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TAMPERE UNIVERSITY OF TECHNOLOGY

SEMANTA RAJ NEUPANE

ROUTING IN RESOURCE CONSTRAINED SENSOR NANONETWORKS

Master of Science Thesis

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Senior Research Fellow, Dr. Dmitri Moltchanov

ABSTRACT

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Nano network is the communication network of nano nodes ranging from one to hundred nano meters in size. Nano nodes are resource constrained due to its small size. Limited battery power, small memory unit and low processing capability are the characteristics of nano network. To make communication between nano nodes possible, protocol stack is envisioned. The protocol stack consists of four layers which are: message process unit, network layer, media access control entity and PHY interface. Among these layers, PHY interface is implemented using Time spread on-off keying (TS-OOK) method and Media access control entity is implemented using Transparent MAC. Similarly network layer is implemented using flooding techniques.

Network layer is the least explored and least studied layer in the protocol stack. Many algorithms are developed for PHY-interface but no significant work has been done on routing technique. In this thesis work, we present the solution to the network layer problem. Simple routing algorithm called Flooding is proposed as the routing technique. Flooding alone cannot solve the network layer problem. A new algorithm is needed which addresses the large number of redundant messages while fulfilling the memory and computation constraints of nano nodes.

To make flooding efficient and suitable for nano network, a new routing model called RADAR routing is proposed. In RADAR model, only some of the nodes will generate message at a given time. This model helps to reduce number of packets which leads to the reduction in collision and increase in network throughput. This model is suitable with regard to energy consumption as well. RADAR model is implemented and studied using simulation tool called Nano-Sim. Simulations are performed by implementing RADAR model and without implementing RADAR model by setting different parameters. The simulation output is processed and probability of a packet to reach the destination is calculated for each simulation run. The result showed that probability value increases by implementing RADAR model as compared to without RADAR model. This demonstrates increased performance of RADAR model.

PREFACE

This Mater of Science Thesis has been written for the completion of Master of Science Degree in Information Technology from the Tampere University of Technology, Tampere, Finland. The research project was carried out as part of on-going research work in Nano Communication Center, Department of Electronics and Communications Engineering during the year 2013 and 2014.

I would like to thank my examiner Professor Dr. Yevgeni Koucheryavy and supervisor Senior Research Fellow, Dr. Dmitri Moltchanov for guiding me throughout the thesis period. I am extremely grateful to my supervisor Dmiti Moltchanov for providing various ideas during the simulation work and showing the correct way in the writing phase of the thesis.

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LIST OF ABBREVIATIONS

CNT	Carbon nanotube
DNA	Deoxyribonucleic acid
GNR	Graphene nanoribbon
DC	Direct Current
FET	Field-effect transistor
EM	Electro magnetic
RF	Radio Frequency
SWNCT	Single Walled Carbon nanotube
MWNCT	Multi-walled carbon nanotube
THz	Terahertz
TS-OOK	Time Spread on-off keying
HITRAN	High resolution transmission molecular absorption database
IP	Internet protocol
RIPv1	Routing Information Protocol Version 1
RIPv2	Routing Information Protocol Version 2
IGRP	Interior Gateway Routing Protocol
TCP/IP	Transmission Control Protocol/Internal Protocol
IS-IS	Intermediate System to Intermediate System
OSPF	Open Shortest Path First
CPU	Central Processing Unit
TTL	Time to Live
MTU	Maximum Transmission Unit
ICT	Information and Communications Technology
TS-OOK	Time Spread on-off Keying
MAC	Media Access Control
WNSN	Wireless Nano Sensor Network

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1. INTRODUCTION

Nanotechnology ranks among the newest topic in scientific research. It is the study and application of extremely small things which is conducted at the nano-scale ranging from one to hundred nanometers. Development of scanning tunneling microscope in 1981 paved the way for modern nanotechnology. This helped to see and work on atomic level. These developments in nanotechnology are leading the way for creation of nano-machines.

1.1 Nano-machine

A nano-machine is a mechanical or electromechanical device whose size ranges from one to hundred nanometers. These are most basic functional units in nano world which can perform very simple computation, sensing and actuation tasks. Nano-machines are primarily in the research and development phase. The different approaches for the development of nano-machine can be broadly classified into two groups: artificial approach and biological approach. The principal of former approach is to create nano-machine by using external technologies. The principal of latter approach is to use the cellular components as the nano-machine. Artificial approach consists of two methods: top down approach and bottom up approach. Biological approach is described by bio hybrid approach.

This thesis deals with the artificial approach for the creation of nano-machines.

1.1.1 Development of Nano-machine

Nano-machines in future can be developed using either top-down, bottom-up or bio-hybrid approach. These methods are briefly described based on [1] as below:

Top-down approach

In this approach, current micro-scale devices are downgraded into nano-scale devices. This can be done using advanced techniques such as electron beam lithography and micro contact printing. The resulting nano-scale devices retain the architecture of micro-scale devices. Nano machines like nano electromechanical components (NEMS) are the example of machines being developed using this concept. The fabrication and assembly of these nano-components is at an early stage. Simple mechanical structures such as nano-gears are successfully created using this approach.

Bottom-up approach

In this approach, nano-machines are created by assembling individual molecules. The process of creating nano-machine by precise and controlled arrangements of molecules is called molecular manufacturing. Nano-machines using this approach have not been manufactured yet practically. But nano-machines such as molecular differential gears and pumps have been designed theoretically.

Bio hybrid approach

In this approach, several biological structures found in cells of living organisms are considered as nano-machines. Different nano-machines in cells are nano-biosensors, nano-actuators, biological data storing components, tools and control units. These nano- machines are connected with each other forming the network structure which can perform complex tasks. The communication between these intra-cell nano-machines is possible by molecular signaling technique. This technique is also used for inter-cell communication.

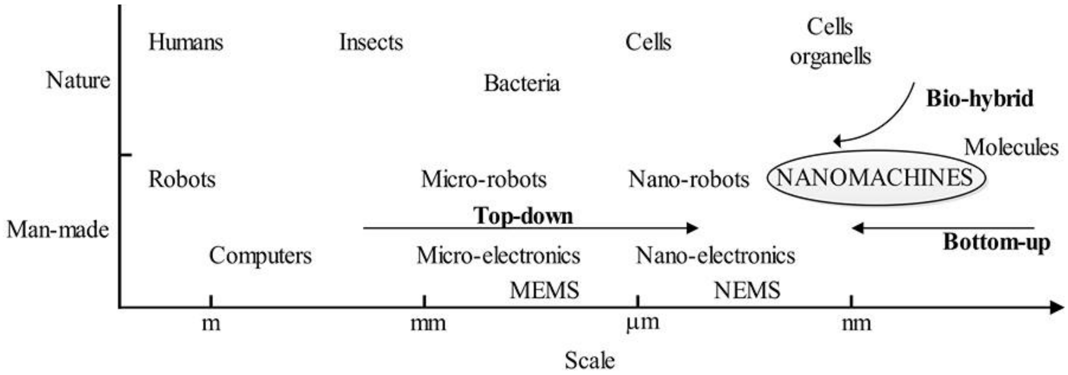

Figure 1.1 *Different approaches for the development of nano machines "taken from [Akyildiz, I.F. Brunetti, F. & Blázquez, C. 2008. Nanonetworks: A new communication paradigm. Computer Networks 52, 12, pp.2260-2279]"*

The different methods of manufacturing nano-machines are only theoretical concept till date. Some primitive machines are designed but lack of fabrication techniques is prohibiting its realization. Future technological breakthroughs may make it possible to build nano-machines. The desired features of nano-machine which can be realized in future are: self-contained machine, self-assembly, self-replication, locomotion and communication. These are shortly described based on [3] as follows:

Self-contained machine

Self-contained machines will hold set of instructions to perform the intended task. These machines will either store or read set of instructions from another structure to perform the task.

Self-assembly

It is the process by which molecules are arranged in a certain structure without external intervention. Self-assembly is important part of bottom-up approach of creation of nano-machines.

Self-replication

It is the process by which nano-machines will create copies of itself. With controlled environment and availability of energy and other ingredients, self-contained machines can create its replicas.

Locomotion

It is the ability to move. Future nano-machines which can move from one place to another will be useful in several application scenarios.

Communication

Communication capabilities will increase the performance of a single nano-machine. The most prominent communication methods are molecular and electromagnetic communication.

1.1.2 Components in Nano-machine

Nano-machine architecture will contain different components. The most complete future nano-machines will contain following components: control unit, communication unit, reproduction unit, power unit, sensors and actuators. These components are described based on [3] as below:

Control unit

It is responsible for executing instructions and performing intended tasks. This unit controls all other components of the nano-machine. It will include storage unit which holds the nano-machine related information.

Communication unit

This unit is responsible for communication tasks. It will include molecular transceivers for molecular communication and Graphene or CNT antennas for electromagnetic communication.

Reproduction unit

This unit is responsible for creating replicas of nano-machine. To realize this, each nano-machine components are fabricated and assembled using external technologies. This unit contains code and instructions to perform the intended task.

Power unit

This unit is responsible for providing power to all nano-machine components. Power unit will collect energy from different energy sources and store it for future consumptions.

