have been reviewed. Classification and comparison study of thirteen MAC protocols was carried out contrasting their features. This is followed by a concise description of ANMAC and MMAC protocols.

2.2 Fundamentals of Smart Antenna System

Smart Antennas are basically an extension of sectoring, in which multiple beams replace the coverage of sectors. Smart Antenna uses a predetermined set of antenna elements in an array. The signals from these antenna elements are combined to form a changeable beam pattern that can be steered, using either Digital Signal Processing (DSP) or Radio Frequency (RF) hardware, to a desired direction that follow mobile units as they move. Smart antennas allow efficient use of the radio signal-processing algorithm to continuously distinguish between desired signals, multipath, and interfering signals as well as to calculate the direction of arrival. There are basically two types of Smart Antennas: Switched-beam or fixed beam antennas and Adaptive array antennas. Switched-beam antenna system consists of a set of predefined directions. A desired signal can be selected by using predefined beams, and those signals arriving from other directions are seen as interference and will be significantly attenuated [2].

The role of DSP in Switched-beam Antennas is limited to signal detection, a fixed beam choosing and switching from one beam to another as the mobile moves. In an Adaptive Array antenna, which is more advanced than a Switched-Beam antenna, the beam structure is adapted to RF signal environment and directs beams towards the desired signals, depressing the antenna pattern in the direction of the interferers using algorithms (e.g. Least Mean Square Algorithm and Recursive Least Square Algorithm)[7]. The difference between both kinds of Smart Antennas is as follows: fixed-beam antennas focus their smartness in the strongest strength signal beam detection, and adaptive array antennas benefit from all the received information within all antenna elements to optimize the output SINR through a weight vector adjustment.

The key benefits of Smart Antennas are; [1]

- Smart Antenna provides enhanced coverage through range extension, hole filing, and better building penetration.
- Initial deployment costs to install Wireless System can be reduced via range extension.
- Link quality can be improved through the management of multipath.
- Smart Antennas can improve system capacity.

The most exciting feature of Smart Antennas is that they can increase the capacity through the beam and null controls. Usually, Omni-directional antennas are used by mobile terminals for communication. This antenna radiates the signal in all directions. The signal would create interference to the other mobile nodes except the target mobile terminal. Consequently, only one source and destination pair could use the same frequency coverage area. Nevertheless, a Smart Antenna steers its beam only in the direction of the target destination node. Besides this, it generates nulls to the directions except the target mobile node. Therefore, simultaneous communications between many source destination pairs are possible, and the spectrum efficiency can be increased. Second, link quality can be improved significantly by the adaptive beam and null controls, which maximize the SINR value depending on each specific radio propagation situation.

Furthermore, Smart digital signal processing algorithms can constructively combine the line of sight and delayed signals from the desired user and make link quality more steady and trustworthy. Third, the antenna array forms the directive beam by combining the signals from all branches, and the link distance would be increased according to the number of branches. Consequently, the required number of hops from source to destination can be reduced, compared to Omni-directional use. Moreover, the transmission power control relaxes the transmission power and realizes lower power consumption. Hence, the use of SDMA by Smart Antennas in a wireless ad hoc network realizes not only throughput improvement but also less delay and longer battery life, simultaneous connections within Omni range, and a larger number of link candidates for Multihop routing to improve reliability and scalability [17].

2.2.1 Switched-Beam Antennas

Switched beam antenna is the simplest form of Smart antennas in which a single transceiver is connected to RF-beamforming unit. If the number of antenna elements is M, one of the predefined set of beams $N \le M$ is selected, based on the maximum received signal power or minimum BER. The best signal is selected for further processing by a standard receiver. If the signal or user moves from one beam to another, the antenna switches to the new beam. Only a single beam pattern is employed at any given time. This technique benefits from its simplicity. However, maxima and nulls of the antenna pattern cannot be put into arbitrary directions, but can only be chosen from N possible positions [9] as shown in Figure 2-1[10].

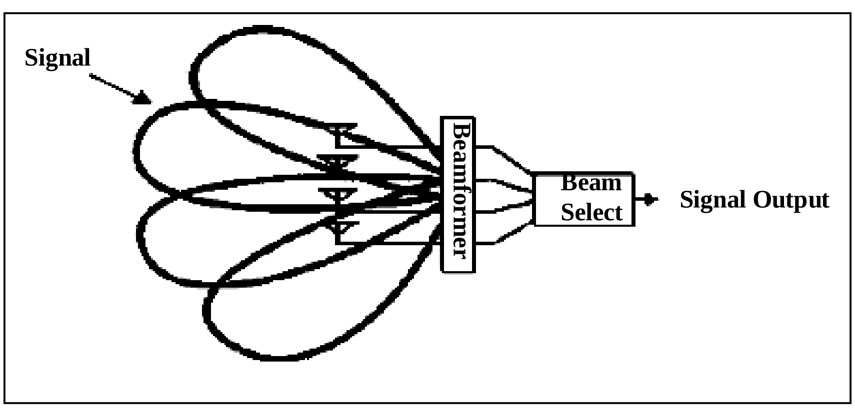


Figure 2-1: Switched-Beam Antennas [10]

2.2.2 Adaptive Antenna Arrays

An adaptive antenna array as shown in Figure 2-2 consists of a set of antenna elements that are spatially distributed at known locations with reference to a common fixed point. By changing the phase and amplitude of the exciting currents in each of the antenna elements, it is possible to electronically scan the main beam and/or place nulls in any direction [9].

Adaptive Antennas use two techniques for communication namely; Estimation of Direction Of Arrival (DOA) Technique and Adaptive beamforming Technique.

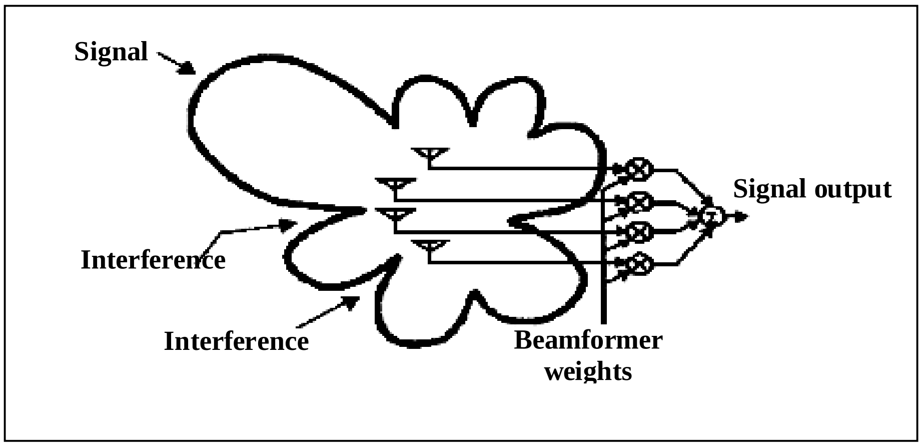


Figure 2-2: Adaptive Array Systems [10]

In Adaptive Antenna Arrays the beam structure is adapted to RF signal environment and directs beams towards the desired signals, depressing the antenna pattern in the direction of the interferers, using algorithms (e.g. Least Mean Square Algorithm (LMS) and Recursive Least Square Algorithm(RLS))[7]. In chapter 3, Adaptive arrays are explained in more details.

Smart Antennas have been studied extensively for use in cellular radio base station applications. In recent times however, low cost array technologies have suggested that Adaptive Antennas are cost effective for Mobile Ad-hoc Network. Adaptive Antenna can be use to increase spatial reuse of wireless channels and communication range in Multi-hop ad-hoc networks. However, it is difficult to find ways to set and control the direction of such antenna at each node in order to achieve the expected performance improvement in a Multi-hop communication environment of Mobile Ad-hoc Networks. This difficulty is mainly due to mobility and lack of centralized control. This may lead to hidden terminal problems, deafness and problem of determination of neighbor’s location, resulting into an expected collision, decrease the system capacity and further the network throughput may decrease significantly; especially when the network load becomes heavy. Thus, developing a suitable MAC protocol in Mobile Ad-hoc Network to exploit the advantages of Smart Antennas for general performance improvement is a challenging task.

The design of IEEE 802.11 implicitly assumes an Omni-directional antenna at the physical layer. Although 802.11 may operate correctly when using directional antennas, performance may get affected. Recently there have been several works that have looked at the problems of MAC design for ad hoc networks where nodes are equipped with directional antennas [10-15]. The directional antennas models include Switched-beam, multi-beam antennas and Adaptive Antenna Arrays. Many protocols were designed to deal with these problems but still these problems remain unsolved in some protocols. Most of these Protocols were applied only in a non-mobile environment.

2.3 Performance Evaluation of MAC Protocols

Generally, an Adaptive Antenna Array with D-elements can effectively suppress D - 1 dominant Co-Channel Interference (CCI) signals. As such, the performance capability of an antenna array system in the presence of a large number of CCI signals is restricted by the number of antenna elements. This is particularly important for mobile hand-held and portable terminals, since the ergonomic considerations such as size, complexity and cost will dictate the number of elements in an adaptive array receiver. This, combined with the fact that practical antenna arrays may have to operate in an environment with a large number of interferers, entails that a linear space-time adaptive processing will fail as the array’s degree of freedom is exceeded. In this congested array situation, selective interference nulling of dominant CCI signals is attractive owing to its linear processing complexity compared to the existing complex overloaded array processing algorithms.

Moreover, portable radios that use Smart Antennas have system level benefits: interference suppression and spatial diversity permit the use of lower transmit power for a specified reliability. This decreases CCI level, increases the battery life of portable terminals, and reduces the probability that a hostile party will intercept the signals. Consequently, future generations of Wireless Communication systems are expected to take advantage of the significant performance and capacity gain promised by Smart Antennas at the mobile terminals [14].

Previously, in the literature, applications of Smart Antennas in wireless networks have been investigated to improve the throughput and delay performances of some MAC Protocols.

2.3.1 Performance Evaluation of a MAC Protocol with Switched-beam Antennas

In [1], the authors proposed ANMAC Protocol that avoids problems through Medium Access Tables in the nodes that keep track of the locations of the destination nodes as well as all communicating neighbors. The ANMAC framework with a location-based scheduler has been extended to support SDMA with random access. The new protocol was named as ANMAC with Location Scheduling (ANMAC-LS). ANMAC-LS fully exploit the advantages of directional transmission in spatially divided channels, while avoiding the hidden terminal problem and deafness, and guaranteeing range extension by using only directional antennas. The location-based scheduler utilizes the location information, which is already available through the medium Access Table of ANMAC Protocol. Through detailed simulations, the performance gains of ANMAC Protocol and ANMAC-LS were quantified against Omni 802.11 transmission and other MAC Protocol that use directional carrier sensing. It had been shown that ANMAC-LS has the best performance in various network topologies. ANMAC has solved the hidden terminal and deafness problems but it is only applicable in a non-mobile environment.

2.3.2 Performance Evaluation of a MAC Protocol with Adaptive Antenna Arrays

In [24], ward et al. presented an Adaptive Antenna Array as a means to improve the performance of a Slotted ALOHA packet radio network. An adaptive array creates a strong capture effect at a packet radio terminal by automatically steering the receive antenna patterns towards one packet and nulling other contending packets in a slot.

They described how an adaptive array could be used in a Slotted system and analyzed the performance of such a system. In their model, a simple ALOHA system had been considered in which a repeater links a network of radio terminals. In the network, terminals transmit messages to each other through the repeater.

An assumption that time is slotted and that the network uses a Slotted ALOHA packet radio protocol was considered. Transmission between terminals occur randomly in each time slot whenever it has one to send, without regard for whether other terminals may be transmitting in that same slot. All packets were transmitted to a central repeater, which retransmit them back to the network. It has been assumed that the repeater is to be a store-and-forward repeater. It demodulates each packet and checks it for errors. The receiving antenna at the repeater was an Adaptive Antenna Array, which aimed the repeater antenna pattern at the first packets to arrive in each slot and then to null subsequent interfering packet. This technique allows one packet to be received successfully, even when several packets arrived in the same slot. Acquisition method was used to form the antenna pattern. The throughput and delay performance of a network with adaptive antenna array was computed by applying the standard Markov Chain analysis of Slotted ALOHA. The Markov Chain was applied to include the effects of the adaptive array with acquisition techniques. It was shown that throughput levels comparable to CSMA are attainable with an adaptive array without the need for stations to be able to hear each other. It had been shown that the performance depends primarily on the number of adaptive array nulls, the array resolutions and the length of the randomization interval within each slot. Typical performance results were presented.

2.3.3 Cross–layer Optimization with Adaptive Antenna Arrays

In [7], Vikram et al. investigated the impact of directional antennas on aggregate throughput and end-to-end delay. The effect of using Smart Antenna has been explored and a signaling mechanism for forming the extended links using the network layer has been proposed. The incorporation of Smart Antenna into Ad-hoc networks had been examined. A Model for simulating the wireless network using Smart Antennas was developed and the use of network layer for extended link formation was proposed. A novel methodology for implementing phased array antennas in

OPNET had been presented. The model supports linear as well as circular arrays and allows adaptive beamforming as well as null steering.

They have illustrated how MATLAB and OPNET simulations can be interfaced to allow the incorporation in OPNET of software and libraries developed in MATLAB. The simulation models that were developed had been used to assess the performance of some of the Medium Access Control Protocols based on IEEE 802.11. Medium Access Control performance assessment was followed by the proposal of the extended link formation using network layer. XuDSR based on DSR for Multihop networks and used simulations to assess the advantage of establishing simulation link using the basic access method had been proposed.

For performance assessment of the wireless networks using directional antennas, baseline models of phased array antenna had been created for single hop as well as Multihop networks. Through simulation they observed that using Directional RTS/CTS packets provides better network throughput as compared to scenarios using Directed RTS and Omni-direction. They mentioned that in mesh networks, the use of an extended link allow the transmission of the data using fewer hops, which resulted in a decrease in the end-to-end delay for the nodes using extended link.

From the results of the simulation they observed that although nodes forming the extended link experience end-to-end delay, the data successfully transmitted using extended links is correlated to the spatial distribution of nodes.

In [14] Ghani et al, explored the performance gains that can be achieved by exploiting the synergy resulting from the combination of the MAC and the physical layer of a wireless network. In their proposed scheme the MAC layer makes slot assignment decisions based on the channel state information from the physical layer. OPNET was used for modeling the MAC layer, whereas the entire physical layer simulation was written in MATLAB. A mathematical framework for characterizing the performance of cellular mobile radio system equipped with Smart Antenna at the mobile handset to suppress a few dominant co-channel interferers (CCI) had been presented. An analytical framework to investigate the benefits of a hybrids antenna using selective interference nulling and maximal ratio combining in mobile radio environment was developed.

2.4 Classifications and Comparisons of Directional MAC Protocols

This section provides the Classifications and Comparisons of MAC Protocols.

2.4.1 Classifications of Directional MAC Protocols

Based on different features of the protocols, there are quite few classifications. In [26] the directional MAC protocols are classified according to whether a protocol is based on IEEE 802.11 or not. Figure 2-3 [26] shows the classification of current directional MAC protocols.

Directional Medium Access schemes can be divided into two main categories: Random Access and Scheduling mechanisms. Random Access based Protocols can be further classified according to different collision avoidance approaches into: 1) Pure-RTS/CTS Protocols; 2) Tone-Based Protocols.

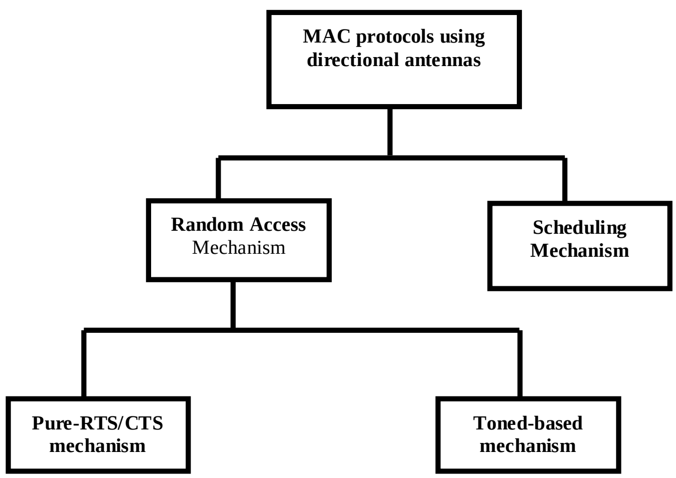


Figure 2-3: Classifications of Directional MAC Protocols [26]

2.4.2.1 Random Access MAC protocols for Directional Antennas

a) Pure-RTS/CTS Protocols

Directional-MAC (DMAC) [28] was one of the earliest protocols. It was designed based on IEEE 802.11 where it assumes that each node is equipped with multiple directional antennas. In this protocol, instead of sending Omni-directional, the nodes exchange Directional RTS/Omni-CTS wherever possible provided that none of the receiver antennas is blocked.

Takia et al., proposed [14] another MAC protocol Directional Virtual Carrier Sensing (DVCS) and DNAV mechanisms similar to the notion of DNAV in basic-DMAC. DVCS does require specific antenna configuration or external devices; instead it only needs information of Angle Of Arrival (AOA) and antenna gain for each signal from the underlying physical device, both of which are commonly used for the adaptation of antenna pattern. It is also applicable in mobile environment.

Korakis et al. [29] proposed a solution free of storing neighbors’ locations. To send a packet, a source node must first send directional RTSs in all directions. If the destined node receives an RTS, the direction of the source is estimated, and a corresponding CTS is then transmitted in that direction. After receiving the directional CTS, the source node estimates the direction of the destination from the received CTS. The drawback of this approach is that RTS scanning through all possible directions may be time consuming.

b) Toned-based Directional MAC Protocols

In this type of directional MAC protocols a Dual Busy Tone is used. In addition to the directional transmission of RTS/CTS and data packets, a tiny busy tone is used to avoid collisions with increased spatial reuse and channel capacity. Two busy tones are used: transmission busy tone and reception busy tone. These tones are assigned two separate single frequencies in the control channel. Once a node hears a transmission/reception busy tone it defers receiving/transmitting, which alleviates both hidden terminal and deafness problems.

Choudhury et al. [30] proposed a Tone- based Directional MAC protocol (TonedDMAC). The protocol uses an explicit notification mechanism to indicate the end of a dialog. Notification has been implemented by transmitting a carefully chosen toned for suitable number of time slots. Nodes, waiting to transmit, use the tones to alleviate the impact of deafness. This approach indicates that under multi-hop UDP traffic, ToneDMAC performs better than DMAC. When TCP traffic is used, the performance benefits are even greater. When channel contention is high, ToneDMAC drops fewer packets in comparison to DMAC. In addition to enhancing TCP performance, this might be a desired metric for certain applications. ToneDMAC retains the benefits of beamforming while mitigating the adverse effects.

Other protocols include Smart 802.11b, Smart Aloha Tone-based MAC and DOA-MAC. Most of these protocols are not applicable in mobile environment.

2.4.2.2 Scheduling MAC Protocols for Directional Antennas

Bao et al. [2] proposes a distributed Receiver-Oriented Multiple Access (ROMA) Protocol. It is a very efficient distributed channel access scheduling protocol for Ad-hoc Networks with Directional Antennas that are capable of forming multiple beams to carry out several simultaneous data communication sessions. ROMA allows both transmitters and receivers to use the directional mode, instead of one end of the communication to stay in Omni-directional mode. ROMA attains collision-freedom for channel access using only two topology information.

2.4.2 Comparison of Directional MAC Protocols

Many early protocols used Switched-beam Antennas instead of Adaptive Array antennas because of the complex beamforming algorithms. However, recently many researchers are exploiting the advantages of Adaptive Array antennas. Applying them to MANET will improve performance. We have compared some of these directional MAC protocols based on some features. Table 2-1 illustrates the comparison of these different protocols. Since Smart Antennas are directional, this directivity makes nodes in a network not to know each other resulting in problems like hidden terminal, deafness and problem of determination of neighbor’s location. Many protocols have been proposed to deal with these problems, but still they are unsolved in others.

Most of these protocols exploit the benefits of Smart Antennas by only using directional transmission and reception. It can also be stated that most of the pure RTS/CTS based directional protocols receives RTS Omni-directionally, meanwhile transmits either directionally or Omni-directionally based on the design of the protocol, to prevent the above mentioned problems. There are some common characteristics that lead to inefficiencies of some of the proposed protocols.

Table 2-1: Comparisons of Directional MAC Protocol [26]

Protocol Name	Sensing Method		Backoff Algorithm	Antenna Types	Radiation Patterns	Side Lobes	Nulling Capability	Range Control	Location Dependent Carrier Sense		Neighbor's Location Information	Mobility
	PHY	VIR							Hidden Terminals	Deafness		
DVCS	both		yes	Adaptive array	realistic	yes	no	no	n/a	n/a	Needed	Low
DMAC	both		yes	Switched beam	Flat-top	no	no	no	n/a	n/a	Needed	n/a
MMAC	both		yes	Steerable single beam antenna	Cone + sphere	yes	no	yes	Proposed but still unsolved	Proposed but still unsolved	Multi-hop RTS routing	n/a
Circular-DMAC	both		yes	Switched beam	Flat-top	no	no	no	Solved	Solved	Location table	n/a
Nasipuri	both		yes	Switched beam	conical	no	no	no	n/a	n/a	Not required	Medium
AN-MAC	both		yes	Switched beam	Ideal/ realistic	no	no	no	Solved	Solved	Medium Access table	n/a
DBTMA/DA	both		yes	Switched beam	Flat-top	no	no	no	Solved	Solved	Needed	n/a
Tone-based MAC	no		yes	Adaptive array	realistic	yes	no	no	Not combat hidden terminal	n/a	AOA in single entry cache	n/a
Tone-DMAC	both		yes	Switched beam	realistic	yes	yes	yes	n/a	Solved	Needed	n/a
Smart-Aloha	no		yes	Adaptive array	realistic	yes	yes	no	Not combat hidden terminal	n/a	Direction in single entry cache	n/a
Smart 802.11b	no		yes	Adaptive array	realistic	yes	yes	no	Not combat hidden terminal	n/a	Direction in single entry cache	n/a
Lal et al.	no		no	Adaptive array	realistic	yes	yes	no	n/a	n/a	Needed and important	n/a
ROMA	no		no	Multi-beam Adaptive array	ideal	no	yes	no	Solved	n/a	Needed and important	Low

Assume that RTS is in Omni mode while the other three transmissions (CTS, DATA, and ACK) are in directional mode. Then the directional mode transmissions must reduce their transmission energy to cover no more than the coverage area of the RTS. This constitute disadvantage of the mentioned MAC protocols as in this way they do not exploit one of the main benefits of Smart antennas, the increase of the coverage range.

Smart antennas suppress unnecessary interference by nulling capability, but some protocols did not exploit the nulling potential and gain limited improvements on system performance. This is because most of them have used Switched beam antennas; this type of Smart antenna doesn’t have this property.

Considering mobility, Smart Antennas (especially Switched-beam Antennas) functioning in mobile environment is a hard task especially when using it in MANET. This is mainly because in MANET there is no centralized station to control the movement of nodes. Few protocols are applicable. The evaluation of Smart Antennas protocols showed that Switched beams causes more delay for mobile users as such some of these protocols are not applicable in this type of environment. Adaptive array antennas seem to be the unique solution for this problem [1].

The vast majority of the performance-evaluation work on these MAC protocols has used discrete-event simulation, to model protocol behavior. Only few works have attempted to model these MAC protocols with Smart Antennas analytically.

Some of the analysis and simulations done in the previous work, for characterizing the network performance of nodes using directional antennas are based on the assumption of an ideal antenna pattern having no side lobes which is practically not realizable.

Most of these protocols are single-channel MAC protocols; as such one common problem with such protocols is that the network performance will degrade quickly as the number of mobile hosts increases, due to higher contention collision. To relieve the contention problem multiple channels must be utilized as shown in [31]. With the advance of technology, empowering a mobile host to access multiple channels is already feasible. Using multiple channels has several advantages; first, while the maximum throughput of a single-channel MAC protocol will be limited by the bandwidth of the channel, the throughput may be increase immediately if a host is allowed to utilize multiple channels. Second, using multiple channels will experience less normalized propagation delay per channel than its single-channel counterpart. Third since using a single-channel is difficult to support quality of service (QoS), it is easier to do so by using multiple channels.

Based on these comparisons it was proposed that, to maintain directional functioning in mobile environment, there is a need for an appropriate MAC and routing protocols and the use of Adaptive Antenna Array. The proposal is to upgrade some of these protocols based on their application in mobile environment. Two protocols have been selected, Multihop-RTS MAC and Angular-MAC protocols. Since the performance-evaluation work on both protocol was carried out using discrete-event simulation to model the behavior of the protocol, the use hybrid simulation have been proposed. Both protocols were designed using Switched-beam Antennas, without using nulling capability to suppress interference and are not applicable in environment. This is because Switched beam antennas do not have this property. The use of multiple channels has been proposed to model these protocols.

To do the simulations the use a realistic antenna pattern of a linear array with sidelobes and nulling capability has been proposed. For the integration of the antenna model into practical simulation scenarios, an antenna model that can be used by users to specify the orientation of the antenna axis with respect to a geocentric axis has been developed. This is necessary to obtain reliable results from simulations, which not only should integrate the constructive contribution of directed beam, but should also be able to take into consideration the effects of side lobes. Besides the development of the antenna model, another challenge has been done to incorporate simulation scenarios involving the use of Adaptive Antenna Arrays into OPNET V11.5.

OPNET 11.5 uses an abstract channel model, which uses a fixed transmission range as a criterion to determine whether the packet being received is valid or noise. In simulations involving Adaptive Antennas we are confronted with spatially varying transmission range of the wireless node depending on the gain of antenna in the direction of transmission. In the next section an overview of the two selected MAC Protocols is presented.

2.5 Multihop-RTS MAC (MMAC) Protocol

MMAC is a MAC protocol that uses multi-hop RTSs to establish links between distant nodes and then transmits CTS, DATA, and ACK over a single hop. It was built base on Basic DMAC protocol. For describing this protocol, two kinds of neighbors were defined: Direction-Omni (DO) neighbors and Direction-Direction (DD) neighbors. As shown in Figure 2-4[32], node B is a DO-neighbor of node A if node B can hear a directional transmission from A even if B is in the Omni-mode. Node B is a DD node for A, if B can hear a directional transmission from A only if B is in directional mode itself and is beamformed in the direction of A. A multi-hop route that passes through multiple DO neighbors to connect to DD neighbors is called a DO-neighbor route.

To communicate along a shorter route, the DD nodes should be beamformed towards each other since a route involving DO nodes is shorter than that having DO nodes. The DD neighbor should somehow request to beamform in the appropriate direction if two DD neighbors are not beamformed towards each other or one of them is in Omni state. This can be completed by sending a control packet through a DO route that join the two DD neighbors provided such a route exist. A and F are DD neighbors and A-B, B-C and C-F are DO neighbors. A first sends a DRTS towards F.

The purpose for sending this DRTS is twofold; one is to silence other transmitters along the route A-F and second to inform F of an incoming DATA packet, in case F is beamformed towards A. Any node that hears the DRTS, defers transmission by setting it's DNAV for RTS time multiply by path length of the DO-neighbor route. If the DRTS fails, A sends forwarding-RTS through the DO-neighbor route. Nodes that hear the forwarding-RTS do not CTS in the same direction. If A does not receive the CTS from F on time, it tries again after an appropriate backoff interval. From Figure 2-4 we can also see that RTS is forwarded from node A to node F through DO-neighbors, if F is not beamformed in the direction of A and is not able to listen to A directly. Once the RTS is successfully received and DD neighbor is free to receive DATA, it now beamforms towards the transmitter and sends single-hop CTS which is followed by DATA and ACK packets [32].

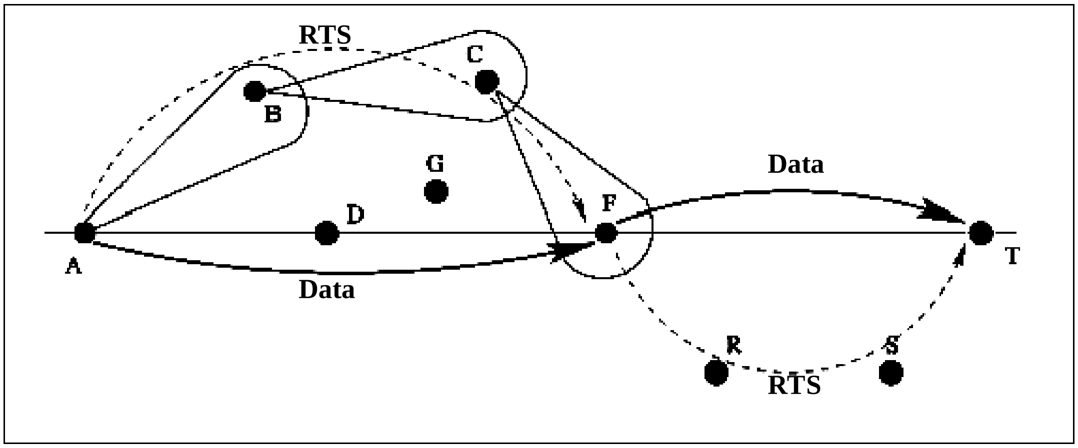


Figure 2-4: Scenario showing how the Multi-hop RTS is forwarded from node A to node F [32]

2.5.1 Problems of MMAC

In MMAC, the nodes which receive the forwarding-RTS packet forward it to their DO-neighbor specified in the DO-neighbor route. The forwarding-RTS packet gets highest priority for transmission. This implies that the time required for 1 RTS transmission is assumed to be constant. This assumption may sometimes turn out to be incorrect. Particularly, if a node in the DO- neighbor route happens to be busy or has a DNAV set for direction of forwarding, it will simply drop the RTS. The forwarding-RTS packets are not acknowledge on receipt. Sometimes it may happen that the forwarding-RTS drops before reaching the destination, or if a node like G, lying outside the DO-range of A, initiates a transmission in the direction of A, then A will not receive the CTS. MMAC does not solve the problems of deafness and hidden terminals. But better use of directional capabilities in MMAC can compensate for their negative impact. MMAC is not applicable in mobile environment, because of its sensitivity to network topology [32].

2.6 Angular MAC (ANMAC) Protocol

Angular MAC Protocol is a MAC protocol that includes location finding whereby the stations exchange angular RTS/CTS for training with each other to determine their respective locations in a much faster and more efficient way. In this Protocol, every station has beams of beamwidth that covers 360^o by four antennas. Stations can monitor the signal level on all beams, and choose the best one. The best beam is defined as the beam over which a station gets a signal with maximum Signal-To-Noise Ratio (SNR). Each station keeps a Medium Access Table, where it stores its best beam number to communicate with a neighbor and the neighbor's best beam number to communicate with itself. The blocking condition for every beam indicates whether that beam is busy or not, so as to avoid deafness and collisions. ANMAC uses modified RTS/CTS messages, namely Angular RTS/CTS to signal the information about the locations of communicating nodes to other stations in the medium, which are used for updating Medium Access Tables in the stations.