Sensor and actuators

This unit acts as an interface between environment and the nano-machine. Different sensors like temperature sensors, chemical sensors can be included in nano-machine. These sensors will collect information from surrounding environment.

1.2 Nano-machine as a sensor device

Miniaturized devices will be of no use if they do not possess sensing capabilities. A nano-machine which makes use of properties of nano-materials and nano-particles to detect and measure new types of event in the nano-scale is called nanosensor device. Nanosensors can detect chemical compounds, presence of different infectious agents such as virus or harmful bacteria. The architecture of nanosensor device consists of following units:

1.2.1 Sensing unit

Graphene Nanoribbons and Carbon Nanotubes provide sensing capabilities to nano-machine. According to nature of the measured magnitude, nanosensors can be classified as: Physical nanosensor, chemical nanosensor and biological nanosensor. These are described based on [2] as follows:

Physical nanosensor

This nanosensor measures magnitude such as mass, pressure, force and displacement. When Nanotubes and Nanoribbons are bent or deformed, change in electronic properties can be seen. Based on this principle, pressure nanosensors, force nanosensors and displacement nanosensors are proposed.

Chemical nanosensor

This nanosensor measures magnitude such as concentration of a given gas, presence of specific type of molecules and composition of a substance. When CNTs and GNRs are exposed to a given gas, it absorbs molecules bringing change in its electronic properties. Based on this working principle, number of chemical nanosensors has been manufactured.

Biological nanosensor

This nanosensor monitors bio-molecular process such as antibody interactions, DNA interactions or cellular communication process. These sensors consist of two components: bioreceptor such as antibody, enzyme, protein or DNA strain and transduction mechanism such as electrochemical detector, optical transducer, and magnetic detector. Based upon the working principle, there are two subtypes of biological nanosensors: Electrochemical and photometric nanosensors. In electrochemical biosensors, change in electric properties is caused by biological components such as protein of DNA attached to the CNTs. The photometric biological nanosensors are based on the use of noble metal nano-particles and the excitation using optical waves of surface Plasmon.

Many challenges need to be addressed in nanosensor design. The recovery time of chemical and biological nanosensors is in the range of ten minutes whereas sensing time is one minute. For practical applications, this recovery time needs to be reduced. Similarly, the selectivity capability of chemical sensor should be precise enough to differentiate between different chemicals.

1.2.2 Actuation unit

This unit helps in the interaction of nanosensor and external environment. Nanoactuators can be classified as: Physical nanoactuators, chemical and biological nanoactuators. These are described based on [2] as follows:

Physical nanoactuators

These actuators are based on the interaction between nano-material, electrical current and electromagnetic wave. One of the examples of physical nanoactuator is Carbon nanotweezer which can be mechanically manipulated by electricity and can be used to manipulate and transfer micro and nano structures.

Chemical and biological nanoactuators

These actuators are based on the interaction between nano-materials, electromagnetic fields and heat. Nano heaters can be used to selectively kill cancer cells and magnetic nanoparticles and gold nanoshells can be used for targeted drug delivery.

Many research challenges need to be addressed for the practical realization of nano actuators. One of the challenges lies in design and fabrication of actuation unit. Another challenge is to make actuators precise enough to work in sensitive application areas like biomedical field.

1.2.3 Power unit

Nanobatteries manufactured using nanomaterials can be used to power the nanodevices. These batteries should be charged regularly. This requirement limits the usefulness of nanobatteries in practical scenarios. To overcome these limitations of nano batteries, concept of self-powered nano-device is introduced. These self-powered devices will convert mechanical, vibrational or hydraulic energy into electrical energy. The energy conversion can be achieved using piezoelectric effect seen in zinc oxide nanowires. Additionally, electromagnetic waves can be converted into vibrational energy, which in turn can be converted into electrical energy using zinc oxide wires. Another method is to use rectifying antennas that convert electromagnetic waves into DC electricity. The major research challenge while designing power unit will be maintaining balance between size of power unit, energy harvested and stored, and capabilities of nanosensor device. [2]

1.2.4 Processing unit

Field effect transistors can be used to build nano-scale processors. These field effect transistors can be developed using CNTs and GNRs. Graphene-based transistors are smaller and faster. Since the nano processing unit will be small, it can accommodate few transistors. This will reduce the capability of nano-processor to perform complex task. But the switching frequency of Graphene based transistors, which is in order of up to a few hundreds of terahertz, is much faster .The main research challenge while building nano-processor will be to integrate transistors into processor architecture.[2]

1.2.5 Storage unit

Nano-memories which utilizes single atom to store a single bit can be used as a storage unit. One of the proposed memory stores a bit by the presence or absence of one silicon atom. It is based on a silicon surface with deposited monolayers of gold which defines tracks. The writing process can be performed by removing silicon atoms from gold lattice. The reading process can be performed by using nano-tip able to detect the presence or absence of silicon atoms. In another concepts proposed by IBM corp. single magnetic atoms can be placed over a surface by means of magnetic forces, with each atom storing a bit. Many research challenges need to be addressed in the design of storage unit. One of the challenges is the need of complex and expensive machinery to perform read and write operations in nano-memory. Another challenge is to mass manufacture nano-memory which will work in practical scenarios. [2]

1.2.6 Communication unit

Communication among nanosensors will increase the capabilities of a single nanosensor device. Electromagnetic communication is one of the prominent communication technique. Nano device should be equipped with nano-antennas and electromagnetic transceiver to communicate with this technique. These are described based on [2] as below:

Nano-antennas

Reducing the size of current sensor antennas may not be feasible in nanosensor device. Instead, Graphene based antennas will be appropriate. The resonant frequency of Graphene based antennas will be up to two orders of magnitude below that of traditional antennas. Some of the proposed antennas are nano-patch antennas based on GNRs and nano-dipole antennas based on CNTs. Many challenges need to be addressed before these antennas can be practically realized. Accurate models for nano-antennas should be defined by providing details on their band of operation, radiation bandwidth and radiation efficiency. Similarly, new nano-antenna designs and radiating nano-structure should be developed by using properties of nanomaterial and new manufacturing techniques.

EM nano-transceivers

Electromagnetic transceivers are responsible for baseband processing, frequency conversion, filtering and power amplification of both transmitted and received signals. Since nano-antennas works in terahertz band, FET transistors able to work in high frequencies are needed. Some Graphene based transistors operating in lower part of terahertz band have been proposed and demonstrated so far. Many challenges need to be addressed before these transceivers can be practically realized. Electronic noise and thermal noise should be characterized and modeled. These noise will reduce signal to noise ratio at receiver and thus limiting the communication range of nanodevices. Similarly, new communication and information modulation techniques, which deal with pros and cons of nano-machine, need to be developed.

1.3 Nanonetwork

Nanonetwork is defined as the communication network between nano-machine. The resulting nanonetwork will provide communication capability to nano-machines. The communication capability will enable nano-machine to work in a synchronous, supervised and cooperative way for achieving common goal. This will increase capabilities and application areas of nano-machine significantly.

Nano-machines like nano-valves, chemical sensors and nano-switches cannot perform complex tasks on their own. The exchange of information among these machines will enable them to perform complex tasks.

Due to small size of nano-machines, it has very limited working space. In a small operational area of few meters, there will be thousands of nano-machines distributed randomly. Deployment of dense and interconnected nano-machine will increase the capabilities of a single nano-machine. This network can perform complex tasks.

In various application scenarios, nano-machines will be distributed in large areas. The small size of the nano-machine will make it difficult to control them. When the nano-machines are interconnected they can be controlled using broadcasting and multichip communication methods.

1.3.1 Communication methods

The different communication mechanisms envisioned in Nano world are: nanomechanical, acoustic, electromagnetic and molecular communication. These methods are described as below:

Nanomechanical communication

In this communication method, nano-machines are physically linked with each other. Information is transmitted through the physical junction between the machines. This communication method has many drawbacks. It is not suitable in application scenarios where nano-machines are deployed over large areas without having direct contact. The coupling between transmitter and receiver should be such that mechanical transceivers are aligned correctly. [1]

Acoustic communication

This communication method is based upon the transmission and reception of ultrasonic waves. Ultra sonic transducers are integrated in the nano-machines. These transducers will sense the variation of pressure produced by ultrasonic waves and emit acoustic signals. Manufacturing transducer with comparable size of nano-machine is the major challenge lying ahead. [1]

Electromagnetic communication

This is based upon the transmission and reception of electromagnetic radiation generated by components based on nanomaterials. Nanomaterials can be described as materials whose single unit has size in nano-scale range of one to hundred nanometers. Different equipment like nanobatteries, nano-memories, nano logical circuitry and nano-antennas are needed to realize this communication paradigm. Future technology in electronics may make it possible to manufacture nano-components. Different features of communication like bandwidths of emission, emitted to transmitted power ratio, time lag of the emission are dependent on the properties of nanomaterials. [2]

Molecular communication

This is based upon the transmission and reception of information using the molecules. Molecular transceivers are integrated in nano-machine. These transceivers can release molecules based on outcome of processing performed in nano-machine. The released molecules can be propagated using following methods: diffusion based, flow based and walkaway based propagation. In diffusion based propagation molecules are propagated using spontaneous diffusion. In flow based propagation, molecules are propagated through diffusion in a fluidic medium. In walkaway based propagation molecules are propagated using active carriers. These active carriers transport molecules through predefined pathways. [2]

Molecular communication can be classified into two groups depending upon the range of communication as: short range communication and long range communication. Short range communication is intra-cell and inter-cell communication that spans from nm to few mm. Similarly, long range communication is intra-specie communication that spans from mm to few km. [1]

Intra cell molecular communication is based upon molecular motors which are found on eukaryotic cells of living organisms. Molecular motors like dynein are proteins or proteins complexes which transform chemical energy into mechanical work. They travel along molecular rail and transport essential materials to organelles. This molecular rail is called microtubules which are widely distributed for intra-cell substance transportation. The ability of molecular motors to move makes it suitable to transport information packets from transmitter to receiver. Additionally, molecular motors and microtubules can be used as bio-hybrid interface between manmade machines and biological structures. [1]

Inter-cell molecular communication is based upon calcium signaling. It is responsible for different cellular tasks such as fertilization, contraction or secretion. Calcium signaling can be used for information flow between cells connected to each other or separated without any physical contact. The information flow using calcium signaling involves different messengers. Certain messengers transports information until certain period and is transferred to another messenger. This information transfer continues until the information reaches the final destination. [1]

Long range communication spans up to few kilometer. Example of long range communication can be found in biological systems. Ants, butterflies and bees uses molecular messages called pheromones to communicate with member of the same species. These messages can be decoded only by specific receivers. Long range communication will have immense application in military field and environmental applications. [1]

This thesis work deals with the electromagnetic communication method.

1.4 Application areas of Nanonetwork

Nanonetwork has numerous application areas. The potential application areas can be classified into four broad groups as: biomedical, environmental, industrial and military applications. These application areas are described based on [2] as follows:

1.4.1 Biological applications

Due to the small size of nano-machine they can interact with tissues and organs without causing harm to them. Some of the application of nano-machine in biological areas is listed below:

Immune system support

The immune system will consist of nano-machines working together to fight with disease. These nano-machines would be collection of nano, micro and macro systems including sensors and actuators working in co-ordinated manner to fight and control pathogen elements. These machines can be used to identify the infected cells and take respective action. These treatment actions will be less harmful to cells as compared to traditional treatment methods.

Bio-hybrid implants

Body organs can be supported or completely replaced by nano-machines. Nanonetwork can provide interface between implant of nervous system and other organs with environment.

Drug delivery system

These are also implant system which will help in regulating mechanism of human body. Nanosensors and smart glucose reservoirs can work in a cooperative manner to compensate glucose deficiency in diseases like diabetes. These systems will be capable to deliver neurotransmitters or other drugs to mitigate the effects of neurodegenerative diseases.

Health monitoring

The Nanonetwork with the help of sensors can constantly monitor health related factors like hormonal disorders, cholesterol levels. The obtained information should be provided to system that will decide and act accordingly.

Genetic engineering

Nano-machines and nanonetwork can have immense impact on genetic engineering. Nano-machines can manipulate and modify molecular sequences and genes.

1.4.2 Industrial and consumer goods applications

Nano-machines and nanonetworks will find much application in industrial sector. It can help in the development of completely new materials, manufacturing process and quality control mechanisms. Some of the potential applications are listed as below:

Food and water quality control

Nanonetworks with the help of sensors can detect bacteria and toxic elements in water and food. These toxic elements may not be detected using traditional methods. Advanced sensor network can detect minute toxic materials and bacteria and help to work accordingly saving people from potential diseases.

Functionalized materials and fabrics

Nano-machines can be embedded in fabrics for creating much functionality. Nano functionalized materials are helping to build antimicrobial and stain repelling textiles. Similarly nanoactuators can be developed which will improve airflow in smart fabrics.

1.4.3 Military applications

Nano-machines and nanonetworks can have several applications in military fields. Application in military field will require variable deployment of nano-machines according to the application scenario. Battle field monitoring and actuation is the application area which requires large area deployment of nano-machines. On the other hand soldier performance monitoring will require small area deployment of nano-machines. Some of the application in military filed is listed as below:

Nuclear, biological and chemical defenses

Nano-machines will be distributed in large areas like battlefields and targeted areas. These nano-machines can detect aggressive biological and chemical agents. The sensors and actuators will take coordinated actions to control the effects of such agents. Similarly nanosensors can be deployed in cargo containers to detect entrance of biological, chemical and radiological materials.

Nano functionalized equipment

Equipment can be made up of materials containing nano-machine. These materials can regulate the temperature beneath the clothes of soldiers. It can even detect injuries taken by soldiers.

1.4.4 Environmental applications

Nano-machines will find many application areas in environmental fields which cannot be performed by traditional techniques. Some of these are listed as below:

Biodegradation

Garbage handling is big problem mainly in populous city areas. Nanonetworks can help in the degeneration of garbage. Nanonetworks can sense and tag different materials which can be located and processed by nanoactuators.

Animals and biodiversity control

Nanonetworks using pheromones as message can be used to trigger certain behavior on animals. Due to this, interacting with those animals and controlling their presence will be possible.

Air pollution control

Nanonetwork will help in air monitoring process. Appropriate air filters could be developed which will remove harmful substances from air and increase air quality.

1.5 Objectives and scope of the research

Communication using nano-machines is currently in research phase. Practical nano-machines are yet to be developed. When these machines will be realized in future, they will need feasible techniques helping them to achieve the goals. Therefore, studies are being carried out regarding different features of nano-machine communication. One of the important features in any communication method is routing. Routing is the process by which message are transferred from one node to the other. Traditional routing algorithms require extensive computation and large memory requirements. Nano nodes do not have such capability. Therefore the routing algorithm should be selected which best suits the limitations of nano-nodes.

Routing algorithms cannot be tested practically since practical nano network has not been realized yet. Hence, simulation tools will be used to test the routing algorithms. Nano-Sim is used as the simulation tool to perform various tests. These tests will give the working performance of routing algorithms. A new routing algorithm called RADAR routing is proposed and tested. Following problem statements can be outlined as the scope of the thesis:

a. Simulation of wireless nano sensor network using RADAR model and without using RADAR model.

b. Calculation of probability of a packet to reach destination in both cases.
c. Comparison of probability of a packet to reach destination in both cases.

With the above mentioned objectives for the research, chapter two and chapter three will include the theoretical background related to nano communication. Chapter two is devoted to overview of various works that has been done in Terahertz communication. Similarly chapter three is devoted to various routing protocols that are available currently. Chapter four describes the RADAR routing model and chapter five is devoted to performance evaluation of the RADAR model. The performance evaluation will be performed using simulation tool. The simulation will be carried out using varying number of nodes and taking varying value of message generation time. The output file obtained after the simulation will be processed. This will give number of transmitted packets and number of received packets. From this information, probability of a packet to reach destination will be calculated. Finally chapter six concludes the thesis.

2. COMMUNICATION IN TERAHERTZ BAND

2.1 Introduction

Miniaturized devices will be of no use if they do not possess sensing capabilities. A nano-machine which makes use of properties of nanomaterials and nanoparticles to detect and measure new types of event in the nanoscale is called nanosensor device. Nano sensors can detect chemical compounds, presence of different infectious agents such as virus or harmful bacteria. The information detected by the nano-machine should be transmitted to other machine before reaching to the external world. This requires communication techniques in the nano-machine. Communication techniques will increase the capabilities of nano-machine enabling them to perform complex task. Among several communication techniques, Electromagnetic communication among nano-machine is the most prominent technique.

Electromagnetic communication will require transceivers to make the information flow possible. These transceivers will transmit the collected information to other machine and receive the information transmitted by other machine. Existing RF transceivers and optical transceivers are not feasible in nano world due to several limiting factors like size, complexity and energy consumption. Reducing current antenna size to few micrometers will make them non resonant subsequently reducing their efficiency. These problems can be removed using materials like Graphene and CNT which lies in the nanoscale range.

Graphene is the two dimensional carbon allotrope in which carbon atoms are bonded together in hexagonal pattern. Graphene is about one million times thinner than paper. It is one-atom thick layer of graphite. Graphene is the building material for both CNT and GNR. CNTs are obtained by rolling up Graphene sheet into cylindrical structure. Single walled carbon nanotube (SWNCT) is obtained by rolling one sheet while multi-walled carbon nanotube (MWCNT) is obtained by rolling up multiple sheets. GNRs are very thin strips of Graphene. One of the important application areas of CNT and GNR is to use them as nano-antenna.

To determine the frequency band of operation of Graphene based antenna, radiation properties of Graphene should be characterized. Two main perspectives for the characterization are RF based and optical based. RF based method interprets radiation in terms of high frequency waves while optical based method interprets radiation in terms of low energy photons. Both methods have the same conclusion that EM communication will take place in terahertz band which ranges from 0.1 to 10THz. [4]

These two approaches are shortly described based upon [4] as below:

RF approach to characterize radiation properties

Based on the traditional antenna theory, decreasing antenna size to nanometer scale will increase resonant frequency drastically. This high resonant frequency will reduce performance of antenna remarkably. Based on this principle, the expected value of resonant frequency associated with nano-antenna will be very high. Due to the fact that propagation of EM waves in Graphene is influenced by two quantum effects called quantum capacitance and kinetic inductance, the resonant frequency of EM wave in Graphene will be two times lower than expected value. This fact makes Graphene suitable to work as nano-antenna. Nano dipole antenna based on CNT and nano-patch antennas based on GNR are proposed so far.