Consider the scenario in Figure 2-5. If node A wants to send a data packet to node B, it sends an AN-RTS packet in each direction, i.e., over all beams. The "Transmitter Beam Number" field in the AN-RTS packet indicates the index number of the beam over which the packet is sent. Upon receiving the AN-RTS message, all surrounding nodes learn about not only the upcoming packet exchange, but also about their own location with respect to the transmitting node, that is they mark the index number of their receivers' best beam 90^o which would be used during communication with the transmitter node.

At the destination node, the beam over which the signal with maximum power is received is marked, and all other beams are blocked. All other nodes block their beams in the direction of data (the best beam over which AN-RTS message is received) so as not to interfere with the data packet. By this way, these beams are blocked according to the duration field of the received AN-RTS packet. Then node B which is the receiver sends an AN-CTS packet in response to AN-RTS. AN-CTS frame is also sent in all directions to prevent the hidden terminal problem. As node A gets the AN-CTS packet, it finds out that the medium is available for communication, and also selects the best beam, beam with highest signal level.

The AN-CTS packet, the beam number in “transmitter’s best beam number” field indicates that this beam was chosen and will be used during data exchange by source node and the beam number in “receiver’s best beam number “field indicates that this beam was chosen and will be used during data exchange by destination node. After angular AN-RTS/ AN-CTS handshake, node A sends the data over its best beam and node B gets the data packet by its best beam. Parenthetically stations do not attempt to transmit any signal over their beam (block the beam) if it is in the direction of the best beam of source, node A or destination, node B, otherwise packets will collide. During the communication between these two nodes, other nodes can transmit a signal only over idle beams. In this manner, idle beams of node C are beam #0 and #2. All the beams of node D are idle during the communication because neither of the beams is facing to the best beam of node A nor node B. ANMAC Protocol solves the deafness and hidden terminal problems but it was applied only in non-mobile environment [1].

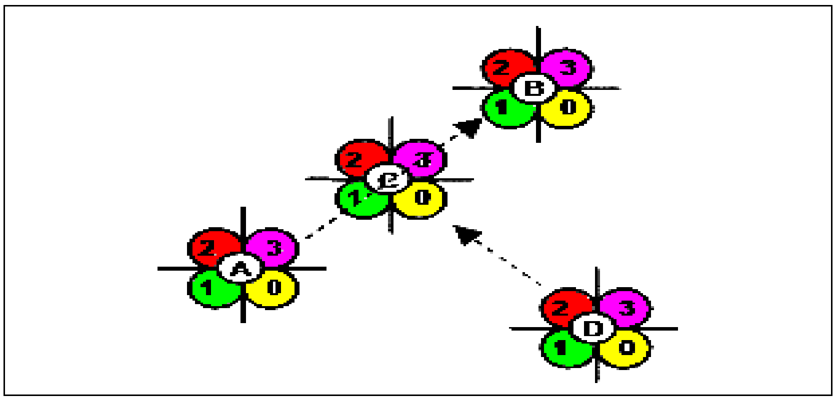


Figure 2-5: Scenario showing operation of ANMAC Protocol [1]

After getting the AN-RTS packet that is sent from node A to node B and decapsulating it, every surrounding node will be aware of packet exchange between node A and node B. Each station reads the receiver address and if a node is the destination, it marks the maximum power received beam, which is in the direction of source node, to be used at data exchange. The nodes other than the destination node block their own beam at that direction (signal direction obtained from received beam as explained previously) so as not to be interfered by the data exchange between nodes A and B, and not to interfere with the communication between nodes A and B. (After its beam in the direction of node A, if that beam does not interfere with A and B’s communication). While blocking the beams, a timer is set after reading the duration field of the received AN-RTS packet. This was called Directional Network Allocation Vector (D-NAV) in [28], which is in fact similar to the NAV of 802.11 but this time, for a specific direction. The beams are released after this timer expires.

After getting the AN-RTS[3,A,B] packet, node B records the name of the station in its neighbors list, the index number of its receiver's best beam (beam numbered as 1 in Figure 2-6), which is to be used during communication between the two nodes. Node B also determines its best beam in the direction of node A, and records it in the appropriate field in its list. The best beam is defined as the beam over which a station gets a signal with maximum SNR.

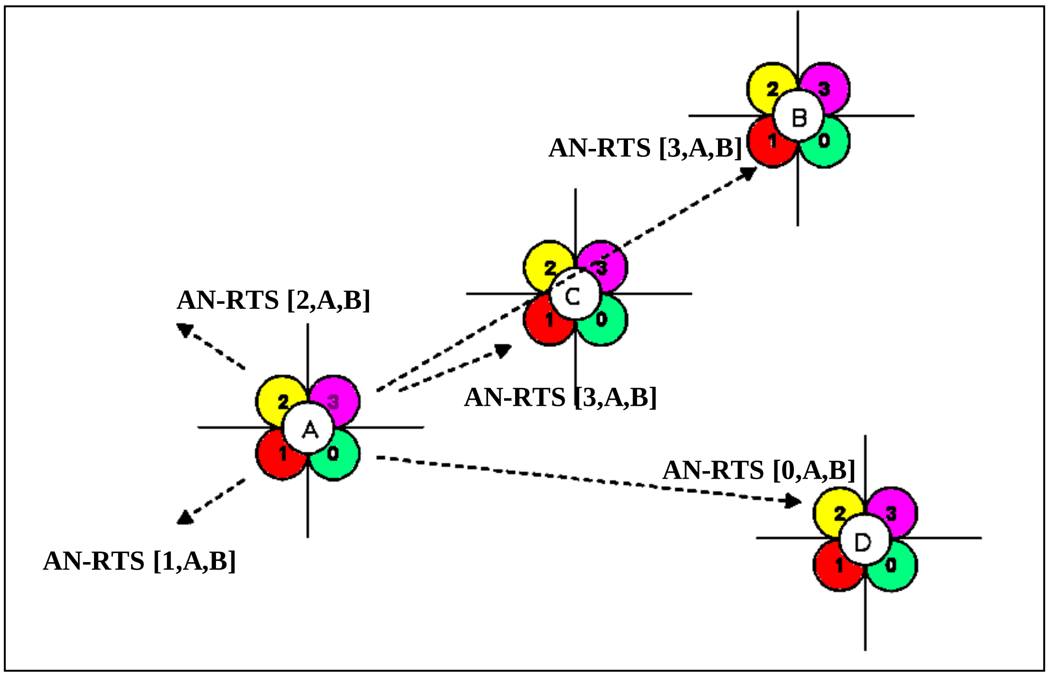


Figure 2-6: Sample topology of nodes [1]

In this case, since the destination is node B, itself, it blocks all the beams except the best beam (beam 1). Now, let us consider one of the surrounding nodes, node C in the same scenario. Node C gets the AN-RTS [3,A,B] packet, decapsulates it and records node A into its neighbors list while noting beam number of node A under neighbor's beam field and best beam of itself in the direction of node A, which is the beam with best reception with respect to A. Node C also marks 'no' to blocking field at that direction because at that moment it is unaware of the location of node B. After getting the AN-CTS from node B, node C will mark this field as 'yes' not to interfere with the data exchange. Figure 2-7 shows the configuration of the table at each node, after the AN-RTS packet is received from node A. AN-CTS frame is sent in all directions, like the AN-RTS frame by node B as shown in Figure2-7. After getting the AN-CTS, node A finds out that medium is available for communication. However other nodes must not interfere with the communication between A and B, otherwise packets will collide. Along getting the AN-CTS, node A chooses its third beam, which is directed to node B, and it sends the data packet over this beam. When node C gets the AN-CTS packet, it sees that node B's first beam is facing to its third beam.

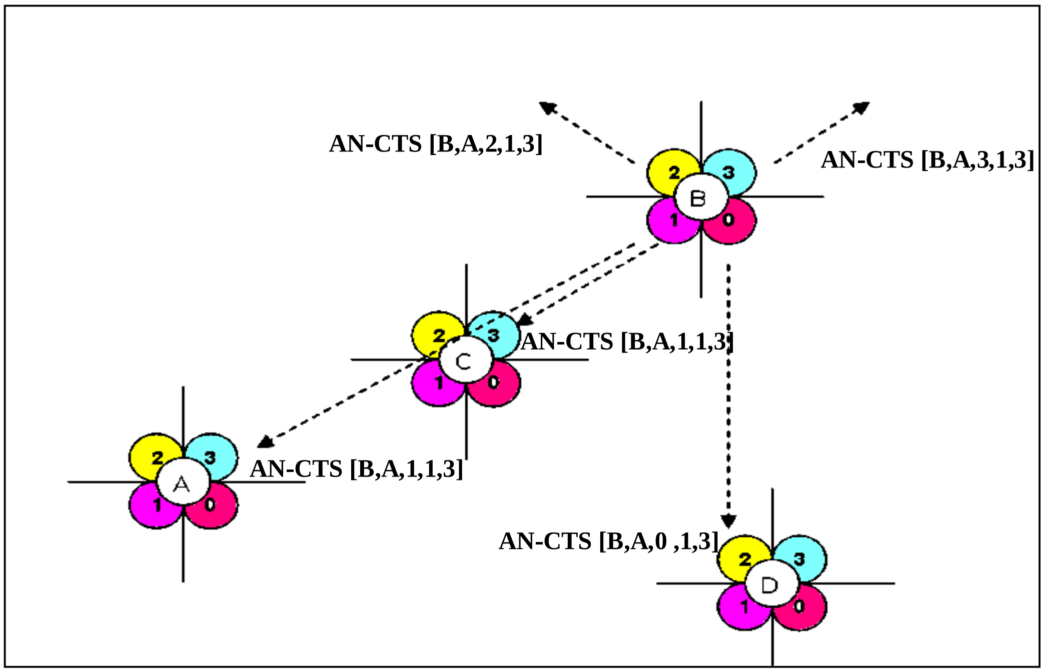


Figure 2-7: Response of node B to AN-RTS with AN-CTS packets [1]

In the AN-CTS packet, the transmitter's best beam field indicates that do not try to transmit to node B over this beam, which is the first beam of node B, otherwise packets, will collide. Therefore node C blocks its third beam. On the other hand, node C reads the receiver's best beam field and detects that node A will communicate with node B over its third beam. If node C wants to transmit a data packet to node A, it will look at the medium access table and see that its first beam is directed to node A's third beam. Finally, if node C tries to send a packet during the communication between node A and node B, the packets will collide. To prevent these collisions, node C blocks its 1st beam and third beam as well. It is only allowed to transmit over beam 0 and 2. Beams stay blocked for the time that is read in the duration field of received packet. Node C updates the table with this information. Node D gets the AN-CTS packet over its second beam. It checks the destination address field and notices that the destination node, node A, is in its list.

As mentioned before, node A will communicate with node B over its third beam. Node D's second beam faces node A's 0th beam, which will be free during the communication. On the other hand, if node D sends a packet over its second beam, it will reach node B at beam number 0. This will not cause interference on the communication between node A and node B. Table 2-2 shows the revised location tables at each node, after the AN-CTS frame. After angular AN-RTS/AN-CTS handshake, node A sends the data over its third beam to node B gets the signal from its first beam. The directional data transmission will essentially reduce the interference and establish a reliable and high quality channel between communicating nodes. During the operation, they have used compass to mark the orientation of the nodes.

Table 2-2: Complete List after getting AN-CTS from node B

My Address	Neighbor's Address	My Beam	Neighbor's Beam	Blocking			
				Beam 0	Beam 1	Beam 2	Beam 3
A	B	3	1	yes	yes	yes	no
B	A	1	3	yes	no	yes	yes
C	A	1	3	no	no	no	no
C	B	3	1	no	yes	no	yes
D	A	2	0	No	no	no	no
D	B	2	0	no	no	no	no

2.7 Summary

Fundamental concepts of Smart Antenna System have been discussed, including the benefits, types and applications. Some of the work from literature that is relevant to this thesis has been reviewed. Some frameworks and methods demonstrating the difference between those studies and our proposed scheme have been introduced and a further review has been done on the existing methods that had tried to solve the problems caused by Smart Antennas in mobile environment. Classifications and Comparisons of thirteen existing MAC Protocols have been done based on some features. ANMAC and MMAC protocols were selected for throughput and delay performance improvement by the use of Adaptive Antenna Arrays. A concise description of these two protocols and some of their drawbacks were given as well.

CHAPTER 3

ADAPTIVE ANTENNA ARRAYS

3.1 Introduction

This chapter gives an overview of Adaptive Antenna Arrays, which is the main scope of the study. The first section covers the fundamentals of Adaptive Array antennas. The Estimation of Angle of Arrival technique (algorithm), ESPRIT is described in section 3.3. In section 3.4 an extensive literature on Adaptive beamforming techniques has been covered under the scope of this work, Least Mean Square (LMS) algorithm was investigated through simulations. Directivity performance of 3D Linear Array with varying parameters like, the number of antenna elements, the inter-element spacing, amplitude and phase excitations were examined in section 3.5.

3.2 Fundamentals of Adaptive Antenna Arrays

An antenna array as shown in Figure 3-1 is a set of antenna elements arranged in space whose outputs are combined to give an overall antenna pattern that can differ from the pattern of the individual elements. An array can achieve the same directional performance of a larger antenna by trading the electrical problems of combining several antenna outputs for the mechanical problems of supporting and turning a large antenna. By varying the phase and amplitude of the individual element outputs before combining, the overall array pattern can be steered in the desired user's direction without physically moving any of the individual elements [21].

Adaptive Antennas are arrays of antenna that can improve reliability and capacity in two ways. First, diversity combining or adaptive beamforming techniques can combine the signals from multiple antennas in a way that mitigates multipath fading. Second, adaptive beamforming using antenna arrays can provide capacity improvement through interference reduction. The use of adaptive arrays is an alternative to the expensive approach of cell splitting, which increases capacity by increasing the number of base station sites. Most Adaptive Arrays that have been considered for such applications are located at the base station and perform spatial filtering. They cancel or coherently combine multipath components of the desired signal and null interfering signals that have different directions of arrival from the desired signal. Currently, however, adaptive arrays are use in mobile communication systems as well.

Array patterns are controlled through algorithms (example, Least Mean Square Algorithm and Recursive Least Square Algorithm) based upon certain criteria. These criteria could be minimizing the Signal-To-Interference Ratio (SIR), minimizing the variance, minimizing the Mean Square Error (MSE), steering toward a signal of interest, nulling the interfering signals, or tracking a moving emitter to name a few. The implementations of these algorithms can be performed using Digital Signal Processing.

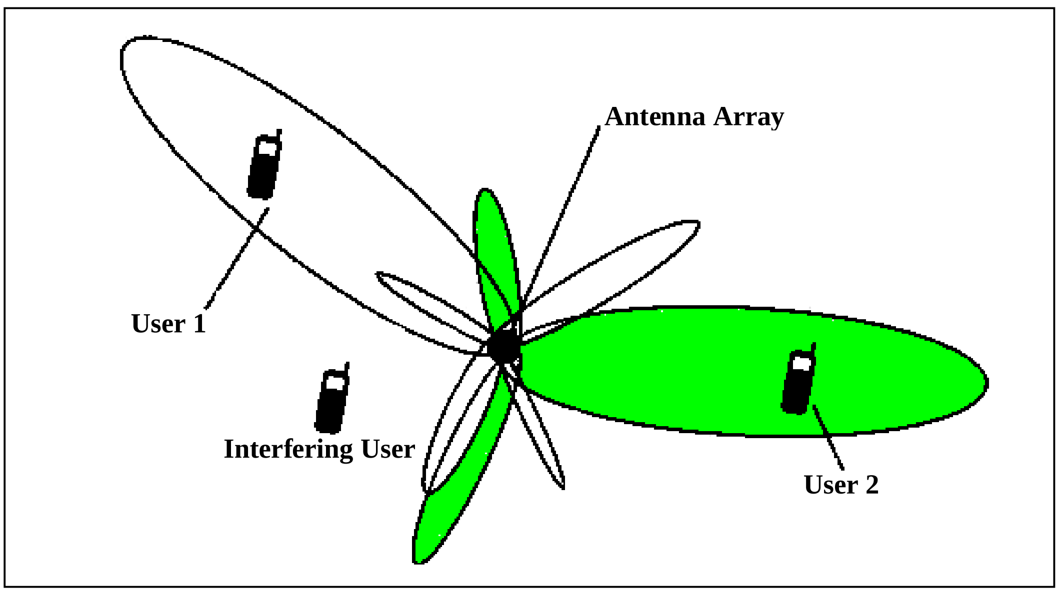


Figure 3-1: Adaptive Array Systems [18]

One of the simplest geometries for an array is a linear array in which the centers of the antenna elements are aligned along a straight line and generally have uniform inter-element spacing. If all of the centers of the elements lie in a plane, the array is a planar array. Examples include the linear array, a circular array, and arbitrarily shaped planar arrays. [18].

For this research linear array with four antenna elements have been used. Adaptive Antennas use two techniques for communication namely; Estimation of Direction Of Arrival Technique and beamforming Technique.

3.3 Direction of Arrival Algorithm

For a beamformer to steer the radiation in a particular direction and to place the nulls in the interfering directions, the direction of arrival has to be known earlier. The Direction of arrival algorithms does exactly the same; they work on the signal received at the output of the array and compute the direction of arrivals of all the incoming signals. Once the angle information is known it is fed into the beamforming network to compute the complex weight vectors required for beam steering. One of the DOA algorithms used for this research is discussed in the following section.

3.3.1 ESPRIT algorithm

ESPRIT stands for Estimation of Signal Parameters via Rational Invariance Techniques. Adaptive Antenna Arrays use this algorithm to estimate the direction of arrival of the incoming signals. The goal of ESPRIT technique is to exploit the rational invariance in the signal subspace which is created by two arrays with a transitional invariance structure. ESPRIT inherently assumes narrowband signals so that one knows the transitional phase relationship between the multiple arrays to be used. ESPRIT assumes that there are $D<M$* narrow-band sources centered at the frequency f_o. These signal sources are assumed to be of sufficient range so that the incident propagation field is approximately planar. The sources can be either random or deterministic and the noise is assumed to be random with zero-mean. ESPRIT assumes multiple identical arrays called doublets. These can be separate arrays or can be composed of subarrays of one larger array [10].

ESPRIT is a novel, subspace fitting, parameter estimation algorithm which is used for obtaining high resolution, unbiased estimates of the frequencies and powers of complex sinusoids in noise. The algorithm involves complex decompositions which require extensive computation. In order to use the algorithm in close to real-time situations it is altered to facilitate faster computation and the use of a parallel architecture.

ESPRIT algorithm can be summarized as follows;

1. Starting with two matrices X and Y which contain the N snapshots for the two *m* antenna arrays, concatenate the X and Y array responses to form a Z array.

*D is the number of signals and M is the is the number of array elements

$$Z = \begin{bmatrix} X \\ Y \end{bmatrix} \tag{3.1}$$

Then estimate the covariance matrix of this array, R_{zz}, by outer product of snapshot data matrix Z.

2. Estimate the basis for the signal subspace. The first d Eigenvectors corresponding to the d largest eigenvalues of the generalized eigendecomposition for $\{R_{zz}\ \Sigma_n\}$ where Σ_n estimated noise covariance matrix.
3. Decompose into vector basis for the signal subspace for the X and Y arrays, E_x and E_y respectively.
4. Compute eigendecomposition of $E_{xy}{}^{*}E_{xy}$ where

$$E_{xy} \stackrel{def}{=} [E_x E_y] \qquad E_{xy}{}^{*}E_{xy} = E\Lambda^{*}E \tag{3.2}$$

Where E is the matrix of eigenvectors and Λ is the diagonal matrix of eigenvalues

5. Partition E into four *dxd* submatrices

$$E \stackrel{def}{=} \begin{bmatrix} E_{11}E_{12} \\ E_{21}E_{22} \end{bmatrix} \tag{3.3}$$

6. Calculate the eigenvalues of $\Psi = -E_{12}[E_{22}]^{-1}$ (3.4)

7. Eigenvalues for complex sinusoids are unit circle from 0 to π radians which represent arrival in the direction finding case or just frequencies form 0 to 0.5 of the sampling frequency in the series case. If the numbers of sources are over estimated, eigenvalues off the unit circle are generated.

To estimated the angle of arrival, given that $\lambda_i = |\lambda_i| e^{j\arg(\lambda_i)}$

$$\theta_i = \sin^{-1}\left(\frac{\arg(\lambda_i)}{kd}\right) \qquad i=1, 2, \ldots\ldots\ldots\ldots, D \tag{3.5}$$

3.4 Adaptive beamforming

Adaptive Beamforming is a technique in which an array of antennas is exploited to achieve maximum reception in a specified direction by estimating the signal arrival from a desired direction (in the presence of noise) while signals of the same frequency from other directions are rejected. This is achieved by varying the weights of each of the sensors (antennas) used in the array. It basically uses the idea that, though the signals emanating from different transmitters occupy the same frequency channel, they still arrive from different directions. This spatial separation is exploited to separate the desired signal from the interfering signals. In adaptive beamforming the optimum weights are iteratively computed using complex algorithms based upon different criteria.

Beamforming is generally accomplished by phasing the feed to each element of an array so that signals received or transmitted from all elements will be in phase in a particular direction. The phases (the interelement phase) and usually amplitudes are adjusted to optimize the received signal. The array factor for an N-element equally spaced linear array is given as [chapter 5],

$$AF(\Phi) = \sum_{n=0}^{N-1} A_n e^{jn\left(\frac{2\Pi d}{\lambda}\cos\Phi + \alpha\right)} \tag{3.6}$$

The phase shift is given by

$$\alpha = -\frac{2\Pi d}{\lambda_o}\cos\Phi_o$$

Where Φ_o is the desired beam direction. At wavelength λ_o the phase shift corresponds to a time delay that will steer the beam Φ_o.

Figure 3-2: provides a schematic of an Adaptive Antenna Array we have used in this research. As illustrated in the figure, the antenna consists of M antenna elements separated from each other by a known distance d. We assumed that a transmitter is at some distance away from the receiver that all the signals $S_i(t)$ arriving at the different antenna elements are parallel. However, since the elements are separated by distance d, the phase of the different signals is different. Let w_i denote the phase and gain that is added to each signal $X_i(t)$. Then $Y(t)$, the output sent to the receiver can be written as,

$$Y(t) = A\sum_{i=1}^{M} w_i X_o(t) e^{-j\beta id\cos\theta} + N(t) \tag{3.7}$$

Where, N (t) is AWGN (Additive White Gaussian Noise), $\beta = 2\pi/\lambda$ is the phase propagation factor, λ is the wavelength, and A is an arbitrary gain constant. The weights w_i used in this thesis only shift the phase of the signal and leave the amplitude untouched. In order to compute the optimum weights, the array response vector from the sampled data of the array output has to be known.

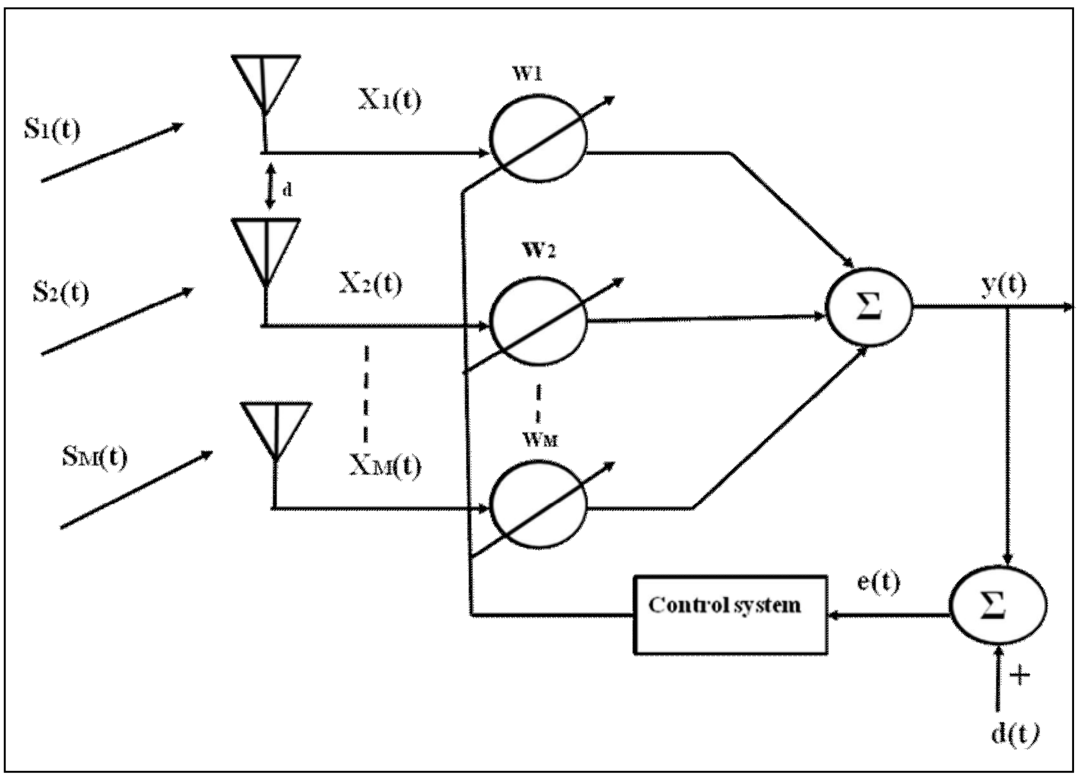


Figure 3-2: Adaptive Beamforming [44]

The array response vector is a function of the incident angle as well as the frequency. The baseband received signal at the *N-th* antenna is a sum of phase-shifted and attenuated versions of the original signal $S_i(t)$.

$$X_N(t) \cong a_N(\theta_i)s_i(t)e^{-j2\Pi f_c \tau_N(\theta_i)} \tag{3.8}$$

The $s_i(t)$ consist of both desired and the interfering signals

$\tau_k(\theta_i)$ is the delay, f_c is the carrier frequency

$$a(\theta_i) = [a_1(\theta)e^{-j2\Pi f_c \tau_1(\theta_i)},\ a_2(\theta_i)e^{-j2\Pi f_c \tau_2} \tag{3.9}$$

The output of the array $y(t)$ with variable element weight is the weighted sum of the received signals $S_i(t)$ at the array elements and the noise $n(t)$ at the receivers connected to each elements. The weights w_m are iteratively computed based on the array output $y(t)$, a reference signal $r(t)$ that approximated to the desired signal, and previous weights. The reference signal is approximated to the desired signal using a training sequence or a spreading code, which is known at the receiver. The format of the reference signal varies and depends upon the system where adaptive beamforming is implemented. The reference signal usually has a good correlation with the desired signal and the degree of correlation influences the accuracy and the convergence of the algorithm.

The representation for the weights is

$$w_i = e^{jbid \sin \theta_i} \tag{3.10}$$

3.4.1 Least Mean Squares (LMS)

The Least Mean Square (LMS) algorithm is an adaptive algorithm, which uses a gradient-based method of steepest decent. LMS algorithm uses the estimates of the gradient vector from the available data. LMS incorporates an iterative procedure that makes successive corrections to the weight vector in the direction of the negative of the gradient vector which eventually leads to the minimum mean square error. Compared to other algorithms LMS algorithm is relatively simple; it does not require correlation function calculation nor does it require matrix inversions. It requires the desired signal to be supplied using a training sequence or decision direction and also a reference signal [45].

From the Figure 3-3, the signal *d(t)* is the reference signal. The reference signal is either identical to the desired signal *x(k)* or it is highly correlated with *x(k)* and uncorrelated with the interfering signals $i_n(k)$ The signal $\varepsilon(t)$ is the error signal such that

$$\varepsilon(t) = d(t) - w^H x(t) \tag{3.11}$$

The square error is given as

$$|\varepsilon(t)|^2 = |d(t) - w^H(t)x(t)|^2 \tag{3.12}$$

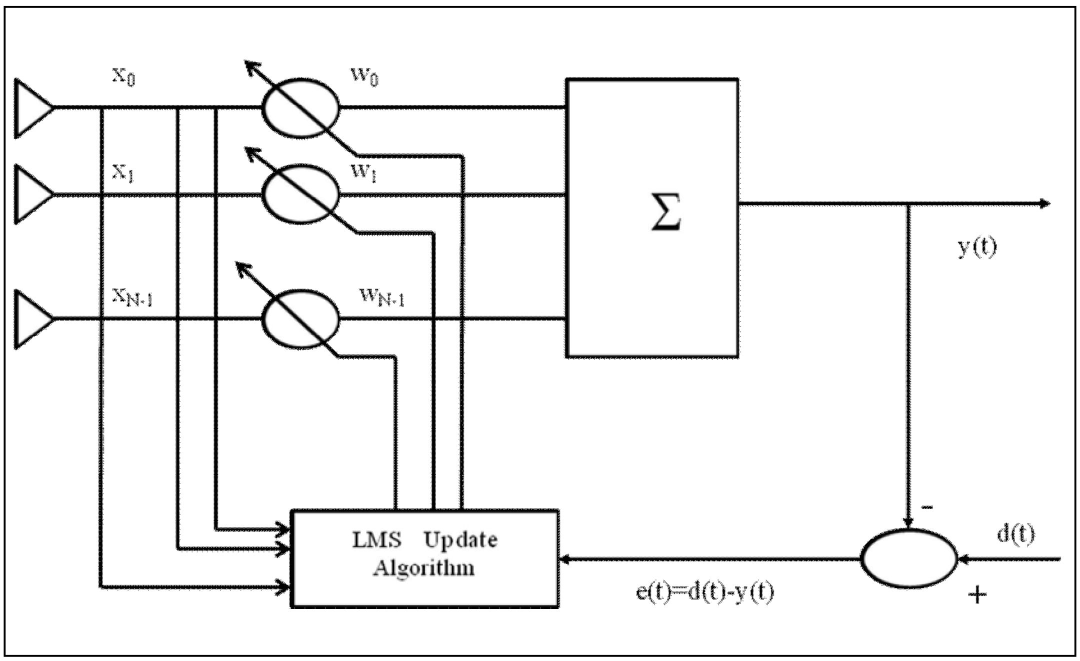


Figure 3-3: Representation of LMS algorithm [45]

Suppressing the time dependence, the cost function is given as

$$J(w) = D - 2w^H r + w^H R_{xx} w \tag{3.13}$$

Where

$$D = E\left[|d|^2\right]$$

By employing the gradient method the minimum of equation (3.13). Thus

$$\nabla_w (J(w)) = 2R_{xx}w - 2r \tag{3.14}$$

The minimum occurs when the gradient is zero. Thus the solution for the weights is the optimum Weiner solution as given by

$$w_{opt} = R_{xx}{}^{-1}r \tag{3.15}$$

The instantaneous estimates for the values of array correlation matrix and the signal correlation vector are given as

$$R_{xx}(t) \approx x(t)x^H(t) \tag{3.16}$$

and

$$r(t) \approx d^*(t)x(t) \tag{3.17}$$

The steepest descent iterative approximation is given as

$$w(n+1) = w(n) - \frac{1}{2}\mu\nabla_w (J(w(w))) \tag{3.18}$$

Where, μ is the step-size parameter and ∇_w is the gradient of the performance surface. If we substitute the instantaneous correlation approximation is given as

$$w(n+1) = w(n) - \mu[R_{xx}w - r] \tag{3.19}$$

$$w(n+1) = w(n) + \mu x(n)[d^*(n) - x^H(n)w(n)] \tag{3.20}$$

$w(n+1)$ denotes weight computed at $(n+1)th$ iteration

Where μ is the gain constant that controls the rate of adaptation, i.e. how fast and how close the estimated weights approach the optimal weights. The convergence of the algorithm depends upon eigenvalue of R (the array correlation matrix), the array correlation matrix. In digital system, the reference signal is obtained by periodically transmitting a training sequence that is known to a receiver, or using the spread code in the case of a direct-sequence CDMA system. The LMS algorithm described here is a basic structure for most dynamic adaptive algorithms.