The propagation speed of EM wave in CNT depends on nano tube dimensions, edge patterns and Fermi energy. The first resonant frequency of CNT based antenna is $f = v_p/2L$, where v_p is the EM wave propagation speed and L is the length of the tube. For a very thin nano tube of diameter 4nm and length 1μm, the resonant frequency will be below 1.17 THz independent of the energy in the nanotube. Increase in diameter will cause nonlinear increase in resonant frequency. Similar effect can be seen in nano patch antenna based on GNR but it has lower resonant frequency compared with nano dipole antenna based on CNT. [5]

Optical approach to characterize radiation properties

The emission of photons from the nano structures due to the interaction between electrons and vibrating ions makes them optical emitters and detectors. EM radiation is produced when electrons collide, with either the edge of the material in which they are travelling or with other particles, releasing photons. This shows that CNT can be used as optical antenna in the terahertz band.

This chapter is dedicated to background theory related to Electromagnetic communication which we are relying upon as basis. It starts with the description of terahertz propagation model which includes its propagation characteristics. This is followed by description of Time spread on-off keying (TS-OOK) method including its working principle and channel capacity. The chapter is concluded describing that network layer is the least studied layer in the protocol stack.

2.2 Terahertz propagation model

Graphene based EM transceivers will operate on terahertz band spanning between 0.1 to 10 THz. This frequency band is least explored and least investigated band. Since nanomachine communicates using short transmission range below one meter, extreme path loss due to molecular absorption will not be seen in any frequency region. Due to this, entire terahertz band can be used for communication. This makes it useful to investigate whole frequency band between 0.1 to10THz. Propagation of EM wave in terahertz channel will be affected by several factors like molecular absorption, path loss and noise. These factors should be analyzed while modeling the terahertz channel. These factors are shortly described based on [4] as follows:

2.2.1 Molecular absorption

When EM waves travels through the medium in THz band, molecules in the medium are excited. Due to this, atoms in a molecule will show periodic motion and molecule as a whole will have translational and rotational motions. This process results in conversion of part of the propagation wave energy into kinetic energy, which is a loss in signal power. Solving the Schrodinger equation for internal structures of molecule will give the vibration frequencies at which a given molecule resonates.

Currently available techniques and methods estimate the molecular absorption for a given medium in microwave and infrared region. To estimate molecular absorption in Terahertz band, High resolution Transmission molecular absorption database (HITRAN) or similar database should be consulted. Combination of HITRN database and radiative transfer theory helps to compute attenuation for a wave travelling up to few meters of distance. This computation starts with the calculation of transmittance of the medium which is defined as the fraction of EM radiation at a given frequency that is able to pass through the medium. The transmittance of the medium is given by Beer-Lambert law as:

$$\tau(f,d) = \frac{P_0}{P_i} = e^{-k(f)d} \tag{2.1}$$

where, f represents the frequency of the EM wave, d gives the total path length, P_i and P_0 are the incident and radiated powers and k gives the medium absorption coefficient. The value of k depends upon the composition of the medium and is expressed as:

$$k(f) = \sum_{i,g} k^{i,g}(f) \tag{2.2}$$

where, $k^{i,g}$ stands for the absorption coefficient for the isotopologue i of gas g. Isotopologue are molecules of the same gas differing only in isotopic composition. The absorption coefficient of the isotopologue i of gas is represented as:

$$k^{i,g}(f) = \frac{p}{p_0}\frac{T_{STP}}{T} Q^{i,g} \sigma^{i,g}(f) \tag{2.3}$$

where, p is the pressure, T is the temperature, p_0 and T_{STP} are the standard pressure and temperature, $\sigma^{i,g}$ represents the isotopologue i of gas g in m^2/molecule and $Q^{i,g}$ is the molecular volumetric density in molecules/m^3. The total number of molecules in a gas mixture is obtained from ideal gas law as:

$$Q^{i,g} = \frac{n}{V} q^{i,g} N_A = \frac{p}{RT} q^{i,g} N_A \tag{2.4}$$

where, n is the total number of moles of gas mixture, V is the volume, N_A is the Avogadro constant, R is the gas constant and $q^{i,g}$ gives the mixing ratio of isotopologue i of gas g. The absorption cross section $\sigma^{i,g}$ included in equation 3 can be further decomposed as:

$$\sigma^{i,g}(f) = S^{i,g}G^{i,g}(f) \tag{2.5}$$

where, $S^{i,g}$ is the line intensity and $G^{i,g}$ is the spectral line shape. The line intensity gives the strength of absorption by specific molecules and can be obtained from HITRAN database.

Calculating shape of molecular absorption

To calculate line shape expressed in equation 5, position of the resonance frequency is obtained first as follows:

$$f_c^{i,g} = f_{co}^{i,g} + \delta^{i,g}p/po \tag{2.6}$$

where, $f_{co}^{i,g}$ is the zero pressure position of the resonance and $\delta^{i,g}$ is the linear pressure shift. These parameters can be obtained from HITRAN database. Absorption from a particular molecule is spread over a range of frequencies. The spreading depends on the collisions between molecules and is defined by Lorentz half-width $\alpha_L^{i,g}$. This is expressed as:

$$\alpha_L^{i,g} = \left[\left(1 - q^{i,g}\right)\alpha_0^{air} + q^{i,g}\alpha_0^{i,g}\right]\left(\frac{p}{p_o}\right)\left(\frac{T_o}{T}\right)^{\gamma} \tag{2.7}$$

where, $q^{i,g}$ gives the mixing ratio for the isotopologue i of gas g, p represents the system pressure, p_o is the reference pressure, T is the system temperature, T_o is the reference temperature and γ represents the temperature broadening coefficient. The value of α_0^{air}, $\alpha_0^{i,g}$ and γ can be obtained directly from HITRAN database.

For the very low frequency case as in terahertz band, Van Vleck-Weisskopf asymmetric line shape is used to represent the molecular absorption. This is expressed as:

$$F^{i,g}(f) = 100c\frac{\alpha_L^{i,g}}{\pi}\frac{f}{f_c^{i,g}}.\left[\frac{1}{\left(f - f_c^{i,g}\right) + (\alpha_L^{i,g})^2} + \frac{1}{(f + f_c^{i,g})^2 + (\alpha_L^{i,g})^2}\right] \tag{2.8}$$

where, f is the frequency of the EM wave, c is the velocity of light. The value of $f_c^{i,g}$ is obtained from equation 2.6 and the value of $\alpha_L^{i,g}$ is obtained from equation 2.8.

Additional adjustment to the far ends of the line shape is performed to consider the continuum absorption. The spectral line shape expressed in equation 2.5 is represented as:

$$G^{i,g}(f) = \frac{f}{f_c^{i,g}} \frac{tanh\left(\frac{hcf}{2k_BT}\right)}{tanh\left(\frac{hcf_c^{i,g}}{2k_BT}\right)} F^{i,g}(f) \quad (2.9)$$

where, h is the plank constant, c is the speed of light in vacuum, k_B is the Boltzmann constant and T is the system temperature. The value of $F^{i,g}(f)$ is obtained from equation 2.8.

The total attenuation that a signal suffers due to molecular absorption is expressed according to equation 2.1 as:

$$A_{abs}(f,d) = \frac{1}{\tau(f,d)} = e^{k(f)d} \quad (2.10)$$

Using equations from 2.2 to 2.9 in equation 2.10, total attenuation can be obtained.

2.2.2 Path loss

Total path loss suffered by an EM wave in the terahertz band is given by the sum of spreading loss and molecular absorption attenuation. This can be written as:

$$A(f,d)[dB] = A_{spread}(f,d)[dB] + A_{abs}(f,d)[dB]$$

where d represents the total path length and f is the signal frequency.

Spreading loss is the free-space loss produced due to the expansion of a wave as it propagates through the medium. This is expressed as:

$$A_{spread}(f,d)[dB] = 20\log\left(\frac{4\pi fd}{c}\right)$$

where, c is the velocity of light in vacuum. The spreading loss in the terahertz band is large which limits the maximum transmission range for communication. Due to this, terahertz band may not be convenient for classical communication. As nano communication employs short range transmission, spreading loss will not be major limiting factor for communication.

2.2.3 Molecular absorption noise temperature

When the electromagnetic wave travels through the medium, EM radiation is produced by the vibrating molecules at the same frequency as that of travelling wave. This is considered as noise and it affects the transmission of EM wave through the medium. Emissivity is the parameter which measures this noise factor and is expressed mathematically as:

$$(f,d) = 1 - \tau(f,d)$$

where, τ is the transmissivity of the medium, f is the frequency of EM wave and d is the path length. The equivalent noise temperature is expressed as:

$T_{mol}(f,d) = T_0 \in (f,d)$
where, T_0 is the reference temperature.