The convergence of the LMS algorithm in Eq. (3.20) is directly proportional to the step-size parameter μ. If the step-size is too small, the convergence is slow and we will have the overdamped case. If the convergence is slower than the changing angle of arrival, it is possible that the adaptive array cannot acquire the signal of interest fast enough to track the changing signal. If the step-size is too large, the LMS algorithm will overshoot the optimum weights of interest. This is called the underdamped case. If attempted convergence is too fast, the weights will oscillate about the optimum weights but will not accurately track the solution desired. It is therefore imperative to choose a step-size in a range that insures convergence. It can be shown that stability is insured provided that the following condition is met.

$$0 \le \mu \le \frac{1}{2\lambda_{\max}} \tag{3.21}$$

Where $\lambda_{\max}$ is the largest eigenvalue of R_{xx}.

Since the correlation matrix is positive definite, all eigenvalues are positive. If all the interfering signals are noise and there is only one signal of interest, we can approximate the condition in Eq. (3.20) as

$$0 \le \mu \le \frac{1}{2trace[R_{xx}]} \tag{3.22}$$

3.4.2 Simulation Study for the LMS algorithm

LMS algorithm has been simulated in MATLAB to see its performance using an antenna element with N= 4 and the spacing d=0.5. The signal was assumed to arrived at the angle θ_o=60 degrees, an interferer at θ_1= -30 degrees. The step size μ = 0.025 and the number of iterations was 100.

The following weights were obtained for the 4 elements

w1 = 1

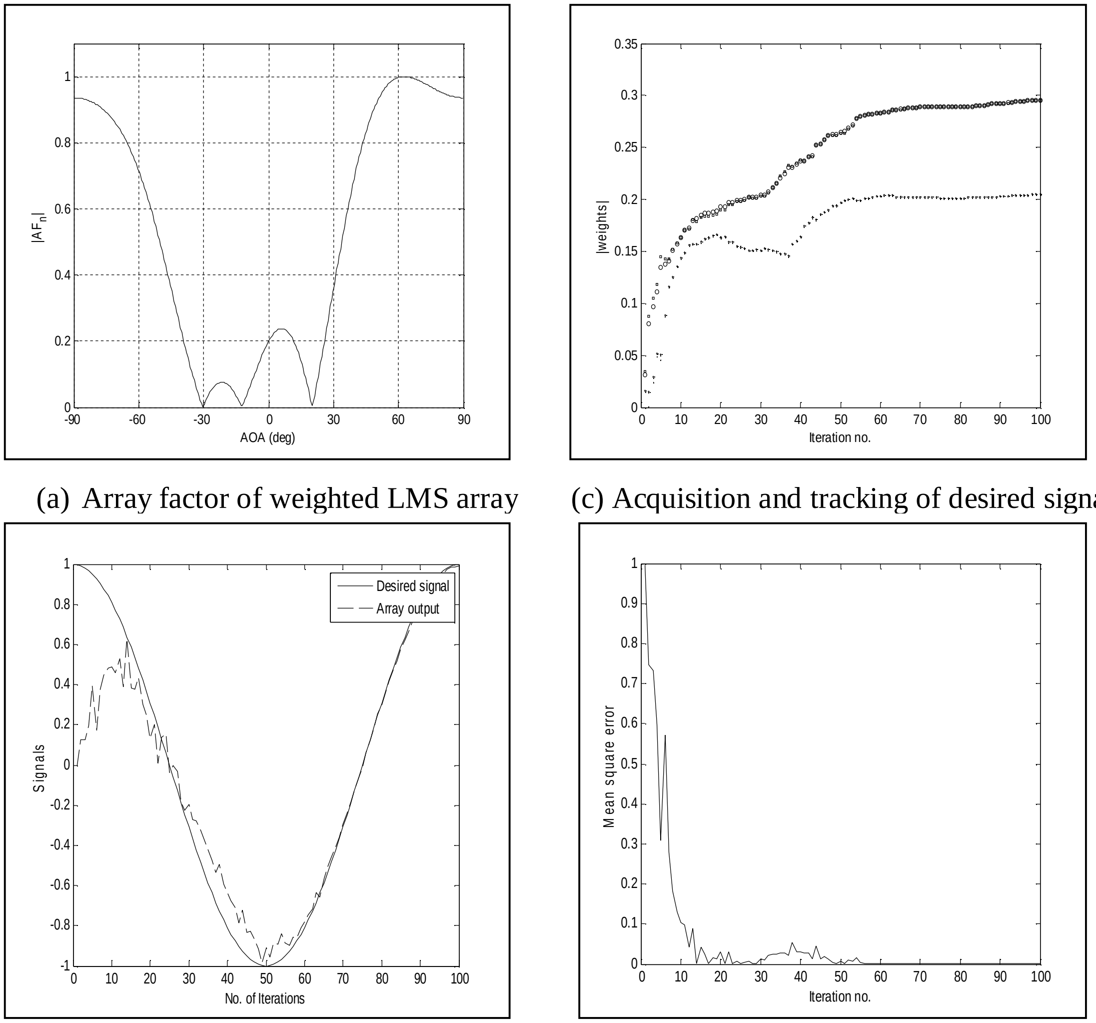
w2 = -1.2365+0.74173i

w3 = 1.1587-0.85843i

w4 = -0.38305+0.92376i

The LMS algorithm is the most commonly use adaptive algorithm because of its simplicity and a reasonable performance. It is the most computationally simple algorithm for finding the weight vector. Since it is an iterative algorithm it can be used in a highly time-varying signal environment. It has a stable and robust performance against different signal conditions. However, as shown in Figure 3-4 it does not have a really fast convergence speed, it congregates until after 65 iterations. It converges with slow speeds when the environment yields a correlation matrix R possessing a large eigenspread. Since in our case (MANET) the traffic conditions are not static, the user and interferer locations and the signal environment are varying with time; as such the weights will not have enough time to converge when adapted at an identical rate. That is, μ the step-size needs to be varied in accordance with the varying traffic conditions.

To increase the speed of convergence the Normalized LMS (NLMS) have been proposed for this study. This algorithm introduces a variable adaptation rate. It improves the convergence speed in a mobile environment.



(a) Array factor of weighted LMS array (c) Acquisition and tracking of desired signal

(b) Magnitude of Array weights (d) Mean square error

Figure 3-4: The Performances of LMS algorithm

In the Normalized LMS, the gradient step factor μ is normalized by the energy of the data vector

$$\mu_{NLMS} = \frac{\alpha}{X_n^H X_n + \sigma} \tag{3.23}$$

where α is usually $\frac{1}{2}$ and σ is a very small number introduced to prevent division by zero. If $X_n^H X_n$ is very small,

$$W_{n+1} = W_n + \frac{1}{X^H X} e_n X_n \tag{3.24}$$

The normalization has several interpretations [46]

- corresponds to the 2nd-order convergence bound
- makes the algorithm independent of signal scaling
- adjusts W_{n+1} to give zero error with current input: $W_{n+1}X_n=d_n$
- minimizes mean effort at time n+1

NLMS usually converges *much* more quickly than LMS at very little extra cost. This has been proved by simulations results as shown in Figure 3-5 Where, NLMS converges after 15 iterations. Comparing this to the number of speed of LMS, we can say that NLMS is suitable for our proposed environment.

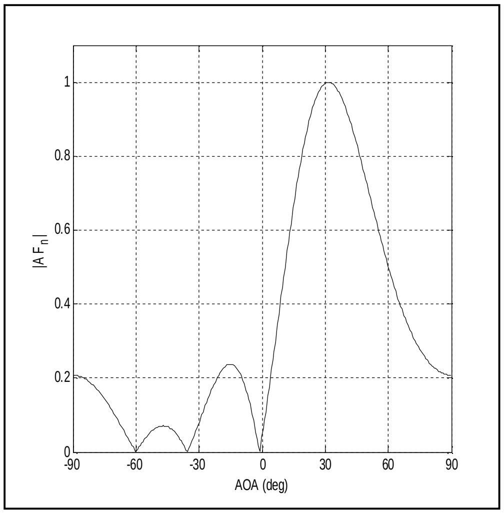
The weights obtained are;

w1 = 1

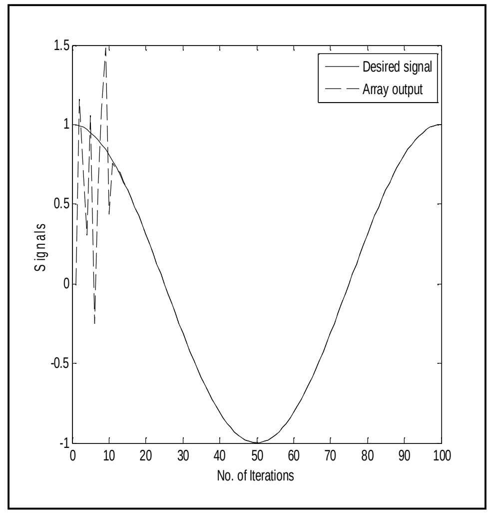
w2 = 0.17584+1.4438i

w3 = -1.423-0.30107i

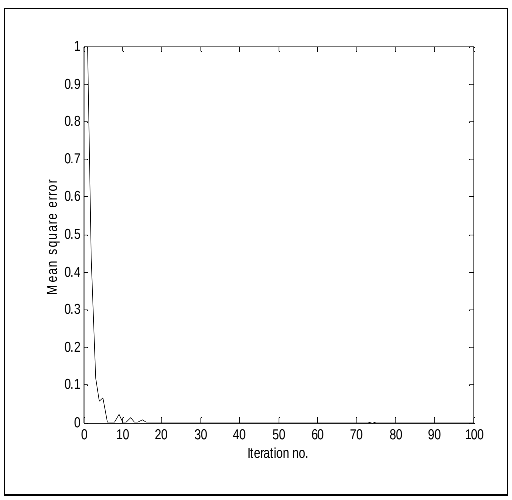
w4 = 0.087202-0.99619i



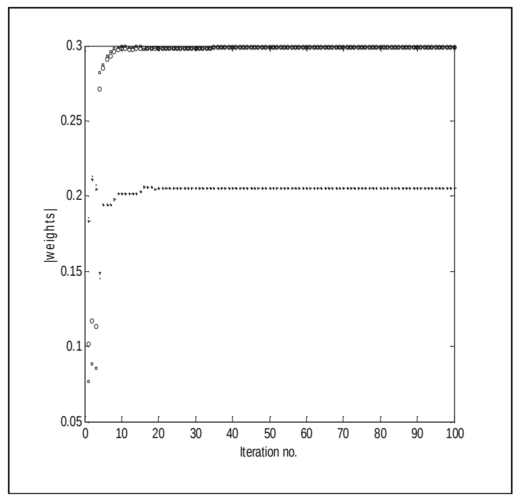
(a) Array factor of weighted LMS array



(b) Magnitude of Array weights



(c) Mean square error



(d) Acquisition and tracking of desired signal

Figure 3-5: The performances of NLMS algorithm

3.5 Performance Evaluation of Adaptive Antenna Arrays

This section provides directivity performance of 3D linear array under various conditions. These investigations were done to examine which type of linear array is suitable for our proposed scheme through simulations in MATLAB.

3.5.1 Performance of 3D Linear Array Adaptive Antenna when varying the Number of Antenna Elements.

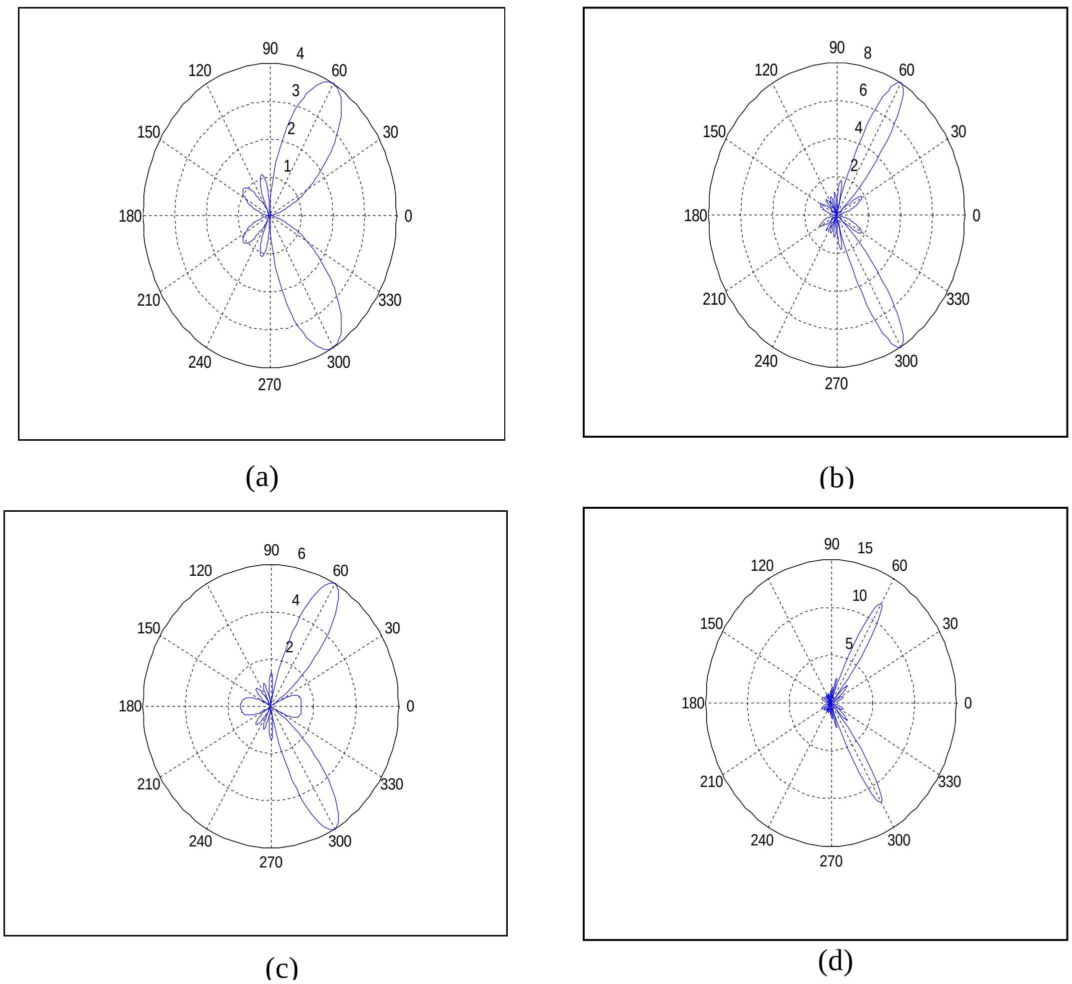


Figure 3-6: Antenna Array Pattern for different numbers of elements *N*: (a) 4 elements (b) 6 elements(c) 8 elements (d) 12 elements

It can be seen from Figure 3-6 that, simulation results on the linear array of Adaptive antennas proves that, increasing the number of antenna elements would produce a smaller 3dB beamwidth; therefore power concentration became more focus by having high array directivity. Although this is an encouraging condition, but it was found that the drawback for increasing the number of elements in linear array would cause more undesirable sidelobes to appear.

3.5.2 Performance of 3D Linear Array Adaptive Antenna when varying the Phase Excitation

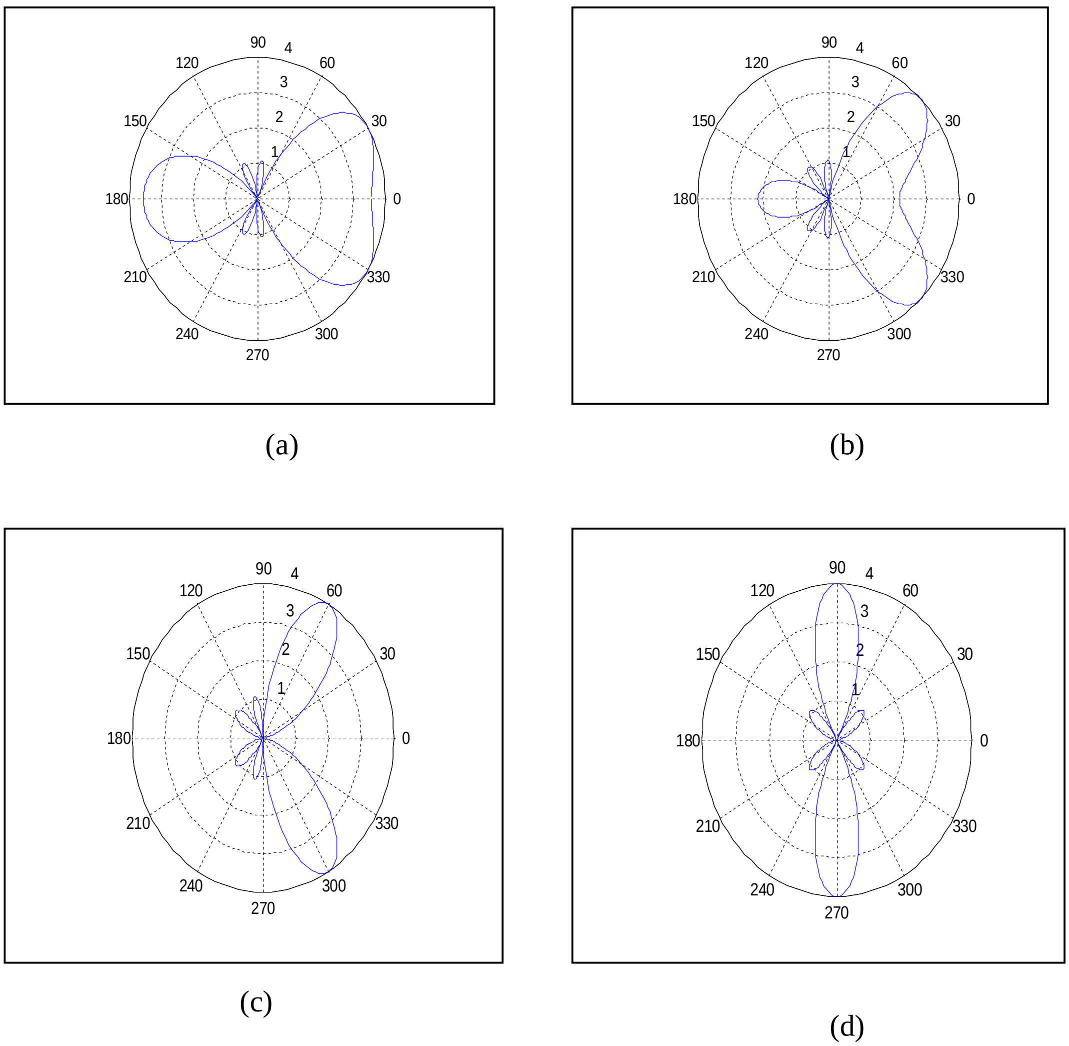
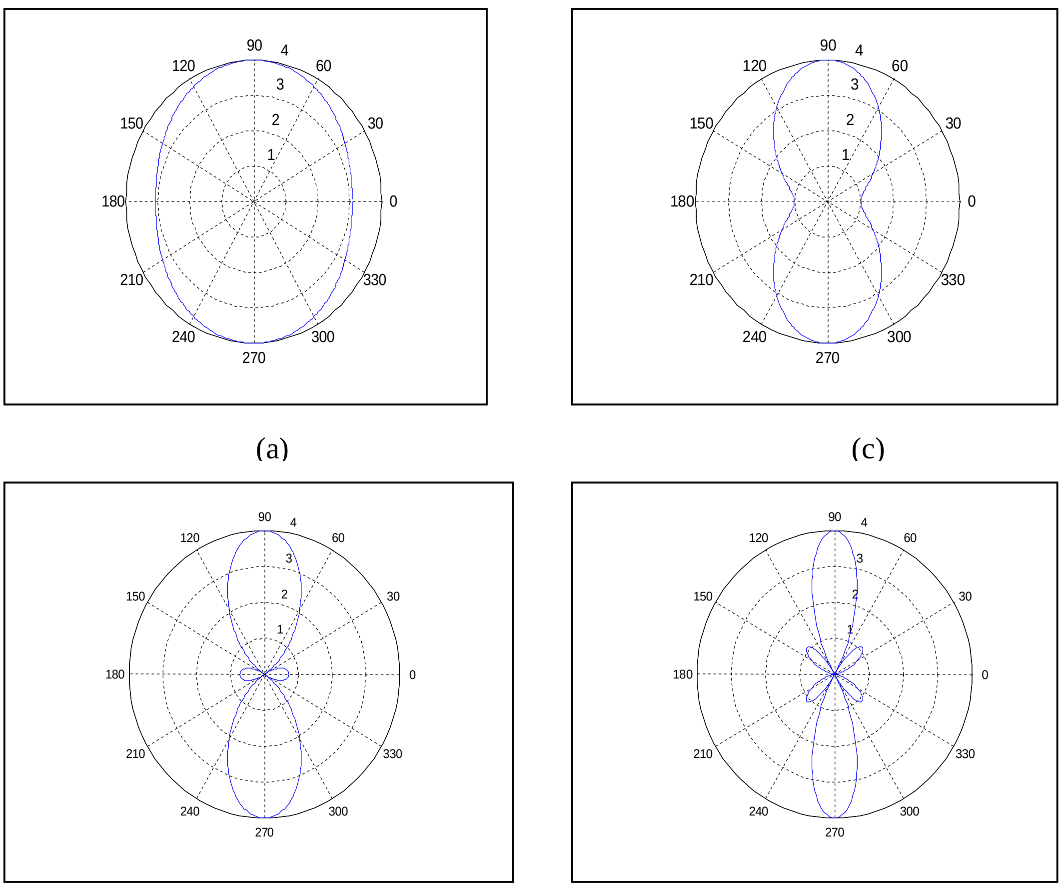


Figure 3-7: Antenna Array Pattern when varying the phase angles β (a) 30 degrees (b) 45 degrees (c) 60 degrees (d) 90 degrees

Figure 3-7 depicts the effect of varying the phase excitation. Shifting the phase allow the mainlobe to be directed towards any direction of interest. It can be seen that as the beam is steered closer (having small angle) to the axis of the array more sidelobes appear with larger amplitudes with respect to the main lobe. This causes a loss in directivity and limits the ability of the array to function correctly further away from the broadside mode it gets resulting into interference. It can be concluded that, shifting phase angle is an encouraging method and the greater the phase angle, the more directional an antenna is.

3.5.3 Performance of 3D Linear Array Adaptive Antenna when varying the Inter-element Spacing *d*



(a) (c)

(b) (d)

Figure 3-8: Antenna Array Pattern when varying the interelement Spacing *d:* (a) 0.1λ (b) 0.3λ (c) 0.2λ (d) 0.5λ

Figure 3-8 shows the effect of varying the inter-element spacing *d*. The directivity is directly proportional to the inter-element spacing. As shown, increasing the inter-element spacing narrows the main beamwidth i.e. the more the value of *d*, the narrower the main beamwidth becomes. When the elements are spaced exactly λ apart, additional lobes that rise to an intensity equal to that of the main lobe would come out.

The general rule for array radiation is that the mainlobe width is inversely proportional to the array length(s) [16].We can conclude that, out of all this, 0.5λ is the best.

3.5.4 Performance of 3D Linear Array Adaptive Antenna when varying the Amplitude Distribution

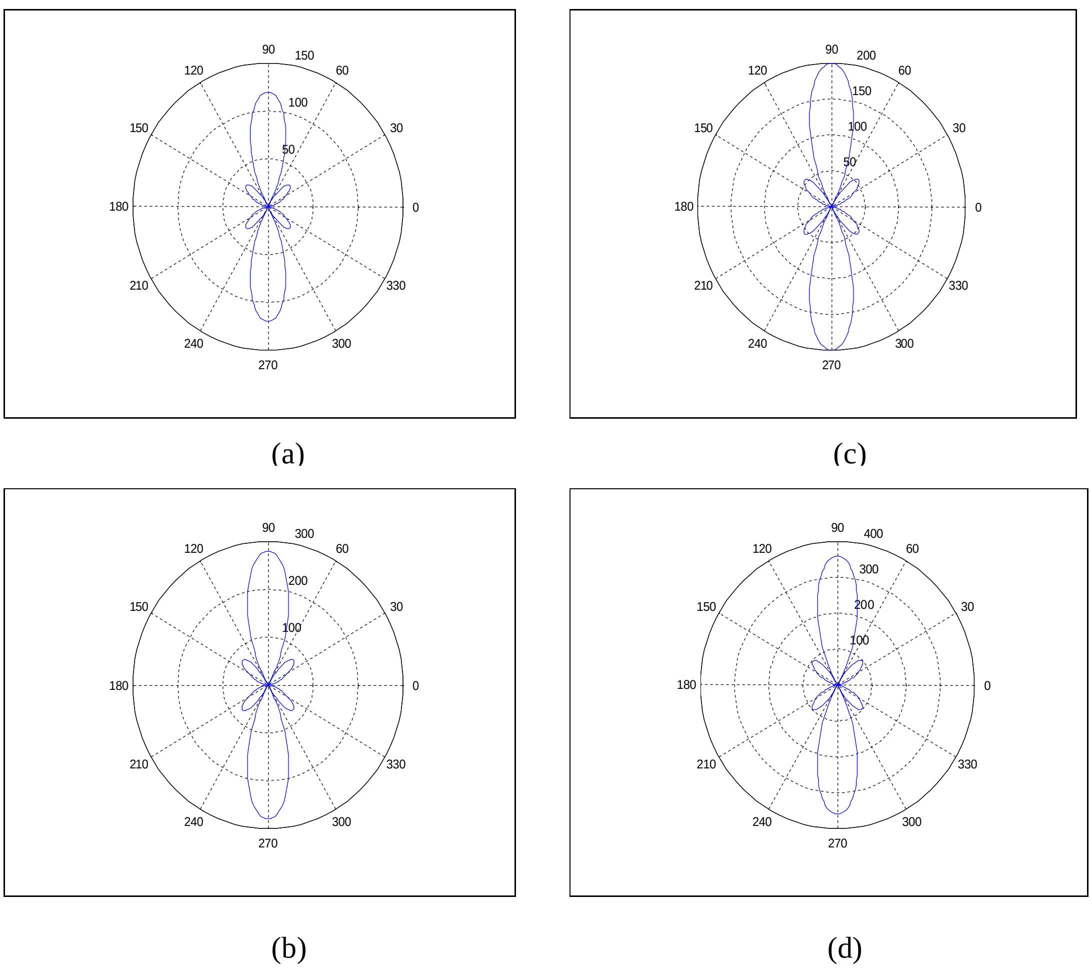


Figure 3-9: Antenna Array Pattern when varying the amplitude distribution *A*: (a) 30 (b) 50 (c) 70 (d) 90

In Figure 3-9, when varying the amplitude distribution, it can be seen that the expected results are, lower sidelobes level and a bigger 3dB beamwidth with lower directivity. Uniform amplitude gives the highest directivity and side lobe level but narrowest beamwidth.

3.6 Summary

In this chapter, the fundamentals of Adaptive Antenna Arrays have been presented; an introduction to ESPRIT algorithm for direction of arrival estimation and the basics of Adaptive Beamforming with arrays have also been given. The equations used in the MATLAB simulation have been provided. More concentration on Least Mean Square algorithm has been paid, which is one of the Adaptive Algorithms. Simulation studies for LMS have been carried out to see if it is suitable for our proposed environment. Results showed that LMS converges slowly. Since the desired mobile nodes and interferer mobile nodes locations and the signal environment are varying with time in MANET, in this case the weights will not have enough time to converge when adapted at an identical rate. Normalized LMS was proposed for our system, this is because it converges faster than LMS. Directivity performance of 3D Linear Array with varying parameters like, the number of antenna elements, the inter-element spacing, amplitude and phase excitations have been investigated. Through these investigations 0.5λ inter-element spacing, 4 elements array, uniform amplitude and variable phase excitations were selected for this study.

CHAPTER 4

ANALYTICAL MODELING AND DESIGNING OF MAC PROTOCOLS WITH ADAPTIVE ANTENNA ARRAYS

4.1 Introduction

This chapter describes the antenna models used to evaluate the effects of Adaptive Antenna Arrays on the throughput and delay performance of the selected MAC Protocols in a Mobile Ad-hoc Network and the antenna model for Baseline Simulation. Next section presents mobility modeling using Random Waypoint Model. This is followed by the Markov analytical modeling used to evaluate the throughput and delay performances of the selected protocols.

4.2 Antenna model

4.2.1 Physical-MAC System Antenna Model

This system consists of four antennas, four transceivers, a receiver sink and a source module all attached to the WLAN-MAC processor, Antenna Pointer and an External System module as shown in figure 4-1. The function of each node is explained below:

- **A *source module*** is to generate packets.
- **A *radio transmitter*** module which provides an interface to transmit the packets on a radio channel.
- **A *radio receiver*** module which provides an interface to receive data packets sent by the transmitter. The receiver radio contains the ragain pipeline which is changed in order to run each of the scenarios specified.
- **A *receiver sink*** module (receiver- sink) which sinks data packets received.
- ***Antenna pointer*** provides the pointing of the main beam lobe to desired angle. By this way, we can change the direction of the main lobe during the simulation.

- ***External system*** module (esys), the module's process model acts as the interface between the external system and the rest of OPNET.

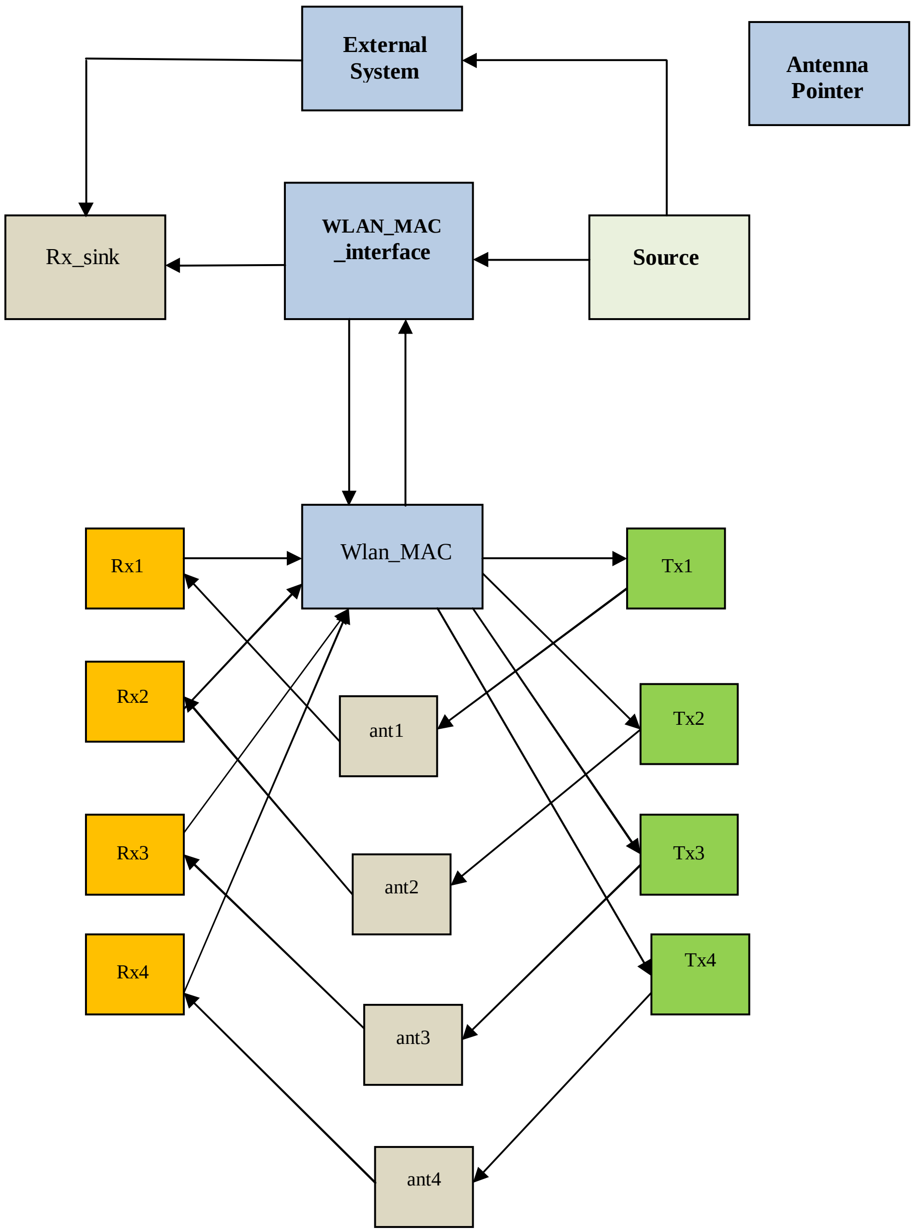


Figure 4-1: PHY-MAC System Antenna Model

4.2.2 Baseline System Antenna Model

In the Baseline System, Enhanced Antenna Positioning System (EAPS) was used. To design the EAP model, we have made use of three-dimensional approach. The information about the location of a node is provided in terms of latitude, longitude and altitude. For using the antenna model, the pointing direction of the antenna must coincide with the positive z-axis of the antenna gain pattern used.

The following diagrams illustrate how the azimuth and elevation angles are computed. First several vectors and angles were defined. Table 4-1 shows the vectors and the angles.

Table 4-1: Vectors and Angles

$\overline{pd}$	Pointing Direction Vector
$\overline{tx}$	geocentric Transmission Object vector
$-\overline{tx}$	opposite of transmitter vector
$\overline{rx}$	geocentric Receiver Object vector
$\overline{d}$	difference vector
n_d	Normal Vector to plane containing $\overline{pd}$ and $\overline{d}$
n_neg_tx	Normal vector to plane containing $\overline{pd}$ and $-\overline{tx}$
ϕ	azimuth angle
θ	elevation angle

Figure 4-2 and 4-3 show the computation of azimuth angle. Vector *d* is determined from the position vectors *tx* and *rx*. Therefore *phi* is the angle made between *pd* and *d*. Phi can range between 0 and 180 degrees. When phi equals to

0, this corresponds to the pointing direction vector coincident with the difference vector or else it can be computed by using, Figure 4-3.

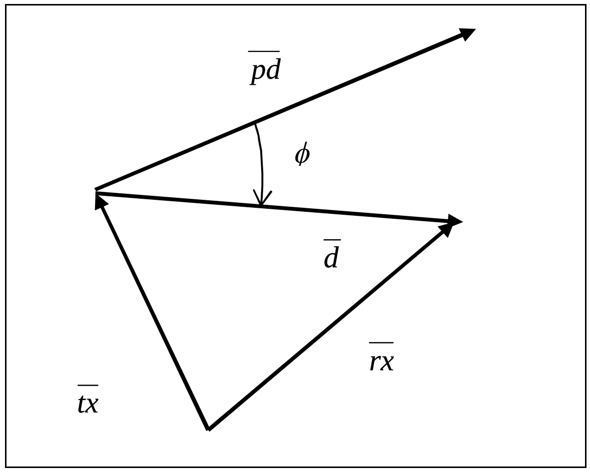


Figure 4-2: Side view of a transmitter, receiver and pointing direction vectors.

$$AB = \overline{pd} \text{ and } AC = \overline{d} = \overline{pd}\cos\phi \tag{4.4}$$

Therefore $\cos\phi = \overline{d} / \overline{pd}$

$$\phi = \cos^{-1}(\overline{d} / \overline{pd})$$

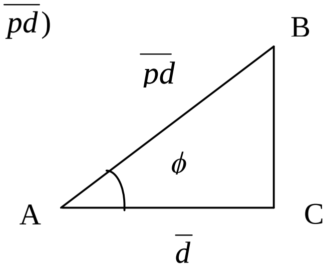


Figure 4-3: Computation of phi (ϕ)

Figure 4-4 shows the computation of the elevation angle θ in degrees using a view standing in front of the antenna looking straight into it. The negative of the transmission position vector is used as a reference. Theta is the counterclockwise angle made by $\overline{d}$ measured from $-\overline{tx}$. The antenna pattern *theta=0* corresponds to the $-\overline{tx}$ vector. In this view the *–tx* and *d* are projected angles, their true angles in 3-D space will differ from the true angle theta.

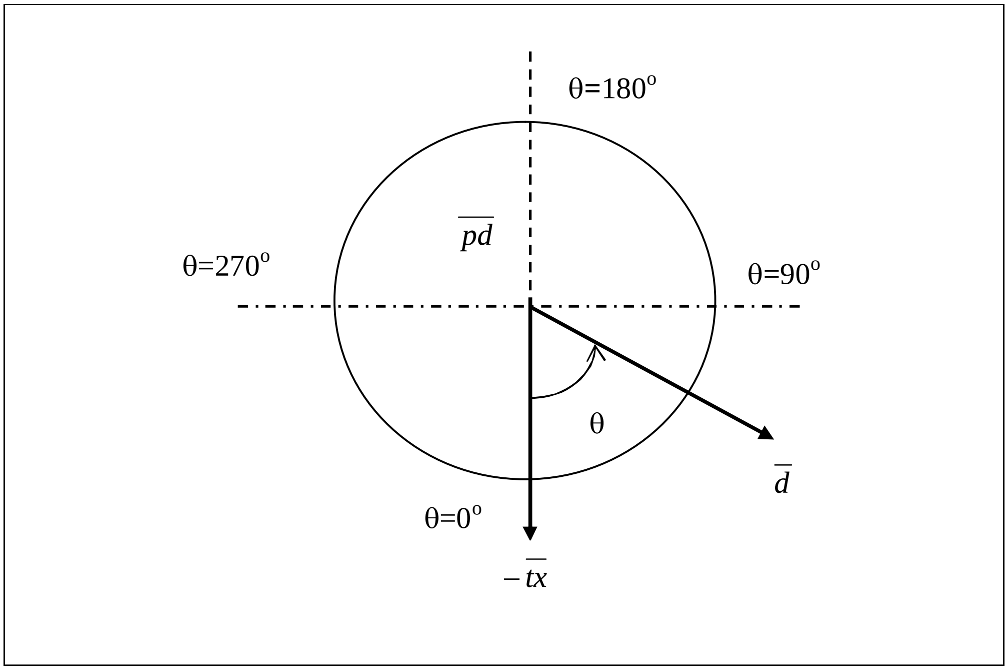


Figure 4-4: Front view of antenna as seen from an observer standing in front of the node

Figure 4-5 depicts the true computation of theta using normal vectors. The normal vector *n_d* is computed from crossing the *pd* vector with the *d* vector. Similarly the normal vector *n_neg_tx* is the cross product $\overline{pd} \times -\overline{tx}$. The normal vectors will both be perpendicular to the *pd* vector and thus in the same plane. The angle for these two vectors is the true measure of theta.

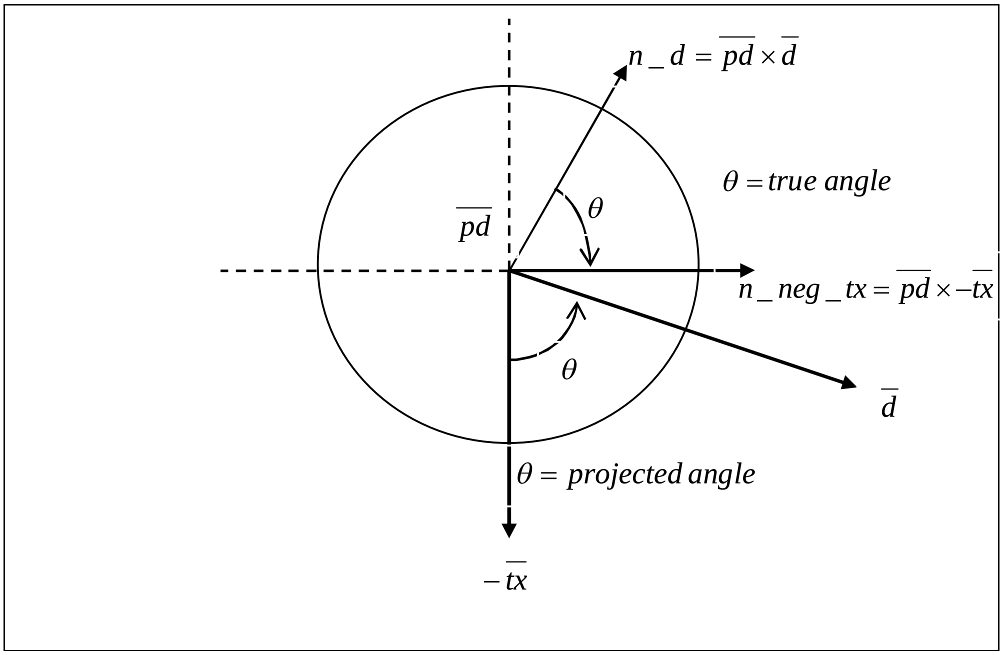


Figure 4-5: The Calculation of theta using normal vectors n_d and n_neg_tx

4.3 Mobility Modeling

To model the movement of the mobile nodes, Random waypoint mobility model is used in which

- Each node selects a random destination in the simulated area
- Each node selects a speed "*v*" from the input range which is *1,………N*
- The node moves to the destination selected with the speed "*v*"
- When the node reaches the destination, it pauses for time "*t*"
- At the end of the pause time, the node re-selects a new destination and speed and the process is repeated

The random walk model in [47] has been modified to form the mobility modeling. The modeling was for a cellular wireless radio system with *N* cells and a number of mobile users. For our case, mobile nodes were used where there is no basestation (MANET). Time is slotted and a node can make at most one move during a slot. The movements are assumed to be stochastic and independent from one node to another. The nodes are model within a specified area.

Four updates approaches are taken:

1. Time-based update
2. Location-based update
3. Speed-based update
4. Distance-based update

In the model, in each slot, a node can be in one of the following four states within the specified area.

- The initial state I
- The stationary (idle) state S
- The right-move state R
- The left-move state L

As illustrated in Figure 4-6 and Figure 4-7, at the initial state of the system, the location, speed and time are initialized. Assume that a node is at position *i* at the beginning of the slot. The movement of a node during that slot depends on the state as follows; if a node is in state *S* then it remain at position *i*, if the node is in state *R* then it moves to position *i+1*, and if the node is in state *L* then it moves to position *i-1*.

Let *X(t)* be the state during time slot *t*. Assume that

$\{X(t); t = 0;1;2............n\}$ is a Markov chain with transition probabilities

$p_{kl} = prob[X(t+1) = l = X(t) = k]$ as follows

$$p_{R,R} = p_{L,L} = q\,,\ p_{L,R} = p_{R,L} = v\,,\ \ p_{S,R} = p_{S,L} = p\,,\ \text{and}\ \ p_{S,S} = 1-2p \qquad (4.1)$$

In time-based update, each node transmit an update message every T slots, while in Location-based update, each mobile node transmits an update message whenever it completes *M* movements at different locations, speed-based update message is send whenever there is a change in the speed of a mobile node and finally in distance-update message, each mobile node transmit an update message whenever the distance in terms of locations, between its current position and the position from which it last reported is changed.

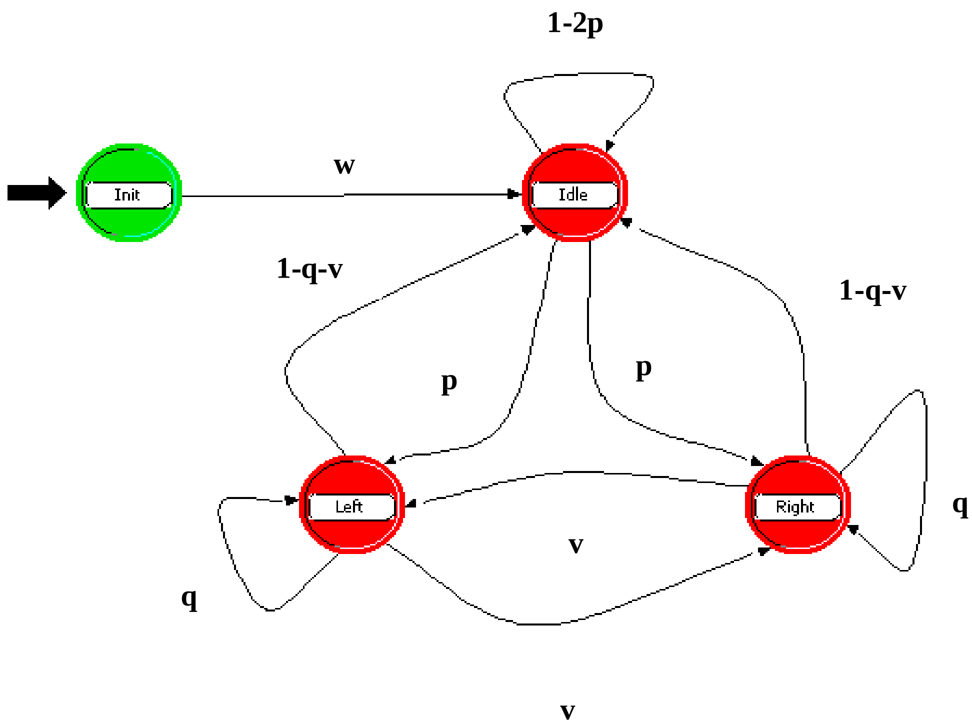


Figure 4-6: A state diagram of the Markov Random Mobility Model

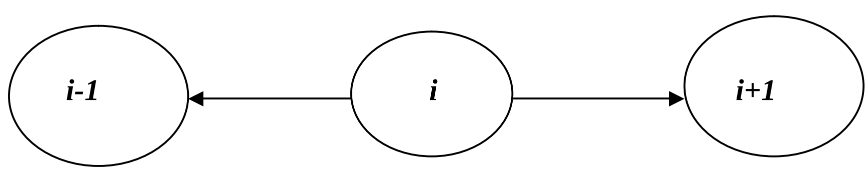


Figure 4-7: Movements of Nodes

a) Time-based, location-based and Distance-based updates

Let *Y(t)* be the distance between position at which a node is located in a slot *t* and the position at which the node last transmitted an update message. As before, positive or negative *Y(t)* indicates that the node is to the right or left of the position at which an update message was last transmitted. The interval is

$$-(M-1) \leq Y(t) \leq M-1 \qquad (4.2)$$

Let $L(t)$=max $\{\pi \le t \mid$ the node reported in slot $\pi\}$. Let $N(t)$ be the number of movements that a node has made during the slots $L(t)+1,........,t-1$ (if $t-1<L(t)$, then $N(t)=0$). Clearly, $0 \le N(t) \le M-1$

To compute the expected number of update messages per slot transmitted by a node U_M, as in [47] Markov chain $\{N(t), X(t), t=0,1,2,.....\}$ with constant probabilities has been used.

$$Q_{m.x} = \lim_{t\to\infty} \Pr ob[N(t)=m, X(t)=x|; m=0,1...........M-1 x \in \{S,R,L\} \qquad (4.3)$$

The following balance equations will be used shortly:

$$Q_{i-1,R} + Q_{i-1,L} = Q_{i,R} + Q_{i,L} \qquad (4.4)$$

$$i = 0,1,.......,M-1$$

Where i-1 is computed modulu M. The node transmits an update message at slot t if and only if $N(t$-$1)=M$-1 and $X(t$-$1)$ is either R or L. Therefore,

$$U_M = Q_{M-1,R} + Q_{M-1,L} = Q_{M-1,L} = Q_{0,R} + Q_{0,L} \qquad (4.5)$$

$$= 1/M - Q_{0,S}$$

$$= 1/M - (1-q-v)2p*(Q_{M-1,R} + Q_{M-1,L})$$

$$= 1/M - ((1-q-v)/2p)U_M \qquad (4.6)$$

The second and the fourth equalities follow from the above balance equations. The third equality follows from the fact that $Q_{m,R} + Q_{m,L} + Q_{m,S} = 1/M$ for all m, which follows from symmetry considerations. Solving for U_M, we have

$$U_M = 2p/M(1+2p-q-v) \qquad (4.7)$$

To compute the expected number of searches necessary to locate a node V_M we will consider an embedded Markov chain that ignores the states in which the node does move. Let $N(t,t^{'})$ be the number of movements that a node has made during the slots $L(t), L(t)+1, \ldots\ldots, t-1$. Recall that t_s is the slot in which a search occurs.

Let $t_m = \max\{t \geq L(t) | J(t_s, t) = m\}$. The embedded Markov Chain is

$\{(Y(t_m), X(t_m)), m = 0,1,2, \ldots\ldots\ldots\}$.

Let $P_m(d, x|x') = prob[Y(t_m) = d; X(t_m) = x | X(t_0) = x']$.

From the definition of t_m, it follows that $Y(t_0) = 0$. Define

$$P'_m(d, x|x') = P_m(d, x|x') + P_m(-d, x|x') \text{ for } d>0, \quad (4.8)$$

and let $$P'_m(d|x') = P'_m(d, R|x') + P'_m(d, L)|x').$$

By using symmetry considerations, we have $P'_m(d|R) = P'_m(d|L)$ for all $d>0$ and $m \geq 0$. The probability that a node will be at an absolute distance d (from the position at which an updated message was last sent) at time t_m namely after m movements, is therefore,

$$P'_m(d) = P'_m(d|R) prob[X(t_0) = R] + P'_m(d|L) prob[X(t_0) = L] = P'_m(d(R) \quad (4.9)$$

Returning to the Markov Chain,

$$prob[Y(t_s) = d] = \sum_{M=0}^{M-1} prob[Y(t_s) = d | N(t_s) m]^* prob[N(t_s) = m]$$

$$= \sum_{M=0}^{M-1} P'_m(d)^* 1/M \quad (4.10)$$

Therefore, the expected number of searches required to locate the node is

$$S_M = 1 + 1/M \sum_{M=0}^{M-1} \sum_{d=0}^{M-1} DP_m(d) \quad (4.11)$$

Where the latter sum is taken only for even $d+m$

To compute the computation, we only need to have the quantities $P_m(d, R|R)$ and

$P_m(d, L|R)$ for

$0 \le d,\ m \le M-1$, and

$$P_0(0, R|R) = (1+q-v)/2 \tag{4.12}$$

$$P_0(0, L|R) = (1-q+v)/2$$

$$P_0(d\,x|R) = 0, d \neq 0; x \in \{R, L\}$$

$$\begin{aligned} P_m(d, R|R) &= (1+q-v)/2 * P_{m-1}(d-1, R|R) \\ &+ (1-q+v)/2 * P_{m-1}(d+1, L|R) \\ &m \geq 1, (M-1) \leq d \leq< M-1 \end{aligned} \tag{4.13}$$

$$\begin{aligned} P_m(d, L|R) &= (1-q+v)/2 * P_{m-1}(d-1, R|R) \\ &+ (1+q-v)/2 * P_{m-1}(d+1, L|R) \\ &m \geq 1, (M-1 \leq d \leq M-1) \end{aligned} \tag{4.14}$$

b) Speed-based updates

For modeling the speed, we assume that the speed of each mobile node is determined by N phases, where each phase corresponds to the speed in a particular space within the specified area. Let the random variable V defined on the state space $[V_{min}, V_{max}]$, where $V_{min} > 0$, denote the speed of a node moving from one position to another.

The initial speed is i with probability V_i, where

$$\sum_{i=1}^{N} V_i = 1 \tag{4.15}$$

The initial speed of the mobile nodes phase i, $i \in \{1,2,............N\}$, is a random variable with probability density function $fv_i(v)$ with a mean and standard derivation μ_i and σ_i respectively.

4.4 Throughput and Delay Analysis

In order to develop an analytical model of the proposed MAC protocols, we set up the basic Markov chain closely follows [22].

[23] uses a cellular network model where Smart antennas are used at the Base station. The Base station can receive transmissions from at most one mobile in one slot. Ward considered an Ad hoc network where a node can transmit to any of its neighbors and the probability of success depends on

1. Whether the intended receiver is idle
2. Whether the receiver beamforms towards the sender during the slot and
3. The nulling capability of the receiver's antenna.

In our case however, we consider Mobile Ad hoc Network, and the probability of success depends on

1. Whether the intended receiver does not transmit and the channel is idle
2. Whether the sender has a successful transmission
3. Whether the receiver beamforms towards the transmitter
4. The nulling capability and sidelobes of the receiver

In a given slot, the total number of packets transmissions can be written as $n_t = n_n + n_r$ where n_r and n_r are the number of new transmissions and the number of retransmission respectively. Following [24] for equations (4.17)-(4.20), we can thus write

$$Q_n(l/i) \underline{\underline{\Delta}} P_r\{n_n = l / x_k = i\}$$

$$= \binom{M-i}{l} \times p_n^l (1-p_n)^{M-i-l}, i \leq M \tag{4.16}$$

$$Q_r(l/i) \underline{\Delta} P_r\{n_r = l / x_k = i\}$$

$$= \binom{i}{l} p_r^l (1-p_r)^{i-1}, i \geq l \tag{4.17}$$

Where

- M is the total number of nodes
- l is the number of packets
- X_k is the state at slot k

p_n is the probability with which an unblocked terminal transmits a packet

p_r is the probability with which a blocked terminal retransmits its backlogged packet

k is the number of slots

Thus, the distribution of the total number of transmission in slot can be written as,

$$Q_t(l/i) \underline{\underline{\Delta}} P_r\{n_t = l / x_k = i\} = \sum_{s=0}^{l} Q_n(s/i) Q_r(l-s/i)$$

(4.18)

For finding the transition probabilities P_{ij}, two cases were considered: $j \le i$ and $j \ge i$

- $j = i-k, i = 0,\dots\dots\dots, M, k = 0,\dots\dots\dots, i$: This can occur only if $n_r \ge k, n_n \ge 0$, and $n_n + k$ transmissions are successful. The probability can be written as,

  $$P_{i,i-k} = \sum_{s=0}^{M-i} \sum_{l=k}^{i} Q_n(s|i) Q(l|i) P_s(l+s, s+k)$$

  (4.19)

  Where, $P_s(a,b)$ is the probability of $b \le a$ successful transmissions given a total transmissions.

- $j = k+1, i = 0,\dots\dots\dots M, k = 0,\dots\dots\dots M-i$: In order for this state transition to occur, exactly $k+1$ unblocked nodes need to become blocked and l blocked nodes need to become successful. The probability of this can be written as,

  $$P_{i,i+k} = \sum_{s=k}^{M-i} \sum_{l=0}^{i} Q_n(s|i) Q_r(l|i) P_s(l+s, s-k) \qquad (4.20)$$

Let $P_s(l,k)$ be the probability that $k \le l$ successful transmissions given l total transmissions.

To compute $P_S(l,k)$ they have used the following simplified model: they have assumed that a node cannot receive a packet if more than one transmission is being sent to it. A packet is successful if a node is able to make nulls in the direction of all transmitters. Thus $P_S(l,k)$ reduces to

1. A combinational problem of determining the probability of there being $s \geq k$ receivers (that are not transmitting)
2. That all these s nodes is the destination for one of the *l* packets transmitted
3. The probability that *k* out of *s* receivers can correctly receive a packet given $(l-1)$ other transmissions, some of which may interfere.
4. Given that all the nodes are unique, there are $(M-1)^l$ different ways in which *l* packets can be transmitted
5. In order to be there exactly *k* successes, *s* nodes out of $M-l$ were identified that will be the receivers.
6. This can be done in $\binom{M-l}{s}$ ways.
7. Of the *l* transmissions, *s* are transmitted to the *s* selected receivers within the remaining $(l-s)$ transmitted themselves. Then ,

$$P_S(l,k) = \begin{cases} 0, k > l, l+k > M, (l=1 \quad \text{and } k=0) \\ 1, l = k = 1 \quad \text{or } 0 \\ \dfrac{1}{(M-1)^l} \sum\limits_{s=k}^{\min(l,M-l)} \binom{M-l}{s}\binom{l}{s} \\ \binom{s}{k} s!(l-1)^{l-s} p_S(l,E)^k \\ (1-p_S(l,E))^{s-k}, l > 1, l \geq k \geq 0 \end{cases} \tag{4.21}$$

Where, $p_S(l,E)$ is the probability of a successful packet reception given *l* total transmissions and that the node can form *E* nulls.

$$p_S(l,E) = \sum_{\alpha=0}^{l-1} \binom{l-1}{\alpha} \left(\frac{\theta}{2\pi}\right)^{\alpha} \left(1-\frac{\theta}{2\pi}\right)^{l-\alpha-1} \tag{4.22}$$

$\times$Pr[No interference] α transmitters in receiver’s beam]

$\times$Pr[No interference from $l-\alpha-1$ transmitters in receiver’s beam]

$$= \sum_{\alpha=0}^{l-1} \binom{l-1}{\alpha} \left(\frac{\theta}{2\pi}\right)^{\alpha} \left(1-\frac{\theta}{2\pi}\right)^{l-\alpha-1}$$
$$\times \left(1-2\frac{\theta}{2\pi}\right)^{\alpha} \times \sum_{\beta=0}^{\min(E,l-\alpha-1)} \binom{l-\alpha-1}{\beta} \tag{4.23}$$
$$\times \left(\frac{\theta}{2\pi}\right)^{\beta} \left(1-\frac{\theta}{2\pi}\right)^{l-\alpha-\beta-1}$$

- Note that the probability that a transmitter's beam (or second lobe) is not pointed at a given receiver is $1-2\frac{\theta}{2\pi}$.

To compute the throughput and delay performance of the mobile nodes we have used the following equations [22],

Given that the system is in state *j*, the probability of a successful packet transmission is the conditional throughput $S(j)$, given by

$$S(j) = \sum_{t=1}^{M} Q_t(l|j) P_s(l) \tag{4.24}$$

The average number of the new packets entering the system in state *j* using irreducible Markov Chain is,

$$S_{in}(j) = (M - j)p_n \tag{4.25}$$

- Finite population
- All states are recurrent non-null
- States are aperiodic

  Then

$$\pi = [\pi(0), \pi(1), \ldots\ldots\ldots, \pi(M)] \tag{4.26}$$

Where

$$\pi(j) = \Pr\{X_\infty = j\} = \lim_{n\to\infty} \Pr\{X_{k+n} = j | X_k = i\}$$

The steady-state probabilities are found by solving the linear system of equations

$$\pi = \pi P \tag{4.27}$$

Along with the constraint that

$$\sum_{j=0}^{M} \pi(j) = 1 \tag{4.28}$$

Given $\pi(j)$, the average number of blocked terminals $\overline{B}$ is

$$\overline{B} = \sum_{j=0}^{M} j\pi(j) \tag{4.29}$$

and the average throughput is

$$\overline{S} = \sum_{j=0}^{M} S(j)\pi(j) \tag{4.30}$$

In the steady state, the average input rate equals the average throughput, so

$$\overline{S}_{in} = S_{in}(\overline{B}) = \overline{S} \tag{4.31}$$

Using Little's theorem, this theorem states that for networks reaching steady state, the average number of packets in a system is equal to the product of the average arrival rate, λ, and the average time spent in the queueing system, then

$$\overline{D} = \frac{\overline{B}}{\overline{S}_{in}} = \frac{\overline{B}}{\overline{S}} \tag{4.32}$$

4.5 Summary

Antenna models that have used to evaluate the effects of Adaptive Antenna Arrays on the throughput and delay performance of the selected MAC protocols in a Mobile Ad-hoc Network and the antenna model for Baseline Simulation have been presented. Movements of mobile nodes have been modeled using Random Waypoint Modeling. The throughput and delay performance analysis using Markov Chain were used for the performance analysis of the selected MAC protocols. The values of theta and phi were computed for the baseline simulation.