2.2.4 Total system noise power

Total system noise power considers the entire noise source present in the system. The antenna noise temperature consists of noise from surrounding devices in addition to the molecular absorption noise. Total system noise power is obtained by summing the noise introduced by receiver with the total antenna noise. The expression for the total system noise is given as:

$$T_{noise} = T_{system} + T_{ant} = T_{sys} + T_{mol} + T_{other}$$

where, T_{sys} is the system electronic noise temperature, T_{mol} is the molecular absorption noise and T_{other} is other additional noise temperature.

2.3 Time spread on-off keying (TS-OOK)

The channel behavior in terahertz band is affected by several factors like molecular absorption, path loss and noise. These factors in addition to power and energy constraints limit the transmission range of a nano-machine up to a few meters. The peculiarities of the terahertz band combined with the limitation of the nano-machine demand for a simple communication scheme. One of the proposed schemes is TS-OOK which is based on the transmission of extremely short pulses.

In traditional communication systems, message signal is modulated using high power carrier frequency. Nano-machines cannot generate such carrier frequency due to the size and energy constraints. As an alternative to the traditional schemes, very short pulses can be generated and radiated. Femto seconds long pulses will be appropriate whose main frequency components lies in the terahertz band.

Based on [6], detail description of working principle and capacity analysis using numerical method of TS-OOK for both single user case and multi user case is presented.

2.3.1 Working principle of TS-OOK

A logical pulse “1” is transmitted by using a Femto second long pulse and a logical “0” is transmitted as silence. This scheme helps to reduce the effect of molecular absorption noise. When a logical one is transmitted using some signal, molecular excitation occurs, resulting in molecular absorption noise. When logical zero is transmitted using silence, molecules remain still. So, no noise is produced which results in reduction of energy consumption. Initialization preambles and constant length packets are used to avoid the confusion between transmission of silence and no transmission. The receiver, after the detection of an initialization preamble will count for the number of symbols.

The time between two consecutive transmissions is much longer than the pulse duration and is kept fixed. Since the inter transmission time is fixed, a user does not need to continuously sense the channel. During the time between two transmissions, a nanomachine can receive bits from other machines or transmits its own data. Reduced need for synchronization among devices makes this method simple and suitable for nanomachine communication.

The signal transmitted by a user using this communication scheme can be mathematically expressed as:

$$s_T^u(t) = \sum_{k=1}^{k} A_k^u\, p(t - kT_s - T^u) \tag{2.11}$$

where, k gives the number of bits per packet, A_k^u is the amplitude of the k-th symbol transmitted by user u, T_s is the time between two symbols and T^u is the random initial time.

The signal received by the user j can be written mathematically as:

$$S_R^j(t) = \sum_{k=1}^{K} A_k^u p(t - kT_s - T^u) * h^{u,j}(t) + w_k^{u,j}(t) \tag{2.12}$$

where, $h^{u,j}(t)$ is the channel impulse response between users u and j and $w_k^{u,j}(t)$ is the molecular absorption noise between two users u and j.

The time between two transmissions T_s is much larger than the pulse duration T_p. Due to this multiple users can share the channel and concurrently transmit without affecting each other. Thus, there is no need of any kind of central entity controlling the transmission process. There are very low chances of having collisions in femtosecond long pulses. But in certain time instance there may be collisions. In TS-OOK, all types of collisions are not harmful. In silence, there is no pulse transmitted. Therefore, there is no collision. In collision between silence and pulse, only receiver of silence will feel the difference. Collision between two pulses will affect both receivers. The harmful collisions will create multi-user interference and limits the capacity of the channel.

In this case, the signal received by the receiver is represented mathematically as:

$$S_R^j(t) = \sum_{u=1}^{U} \sum_{k=1}^{K} A_k^u p(t - kT_s - T^u) * h^{u,j}(t) + w_k^{u,j}(t) \tag{2.13}$$

where, U is the total number of users.

2.3.2 Numerical analysis of network capacity

The channel capacity in single user case is represented mathematically as:

$$C_{u-sym} = \max_X \{ -\sum_{m=0}^{1} pX(x_m) \log_2 px(x_m) - \int \sum_{m=0}^{1} \frac{1}{\sqrt{2\pi N_m}} e^{-1/2 \frac{(y-a_m)^2}{N_m}} \mathrm{pX}(x_m). \log_2 \left(\sum_{n=0}^{1} \frac{pX(x_n)}{pX(x_m)} \sqrt{\frac{N_m}{N_n}} e^{-1/2 \frac{(y-a_n)^2}{N_m} + 1/2 \frac{(y-a_m)^2}{N_m}} \right) dy \} \text{ [bit/symbol]} \tag{2.14}$$

The capacity in bits/seconds can be obtained by multiplying the bits/symbol with the rate at which symbols are transmitted. The rate is given as:

$$R = {}^{1}/_{T_s} = {}^{1}/_{(\beta T_p)}$$

where Ts is the inter symbol time, Tp is the pulse duration and β is the ratio of inter symbol time and pulse duration. Considering, BTp≈ 1, where B is the channel bandwidth, the capacity of the channel is given as:

$$C_u = \frac{B}{\beta} C_{u-sym} \text{bit/second} \tag{2.15}$$

Solution of the equation (2.15) above will give the capacity of the channel in single user case. Solving this equation analytically is not feasible, so numerical solution is preferred. Total path loss and molecular absorption noise can be calculated using terahertz propagation model. Transmitted pulses are taken as first-order time-derivative of a 100-femtosecond long Gaussian pulse. Similarly, total pulse energy is taken as 1pJ and transmission distance 10 micrometers to 10 meters is taken. When β is taken 1000, channel capacity is 10 Gigabit/second and when value of β is taken 10 channel capacity is 1 Terabit/second. When the transmission distance is increased, capacity decrease up to certain point increases again and remains constant after that.

Similar network parameters for distance, power and losses as in single user capacity analysis are taken in multi user capacity analysis. Value of β is taken as 1000.The capacity can be calculated as a function of distance and number of users. When the number of users is low, the capacity of each individual user behaves in the same way as that of single user capacity. So the capacity is in few terabits per second. With the increase in transmission distance capacity decreases but does not become zero. When the number of users is increased there will be a point when individual capacity will be zero.

2.4 Network layer: least worked in protocol stack

To make communication between two nodes possible, different functions has to be performed in each node. These functions are defined and performed in different layers of protocol stack. Protocol stack of traditional TCP/IP model is not suitable for nano communication. Therefore, new protocol stack for nano network is envisioned. This protocol stack consists of four layers which are: Message Process Unit, Network layer, Media access control entity and PHY interface. Message process unit is responsible for generating and processing messages. Similarly, Network layers handles routing operations. Media access control entity is responsible for managing flow of packets in the network and PHY interface describes the transmission technique.

Considerable work has been done related to implementation of PHY interface. Communication techniques based on transmission of short pulses are proposed. One of the most promising communication methods is Time spread on-off keying (TS-OOK). In TS-OOK message is sent by using sequence of pulses. A logical pulse “1” is transmitted by using a Femto second long pulse and a logical “0” is transmitted as silence. Channel capacity of TS-OOK method is estimated for single user case and multi user case using both analytical and numerical methods.

Asynchronous techniques are proposed as channel access procedures. Smart MAC and Transparent MAC describe two methods for channel access control. Smart MAC includes many computation requirements.

Network layer handles routing operations. Complex routing algorithms requiring different computational calculations cannot be implemented in nano node. This limitation demands for a simple routing technique like flooding. Simple flooding techniques suitable for nano communication are not proposed so far. Some variants of flooding are proposed on various works but require extensive computations.

In this thesis work, simple flooding algorithm is proposed and is implemented by RADAR routing method. This work will try to solve the network layer problem. In simple flooding algorithm, each node transmits packets to all other nodes except the one from which the packet came. Every node keeps information of five previously transmitted packets to reduce redundant messages. This will significantly reduce the memory and processing requirements. Since there will be large number of packets in the network, collision will occur. To reduce the collision and packet loss associated with collision RADAR routing algorithm is implemented. In this method only nodes in certain area are in on stage at a particular time and other nodes are in off stage. This will reduce number of packets in the network at a particular time and subsequently will reduce the collision in the network.

3. ROUTING PROTOCOLS

3.1 Introduction

The purpose of any communication system is to transport information from one place to another. Different communication systems implements different techniques to do this job. These techniques are called routing techniques, which helps to transport information. The routing in communication network, called network routing, is defined as the capability of an electronic communication network to send information from one place to another. Different factors defining routing are addressing, routing path discovery and efficiency.

Addressing gives information about the destination place. Addressing in modern communication network like internet is called Internet Protocol (IP) addressing. Internet is defined as the network of network and consists of millions of devices connected with each other. Each device has its own unique IP address with which these devices can be distinguished. Routing protocols send information using IP address from source to destination. To help in this process, there are routers and gateways. Additional protocols are needed to handle several issues that arise in communication network. The delivery of information is not sufficient, it should be reliable too. If several packets are sent together, there may be congestion in the network. Similarly, if more than one device sends the information together, there may be collision. To handle all these issues there will be many protocols in addition to routing protocols. Network architecture defines the functionality given to different protocols and relationship between them.

In traditional computer network, routing is performed in network layer of TCP/IP architecture. The dedicated machines which perform routing are called routers. The routing algorithms run in the router machine. Each machine in the network has the unique address called IP address. The IP address consists of 32 bit address separated into two parts: Host id and network id. All the routing protocols use IP address to perform routing.

There are many routing protocols available having its own advantages and disadvantages. Routing protocols are broadly classified into two groups: adaptive and non-adaptive routing. In non-adaptive routing, current topology or traffic is not taken into account while making routing decisions. All routes are decided in advance and downloaded into network. These are also called static routing algorithms. In adaptive routing, network parameters like topology, network traffic are taken into consideration while making routing decisions. These are also called dynamic routing algorithms. These algorithms are described based on [7] as follows:

Static routing algorithms

Two of the commonly used static routing algorithms are shortest path algorithm and flooding. In shortest path algorithm, shortest path between two routers are obtained using Dijkstra's algorithms. The packets are routed using the shortest path. In flooding, each packet is sent to every other links except the link from which the packet comes.

Dynamic routing algorithms

These are complex routing algorithms implemented in most of the modern day computer network. Two types of dynamic routing algorithms are available which are: Distance vector routing and link state routing.

Distance vector routing

In this algorithm, each router maintains a table called the routing table. This table stores the best known distance to each destination and the corresponding link. These tables are regularly updated by the exchange of information with the neighbors. The distance can be number of hops or propagation delay. The main drawback of distance vector routing is slow convergence. Convergence is defined as settling of routes to the best paths. Some of the commonly used distance vector algorithms are RIPv1, RIPv2 and IGRP.

Link state routing

Long convergence time in distance vector routing presses for a new routing algorithm. Accordingly distance vector routing is replaced by link state routing algorithm. The working of link state routing is described as below:

a. Each router discovers its neighbors and learns their network addresses.
b. Each router constructs sets the distance to each of its neighbors.
c. Each router constructs a packet having all the information it has learned.
d. Each router then sends this packet to and receives packets from all other routers.
e. Each router computes the shortest path to every other router.

Some of the commonly used link state routing algorithms are IS-IS and OSPF. This chapter starts with description of different router functionalities. This is followed by section which examines the usefulness of traditional routing algorithms in nano network. The next section describes flooding algorithm including different types of flooding. Final section examines the flooding method most suitable in nano network.

3.2 Basic router functionalities

The basic components in a router are: network interfaces to the network, processing module, buffering module and an interconnection unit. A router receives packets at an incoming network interface, is processed by the processing module and finally stored in the buffering module. Now, these packets are forwarded to the outgoing interface through internal interconnection unit. The outgoing interface transmits these packets to the next hop. [8]

The basic architecture of an IP router consists of: Controller card having the CPU, router backplane and interface cards. The main functionality of CPU is to perform path computations, routing table maintenance and reachability propagation. The interface card consists of adapters which performs inbound and outbound packet forwarding. The router backplane transfers packets between the cards. So the basic functionalities of IP router are categorized as: route processing, packet forwarding and router special services. Route processing includes path computation, routing table maintenance and reachability propagation. [8]

The basic router functionalities are described based on [8] as follows:

3.2.1 Route processing

This is responsible for routing table construction and maintenance using routing protocols like RIP or OSPF.

3.2.2 Packet forwarding

IP packet forwarding includes steps which are described as below:

IP packet validation

The router first of all checks whether the packet is properly formed for the particular protocol or not. This requires checking the version number, checking the header length field and calculating header checksum.

Destination IP addresses parsing and table lookup

The router has to perform a table lookup to find the output port on which packet should be directed and to determine the next hop to which packet should be sent. This process is carried out by using destination IP address and subnet masks.

Packet lifetime control

Time to live (TTL) determines how long packet can be in the network. The router sets the TTL value to prevent packets from circulating endlessly in the network. At each hop, value of TTL is decremented and the packet is discarded if the value is zero.

Checksum calculation

The header checksum should be computed if value in certain header fields is changed. Similarly, routers have to perform fragmentation if the packet size exceeds the maximum transmission unit (MTU) limit.

Special services

These are services which lie beyond core routing functionality. This includes packet translation, encapsulation, traffic prioritization, authentication and packet filtering.

3.2.3 Route table lookup

When router gets the packet with certain destination IP address, it performs a routing table lookup. This lookup gives the best match in the table telling the router which interfaces to use to forward the packet and the IP address of next hop. The matching in routing table is performed using longest prefix match algorithm. It is performed using binary trees like the radix tree or modified Patricia tree. These lookup algorithms have complexity proportional to the number of address bits. Some better methods are also proposed to reduce complexity and processing requirements. But still, route lookup is very expensive procedure.

3.3 Traditional routing protocols and nanonetwork

The traditional routing protocols require large memory and powerful processors to perform complex computations. Regular route updates, routing table lookup, checksum computations and other operations requires complex processors. The memory should be large enough to store routing program, routing table and complex calculations. On the other hand, nano-machines have the size of up to hundred nanometers with primitive memory and processing capabilities. Nano-machines do not have the memory capability to store routing table, neither they have processing capability to perform route lookup. The traditional routing model and corresponding routing protocols will not work on nano-machines due to memory, processing and power constraints. Instead, a simple forwarding algorithm is required. The algorithm should not include decision making procedures, route discovery procedures and other complex calculations. This will minimize the need of complex circuits and large memory space.

Flooding can be the envisioned as the routing protocol which will work in nano machine.

3.4 Flooding

Flooding is one of the simplest routing algorithms. In this technique, each incoming packet is sent to all the outgoing links except the one from which the packet comes. Flooding generates large number of duplicate packets consuming large amount of bandwidth. There should be some mechanism to control duplicate packets. One of the methods is to put hop counter in the header of each packet. The hop counter can be assigned certain value which decrement at each hop. When the value becomes zero the packet is discarded. Another method is to keep track of the packets that are flooded once. If the packet comes next time, these are discarded.

Flooding is not useful in most applications. But flooding has certain advantages over other algorithms. Flooding ensures the delivery of packet to each node in the network. If there is only one destination node, it is wasteful to send packets to each destination. On the other hand, if the packet is destined to many nodes, flooding is useful. Another advantage of flooding is its robustness. If most of the links from source to destination did not work due to certain reasons, it will ensure delivery of packet if there is one path available. There are various types of flooding techniques available like: simple flooding method, probability based method, Location-based method, Neighbor knowledge based method, and Distance based method.

3.4.1 Simple flooding method

A source node broadcasts packets to all its neighbors. After receiving the packet, the neighbor node transmits the packet to their neighbor nodes. Each node transmits the packet only one time. The transmitting nodes do not keep other nodes information. These simple flooding algorithms can be classified as:

Pure flooding

Pure flooding or blind flooding is the simplest flooding technique. In this algorithm, every node in the network transmits the flooding message if the packet is new to the node. So, n transmissions are required in a network of n nodes. This scheme guarantees that a flooding message will reach every node in the network. The drawback of this algorithm is that it will generate excessive amount of packets in the network. This will consume energy and cause congestion in the network. If all the nodes transmit at the same time, collision may occur, causing more retransmissions. This may also cause some nodes to fail to get the message. [9]

The drawbacks of pure flooding can be listed based on [9] as follows:

Redundant rebroadcasts

When a mobile node broadcasts to neighboring nodes, the neighbors may already have that message causing redundancy.

Contention

When a node broadcasts a message, if most of its neighbors also rebroadcast the message, interference occurs.

Collision

In the absence of back off mechanism and collision detection algorithms, collisions may occur.

3.4.2 Probabilistic flooding scheme

The problems faced by simple flooding algorithm can be reduced by disallowing some nodes from transmission. In this scheme, each node transmits a message with probability ‘p’ after receiving it for the first time. This requires considering different parameters to calculate the probability. This method is equivalent to pure flooding when p=1. [10]

3.4.3 Counter based method

Counter based method is the variant of probability based method. This method takes into consideration network dynamics while making decision whether to forward the packet or not. The counter based method uses two metrics called timer and counter. The timer value is randomly chosen between zero and T_{max}. The timer value is decremented and counter is incremented by one when the same packet comes another time. The value of counter is compared with certain threshold value when the value of timer reaches zero. If this counter value exceeds the threshold value, packet is discarded. This method is relatively simple and adapts according to network topology. In dense network, certain nodes will not broadcast packets whereas in sparse network all of the node will broadcast. [11]

3.4.4 Location based method

Location based method uses location information to make decision whether to forward the message or not. This method selects the node which is closest to the destination. The main shortcoming of this method is that each node should have the knowledge of location information of neighbor nodes. This can be solved by exchanging location information with each other but it incurs too many overhead in message exchanges. [11]

3.4.5 Distance based method

In this method, relative distance between hosts is taken into consideration while making forwarding decisions. Let us consider d is the distance between node that receives the message B and node that transmits the message A. If d is small then B could not have large coverage when it retransmits the message obtained from A. When B got the packet from A, other nodes neighboring to B may have got the message. This is due to the fact that A and B are near to each other. When d is large, B will have large coverage area since neighbors of B and neighbors of A are different. So to implement the distance based method, a threshold distance D is maintained and compared with the distance between transmitter and receiver d. If $d<D$, message is not transmitted and if $d>D$, message is transmitted. [10]

3.4.6 Cluster based method

Cluster based flooding is based upon graph modeling of the network. Each host in the network has a unique ID. The host which has minimal local ID is declared as cluster head with all surrounding nodes as members of the cluster. The cluster head has reachability to every node inside the cluster. Within the cluster, a node that can communicate with node in another cluster is called gateway. The propagation of message from one cluster to another cluster is handled by gateway node. So, all nodes except gateway and head do not retransmit messages. When a message is heard inside the cluster, different actions are taken depending upon whether the node is head, gateway or simply member. If the node is simple member the rebroadcast is not performed. Otherwise, one of the flooding schemes like probabilistic or location based is used to decide whether to re-transmit the message or not. [10]

3.4.7 1-hop neighbor knowledge methods

In these methods, each host keeps the information of 1-hop neighbors. This information can be obtained by using HELLO message with each other. Now, subset of neighbors is selected which will rebroadcast the message. There are two strategies for selecting these forwarding nodes: sender based and receiver based. In the sender based method, each sender selects neighboring nodes which will act as forwarding nodes. In receiver based method, each receiver decides on its own whether it should forward the message or not.