CHAPTER 5

SIMULATION MODEL

5.1 Introduction

This chapter describes the simulation models developed to observe and evaluate the effects of Adaptive Antenna Arrays on the throughput and delay performance of the selected MAC Protocols in a Mobile Ad-hoc Network and antenna models for gain calculations. Two different methodologies are presented, one for the PHY-MAC layer simulations, where some of the pipeline stages are modified and the two layers are interfaced. The second methodology presents the Baseline simulations in which EAPS has been used to modify the pipeline stages.

The main purpose of the simulation studies models is to examine and analyze the performance gains achieved due to the use of Adaptive Antenna Arrays and the EAPS. The simulations for the network performance have been performed using OPNET Modeler version 11.5 and the physical layer in MATLAB. OPNET is commonly use for network simulation and provides rich library of model for implementing wired and wireless networks.

OPNET Modeler is an environment for network modeling and simulation, allowing you to design and analyze communication network devices, protocols and applications in differential levels. In OPNET, Discrete event simulations are used as the means of analyzing system performance and their behavior. This complicated package comes complete with a range of tools which allows us to specify models in great detail, identify the elements of models of interest, execute the simulation and analyze the generated output data.

Modeler is an object-oriented modeling tool based on a three levels hierarchy. These levels are network model, node model and process model.

The Network editor graphically represents the topology of a simulated communications network. Networks consist of nodes and link objects for wired networks otherwise no links. To build network user can use editor’s object palettes or he/she can import object features. Design area can be configurable by real parameters (size in meters or real maps). Network model is the first and the simplest step in configuration of individual network elements. Protocol menu can be use for quickly configure protocols.

The Node editor describes the architecture of individual network element by displaying the data flow between functional modules. Each module can generate, send, and receive packets from other modules. Modules typically represent applications, protocol layers, algorithms and physical resources (for example buffers, ports, and buses).

The Process models are used to specify the behavior of processor and queue modules which exist in the node domain. The process editor uses a “finite state machine (FSM)” approach to support specification, at any level of detail (of protocols, resources, applications, algorithms, and queuing policies). Individual state of a process model uses C/C++ code.

In this chapter, to perform the methodologies, we started with a concise discussion of modeling and simulation methodology done in OPNET. The next section presents discussions on the basic methodology for interfacing MATLAB and OPNET, where Adaptive Antenna Arrays are implemented in MATLAB. MATLAB code has been included into the antenna model to allow the reuse of antenna null and beamforming algorithms previously developed in MATLAB. This is followed by a baseline simulation modeling. In the next section an Adaptive MAC scheme with spatial diversity for ANMAC and MMAC protocols. The last section summarizes the chapter.

5.2 System Implementation

This section presents an overview of the implemented system. It describes how the adaptive MAC system is implemented in OPNET. The models created to simulate our work are explained. The details on how interfaces between the physical and MAC layers (co-simulation) are established and the procedural steps used to implement the physical layer within the co-simulation.

5.2.1 PHY-MAC layer implementation

5.2.1.1 System Overview

The system consists of fixed and mobile nodes, as shown in the palette of Figure 5-1. In the following subsection we will give a detail description of each of these nodes.

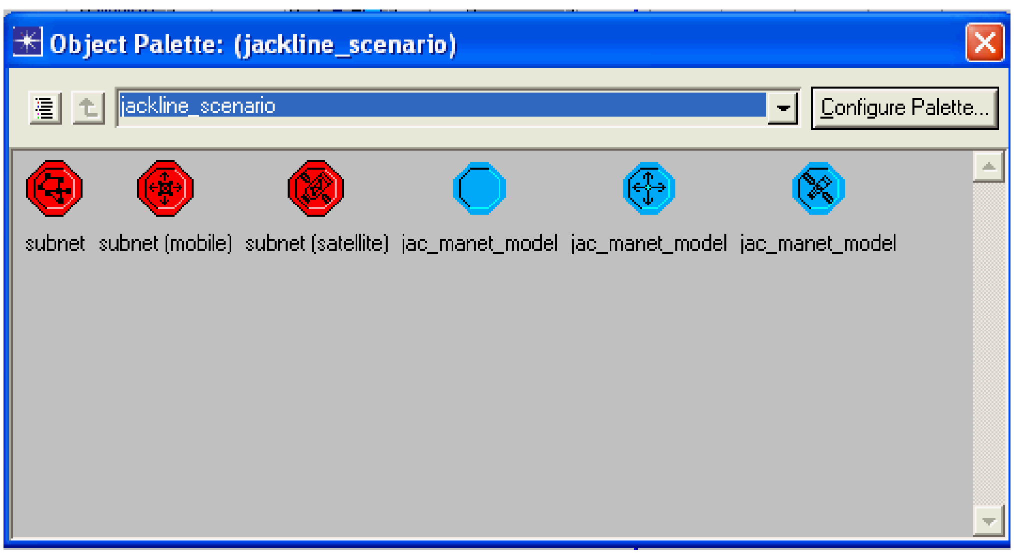


Figure 5-1: Object Palette of the Mobile nodes

5.2.1.2 The node model

The node model of the proposed plan designed in OPNET is shown in Figure 5-2. In the model, there are two kinds of connections between processors. The first one is the packet stream line. It is utilized in packet-based communication and used for information exchange between subsystems. The packets in these streams are sensed via interrupts generated by data sensing which is organized by simulation kernel. The second one is the statistics wires. They are used for exchanging values between the attached source/destination ports and for physical carrier sensing that are invoked by simulation kernel. The values are passed to processors to keep track of changes in the transmitter/receiver status.

The existing 802.11 MAC model has been modified to implement the two selected MAC protocols and to provide all necessary interfaces with the antenna models. The designed model as shown in Figure 5-2 consists of four antennas and four transceivers, each covering different zones, are attached to the WLAN-MAC processor, Antenna Pointer and an External System module.

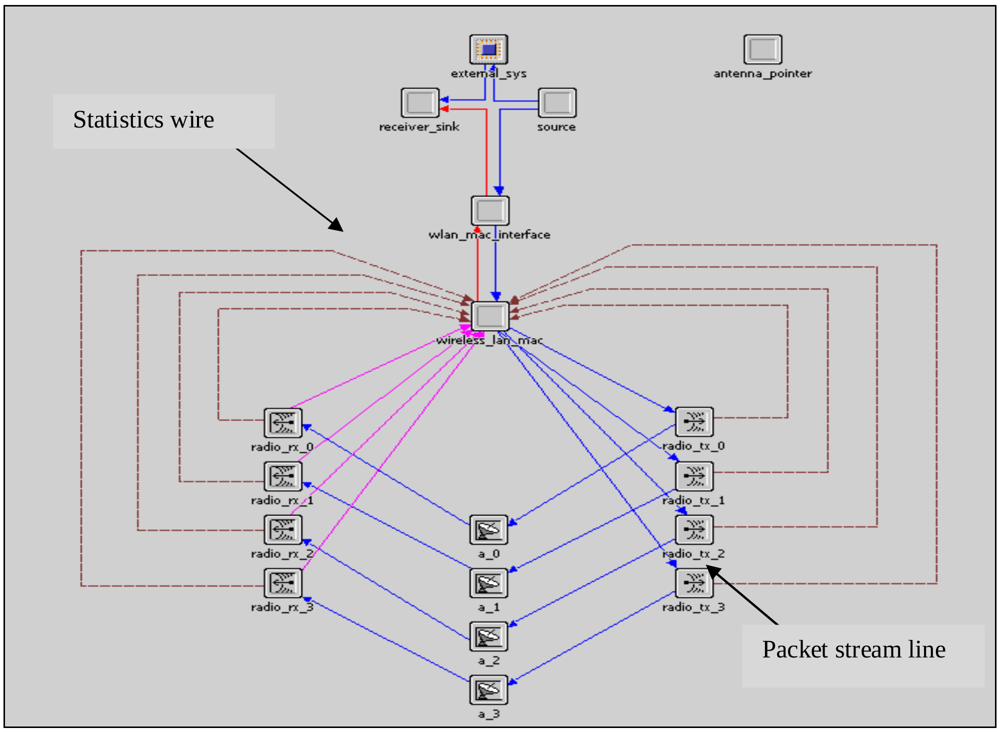


Figure 5-2: The Node Model

The node model consists of the following;

- **A *source module*** which uses OPNET's simple source process model to generate packets. The probability distribution functions of the packet size and packet inter-arrival time used within the simple source may be set as desired from those available within OPNET.

- **A *radio transmitter*** module which provides an interface to transmit the packets
- **A *radio receiver*** module which provides an interface to receive data packets sent by the transmitter. The receiver radio contains the ragain pipeline which is changed in order to run each of the scenarios specified.
- **A *receiver sink*** module (receiver- sink) which sinks data packets received.
- ***Antenna pointer*** provides the pointing of the main beam lobe to desired angle. By this way, we can change the direction of the main lobe during the simulation.
- ***External system*** module (esys), the module's process model acts as the interface between the external system and the rest of OPNET.

The source and the sink models are used to simulate the higher layer. The attributes of some of the modules are shown below;

Figure 5-3 shows the Source module attributes. The attributes are the process model, the icon name, packet format, packet Interarrival Time, packet size, start time, stop time and beginsimulation intrpt. Simple source was selected for the process model and the packets size was set to 512 bytes.

Attribute	Value
name	source
process model	simple_source
icon name	processor
Packet Format	wlan_control
Packet Interarrival Time	constant (1.0)
Packet Size	constant (1024)
Start Time	10.0
Stop Time	Infinity
begsim intrpt	enabled

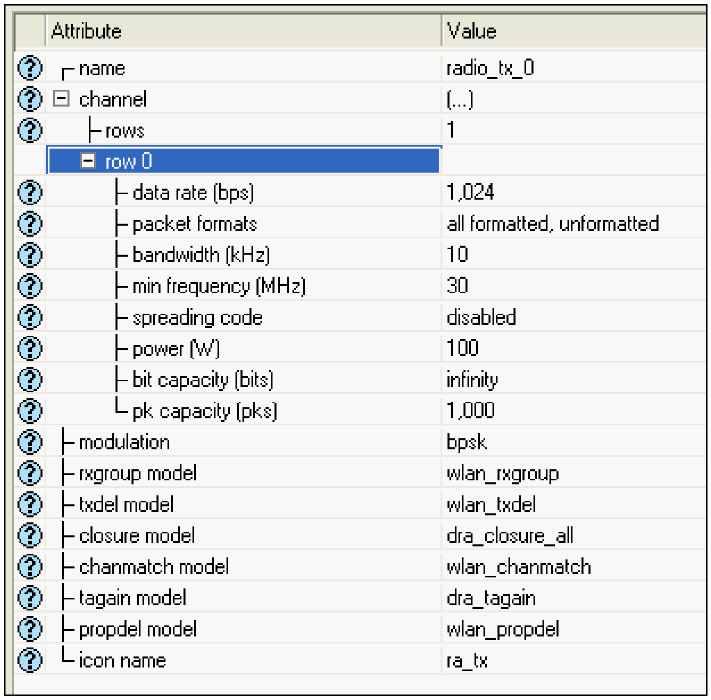
Figure 5-3: Source module Attributes

Figure 5-4 depicts the Receiver sink module attributes. Sink was chosen for the process model.

Attribute	Value
name	receiver_sink
process model	sink
icon name	processor

Figure 5-4: Receiver sink module Attributes

Figure 5-5 illustrates the Radio transmitter attributes. The transmitters employ the BPSK modulation.Wlan_rxgroup, wlan_txdel, dra_closure_all, Wlan_chanmatch, dra_tagain and wlan_prodel pipeline stages were selected for the following rxgroup model, txdel model, closure model, chanmatch model, tagain model and propdel model respectively.



Attribute	Value
name	radio_tx_0
channel	(...)
rows	1
row 0	
data rate (bps)	1,024
packet formats	all formatted, unformatted
bandwidth (kHz)	10
min frequency (MHz)	30
spreading code	disabled
power (W)	100
bit capacity (bits)	infinity
pk capacity (pks)	1,000
modulation	bpsk
rxgroup model	wlan_rxgroup
txdel model	wlan_txdel
closure model	dra_closure_all
chanmatch model	wlan_chanmatch
tagain model	dra_tagain
propdel model	wlan_propdel
icon name	ra_tx

Figure 5-5: Radio transmitter Attributes

Figure 5-6 illustrates the Radio receiver attributes. The receivers also utilize the BPSK modulation. The pipeline stages shown in the figure were selected for the attributes of the receiver as listed below.

Attribute	Value
name	radio_rx_0
channel	(...)
rows	1
row 0	
data rate (bps)	1,024
packet formats	all formatted, unformatted
bandwidth (kHz)	10
min frequency (MHz)	30
spreading code	disabled
processing gain (dB)	channel bw/dr
modulation	bpsk
noise figure	1.0
ecc threshold	0.0
ragain model	dra_ragain
power model	wlan_power
bkgnoise model	dra_bkgnoise
inoise model	dra_inoise
snr model	dra_snr
ber model	wlan_ber
error model	wlan_error
ecc model	wlan_ecc
icon name	ra_rx

Figure 5-6: Radio Receiver Attributes

5.2.1.3 The Process model Basics

In OPNET, as mentioned above, a node model is made up of individual nodes, and a node is made of modules. The hierarchy of packets flowing through the different modules in a node effectively models the different layers in a networking system. The process model defines a module's behavior. Certain modules are limited in the types of behavior they can represent.

OPNET thus provides a suitable stage for building higher layers modified to exact user-defined behavioral specifications or protocol standards through the building of process models. A process model is a finite state machine (FSM). It represents a module's logic and behavior. An FSM consist of any number of states that a module may be in and the necessary criteria for changing states. OPNET simulations are made up of events. Process models respond to events (such as packet arrivals) and may schedule new ones. In OPNET simulation, when an event occurs that affects a module, the simulation kernel passes control to the module's process model through an interrupt. The process model executes related user-define code and returns control to the simulation kernel.

Consequently, the functionality provided by a layer in a network is easily modeled by a module with a process model that follows the sequence of packet operations in that layer.

a) The Protocols Process Models

The process model of 802.11 was modified to build up this process. This process model of 802.11 was modified to build up this process. The Process Model has nine states as shown in Figure 5-7. During simulation, it performs transitions between these states and executes appropriate functions. In **INIT** state, WLAN process registration is completed; all state variables and MAC auto-addressing are initialized. In **BSS_INIT** state, MAC auto-addressing is completed, network configuration is validated and for PCF enabled networks, a list of CF-pollable stations is formed. In **IDLE** state, transmission buffer is emptied and wait for appropriate interrupts.

In **DEFER** state, receiver status and network allocation vector (NAV) is checked, if busy, wait until it gets idle and if idle, wait for inter-frame spacing (SIFS, PIFS, DIFS, or EIFS) before advancing to the next state. In **BKOFF_NEEDED** state, decide whether back-off is needed, if needed, check whether starting a new back-off or resuming and compute total back-off duration. In **BACKOFF** state, wait for the completion of back-off period and if the back-off is suspended, compute the remaining back-off duration. In **TRANSMIT** state, transmit Data/Control/Dummy packets and detect collisions if any packet is received during transmission. In **FRM_END** state, detect collisions if any packet is received during transmission. In **WAIT_FOR_RESPONSE** state, wait for the response message until the expected ACK or any type of message is received, or ACK-waiting timer expires. All these nine states define the behavior of the selected MAC protocols.

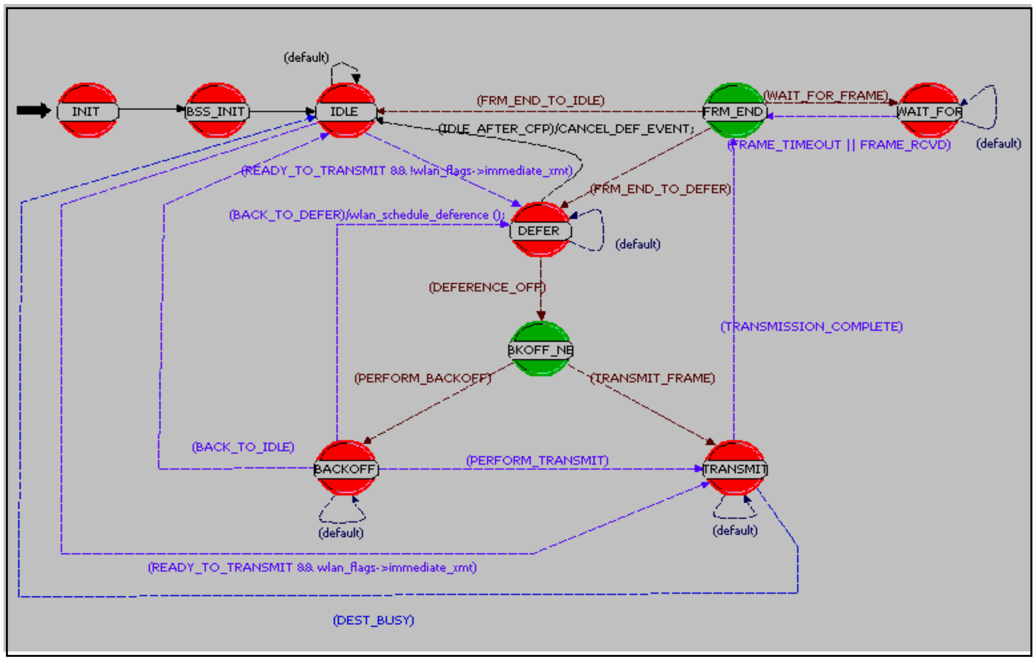


Figure 5-7: Process Model of AN-MAC and MMAC Protocol

b) WLAN-MAC Interface Process Model

The process model of WLAN-MAC interface is shown in Figure 5-8. This process accepts packets from any number of sources and discards them regardless of their content or format. It consists of six states, init, init2, wait, idle, appl layer arrival and mac layer arrival. The wait state checks if this is a valid address from the pool of addresses available.

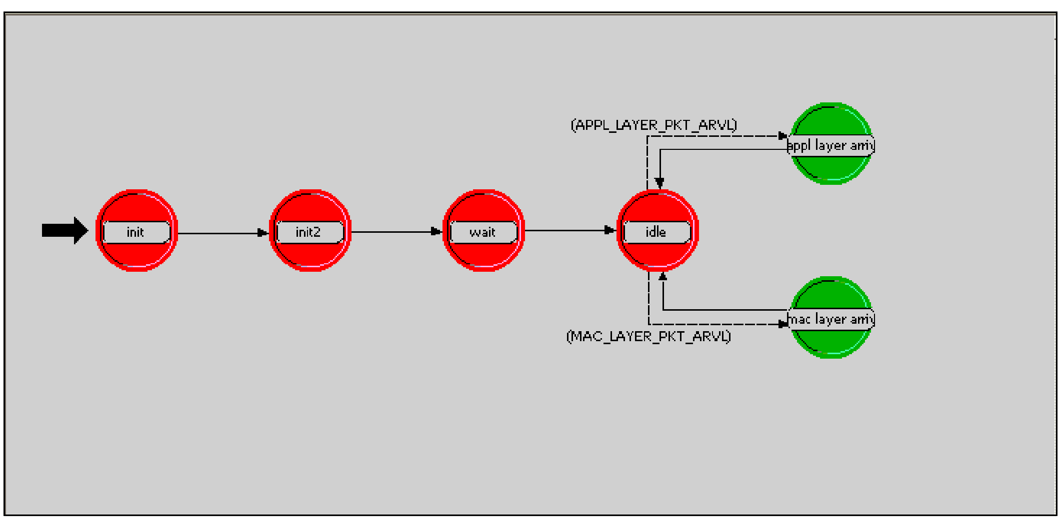


Figure 5-8: The process model of WLAN-MAC interface

c) Receiver-sink Process Model

Figure 5-9 shows the process model of the receiver sink model. It consists of two states;

init state: initialization of state variables when the process is first invoked

sink state: packets are destroy or discard

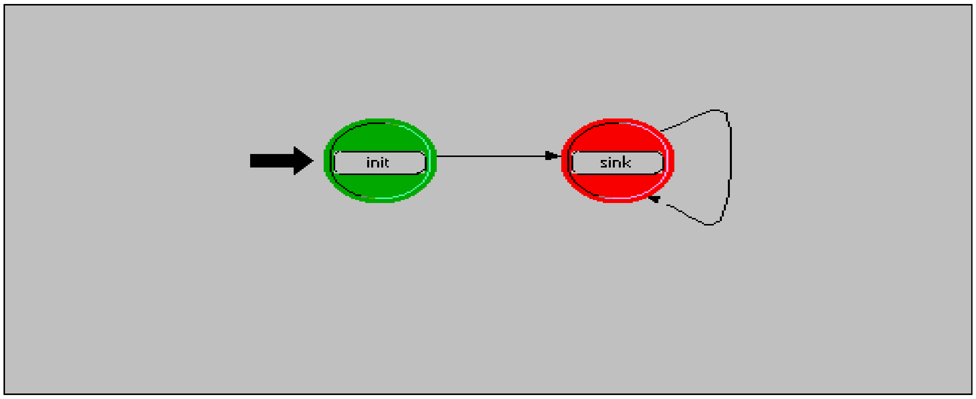


Figure 5-9: The Process Model of Receiver-sink model

d) Source Process Model

The FSM for this module consists of three states as shown in Figure 5-10:

init: is the initialization state. This state reads the values of source attributes and schedules a self interrupt that will indicate the start time for packet generation.

START/ss_packet_generate( ): this triggers an interrupt for packet generation. Two different types of packet formats are generated, these are; the control packets that are generated once every 10 seconds and the information packets that are generated with a mean interarrival rate of 1 second. The packets are sent through different output streams into the subsequent stages.

generate: at the enter execs of the generate state; the arrival of the next packet is scheduled. This is taken care of using the interarrival time specified by the user in the attributes section of the node model.

stop: when the control enters into this state, it is the time to stop generating traffic. The state cancels the generation of the next packet and goes into a silent mode by not scheduling anything.

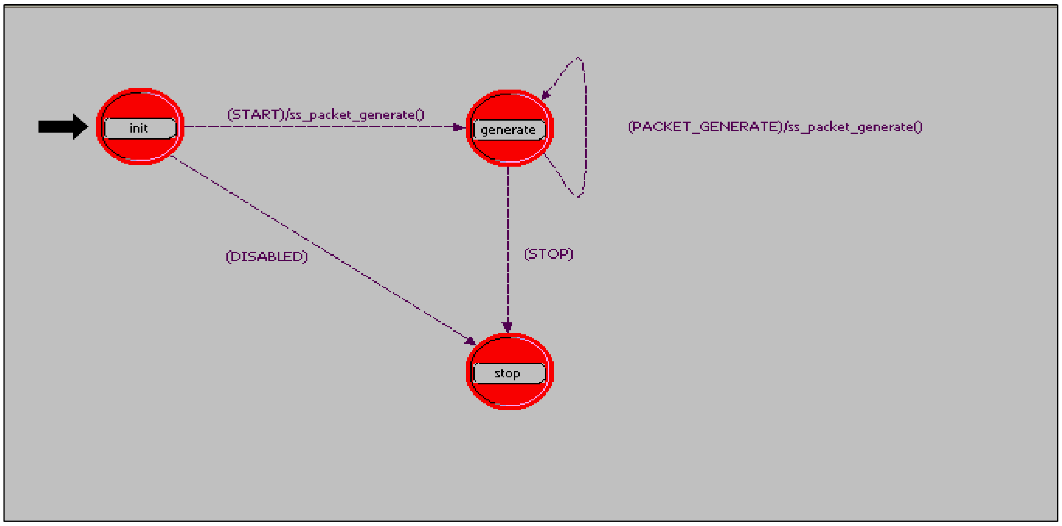


Figure 5-10: The Process Model of the Source-module for the proposed scheme.

e) Antenna-Pointer Process Model

Consist of two states as illustrated in Figure 5-11;

init: initialization of state variables when the process is first invoked.

start: allows antenna rotation and set target of antenna in direction of forward movement.

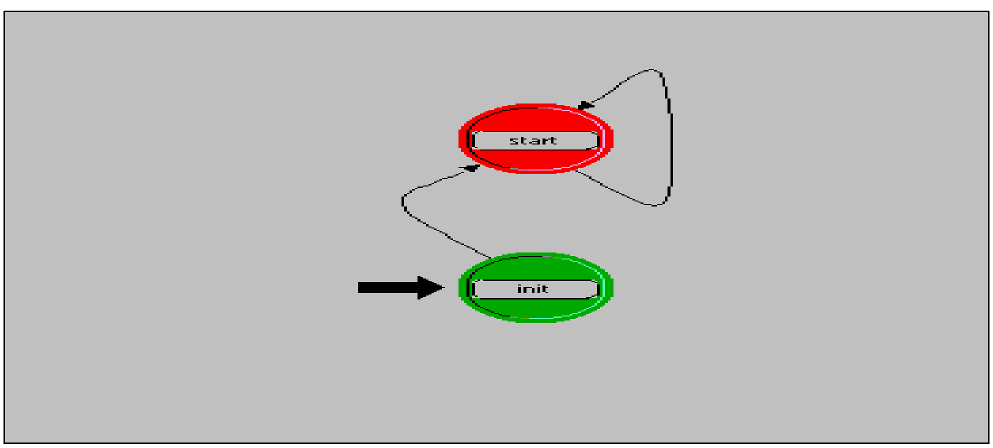


Figure 5-11: Process model of antenna-pointer

f) External System Process Model

The external system process model consists of two states as shown in Figure 5- 12, the init and wait_pkt states.

init: initialization of state variables when the process is first invoked.

Wait_pk: wait for packet arrival. The packet can be either ESYS_ARRIVAL or STRM_ARRIVAL.

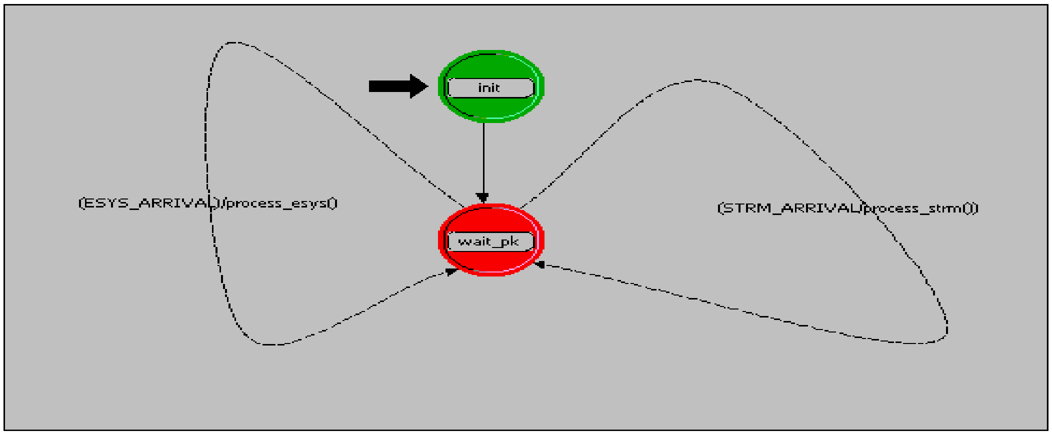


Figure 5-12: The process model of the external_sys interface

g) The Mobility Process Model

Figure 5-13 shows the process model of the mobility model. It consists of three states; the **init** and **idle:** states are the same like in the previous process models.

position: Update the position of the node containing the current mobility process

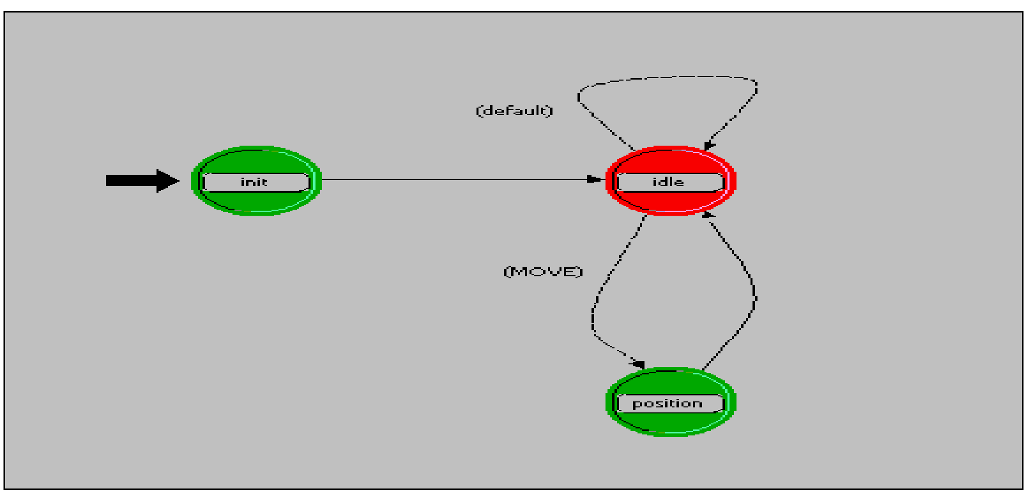


Figure 5-13: The mobility process model

h) Receive and Transmit Antenna Process Models

OPNET uses dra-tagain and dra-ragain models to determine the value of transmit or receive gain attributes. For the proposed Adaptive beamforming, the transmit and receive pipelines are implemented using dra_tagain and dra_ragain respectively. In the Adaptive antenna model the value of the antenna gain in the direction of transmission is determine using the behavior of the antenna. The MATLAB simulation uses the antenna and channel parameters obtained from the OPNET simulation to determine the weights so as to form a beam towards the desired signal while forming nulls towards the interfering users. The weights obtained by the MATLAB simulation are passed back to the OPNET simulation and used to form the receive antenna pattern. The weights of the antenna elements, which are required for the calculation of the antenna gain, are obtained through the execution of Normalized Least Mean Square (NLMS) Antenna Array algorithm that is implemented in MATLAB.

5.2.2 Physical Layer Description

At the physical layer, the Normalized Least Mean Square (NLMS), Smart Antenna algorithm was implemented for each of the receiver and transmitter using MATLAB, an exponential path loss is assumed, and AWGN is generated to simulate the noise introduced in each receiver chain. The following gives a detailed description of the underlying operations being modeled in the physical layer simulation.

Modulation

Each node in a modeled system uses BPSK Modulation generated on a symbol by symbol basis implementation at baseband using a complex envelope representation where a symbol is given by

$$b(t) = \sqrt{P_i}\, b_k e^{j\Phi_k}\, p(t) \tag{5.1}$$

Where b_k is the original baseband symbol, k, Φk is the phase of symbol k, and P_i is the transmit power of a node, *p(t)* is the square pulse of T seconds duration.