Flooding with self-pruning (FSP)

It is the simplest flooding method based upon 1-hop neighbor knowledge method. It is receiver based algorithm. A sender transmits message to all of its 1-hop members attaching the node list which shows all the members to which message is transmitted. The receiver compares its neighbors list with the node list and do not transmit the message if the two list matches with each other, otherwise it transmits the message. The overhead in flooding with self-pruning lies in the requirement of exchanging neighborhood information. [12]

Edge forwarding

Edge forwarding is one of the efficient flooding algorithm which uses location information to control the flooding traffic. There are two forwarding rules in edge forwarding: basic forwarding and advanced forwarding. When a node forwards a message it adds its ID to the packet header. In this method, each node’s transmission range is divided into 6 regions as in figure 3.1. Let us consider transmission range of node S which is divided into six regions P1 to P6. If there is a node O in P1, which gets the message from S, then transmission region of O is also divided into 6 regions. [13]

The intersection region between P1 and 6 regions of O can be labeled as S_{P1-6}.In basic forwarding technique, S checks for the node in this intersection region. If there is any single node in one of these regions, S will not transmit, and otherwise it will transmit the message to the neighbor nodes. [13]

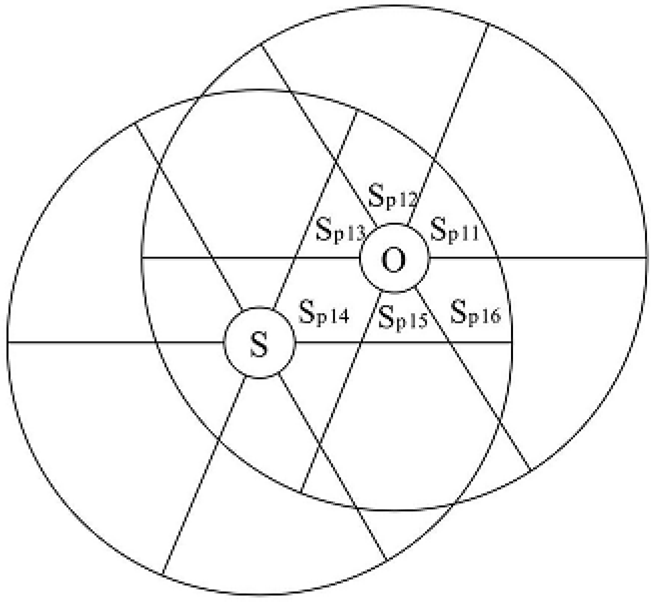

Figure 3.1 *Node O divides SP1 into 6 partitions "taken from [Cai, Y., Hua, K. A. & Phillips, A. 2005. Leveraging 1-hop neighborhood knowledge for efficient flooding in wireless ad hoc networks. Performance, Computing and Communications Conference, April 7-9, 2005. IEEE. pp. 347-354]"*

In advanced forwarding technique, O does not forward message obtained from S if following conditions are valid:

a. There is at least one node in region of S_{p11}, S_{p12}, S_{p13}.
b. All of O's P_3 neighbors beyond 1-hop distance to S are within 1-hop distance to hosts inside S_{p12}.
c. All O's P_5 neighbors beyond 1-hop distance to S are within 1-hop distance to hosts inside S_{p16}.

Vertex forwarding

This algorithm tries to minimize network traffic by using location information of 1-hop neighbor nodes. This is sender based algorithm which assumes that nodes are arranged in hexagonal structure in network field.When a node gets a message, it assumes that it is at the vertex of the hexagonal structure. Now it selects the node that are located at the adjacent vertices. If there is no node at the adjacent vertices then node located nearest to the vertices are selected. [14]

3.5 Flooding in nanonetwork

Several flooding techniques are described above. Each technique has its own advantages and disadvantages. Pure flooding algorithms are simple and has low complexity but network suffers from excessive packets. Probabilistic flooding reduces the number of packets in the network but requires the computation of right probability value. Flooding with self pruning also reduces number of packets and reduces flooding costs. But complex calcualtions are needed to find appropriate neighbor nodes. Similarly, edge forwarding and vertex forwarding reduces the number of redundant messages but complex calculations are needed to find the appropriate neighbors.

Nanonetwork has constraint of memory, computaion and energy resources.While choosing flooding algorithm, these constraints should be taken into account.The simplest flooding technique in terms of complexity is pure flooding. It forwards packets to every outgoing nodes except the one from which the packets came. It donot need complex algorithms to decide which node should be the next forwarder. Due to these reasons, pure flooding will be the routing technique suitable for nano network.

Pure flooding has many drawbacks that should be addressed. Since, it forwards packets to all outgoing links there will be flury of packets in the network. The packets can circulate in the network forever if no mechanisms are implemented. To control the infinite looping of packets, TTL value can be used in the data packet.When the TTL value is reached the packet will be discarded. The overflooding will cause congestion in the network and will consume bandwidth. Since nodes transmit redundant packets, network resources like battery power will be used unnecessarily.

One solution is to maintain a table that will store source ID and packet ID of the packet that are once forwarded by the node. When a node receives a packet, it will check whether it has previously forwarded this packet or not. The node will forward the packet only if it is the new packet. This will greatly help to reduce the number of duplicate packets. But this method has certain drawbacks when implemented in nano network. Each device has to store long source ID and packet ID. Then it has to perform comparison operation for every incoming packet. This will require large memory and computation operation which are limiting resources for nano machine.

These problems can be removed by introducing some centralized support in nano sensor networks.This centralized support can be a equipment which can emit certain radiation beam and rotates at regular time interval. The sensor nodes will be turned to on stage after coming in coverage area of the radiation. Since the equipment rotates regularly at certain angle, some sensors will be in off stage and some sensors will be in on stage. The sensors that will be in off stage will not forward any flooded messages. This will greatly reduce number of redundant message. Also the sensors in off stage will not use any battery power resulting in saving of energy which is a scarce resource. Similarly the nodes do not have to store large ID to identify whether certain message is the new message or not.This will reduce the memory requirements of the nano-machine.

4. RADAR ROUTING

4.1 Introduction

Routing is the process of forwarding the message from one node to the other in the network. There are several routing strategies available. Among these techniques, simple flooding is the most appropriate technique in nanonetwork. In simple flooding, each node transmits packets to all outgoing links except the one from which the packet came. In addition to this, a node will transmit only those packets which it has not transmitted in the past. To achieve this, every node should store the information of packet ID and node ID corresponding to each packet. This will reduce the number of packets in the network by not forwarding the redundant messages.

Nanonetwork consists of nano-nodes having low storage and limited computational capabilities. These nodes do not possess capabilities to store the pair of packet ID and node ID for large number of nodes. This requires a new routing model that will reduce the redundant message and also satisfies the resource constraints of nano-nodes. So, a new routing model called RADAR routing is proposed.

In radar model, all nodes are assumed to be uniformly distributed in a circular area. There will be a central entity which rotates regularly at certain angle. The angle of rotation can be varied according to the application scenario. The rotating entity will emit radiation that will change the state of sensors into on and off stage. All other nodes which are not in the region of radiation will be in off stage. The sensors in off stage will neither generate nor forward messages and will not consume any battery power. Only the sensors in on stage will generate and forward messages. This will drastically reduce the number of messages in the network. This will lead to the reduction in collision and increases network throughput. Since the sensors in off state will not consume battery power, this model is suitable with regard to energy consumption. To study the RADAR model in detail, simulation technique is used. Nano-Sim is used as the simulation tool to study nanonetwork.

This chapter begins with the introduction about Nano-Sim as a simulation tool. The next section is dedicated to network architecture of nano sensor network including network entities and protocol stack. This is followed by description of simulation parameters. The next section gives an overview of working procedure of simulation tool. The chapter is concluded with the introduction of a parameter called probability of a packet to reach destination.