Channel

Additive White Gaussian Noise is introduced at the receiver. The path loss between the effective transmitted power and received power is given as

$$PL = \frac{\lambda^2}{(4\pi)^2 d^2} \tag{5.2}$$

where

λ is the wavelength

d is the distance between transmitter and receiver

Normally the gain of an antenna is described as a function of the horizontal angle θ and the vertical angle Φ from a fixed line reference. The gain of an antenna can be defined as

$$G(\theta,\varphi) = \eta \frac{U(\theta,\varphi)}{U_{ave}} \tag{5.3}$$

Where $U(\theta, \varphi)$ is the power density in direction (θ, φ), U_{ave} is the average power density over all directions and η is the efficiency of the antenna.

The wireless communication channel in OPNET is modeled by 13 pipeline stages including antenna gains, propagation delay, signal-to-noise ratio, calculation of background noise, transmission delay, etc. For our proposed scheme we modified only the transmitter and receiver pipelines, while the rest we take the default values. The closure model was set to *dra_closure_all* to ensure link closure irrespective of earth curvature.

5.3 Integration of OPNET and MATLAB

The interface between OPNET and MATLAB is implemented using MATLAB engine routines. As part of the initialization routine of the Adaptive Antenna Array pipeline, the MATLAB engine is initialized and stored in an Engine variable. This variable is then passed on to the MATLAB antenna array pipeline function. This allows OPNET to maintain multiple simultaneous MATLAB engines which may be useful when separate variable namespaces are required. We made use of the MX interface provided by MATLAB, which allows C programs to call functions developed in MATLAB. For calling MATLAB functions the following files were included in the *bind_shobj_flags* environment attribute.

- libmat.lib
- libeng.lib
- libmex.lib
- libmx.lib

5.3.1 Operations Performed in OPNET

- Identifying if the arriving packets are control or information packets
- Updating the positions of all relevant nodes (since nodes are mobile)
- Initialing MATLAB engine
- Storing antenna weights between calls to MATLAB
- Assigning the gain to the packet

5.3.2 Operations Performed in MATLAB

- Calculating AOA for each transmitting node.
- Calculating phase difference between each antenna element in the receiving node
- Generating transmitted signal at each antenna for each transmitted signal
- Performing channel operations
- Updating antenna weights using NLMS Adaptive Antenna Array algorithm
- Determining the gain in the direction of the transmitting node

Figure 5-14 shows the process flow for the ragain pipeline stage for the MATLAB implementation. We have used C functions, OPNET Kernel Procedures (KPs) and MATLAB function. Kernel Procedures are procedures that can be called from within process models, transceiver pipeline stages, C/C++ functions that have been scheduled as interrupts or simply C/C++ functions that are directly or indirectly involved from one of these contexts. We use C only to initialize parameters, to start MATLAB Engine, and to serve as an interface between OPNET and MATLAB.

The use of C routine to interface with MATLAB encapsulates the details of calling and using the MATLAB routines. It can be seen that, during the processing, AOA, Path Loss and the weights for the mobile nodes are calculated with respect to the currently receiving node.

As shown in Figure 5-14 the process begins with the function-in (FIN). Then the MATLAB engine is first call by OPNET using the function engOpen(). MATLAB is call when the physical layer parameters simulated need to be calculated or updated; else OPNET KP is call directly. After the first call the transmitter power is determined and the antenna elements positions (DOD) and weights are initialized. This is followed by the initialization of MATLAB engine.

The receiver id and the transmitter id are determined using OPNET kernel procedures. This is followed by the update of the mobile node positions using the mobility process model designed in OPNET or KPs. After finding all these parameters MATLAB interface is call using C function. The DOA of the signals is determined in MATLAB using ESPRIT algorithm. These parameters are as well computed in MATLAB;

1. Path loss
2. Phase difference
3. Node antenna elements signals

The NLMS algorithm is executed after determining the above parameters. Then the antenna gain is computed. Subsequent to these, the RA-RX-GAIN is assigned to the packet using OPNET KPs. Lastly the FOUT ends the process.

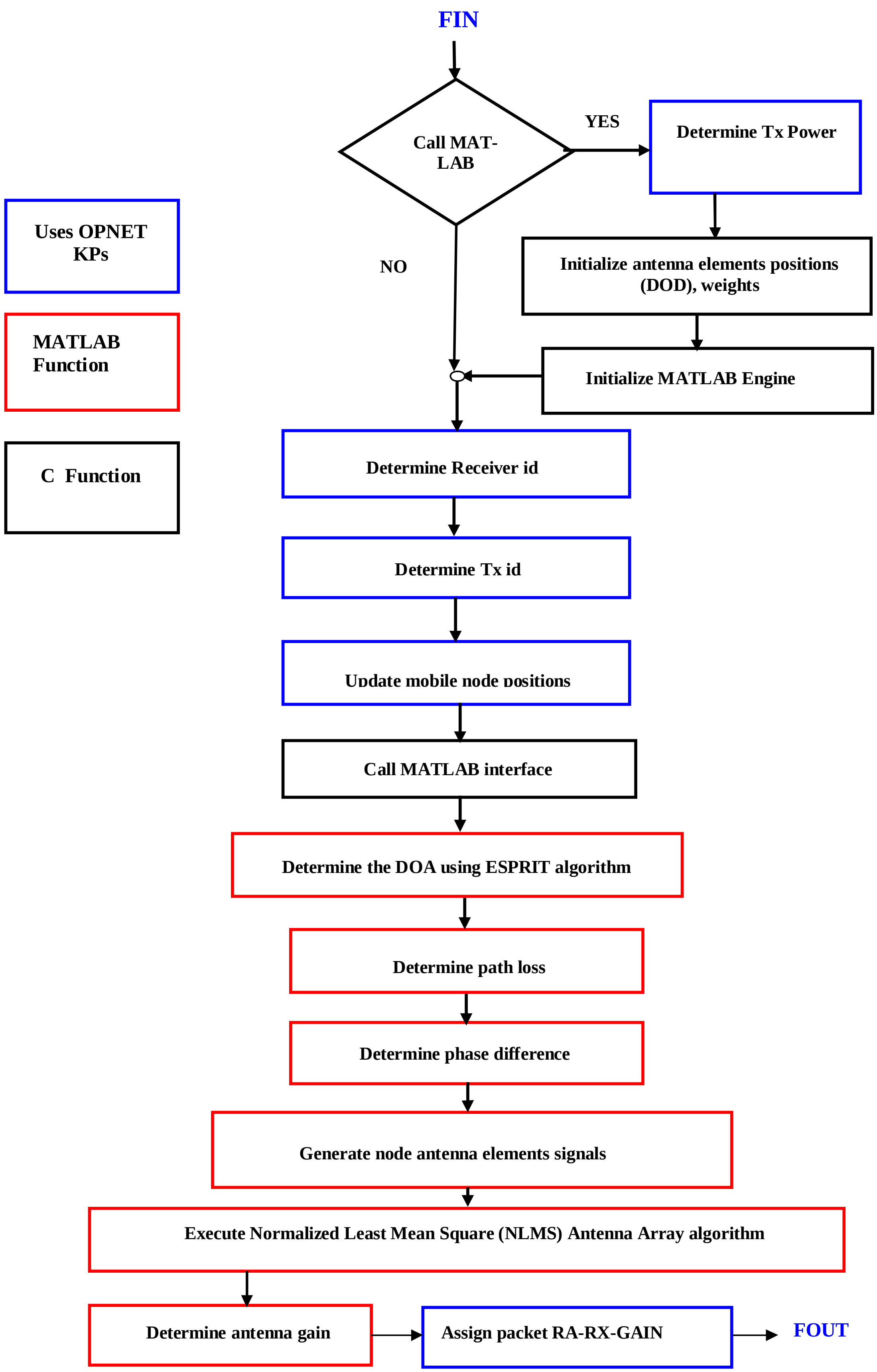


Figure 5-14: Modified Process Flow for Ragain for Physical Layer Simulation Using MATLAB

5.3 Baseline Simulation Model Description

For the baseline simulation, modifications were made on the standard OPNET pipeline stages. There is no interface as all operations are performed using OPNET KPs (Kernel Procedures). An Enhanced Antenna Positioning System was used to model the antenna system. The Transmitter Antenna Gain and the Receiver Antenna Gain pipeline stages were modified. The role of the pipeline stage is to compute the antenna gain, SNR, BER, for each transmission given some position and orientation information about the transmitter and receiver. This information is used to determine a point on an antenna pattern model which is in the direction of the transmitter or receiver. The antenna pattern model is a lookup table for gain in dB given any angle Phi (ϕ) and Theta (θ). Phi and theta are angular measurements determined from the position and orientation of the transmitter and receiver as well as the position and orientation of the antenna mounted to either or both objects.

To make use of this antenna model enhancement, the pointing direction of the antenna must coincide with the positive z-axis of the antenna gain pattern used. New attributes like Antenna_Positioning, Antenna_Positioning_Parameters and Antenna _Positioning_Values were added in the antenna model attribute as shown in Table 5-1. The Enhanced Antenna Positioning System when enabled works in two modes: Fixed to Object and Locked to Target. When not enabled, the antenna positioning parameters and values are all ignored resulting in the original standard antenna parameters and default pipeline stages being used. The Fixed to Object mode is intended for describing the movement of an antenna mounted to the mobile node and moves with the node. The Locked to Target mode is intended for describing an antenna which repositions itself so as to always points at a specific target. Both modes allow the use of a rotation angle parameter which causes rotation of the antenna about its pointing axis.

When the mode is Fixed to Object more information is needed to describe the trajectory than what exists in the current models.

Table 5-1: Antenna Positioning Parameters

Attribute	Value
name	ant_rx
pattern	promoted
pointing ref. phi	0.0
pointing ref. theta	180
target latitude	10
target longitude	20
target altitude	30
icon name	antenna
Antenna_Positioing	Detailed Antenna
Antenna_Positioning_Parameters	(...)
Mode	Fixed to Object
Fixed to Object	(...)
Mount Angle Phi (Degrees)	0.0
Mount Angle Theta (Degrees)	0.0
Antenna Rotation (Degrees)	0.0
Locked to Target	(...)
Target Latitude (Degrees)	0.0
Target Longitude (Degrees)	0.0
Target Altitude (Meters)	0.0
Antenna Rotation (Degrees)	0.0
Antenna_Positioning_Values	(...)
rows	0

Table 5-2 depicts the Antenna Positioning Values used, where we have time in seconds, the Pointing Directional Bearing (degrees), the Pointing Vertical Angle (degrees) and the Rotation Angle (degrees). These three variables as a function of time describe the orientation of a node.

Table 5-2: Antenna Positioning Values

Time (Seconds)	Pointing Directional B...	Pointing Vertical Angl...	Rotation Angle (Degrees
0.0	NW	30	60
200	NE	0.0	0.0
250	120	0.0	-30
3,200	90	0.0	0.0
3,500	NE	20	0.0
4,000	NW	0.0	-45

The system consists of three types of nodes, Figure 5-17: transmitters, receivers, and jammers. Each of these nodes is a mobile. The following gives a description of each of these nodes.

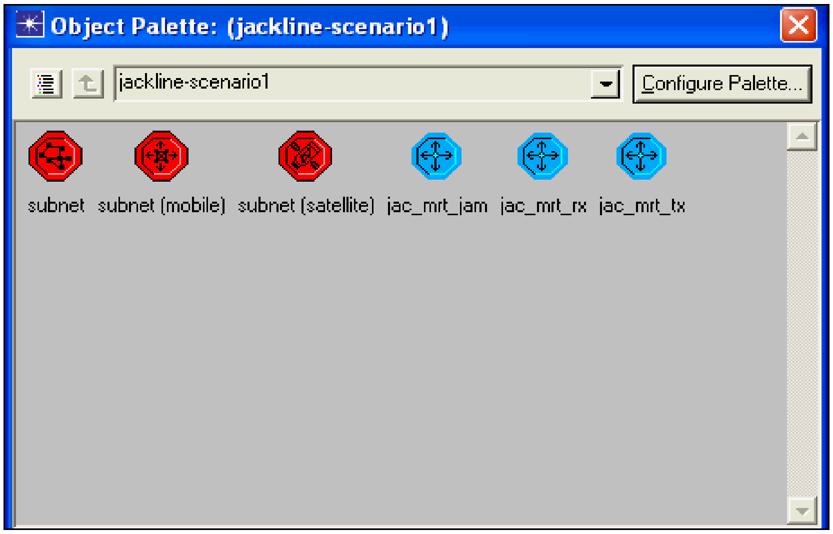


Figure 5-15: The baseline System Palette

5.4.1 Transmitter

The transmitter node model, as shown in Figure 5-18, consists of a simple source module that generates packets and is generally treated as a desired node, transmitter and an antenna. The probability distribution functions of the packet size and packet inter-arrival time used within the simple source may be set as desired from those available within OPNET, and are set as constant in this case. The second module is the antenna_target_tracker module, which is use to track the antenna location or positions of the antenna. After generation, packets move through a packet stream to the radio transmitter module that transmits the packets on a radio channel. The transmitter node's power attribute is promoted so it can be set at run time by the user.

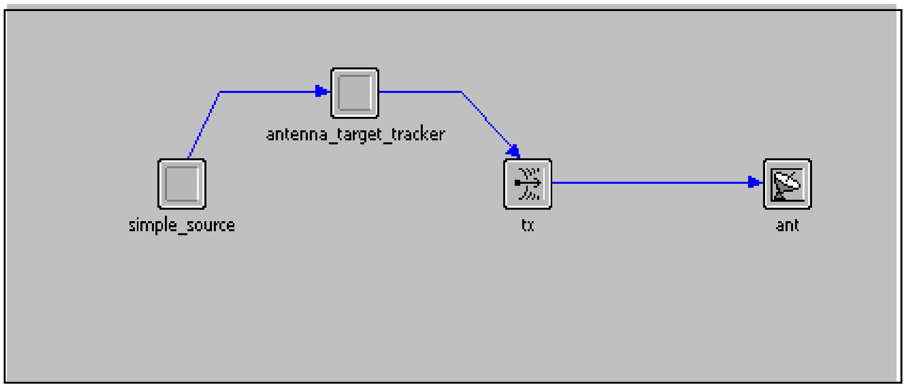


Figure 5-16: Transmitter Node Model

5.4.2 Jammer

The network jammer node, whose node model is shown in Figure 5-19, introduces interference into the network. Like the transmitter node, it consists of a simple source packet generator module and a radio transmitter module. Its behavior is similar to the transmitter node, but its signal modulation is set to jammod. The jammer node's power attribute is also promoted so it can be set at run time by the user.

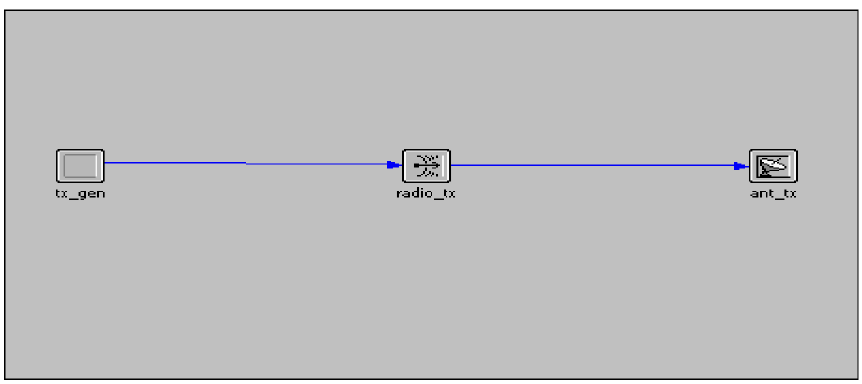


Figure 5-17: Jammer Node Model

5.4.3 Receiver

The receiver node, as shown in Figure 5-20, consists of an antenna module, radio receiver module, and a sink processor module. The radio receiver (rx) contains the ragain pipeline which is changed in order to run the scenario as specified for the system. The function of the sink module is the same as explained in the PHY-MAC layer implementation.

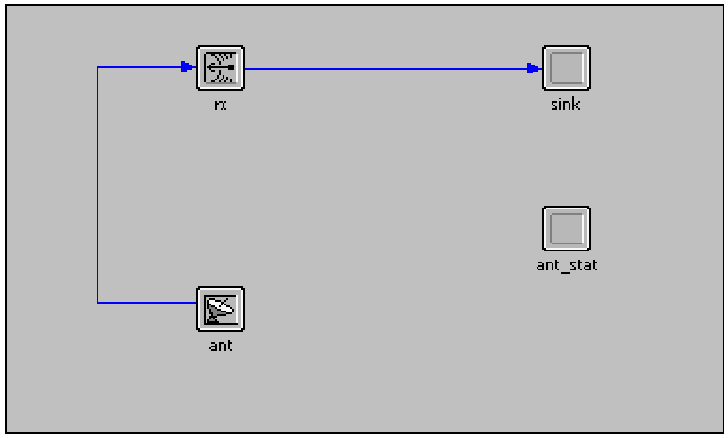


Figure 5-18: Receiver Node Model

5.5 An Adaptive MAC scheme with Spatial Diversity, based on the RTS/CTS mechanism for ANMAC and MMAC Protocols

Multihop-MAC Protocol and AN-MAC Protocol were designed using Switched-beam Antennas. In AN-MAC Protocol no sidelobes and nulling capability, as such AN-MAC is not applicable in mobile environment [1]. In MMAC no nulling capability and as such it was only applied in a non-mobile environment. Both protocols assumed that when a node is in an idle state it listens Omni-directionally. Since different antenna patterns lead to different antenna gains, the asymmetry in directional transmission/reception and Omni-directional listening may result in the hidden terminal problem. For example in MMAC; assume that node A (see Figure 5-21) transmits a directional RTS packet to node B, while node C is idle. Upon receiving RTS packet, node B sends directional CTS to node A. Then, node A and B are engaged in DATA transmission, both using directional antennas with gain Gm. Note the coverage range is determined by both transmit and receive antenna gain. Let $G0$ denote the gain of omnidirectional antennas. The total antenna gain taking into accounts both directional transmission and omnidirectional listening is $G0Gm$, smaller than $G2\ m$ when directional antennas are used for both transmission and reception. Therefore, node C using omnidirectional listening may not detect the directional CTS packet from node B. But, when the DATA packet from node A to node B is in progress, it is likely that the directional/Angular RTS from node C (with the directional beam toward node B) can cause a collision, leading to a hidden terminal problem [42].

To make these two protocols applicable in mobile environment, we propose that when a node is idle it listens directionally as in [42]. This is to avoid hidden terminal problems. We have also proposed to use multi channel for communication. The idea is to isolate control packets from data in the wireless medium and exploit spatial reuse of the data. The total bandwidth *W* is divided into *N+1* channel, one control channel and the rest data channels.

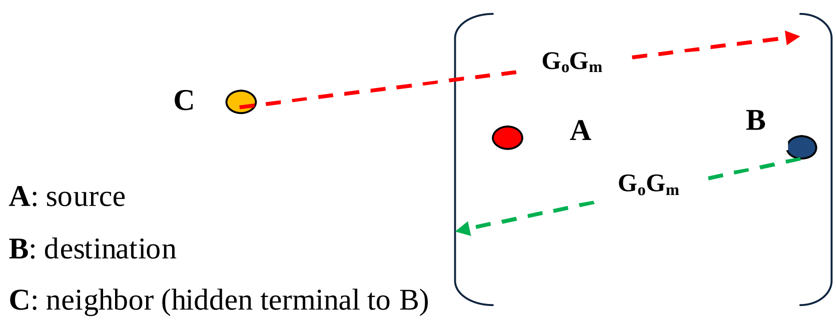


Figure 5-19: A hidden terminal problem due to asymmetry in antenna gain [42]

When a node has a data to send, it goes through two phases: the control phase and the data phase. In the control phase, which involves the control channel, the node exchanges control frames like RTS/AN-RTS, CTS/AN-CTS with the receiver and other neighboring nodes to negotiate the data channel to be used, and to indicate the channel reservation. All nodes used the control channel for listening when they are not sending or receiving frames. In the data channel data is exchange between the sender and the receiver.

Our model is similar to [42] but the only difference is they have used single channel while for our case we have used multi-channel. One common problem with single channel protocols is that the network performance will degrade quickly as the number of mobile hosts increases, due to higher contention collision [43]. To relieve the contention/contention problem multiple channels must be utilized. Therefore, roughly each node can be viewed as listening with Adaptive Antenna array beams pointing to multiple transmissions. Since listening, transmission, and reception are all directional and with the same antenna gain pattern, with a general Adaptive Antenna model with sidelobes and nulling capability, the hidden terminal problem and deafness problem can be resolved for these two protocols when applying them in mobile environment.

Suppose that each node obtains network connectivity by broadcasting its HELLO packets. Upon receiving such packets, the neighboring nodes can estimate and update the DOA of the broadcasting node. Thus, in the Adaptive MAC design, we assume that the DOA of the destination node is known to the source node. The ANMAC and MMAC MAC protocols were developed for Mobile ad hoc networks with directional listening, directional transmission, and directional reception using Multi-channel. For exploiting the benefits of directional antennas, two tables are used, namely the antenna pattern lookup table and the directional NAV (D-NAV) table. In the antenna pattern lookup table, the antenna gain is listed with respect to the azimuth direction. The D-NAV table consists of the RTS/CTS mode, node index, DOA, the signal power corresponding to each DOA, and NAV derived from the received RTS/CTS packet. The proposed Adaptive MAC scheme of the two selected protocols using Adaptive Antennas can be outlined as follows.

- *RTS transmission:* The source node, denoted *Sk*, receives a packet from the upper layer, and obtains the direction of the (next hop) destination node in its connectivity table. Then, the source node *Sk* performs virtual carrier sensing by using both its D-NAV table and antenna pattern table. Simply put, *Sk* calculates the effective interference power for the nodes in the D-NAV. Then *Sk* send the RTS frame containing its own free channel list.
- *RTS/CTS listening:* All idle nodes in the neighborhood overhear the RTS/CTS packets directionally by using Adaptive Antenna Array techniques, and then update their D-NAV tables. They remove the indicated free channel from their free channel list. The nodes employ virtual carrier sensing to refrain from sending on the indicated data channel.
- *RTS reception and CTS transmission:* The destination node *Dk* overhears the RTS packet using directional/angular reception beamforming. Upon receiving the RTS packet correctly, *Dk* conducts virtual carrier sensing as done for the *RTS transmission*. *Dk* also checks its own local free channel with the free channels listed in the RTS frame. If there is at least one channel which is the

same like its own then *Dk* forms a directional beam and performs physical carrier sensing. If the channel is idle for a duration SIFS, the node transmits the directional CTS packet to *Sk*. If there is no free channel, the CTS transmission is cancelled.

- *CTS reception and DATA transmission:* After the RTS transmission, *Sk* forms a directional receive antenna pattern and waits for the CTS packet. If *Sk* receives the CTS packet, it performs virtual carrier sensing and physical carrier sensing sequentially. If the channel is idle for duration of SIFS, the DATA packet is then transmitted directionally. If the CTS packet does not arrive within a predetermined time-out window, *Sk* will resend the RTS packet.
- *DATA reception and ACK transmission:* After sending out the CTS packet, *Dk* moves to the DATA reception phase. When the DATA packet is received, *Dk* confirms the reception by sending a ACK packet to *Sk* directionally.

5. 6 Summary

This chapter discussed an overview of the methodology used in the development of the overall proposed system, which includes the network system, the node model and the process model developed in OPNET. 802.11 systems were modified to present four-element Adaptive Antenna Arrays and the physical channel models in OPNET. The physical layer is included with a minimum amount of change in the normal OPNET processing through the modification of a single pipeline stage that is ragain. A co-simulation interface model of OPNET and MATLAB were developed to solve optimization problem in packet scheduling problem, and Optimization Toolbox provided by MATLAB have been used. For interfacing, mx interface provided by MATLAB was used. This is very useful if one needs to use MATLAB algorithms when simulating complex communications systems with discrete event simulator.

An Adaptive MAC scheme with Spatial Diversity, based on the RTS/CTS mechanism for AN-MAC and MMAC Protocols is proposed.

Lastly Baseline simulation model was implemented and explained in details for gain calculation in presence of interference (jam). An enhanced model for Antenna Positioning System was modeled for the baseline simulation.

CHAPTER 6

ANALYSIS AND DISCUSSIONS

6.1 Introduction

This chapter describes the specific network environment built, parameters used in the simulation and presents the results of the simulations performed using the two different methodologies. The first section describes the Physical-MAC layer simulations, parameters used and the results obtained. This is followed by discussions on the comparison between the performances of the protocols. The next section describes the Baseline simulations, parameters used and the results obtained. Comparison between the performances is also presented.

6.2 Physical-MAC layer Simulations

6.2.1 Scenario Description

The network model consists of four mobile nodes and four fixed nodes, as shown in Figure 6-1, where we illustrated the simulation scenario in which the mobile nodes are using the developed antenna model in an area of 300x300 meters. The fixed nodes are the

- **Application_config:** The "Application Config" node can be used for the following specifications:

  1. "ACE Tier Information":

     Specifies the different tier names used in the network model. This attribute will be automatically populated when the model is created. The tier name and the corresponding ports at which the tier listens to incoming traffic is cross-referenced by different nodes in the network.

  2. "Application Specification":

     Specifies applications using available application types. You can specify a name and the corresponding description in the process of creating new applications.

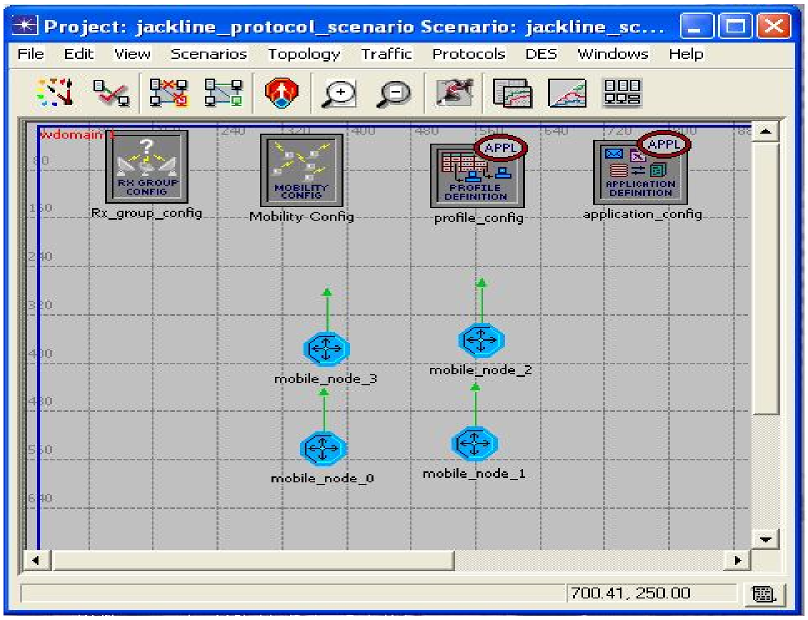


Figure 6-1: Network Scenario for the Physical layer implementations

For example, "Web Browsing (Heavy HTTP), email browsing etc.

- **Profile_config:** This node can be used to create user profiles. These user profiles can then be specified on different nodes in the network to generate application layer traffic.
- **Mobility_config:** This node is used to define mobility profiles that individual nodes reference to model mobility. It controls the movement of nodes based on the configured parameters.
- **rx_group_config:** This is used to compute the set of possible receivers that nodes can communicate with. It is computed based on the following three criteria:

  1) Channel Match

  2) Distance Threshold

  3) Path loss Threshold

  All possible receivers that have a channel match with the transmitter channel(s), and fall within the distance and path loss thresholds, are receivers that a node can communicate with.

The antenna attributes are configured according to the description mentioned in the previous chapter and the mobile nodes are enabled to plot their antenna patterns during simulation. Before starting the simulation, the animation viewer is started by executing *op_vuanim* in the OPNET console window. At the beginning of simulation, the MATLAB engine is started by OPNET and, subsequently, the antenna patterns are formed in accordance to antenna attributes and commands received from upper layers. Random Waypoint Mobility model is used, where by the nodes move randomly.

To enhance simulation flexibility, the transmitter and receiver nodes' power attribute is promoted so that it can be set at run-time by the user. The transmitter and the receiver modules use different frequency bands in order to provide different logical channels for exchange of control and data packets. Table 6-1 shows the transmitter/receiver attributes used.

Table 6-1: Transmitter/Receiver Attributes

Parameters	Type/value
Modulation	BPSK
Power	Promoted to be set by user at run time
Data rate	100 kbps
Bandwidth	100KHz
Min frequency (tx_tx)	1.8GHz
Min frequency (tx_rx)	2GHz

The existing IEEE 802.11 MAC was used as a benchmark to compare and evaluate the performance of the two MAC protocols. Our evaluation is based on two criteria: average throughput and average end-to-end delay.

Network throughput versus simulation time and delay versus simulation time was examined. Throughput versus traffic load was also examined. The following Protocols were simulated in three different scenarios,

- IEEE 802.11
- ANMAC-SW when using Switched-beam Antenna
- ANMAC-AA when using Adaptive Antenna Array

For IEEE 802.11, the stations use Omni-directional antennas and initiated communication one by one. The 4 nodes in the network choose their destination randomly.

6.2.2 Results Captured

This section lists the results obtained for the PHY-MAC layer simulation method done as the first part of this simulation. Specifically, throughput in bits/sec presuming packet rejection when any errors occur in the packet and delay were measured in the above mentioned scenario. The first part presents the results obtained when using 802.11, ANMAC-SW and ANMAC-AA. The second part presents results obtained when using ANMAC-AA and MMAC.

Figure 6-2 shows the throughput and delay results captured for AMNAC Protocol. The average throughput and the delay are plotted against the simulation time. It can be seen that initially the throughput was 0 due to the delay but as the delay started to dropped the throughput reaches its maximum. This is due to the initialization process.

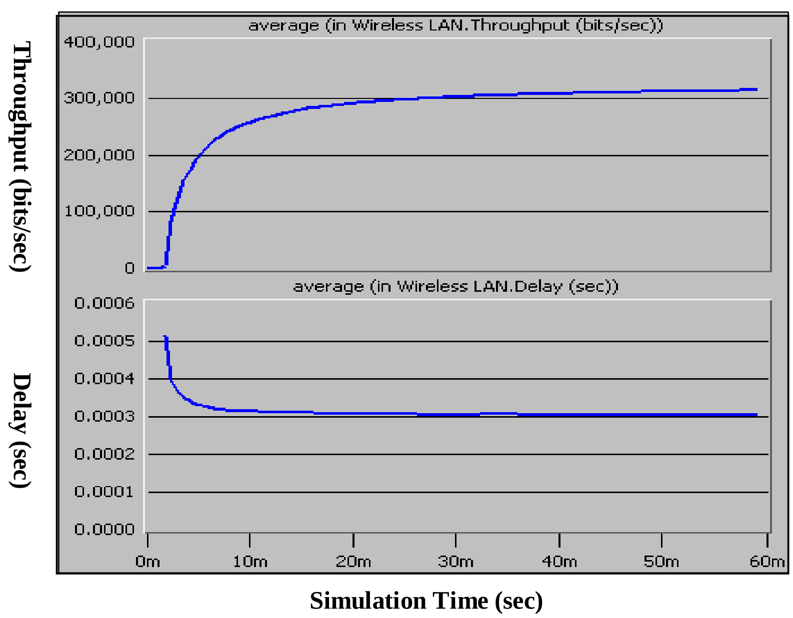


Figure 6-2: Throughput and Delay Performances of ANMAC Protocol

Figure 6-3 shows the throughput and delay results captured for MMAC Protocol. The average throughput and the delay are plotted against the simulation time. It can be seen that initially the throughput was 0; this is due to the initialization process. After 10 minutes the throughput reaches its maximum.

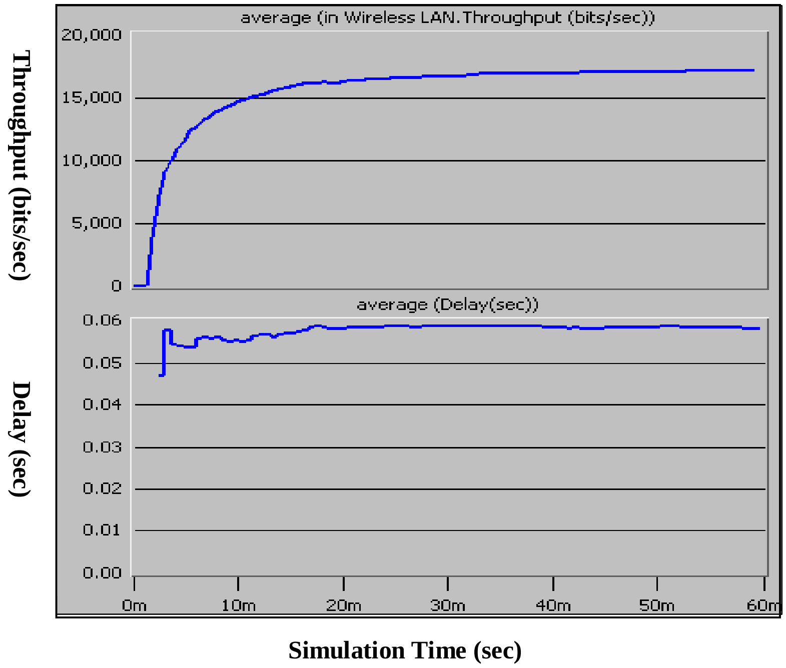


Figure 6-3: Throughput and Delay Performances of MMAC Protocol

Figure 6-4 shows the throughput performance of the three protocols versus time. A comparison study has been made. The throughput is computed as the total number of bits delivered successfully at destination. The first curve shows the performance of ANMAC-AA when using Adaptive Antenna Array, the second shows the performance of ANMAC-SW and the last one shows the performance of IEEE 802.11. It can be seen that IEEE 802.11 performs worse as compare to the other two. This is because IEEE 802.11 was implemented using Omni-directional antennas, which have gain in all directions. Since the nodes are mobile and the antennas are Omni-direction, these cause more interference resulting into no packets received for the entire simulation time.

It has been observed that using Adaptive Antenna Arrays makes some difference in the throughput as compared to Switched-beam Antennas. This is because Adaptive Antennas can avoid interference by forming nulls towards them and placing the main beam towards the desired user. It can also be seen that ANMAC-AA outperforms ANMAC-SW by 2%.

With an increasing data rate, average throughput increases sharply in ANMAC as shown in Figure, once RTS/CTS handshaking is done, a node transmits and receives data and acknowledgment directionally with high gain. So, the possibility of missing the data at the receiver end or the acknowledgment at the transmitter end is reduced. But, in 802.11, the chance of missing data is even more than that of RTS/CTS. This is due to two reasons:

(1) Data is sent with the same gain as in RTS/CTS Omni-directionally and received Omni- Directionally.

(2) Data is a large packet compared to RTS/CTS and proper reception requires the SINR level to remain high for a longer period of time.

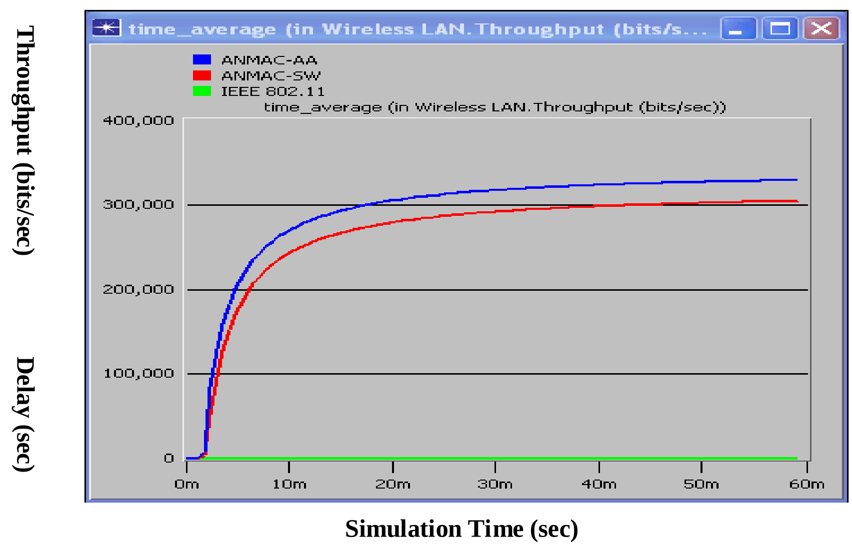


Figure 6-4: Throughput Performances of ANMAC-SW, ANMAC-AA and IEEE 802.11 vs. simulation time

Figure 6-5 depicts the delay performances versus simulation time of the three protocols. It can be seen that IEEE 802.11 causes more delay, followed by ANMAC-SW and ANMAC-AA performs the best. This is because 802.11 uses Omni-directional antenna, which is not suitable for MANET. In MANET there is no central system to control the behavior of the nodes.

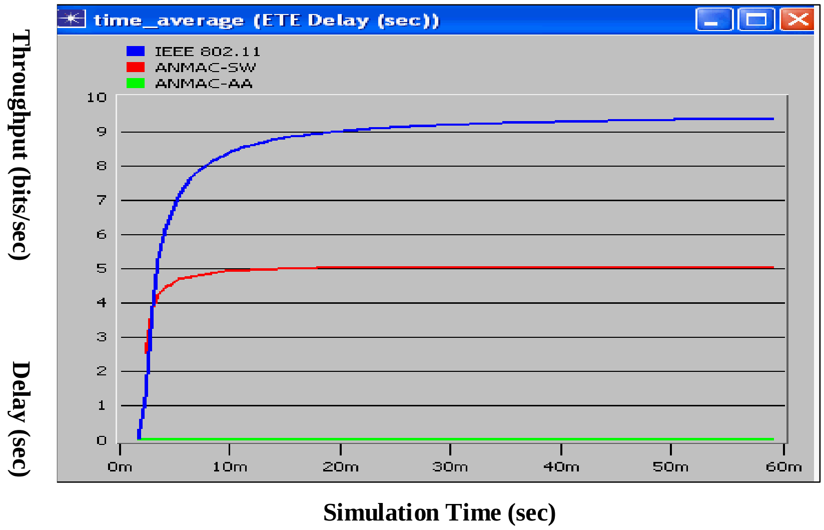


Figure 6-5: Delay performances versus simulation Time

Figure 6-6 depicts the throughput values measured for different traffic loads. The throughput is also computed as the total number of bits delivered per second. It can be seen that the performance of our proposed scheme is better than all the other schemes. At higher offered loads 802.11 exhibits the lowest throughput. This is due to the packets being dropped. It can also be seen that the performance of ANMAC-AA as compared to the performance of ANMAC-SW is better, this is because adaptive antenna arrays provides better coverage and increases system capacity even if there is heavy load. It can be concluded that ANMAC-SW outperforms the throughput of Omni 802.11 by 25 % and ANMAC-AA outperforms the throughput of 802.11 by 90%. It can also be observed that ANMAC-AA outperforms ANMAC-SW by 60%.

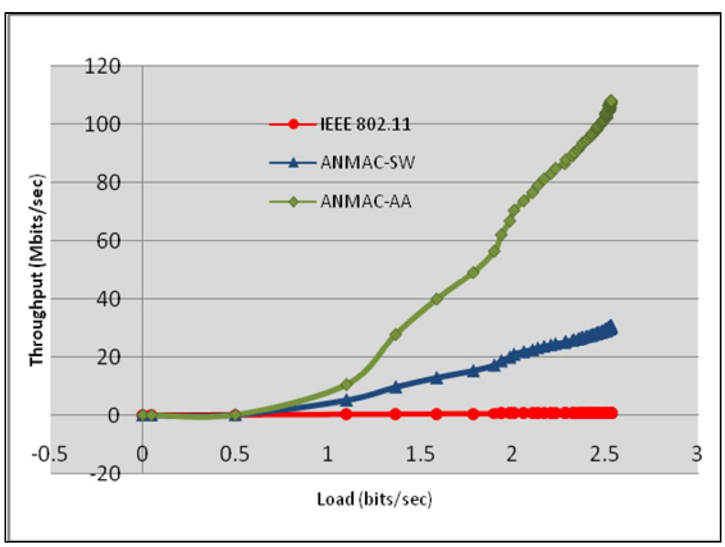


Figure 6-6: Throughput versus Traffic load

Secondly, three scenarios have been tested for three Protocols, AN-MAC, MMAC and 802.11 using the proposed scheme in the same area. There are 6 nodes inside the area, each moving in a Random Waypoint Mobility pattern. The number of nodes is chosen small enough for good connectivity as well as to make it easy to investigate the performance of the selected protocols. From the results of the simulation, it can be observed that ANMAC Protocol performs the best as compared to the other two as shown on Figure 6-7. Also comparisons of the delay performances have been done.

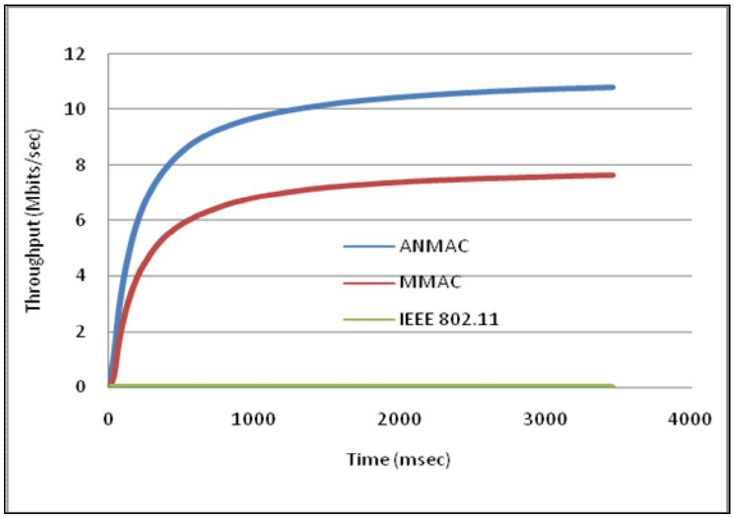


Figure 6-7: Throughput Performance vs. Simulation time

From figure 6-8 it can be seen that the delay performance of 802.11 is worse due the amount of packets dropped and the use of Omni-directional antenna.

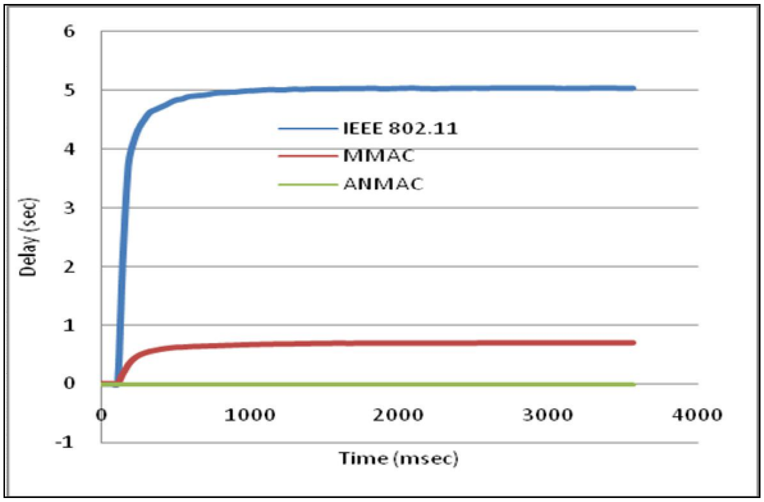


Figure 6-8: Delay Performances vs. Simulation Time

Thirdly, the scenarios have been tested in the same area but with 12 nodes. Figure 6-9 shows the results obtained. Even though the number of nodes has been increase still the two selected protocols perform well based the proposed scheme. It can be concluded that the proposed scheme improves the performances of both protocols but ANMAC outperforms MMAC by 30%.

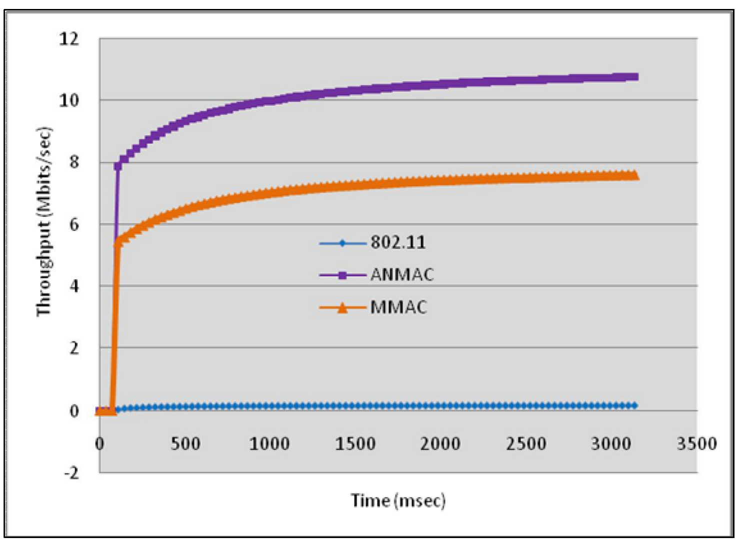


Figure 6-9: Throughput Performance vs. Simulation Time

From all the results above it can be concluded that in Omni-directional 802.11, nodes have to enter in a back-off state more often as they find the medium busy. With an increasing data rate, contention in MAC increases. But with the use of adaptive antennas, and the implementation of directional virtual carrier sensing, ANMAC and MMAC create an environment of lower contention that “802.11” cannot create with an Omni-directional antenna.

6.2.3 Theoretical Results Captured

This part shows the theoretical results captured. From Figure 6-10 and Figure 6-11 it can be observed that with the increasing number of load, average throughput increases in both, when using 4 and 8 antenna elements for both ANMAC and MMAC Protocol but the performance of when using 8 elements is greater as compared to the one when using 4 elements. This is because increasing the number of antenna elements produces a smaller 3dB beamwidth; therefore power concentration became more focus by having high array directivity. From these two figures it can be concluded that the simulation result agrees with the analysis.

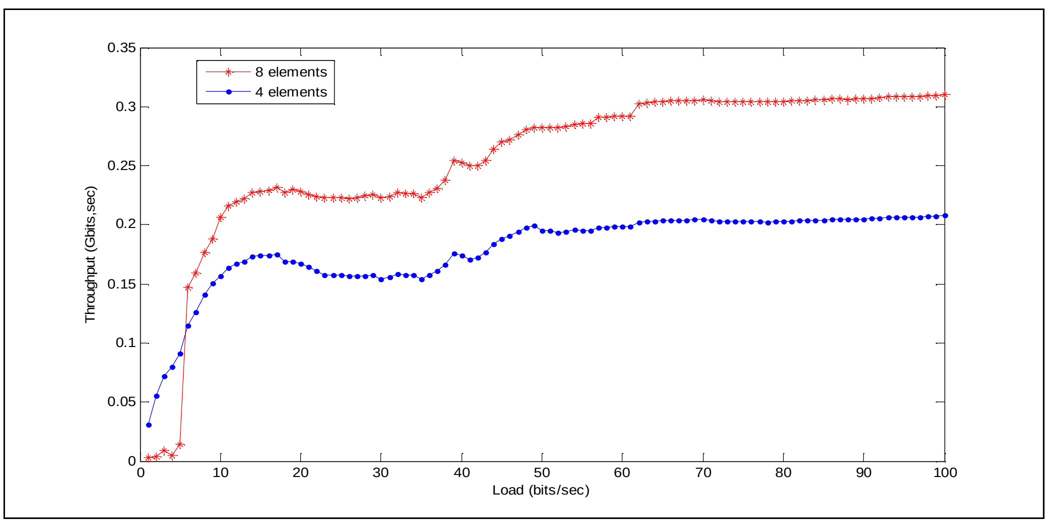


Figure 6-10: Theoretical results obtained when using 4 and 8 antenna elements for ANMAC Protocol

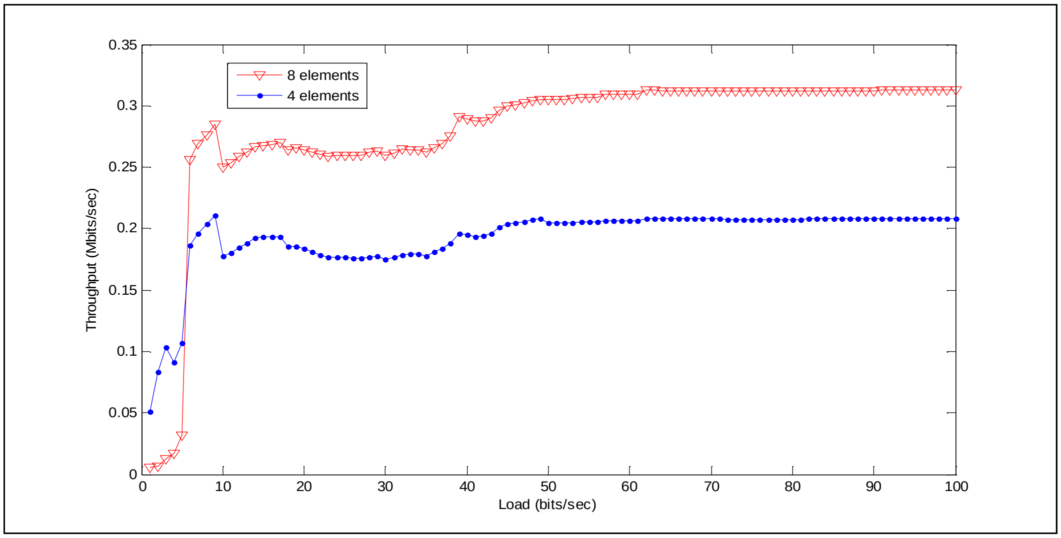


Figure 6-11: Theoretical results obtained when using 4 and 8 antenna elements for MMAC Protocol

6.3 Baseline Simulations

6.3.1 Scenario Description

The system consists of a fixed transmitter and a mobile receiver with a mobile jammer moving in a trajectory, as shown in Figure 6-12, all in an area of 300x300 meters. The receiver is model by using Random Waypoint Mobility. The purpose of the jammer node is to create radio noise. The jammer's trajectory takes it in and out of the radio range of the receiver node, increasing and decreasing interference at the receiver. To enhance simulation flexibility, the transmitter and receiver nodes' power attribute are promoted so that it can be set at run- time by the user.

The transmitter and the receiver modules use different frequency bands in order to provide different logical channels for exchange of control and data packets. The jammer follows changes to a new position every minute completing its path around the receiver. Simulation time is 500 seconds during which the jammer completes rounds around the receiver moving at a rate of approximately 3 m/s. Three scenarios were built. In the first scenario both the transmitter and receiver were modeled using Isotropic antenna. The tx and the rx nodes were implemented for the second scenario with the Isotropic antenna and Enhanced Antenna Positioning System respectively. For the third scenario both the transmitter and the receiver were implemented using

EAPS. In order to run the baseline simulation, the *jac_dra_ragain* pipeline stage is selected and the *pattern* parameter in the rx_ant antenna module is set to,

a. Isotropic_antenna

b. Full_cone_antenna

The closure model was set to *dra_closure_all* to ensure link closure irrespective of earth curvature.

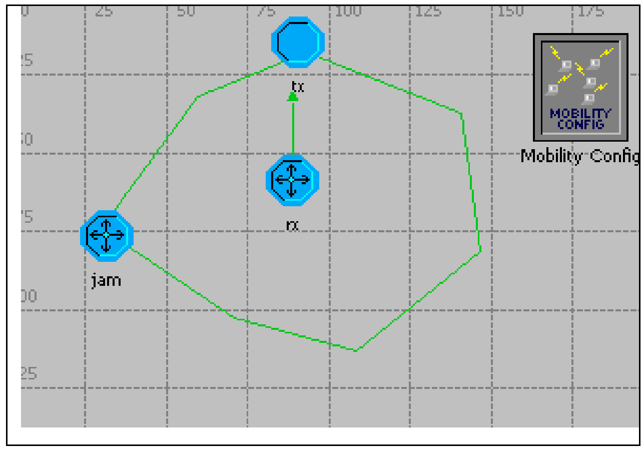


Figure 6-12: Baseline Simulation Scenario

Table 6-2 shows the parameters used for Baseline simulation. Note that the selection of the transmission rate is determined by a link adaptation scheme, *i.e.*, a process of selecting the best coding rate and modulation schemes based on channel conditions.

Table 6-2: Transmitter/Receiver Attributes

Parameters	Type/value
Physical Characteristics	Direct Sequence
Modulation	BPSK
Power	Promoted to be set by user at run time
Data rate	100 kbps
Bandwidth	100KHz
Min frequency (tx_tx)	1.8GHz
Min frequency (tx_rx)	2GHz

6.3.2 Results Captured

This section list the results obtained for the Baseline Simulation methods done. Specifically, Bit Error Rate (BER) and throughput in packets/sec presuming packet rejection when any error occurs in the packet were measured in the above mentioned scenarios. The received power was also measured. Note as the jammer and the transmitter actually generate packets asynchronously and independently, the BER and throughput are artificially improved due to transmit packets arriving when no jammer packet is present. This yields packets with no interference and thus exceedingly high SINR. To provide a more realistic interpretation of the operation of the Enhanced Antenna Positioning System, throughput is plotted on a packet-by-packet basis instead of a time-average basis as shown in figures below.

Figure 6-13 shows the Bit Error Rate and Throughput for Isotropic Antenna. The graph for the isotropic antenna pattern shows that the bit error rate at the receiver node gradually increases as the distance between the jammer and receiver nodes decreases. The bit error rate reaches a maximum of about 0.2 errors/bit when the distance between the jammer and the receiver is smallest. The isotropic receiver antenna receives jammer interference during the entire simulation as such the throughput was zero.

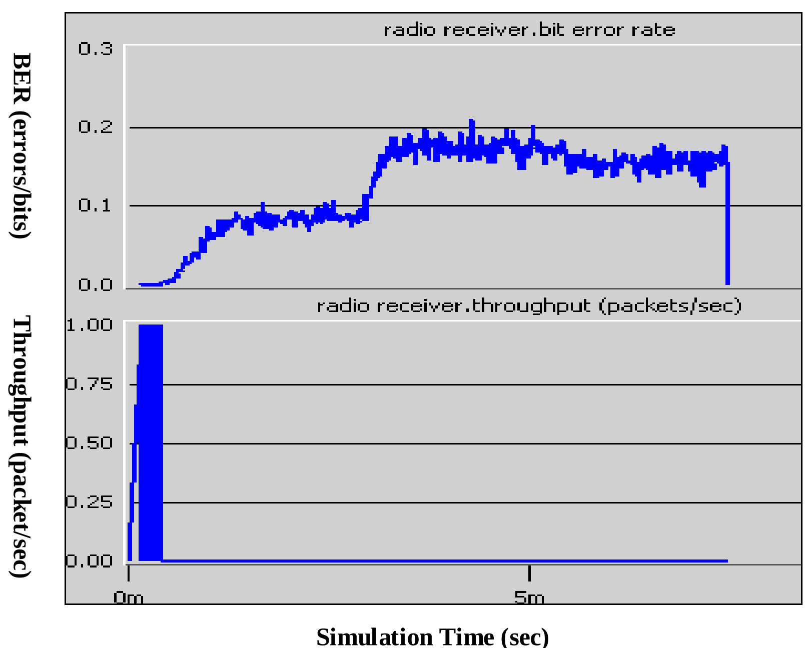


Figure 6-13: BER and Throughput of the Isotropic Antenna

Figure 6-14 shows the BER and throughput for the Receiver when using EAPS at the Receiver only. The bit error rate reveals that the bit error rate at the receiver node was zero initially as the distance between the jammer node and receiver node is large. However, after about 5 minutes, the direction vector between the jammer antenna and the receiver antenna was in line with the direction of greatest gain for the receiver antenna. Therefore, the receiver node started to receive interference from the jammer node and the bit error rate at the receiver approached 0.15 errors/bits. This increase radically decreased the number of packets received from the stationary transmitter node. It can also be seen that after the jammer passed the transmitter the BER dropped to 0. This drop drastically increased the receiver throughput.

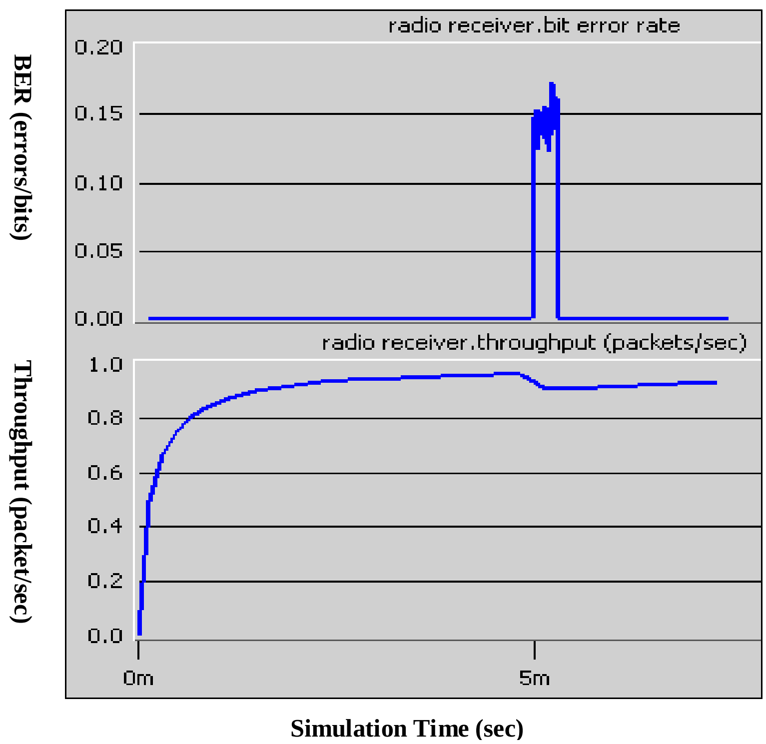
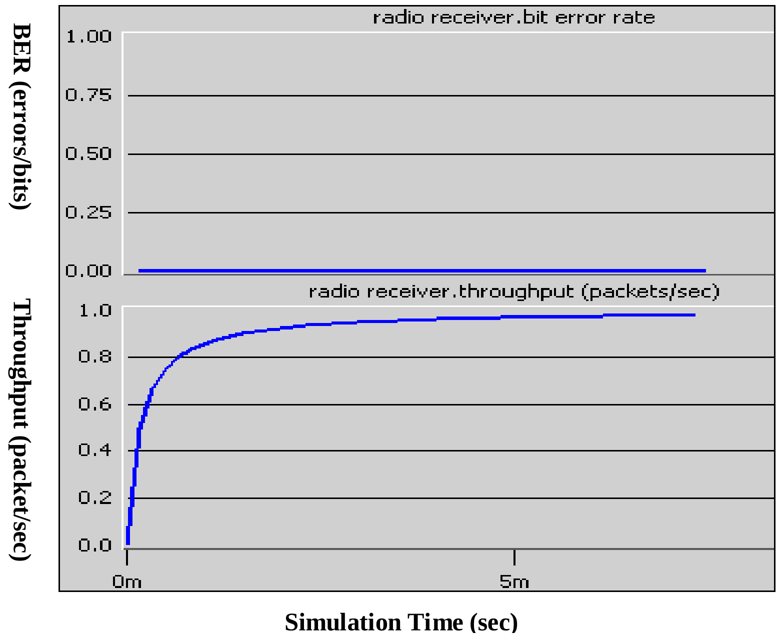
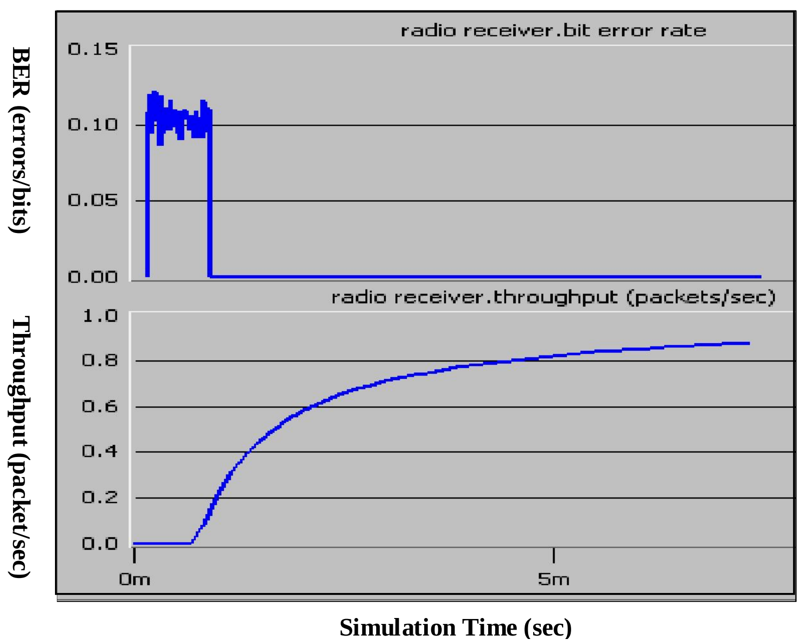


Figure 6-14: BER and Throughput of the Receiver when using the proposed scheme at the Receiver only

Figure 6-15 (a) and (b) depict the BER and Throughput of the System at different speeds. As the jammer moves along the prescribed path at a speed of 3m/s, it can be seen from Figure 6-15 (a) that the throughput of the receiver increases and the BER was zero for the entire simulation time. This is because whenever the distance between the jammer and receiver or transmitter is decreasing the transmitter and receiver antennas using the EAPS can place their antennas in the specified direction ignoring the interference signal. In figure 6-15 (b) when the speed was increased it can be seen that the throughout was 0 initially. In this case it can be concluded that the simulations indicate negligible effects for speeds up to 3 m/s.



(a)



(b)

Figure 6-15: BER and Throughput of the receiver when using EAPS at both the Receiver and Transmitter

For all the Baseline simulations, it can be concluded that for, the Isotropic antenna pattern, the average number of received packets declined during the simulation. When using EAPS at the receiver side only, packet throughput drops whenever the direction vector connecting the jammer and receiver antennas was in line with the receiver antenna's direction of greatest gain. However, after about 5 minutes—when the jammer was no longer in the direction of greatest gain for the receiver—the number of received packets began to increase. When using EAPS at both the transmitter and receiver sides, packet throughput was Excellent.

6.4 Summary

The use of Adaptive antennas in an ad hoc wireless network can significantly improve system performance, if a proper MAC protocol can be designed. This is indicated by the throughput and delay performances and also the bit error rate performance. The proposed model has been simulated in a non-stationary (mobile) environment using an event-driven simulation tool OPNET 11.5. For the Physical-MAC layer design, to perform the improvements, simulation environments were built using different parameters. All nodes were equipped with a four-antenna array, mobile and were moving randomly. Three scenarios for the same network when using ANMAC-SW, ANMAC-AA and 802.11 were built. The throughput and delay performance of ANMAC-SW and ANMAC-AA protocols was evaluated in details against regular Omni 802.11 stations. Also throughput versus load of these protocols was evaluated. Our results promise significantly enhancement over Omni 802.11, with a throughput of 25% for ANMAC-SW and 90% for ANMC-AA .The extent of the performance improvement depends on the node mobility taking into considerations the speed, location, time and the network topology. ANMAC-AA can result in higher throughput if the network topology has parallel diagonals where nodes in each diagonal try to reuse the channel again and again.

Simulation experiments indicate that by using the proposed scheme with 4 Adaptive Antenna Array per a node, the average throughput in the network can be improved up to 2 to 2.5 times over that obtained by using Switched beam Antennas. Another network was built with three scenarios for ANMAC, MMAC and 802.11. ANMAC outperforms the other two protocols. The performance of the ANMAC and MMAC using the proposed scheme was expected to degrade with increase node mobility.

Since mounting of antennas on a mobile object can result in complex antenna movement, an Enhanced Antenna model was used here to allow users to describe antenna positioning in more detail than before. Allowing for six degrees of freedom, three for positioning and three for orientation is accommodated here so that users can fully describe node movement. Simulation comparisons were done for three different scenarios from which it can be concluded that using EAPS at both Receiver and Transmitter gives better result as compared to the performance of Isotropic Antenna and when using EAPS at the Receiver only for MANET. We expected the performance of the mobile nodes using the EAPS also to degrade with increase node mobility. However, the simulations indicate negligible effects for speeds up to 3 m/s. Results for higher node speeds may be more accurately captured using experimental setup.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

Using Smart Antennas in the context of Mobile Ad-hoc networks can largely reduce the radio interference, provide higher gain; thereby improving the utilization of Wireless Medium and consequently the network performance. Pairs of nodes located in each other's vicinity may potentially communicate simultaneously increasing spatial reuse of the wireless channel as compared to Omni-directional antennas. With the development of Smart Antennas, in this research an interest in integrating them specifically Adaptive Antenna Arrays into Mobile environment to realize the benefits of Space Division Multiple Accesses has been shown. The main focus of this thesis is, to improve the throughput and delay performance of MAC protocols, illustrate typical scenarios using simulations in OPNET and to use analytical methods to evaluate the corresponding throughput and delay performance.

To achieve this goal the following tasks have been done. Firstly, an extensive comparison study on some of the relevance MAC Protocols that use Smart Antennas by contrasting their features was performed. Most of these protocols were applied in a non-mobile environment, were designed using Switched-beam Antennas and the hidden terminal-deafness problems remain unsolved. These investigations discussed the challenges in improving the throughput and delay performance of some of these Directional antenna-based MAC Protocols. Two Protocols were selected, MMAC and AN-MAC protocols.

Secondly, since the simulation environment of the proposed scheme was a mobile environment, simulation studies for LMS (one of the beamforming algorithms) have been carried out to see if it is suitable for this environment. Results showed that LMS converges slowly. In view of the fact that the desired mobile nodes and interferer mobile nodes locations and the signal environment are varying with time in MANET, in this case the weights will not have enough time to converge when adapted at an identical rate. Normalized LMS was proposed for our system, this is because it converges faster than LMS.

Thirdly, directivity performance of 3D Linear Array with varying parameters like, the number of antenna elements, the inter-element spacing, amplitude and phase excitations have been investigated through simulations. Through these investigations 0.5λ inter-element spacing, 4 elements array, uniform amplitude and variable phase excitations were selected for our suggested system.

Fourthly, a methodology to specify orientation of antenna in three dimensional spaces using an Enhanced Antenna Positioning model. An Adaptive MAC scheme with Spatial Diversity, based on the RTS/CTS mechanism was developed for the two selected protocols.

Lastly, an overview of the methodology used in the development of the overall system, which includes the network system, the node model and the process model developed in OPNET were presented. 802.11 systems were modified to present a four-element Adaptive Antenna Arrays and the physical channel models in OPNET. The physical layer is included with a minimum amount of change in the normal OPNET processing through the modification of a single pipeline stage that is ragain. In order to solve optimization problem in packet scheduling problem we developed a co-simulation interface model of OPNET and MATLAB, and used Optimization Toolbox provided by MATLAB. For interfacing, mx interface provided by MATLAB have been used. Baseline simulation model was implemented and explained in details for gain calculation in presence of interference.

For the Physical-MAC layer design, to carry out the improvements, simulation environments were built using different parameters. All nodes were equipped with a four-antenna array, mobile and were moving randomly. Three scenarios for the same network when using ANMAC-SW, ANMAC-AA and 802.11 were built. The throughput and delay performance of ANMAC-SW and ANMAC-AA protocols was evaluated in details against regular Omni 802.11 stations. Also throughput versus load of these protocols was evaluated. Our results promise significantly enhancement over Omni 802.11, with a throughput of 25% for ANMAC-SW and 90% for ANMC-AA.

The extent of the performance improvement depends on the node mobility taking into considerations the speed, location, time and the network topology. ANMAC-AA outperforms ANMAC-SW protocol by 60%. Simulation experiments indicate that by using the proposed scheme with 4 Adaptive Antenna Array per a node, the average throughput in the network can be improved up to 2 to 2.5 times over that obtained by using Switched beam Antennas. Another network was built with three scenarios for ANMAC, MMAC and 802.11. ANMAC outperforms the other two protocols. The proposed scheme improves the performances of both protocols but ANMAC outperforms MMAC by 30%.The throughput and delay performances of the ANMAC and MMAC using the proposed scheme was expected to degrade with increase node mobility. However, our simulations indicate negligible effects for speeds up to 3 m/s. Results for higher node speeds may be more accurately captured using experimental setup.

In the Baseline simulations, Simulation comparisons were done for three different scenarios from which it can be concluded that using EAPS at both Receiver and Transmitter gives better result as compared to the performance of Isotropic Antenna and when using EAPS at the Receiver only for MANET.

7.2 Contributions

This part presents the contribution of this thesis. It is classified into two, one gives the major contribution and the other gives the contributions based on previous work.

Major Contribution

- Throughput and delay performance improvement of two MAC protocols using Physical-MAC layer design.

Contribution based on Previous work

- Use of Enhanced Antenna Positioning system for gain calculations.
- Application of analytical methods using a discrete time Markov-chain based model to analyze the average throughput and delay performance of the selected MAC Protocols with Adaptive Antenna Arrays in MANET when using spatial diversity.

- Proposal of an Adaptive MAC scheme with Spatial Diversity, based on the RTS/CTS mechanism.
- Development of a methodology to specify orientation of antenna in three dimensional spaces using an Enhanced Antenna Positioning model.

7.3 Future work

In this thesis, some simplifying assumptions have been made, such as those regarding uniform node location distributions and uniform traffic distributions in our models. Although minor factors have been taken into account in our simulations and model, we intentionally omit them in our model development so that we can focus on the essential factors when designing solutions to hidden terminals and deafness problems. Therefore, there is still much to be done to extend and enrich our work.

The performance of adaptive antenna array in terms of varying design parameters is evaluated using 3D linear array. The 2D linear array, circular and cubic array could be followed up to examine their performance and make comparisons.

In this thesis Adaptive Antenna with Uniform Linear Array (ULA) has been used, using ESPRIT-direction of Arrival estimation algorithm and Normalized LMS beamforming algorithm. As future work different geometries, different DOA algorithms should be applied. Algorithms like RLS, CMA and the combination of both etc. should also be applied.

The use of Adaptive Antenna Arrays in Mobile Ad-hoc Networks enables users to divide medium into sectors and communicate individually in each sector. The scheme has been proposed for mobile users. The evaluation of Adaptive Antenna Arrays showed that switched beams causes more delay for mobile users. Adaptive arrays seem to be much better, which is an active research area. On the other hand, the problems of spatial usage have to be fully solved in order to reach the expected capacity with Adaptive Antenna systems.

Finally, the performance improvement of Adaptive Antenna Arrays for MANET systems depends on the time, speed and the location of mobile nodes. Random Waypoint Mobility model has been used. By investigating different and complex mobility models, the MAC protocols can be characterized more efficiently.

In conclusion, this thesis provides the throughput and delay performance improvement of two MAC protocol using Adaptive Antenna Arrays for mobile environment.

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APPENDIX A

MATLAB Functions

LMS Algorithm

```
%----- Givens -----%

d = 0.5; % element spacing in terms of wavelength d = lambda/2
%N = input('    How many element do you want in uniform linear array?    ');    % number of elements in array
N=4;
thetaS = input('   What is the desired users AOA (in degrees)?   ');
thetaI = input('   What is the interferers AOA(in degrees)?   ');
%----- Desired Signal & Interferer -----%
T=1E-3;
t=(1:100)*T/100;
it=1:100;
S=cos(2*pi*t/T);
thetaS = thetaS*pi/180;                 % desired user AOA
I = randn(1,100);
thetaI = thetaI*pi/180;                 % interferer AOA

%----- Create Array Factors for each user's signal for linear array -----%

vS = []; vI = [];
i=1:N;
vS=exp(1j*(i-1)*2*pi*d*sin(thetaS)).';
vI=exp(1j*(i-1)*2*pi*d*sin(thetaI)).';

%----- Solve for Weights using LMS -----%

w = zeros(N,1);     snr = 60;  % signal to noise ratio
 X=(vS+vI);
Rx=X*X';
mu=1/(4*real(trace(Rx)))
mu = input('What is step size?')
wi=zeros(N,max(it));
for n = 1:length(S)
   x = S(n)*vS + I(n)*vI;
   %y = w*x.';
   y=w'*x;

   e = conj(S(n)) - y;      esave(n) = abs(e)^2;
%    w = w +mu*e*conj(x);
   w=w+mu*conj(e)*x;
   wi(:,n)=w;
   yy(n)=y;
end
```

```
w = (w./w(1));    % normalize results to first weight

%----- Plot Results -----%

theta = -pi/2:.01:pi/2;
AF = zeros(1,length(theta));

% Determine the array factor for linear array

for i = 1:N
   AF = AF + w(i)'.*exp(1j*(i-1)*2*pi*d*sin(theta));
end

figure
plot(theta*180/pi,abs(AF)/max(abs(AF)),'k')
xlabel('AOA (deg)')
ylabel('|AF_n|')
axis([-90 90 0 1.1])
set(gca,'xtick',[-90 -60 -30 0 30 60 90])
grid on

figure;
plot(it,S,'k',it,yy,'k--')
xlabel('No. of Iterations')
ylabel('Signals')
legend('Desired signal','Array output')

disp('%------------------------------------------------------------------------%')
disp(' ')
disp(['   The weights for the N = ',num2str(N),' ULA are:'])
disp(' ')
for m = 1:length(w)
   disp(['   w',num2str(m),' = ',num2str(w(m))])
end
disp(' ')

figure;plot(it,abs(wi(1,:)),'kx',it,abs(wi(2,:)),'ko',it,abs(wi(3,:)),'ks',it,abs(wi(4,:)),'k+','
markersize',2)
xlabel('Iteration no.')
ylabel('|weights|')
figure;plot(it,esave,'k')
xlabel('Iteration no.')
ylabel('Mean square error')
```

Estimation of AOA using ESPRIT algorithm and Adaptive Beamforming functions

```
%
%Antenna Array Of Four Elements Operating On 2 GHz With A Separation Distance 0.5 Meters %
%Narrowband (Uncorrelated or Partially Correlated) Signals Are Assumed %
%An Authentication Code Of 10 Bits Is Sent First %
%Two Users Are Served Only In The Presence Of Additive White Gaussian Noise Only %
%Operation Is Subdivided Into Three Stages : Angle Of Arrival Estimation ( ESPRIT ) , Adaptive Beamforming , Signal Regeneration %
%-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------%
%Input Received Signals Arrival
P = input ('The Channel Signal To Noise Ratio : ') ;
for I = 1 : 2
   A ( I ) = input ('The Signal Arrival Phase Angle : ') ;
   A ( I ) = A ( I ) * pi / 180 ;
end
H = randint ( 2 , 10 ) ;
%Estimation of The Covariance Matrix
S = zeros ( 4 , 2 ) ;
R = zeros ( 4 , 4 ) ;
ZZ = zeros ( 4 , 10 ) ;
for K = 1 : 10
   for J = 1 : 2
      for I = 1 : 4
         S ( I , J ) = exp ( i*( pi  * ( I - 1 ) * cos ( A ( J ) ) ) )  ;
      end
   end
   S = awgn ( S * H ( : , K ) , P ) ;
   ZZ ( : , K ) = S ;
   R = R + S * S' ;
end
R = R / 10 ;
[ V , E ] = eig ( R , 'nobalance' ) ;
%ESPRIT Algorithm Estimation
VV = V ( : , [ 3 4 ] ) ;
VV1 = VV ( [ 1 2 3 ] , : ) ;
VV2 = VV ( [ 2 3 4 ] , : ) ;
Cv = [ VV1' ; VV2' ] * [ VV1  VV2 ] ;
[ Vc , Ec ] = eig ( Cv , 'nobalance' ) ;
G1 = Vc ( [ 1 2 ] , [ 3 4 ] ) ;
G2 = Vc ( [ 3 4 ] , [ 3 4 ] ) ;
Lg = -G1 * inv ( G2 ) ;
Eg = eig ( Lg ) ;
G  = asin ( angle ( Eg ) / pi) ;
```

```
%Estimation The Weight Vector of A Null Steering Beamformer
for I = 1 : 2
  for J = 1 : 4
     SS ( I , J ) = exp ( i*( pi * ( J-1 ) * cos ( G ( I ) ))) ;
 end
end
B = eye ( 2 ) ;
for J = 3 : 4
   Z = B ( J-2  , : ) ;
   W = SS \ Z' ;
   MM = 0 ;
   %Plot of The Output Radiation Pattern And The Output Valid Digital Data of The
Null Steering Beamformer
   TT = 0 : 0.005 : pi ;
   for I = 1 : 4
     HH = exp ( i*( pi * ( I-1 )*cos ( TT ))) ;
     MM = MM + ( HH * W(I) ) ;
   end
   TT = ( TT * 180 ) / pi ;
   MM = 20 * log10 ( abs ( MM )/ max ( abs ( MM ) ) ) ;
   for K = 1 : 10
     OO ( K ) = W.' * ZZ ( : , K ) ;
   end
   OO = abs ( OO / max ( OO )) ;
   OO ( 11 ) = 0 ;
   U = J - 2  ;
   UU =  J  ;
   UUU = J + 2 ;
   figure ( U ) , plot ( TT , MM ) , xlabel ('Phase Angle In Degrees') , ylabel ('Electric
Field In dB') , title ( 'A Choice Radiation Pattern Of A Spatial Beamformer') ,  axis ( [
0 180 -10 0 ] ) , grid on ;
   figure ( UU ) , stairs ( OO , 'linewidth' , 2 ) , title ('A Choice Output Digital Data') ,
xlabel ('The Bit Transition Period') , ylabel  ('The Output Digital Signal') , grid on ;
   %Comparator Operation
   for I = 1 : 10
      if OO ( I ) > 0.5 OO ( I ) = 1 ;
      else OO ( I ) = 0 ;
      end
   end
   figure ( UUU ) , stairs ( OO , 'linewidth' , 2 ) , title ('The Output Valid Digital
Data') ,  xlabel ('The Bit Transition Period') , ylabel  ('The Output Digital Signal') ,
grid on ;
end
```

```
% element numbers
N = 4;

% element spacing
d = 0.5;

% theta zero direction
% 90 degree for braodside, 0 degree for endfire.
theta_zero = 60;
theta_1 = 60

An = 1;
j = sqrt(-1);
AF = zeros(1,360);

for theta=1:360

   % change degree to radian
   deg2rad(theta) = (theta*pi)/180;

   %array factor calculation
   for n=0:N-1
      AF(theta) = AF(theta) + An*exp(j*n*2*pi*d*(cos(deg2rad(theta))-cos(theta_zero*pi/180))) ;
   end
   AF(theta) = abs(AF(theta));

end

% plot the array factor
polar(deg2rad,AF);
```

APPENDIX B

OPNET Functions

Functions for External system interface

The header block

```
#include "stdlib.h"
#include "stdio.h"
#include "string.h"
#include "comm_support_1532.h"
#define STRM_ARRIVAL (op_intrpt_type () == OPC_INTRPT_STRM)
#define ESYS_ARRIVAL (op_intrpt_type () == 
OPC_INTRPT_ESYS_INTERFACE)
#define OUT_STRM     0
```

The Function Block

```
void
process_strm ()
	{
	Packet      *pkptr;
	Vvec_Vector *pk_vvec;
	FIN (process_strm);
	/* The incoming packet is intended for the outgoing esys */
	pkptr = op_pk_get (op_intrpt_strm ());
	/* Convert packet to vvec */
	pk_vvec = (Vvec_Vector *) op_prg_mem_alloc (sizeof (Vvec_Vector));
	op_pk_convert_to_vvec (pkptr);
	op_pk_vvec_get (pkptr, pk_vvec);
	op_esys_interface_value_set (out_iface, op_sim_time(), pk_vvec, 0);
	op_pk_destroy (pkptr);

	FOUT;
	}
void
process_esys ()
	{
	Packet       *pkptr;
	Vvec_Vector   *pk_vvec;
	FIN (process_esys);
	/* The vvec on the esys just needs to go out on the strm */
	op_esys_interface_value_get  (op_intrpt_esys_interface(),  (void*)&pk_vvec,
0);
	/* Convert from vvec to OPNET pk */
	pkptr = op_pk_create_vvec ();
	op_pk_vvec_set (pkptr, *pk_vvec);
	op_pk_convert_from_vvec (pkptr, "data_pk_1532");
	op_pk_send (pkptr, OUT_STRM);
	FOUT;
	}
```

Init: Enter Execs

```
out_iface = op_id_from_name (op_id_self(), OPC_OBJTYPE_ESINTERFACE, "out");
```

Functions for Reciever-sink

Init: Enter Execs

```
/* register stat handles */
local_ETE_delay_stat = op_stat_reg("Broadcast Node.ETE Delay (msec)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
global_ETE_delay_stat = op_stat_reg("Broadcast Node.Global ETE Delay (msec)", OPC_STAT_INDEX_NONE, OPC_STAT_GLOBAL);
local_thruput_bits_stat = op_stat_reg("Broadcast Node.Throughput (bits/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
global_thruput_bits_stat = op_stat_reg("Broadcast Node.Global Throughput (bits/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_GLOBAL);
local_thruput_pkts_stat = op_stat_reg("Broadcast Node.Throughput (packets/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
global_thruput_pkts_stat = op_stat_reg("Broadcast Node.Global Throughput (packets/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_GLOBAL);
global_pkts_rcvd_stat = op_stat_reg("Broadcast Node.Total Packets Received", OPC_STAT_INDEX_NONE, OPC_STAT_GLOBAL);
```

Sink: Enter Execs

```
/* get packet from input stream */
pkptr = op_pk_get(op_intrpt_strm());
pkts_rcvd++;
/* calculate global ETE delay */
ETE_delay = op_sim_time()-op_pk_creation_time_get(pkptr);
/* calculate throughput */
bit_count = op_pk_total_size_get(pkptr);
/* write stats */
op_stat_write(local_ETE_delay_stat, (ETE_delay*1000));
op_stat_write(global_ETE_delay_stat, (ETE_delay*1000));
op_stat_write(local_thruput_bits_stat, (bit_count));
op_stat_write(global_thruput_bits_stat, (bit_count));
op_stat_write(local_thruput_pkts_stat, 1);
op_stat_write(global_thruput_pkts_stat, 1);
#if 0
op_sim_info_get (OPC_DOUBLE, OPC_SIM_INFO_EXECUTED_EVENTS, &events);
printf ("RECEIVED PACKET at event %f, about to write pkts rcvd stat\n", events);
if ((op_stat_valid (global_pkts_rcvd_stat) == OPC_FALSE) && (num_errs_reported < 100))
	{
	op_sim_message ("Global Total Packets Received statistic is invalid", "");
	num_errs_reported++;
	}
```

```
#endif

op_stat_write(global_pkts_rcvd_stat, pkts_rcvd);
/* destroy the packet */
op_pk_destroy(pkptr);
```

Mobility function
Init state: Enter Execs

```
// Initialize the mobility process model (variable,...)
// init every id relative to the current process
my_node_id=op_topo_parent (op_id_self());
my_process_id=op_id_self();
my_net_id=op_topo_parent(my_node_id);
// read the simulation attributes
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_POS_TIMER", &POS_TIMER);
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_STEP_DIST", &STEP_DIST);
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_XMIN", &XMIN);
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_XMAX", &XMAX);
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_YMIN", &YMIN);
op_ima_sim_attr_get(OPC_IMA_DOUBLE, "mobil_YMAX", &YMAX);
// initialize the distributions for the random movements
one=op_dist_load ("uniform",-1,1);
// initilaze the first random direction followed by the node containing the current mobility process
angle=op_dist_outcome (one)*PI;
// schedule the first "mouvement" interuption
op_intrpt_schedule_self(op_sim_time()+POS_TIMER,0);
```

Mobility Position state

```
 MOBILITY POSITION STATE
// Update the position of the node containing the current mobility
// process/////////////////////////////////////////////////////////////
//fp=fopen("C:\\Documents and Settings\\Stef\\Desktop\\Video over WMN\\file prova opnet\\mobil.txt","a");
// Get the actual position of the node containing the current process
op_ima_obj_attr_get(my_node_id,"x position",&x_pos);
op_ima_obj_attr_get(my_node_id,"y position",&y_pos);
// calcul the new x and y position according to the STEP_DIST and the current direction (angle)
x=x_pos+STEP_DIST*cos(angle);
y=y_pos+STEP_DIST*sin(angle);
// if the new x position is outside the network grid boundaries
if ((x<XMIN)||(XMAX<x))
	{
	// if the new y position is also outside the network grid boundaries
	if ((y<YMIN)||(YMAX<y))
```

```
            {
            // come back to the previous position (on x and y)
            x=x_pos-STEP_DIST*cos(angle);
            y=y_pos-STEP_DIST*sin(angle);
            // and calculate a random new direction
            angle=op_dist_outcome(one)*PI;
            }
      // if new y position are still in the network boundaries
      else
            {
            // come back to the previous position (only on x)
            x=x_pos-STEP_DIST*cos(angle);
            // and calculate a random new direction
            angle=op_dist_outcome(one)*PI;
            }
      }
// if only the new y position is outside (x and y outside handle before) the network
boundaries
if ((y<YMIN)||(YMAX<y))
      {
      // come back to the previous position (only on y)
      y=y_pos-STEP_DIST*sin(angle);
      // and calculate a random new direction
      angle=op_dist_outcome(one)*PI;
      }
printf(" my_id : %d previous pos (%f,%f), new position (%f,%f), direction
%f\n",my_node_id,x_pos,y_pos,x,y,angle);
//fprintf(fp,"\n my_id : %d previous pos (%f,%f), new position (%f,%f), direction
%f\n",my_node_id,x_pos,y_pos,x,y,angle);
// set the new position of the node
op_ima_obj_attr_set(my_node_id, "x position",x);
op_ima_obj_attr_set(my_node_id, "y position",y);
// schedule the interuption for the next movement (position updating)
op_intrpt_schedule_self(op_sim_time()+POS_TIMER,0);
// breakpoint for debugging purpose
if (1)
      {
      op_prg_odb_bkpt("position");
      }
```

Antenna_pointer functions

Init state

```
/* id of node containing this antenna pointing module*/
      tx_node_id = op_topo_parent (op_id_self ());
      /* id of antenna module inside this node */
      ant_node_id = op_id_from_name (tx_node_id, OPC_OBJTYPE_ANT, "ant");
      /* position of this node loaded into x_pos, y_pos, z_pos */
      op_ima_obj_pos_get (tx_node_id, &latitude, &longitude,&altitude, &x_pos,
&y_pos, &z_pos);
```

```
        previous_latitude = latitude;
        previous_longitude = longitude;
        previous_altitude = altitude;
        input_theta_lsh = op_stat_reg("Input Theta", OPC_STAT_INDEX_NONE,
        OPC_STAT_LOCAL);
        theta_pointing_at_ground_lsh = op_stat_reg("Theta Pointing At Ground",
        OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
        op_ima_obj_attr_get( op_id_self(), "Ant Pattern Theta Pointing Down",
&theta);
        /* set the lookup theta pointing straight down */
        theta = theta + 180;
        if (theta > 270.0)
                theta = theta - 270.0;
        else
                theta = theta + 90.0;
```

Start state

```
op_ima_sim_attr_get (OPC_IMA_TOGGLE, "Allow Antenna Rotation", &att );
if (att == OPC_BOOLINT_ENABLED)
{
        /* id of node containing this antenna pointing module*/
        tx_node_id = op_topo_parent (op_id_self ());
        /* id of antenna module inside this node */
        ant_node_id = op_id_from_name (tx_node_id, OPC_OBJTYPE_ANT, "ant");
        /* position of this node loaded into x_pos, y_pos, z_pos */
        op_ima_obj_pos_get (tx_node_id, &latitude, &longitude,&altitude, &x_pos,
&y_pos, &z_pos);
        /* change in position of this node from previous position */
        //delta_lat = 2.0 *(latitude - previous_latitude);
        //delta_long = 2.0 *(longitude - previous_longitude);
        //delta_alt = 2.0 *(altitude - previous_altitude);
        /* set target of antenna in direction of forward movement */
        op_ima_obj_attr_set (ant_node_id, "target latitude", 0.0);
        op_ima_obj_attr_set (ant_node_id, "target longitude", 100.0);
   op_ima_obj_attr_set (ant_node_id, "target altitude", 20.0);

        /* make antenna pattern rotate 1 degree about poniting direction */
        op_ima_obj_attr_set (ant_node_id, "pointing ref. theta", theta);
        theta = (double) ( ( (int)theta + 10) % 360);
        op_stat_write( input_theta_lsh, theta);
        if (theta > 270)
                op_stat_write( theta_pointing_at_ground_lsh, theta - 270.0);
        else
                op_stat_write( theta_pointing_at_ground_lsh, theta + 90.0);
        }
/* send packet along to antenna */
op_pk_send(op_pk_get(op_intrpt_strm()), 0);
```

Initialization Process for calling MATLAB functions from OPNET

Step 1: Locate the directory where the lib files related to the Matlab Engine such as libmat.lib or libmx.lib are located. In my machine, the directory path is:

C:\Program Files\MATLAB7\extern\lib\win32\microsoft

Step 2: Go to OPNET → Edit → Preferences.

> **Step 2a:** Search for the tag bind_shobj_flags and set its value as: /LIBPATH: C:\PROGRA~1\MATLAB7\extern\lib\win32\microsoft, which is the directory path of the lib files as located in Step 1 above. For some reasons, it could get the setup to work only if you enter the DOS version of the path (i.e., C:\PROGRA~1 instead of C:\PROGRAM FILES).
>
> **Step 2b:** Search for the tag bind_shobj_libs and set it to the list of the entire lib files that are available in the above directory. Space is used to separate the files. In this case, i have the following setting: libmat.lib libeng.lib libmex.lib libmx.lib
>
> **Step 2c:** Save the updated preferences.

Step 3: Set the environment variable $PATH$ in your machine to contain the directory that contains the engine.h file. In my machine, it is C:\Program Files\MATLAB7\extern\include.

LIST OF PUBLICATIONS

1) **J.A.Guama,** N.M Saad, "A Comparison Study of Directional MAC Protocols With Smart Antennas for Mobile Ad Hoc Network", 3rd International Colloquium On Signal Processing and Its Applications (CSPA07) 9-11March 2007, Melaka, Malaysia.
2) **J.A.Guama,** N.M Saad, "Using Adaptive Antenna Arrays in Mobile Ad Hoc Network With Multihop-RTS MAC Protocol", Wireless and Optical Communication Networks (WOCN2007) 2-4 July 2007, Grand Hyatt, Singapore.
3) **J.A.Guama,** N.M Saad, "Improving the Performance of Directional Medium Access Control Protocols With Smart Antennas For Mobile Ad Hoc Network" Wireless and Optical Communication Networks (WOCN2007) 2-4 July 2007, Grand Hyatt, Singapore.
4) **J.A.Guama,** N.M Saad, "Cross-layer Optimization for the Physical and Medium Access Control Layers in Mobile Ad Hoc Network With Smart Antennas", International Conference on Intelligent and Advanced Systems (ICIAS2007) 25-28 November 2007, Kuala Lumpur, Malaysia.
5) **J.A.Guama,** N.M Saad, "Throughput and Delay Performance Improvement of Angular-MAC Protocol Using Adaptive Antenna Arrays for Mobile Ad Hoc Network", Curtin University of Technology Sarawak Engineering Conference (CUTSE07) 26-27 November 2007, Miri, Sarawak, Malaysia.
6) **J.A.Guama,** N.M Saad, "Using An Enhanced Antenna Positioning System for Performance Analysis of MANET", 4th International Colloquium On Signal Processing and Its Applications (CSPA08) 7-9 March 2008, Kuala Lumpur, Malaysia.