4.2 Simulation of wireless nano sensor network using nano-sim

Future technological advancement can make realization of practical nano-machines possible. These nano-machines will be equipped with sensing, storage, processing and communication capabilities. They will have diverse application areas in biomedical, industrial, ICT and military fields. Current research activities are focused on feasible communication methods, communication channel modeling, antenna design, energy resources and so on. To help these research activities, simulation platform is envisioned for nanonetworks. The research community can devise, add and test new protocols and solutions using the simulation tool. The simulation platform will help research activities directed towards common goals and will also help to analyze the performance of different protocols.

Nano-Sim is proposed as the simulator for EM-based nanonetworks. It is written in C++ using the object oriented paradigm and runs on top of NS-3 which is an emerging discrete event and open source network simulator. Nano-Sim is freely available and has modular structure to allow for future upgrades. The main features of Nano-Sim are: physical interface which is based on TS-OOK modulation scheme, Simple MAC protocol, routing module based on the flooding technique and a unit for generating and processing messages.

4.3 Network Architecture

4.3.1 Network entities

A general WNSN is composed of three types of nodes which are: nanonodes, nanorouters and nanointerfaces.

Nanonodes

These are the simplest and smallest nano-machine which can perform simple computation tasks. These nodes have limited memory and can transmit over short distances.

Nanorouters

These are devices having larger computation capability than nanonodes. They will perform as an aggregator of information coming from nanonodes. They will also control the behavior of nanonodes by exchanging simple control commands.

Nanointerface

Nanointerface will aggregate the information coming from nanorouters and will deliver it to the micro scale world. So, nano interface will work as a gateway between nano world and external world.

In the RADAR model, we have envisioned two types of nodes which are nanonodes and nanointerface. Nanorouters are complex devices than nanonodes increasing the complexity of the network. Hence, routers are not considered in our model. Nanonodes collect the information, routes it to other neighbor nodes and finally delivers to the nanointerface.

In Nano-Sim, these devices are represented by using different classes. Each device is represented by a unique ID and contains several entities like physical interface, MAC entity, network layer and message process unit.

4.3.2 Protocol stack

Due to the limitation on size, storage, energy and processing capabilities, traditional prototype stack cannot be used in nanonetwork. Hence TCP/IP cannot be used directly in nano world. A new prototype protocol stack is used in Nano-Sim which consists of following unit:

a. Message Process Unit
b. Network layer
c. Media access control entity
d. PHY interface

These units are shortly described based on [15] as follows:

Message Process Unit

The message process unit is responsible for generating and processing messages. A constant bit rate source produces fixed length packets periodically. The size of packet and the inter-arrival time can be varied by the user. A new message created by message process unit is send to the physical interface through the protocol stack. When a new packet is received in the channel, it will be delivered to the network layer. The network layer will verify whether the packet is targeted to this node or not. If this is the destination node, packet will be sent to message process unit otherwise packet will be routed to other nodes.

Network layer

Network layer handles routing issues. Once a device receives a packet, it will send it to all nodes in its transmission range using flooding algorithm. When network layer receives packet from message process unit, it add a header composed of different fields. The fields in the header are source ID, destination ID, packet ID and time to live (TTL). Source ID identifies the node which generates the message and destination ID identifies the destination device. Packet ID is assigned by message process unit using some sequential method and TTL is set to the value of 100 which decreases by one on each hop.

A packet that comes from MAC layer and not directed towards the device will be forwarded to other nodes using flooding algorithm. To control the transmission of duplicate messages, each node stores information about five recently received packets. Each packet is identified by the pair of source ID and packet ID. So packets will be checked whether they are already transmitted by the node in past or not. If so, the packets are discarded.

Media access control unit

MAC layer is implemented as a simple transparent MAC. It does not handle acknowledgement and retransmission of packets. There are no additional headers in this layer. So a packet from network layer is passed to the physical layer without executing any sorts of control operation.

PHY interface

In traditional network, the communication algorithms are based upon transmission of signals with very long duration. Due to constraints of nano world this technique is not possible. Since the nano world works in the terahertz band, transmission technique based on short pulses is suitable. The modulation technique used is Time spread on-off keying (TS-OOK). In TS-OOK, short pulse is encoded as 1 and absence of pulse as 0.

4.3.3 Channel and physical models

Nano machine communicates in the terahertz band. The bandwidth associated with terahertz band is few terabits/sec and transmission range of nano-machines ranges up to hundred nanometers. Considering the huge capacity available, communication methods based on the transmission of short pulses are considered. One of the most promising methods is time spread on off keying (TS-OOK). Nano-Sim provides the physical layer based on TS-OOK. In TS-OOK message is sent by using sequence of pulses. Simulating the transmission and reception of each pulse will make functioning of Nano-Sim complex due to the availability of large number of nodes. So, the packet transmission is handled in the system level and is described based on [16] as follows:

a. First of all, the MAC entity calls the PHY interface method. This interface is responsible for packet transmission.
b. The physical layer creates the data structure representing the signal. The data structure stores parameters such as transmission start time, pulse duration, pulse transmission interval and transmission duration. Based upon these parameters, total transmission time is calculated.
c. The data structure created above will be delivered to the channel. From the channel, the data structure is delivered to all the nodes in the range of the sender node.
d. The destination node checks whether there are any collisions or not. A collision is said to occur if pulses of different transmissions overlap with each other in time domain. If the packet is correctly received it is forwarded to the upper layer otherwise it will be discarded.

4.4 Simulation parameters

We need several parameters to run the simulation. The value of these parameters can be set according to the need of the user. The network response will be different based upon the simulation parameters. These simulation parameters can be described as below:

Number of Interface

Interface is the most complex node in the nanonetwork which acts as a gateway between the nano and the external world. Interface receives the message generated and propagated by the nanonodes. In our experiments with or without using RADAR model, number of Interface is one. This is located at the center point of distribution area of nodes.

Initial TTL value

TTL value gives the maximum number of hops a packet can travel in the network. If the packets do not reach the destination till this value is reached, the packet is discarded. TTL is included in the header fields of packet and is decreased by 1 on each node it travels. In our experiments, Initial TTL value is set as 100.

Packet size

The packet size represents the number of bits one message packet can hold. The packet size is the sum of both header fields and data. In our experiments packet size is taken as 100 bits.

Pulse energy

Pulse based communication algorithms are suitable for communication between the nanonodes. A logical “1” is transmitted by using a femtosecond long pulse and a logical “0” is transmitted as silence. The energy required to transmit a pulse is called the pulse energy. In our experiment pulse energy is taken as 100 Pico joules.

Pulse duration

It is the time for the transmission of single pulse. In our experiment the value of pulse duration is taken as 100fs.

Pulse inter-arrival time

It is the gap in time between two pulses. In our experiment the value of pulse inter-arrival time is taken as 10ps.

TX range of Nano nodes

It is the distance to which one node can transmit the message. The transmission range of nano-machines cannot exceed few tens of millimeters. In our experiment the transmission range is taken as one millimeter.

X-range and Y-range of nanonodes distribution

This gives the geographical distribution of nanonodes. In our experiment, the nodes are generated in a circle of radius 1cm and are distributed uniformly. The interface is positioned at the center of circle.

Number of nodes

We can run simulation using any number of nodes. It depends upon the need of the user. We have used 200, 500 and 1000 as number of nodes in our experiments.

Message generation time

Message generation time indicates the time for which message is generated. Its value varies according to the application. Value of 0.1, 0.5, 1, 5, 10 and100 micro seconds is taken as the message generation time in our experiments.

Angle of rotation

This gives the angle through which the central entity will be rotated. The angle of rotation will determine the number of nodes which are in on stage and in off stage. While implementing the radar model the angle of rotation is taken as 30, 60 and 90 degree in our experiments.

4.5 Simulation description

The wireless nanonetwork in our simulation consists of 200, 500 and 1000 nodes and one interface. The nodes are distributed uniformly in a circular area of radius 0.1m. The Interface is located at the center of circle. The nodes are distributed according to the random function. All the nodes and the Interface are supposed to be static in nature. The nanonodes sense the environment and produces packets periodically with the packet interval of 0.5 second. These packets are routed to the final destination which is the nanointerface. Since a single node does not have the capabilities to send the packet directly to the nanointerface, it sends to the nearby nodes using flooding technique. The centrally located interface sends this information to the external world.

The physical layer parameters are set by assuming a standard medium with 10% of water vapor. The transmitter encodes logical “1”s by using the first time-derivative of 100 femtosecond long Gaussian pulses. The energy of a pulse is limited to 100 pJ.
The simulation will run according to the set parameters and the output file will be obtained. To get the useful information from the output file, post processing must be done. Post processing can be done using a program written in PHP programming language. PHP program takes the output of simulation as input and produces the file having desired information.

To make the data analysis easier, plotting should be done. For plotting, gnu plot is the tool that is used. Gnu plot is command line program which can generate two-dimensional and three dimensional plots of functions and data.

Figure 4.1 *Block diagram showing different stages of post processing*

The output from the simulation run is stored in .txt format. This file is very large and we cannot analyze it manually. This output file is fed into php program and it filters this file and keeps only required information in output file. This output file is used to calculate probability of a packet to reach the destination.

4.6 Probability of packet to reach destination (ppd)

The output file after processing gives the number of transmitted packets and number of received packets. The ratio of number of received packets and the number of transmitted packets gives the probability of a packet to reach the destination. This value is used as a parameter to analyze RADAR routing. If the probability of packet to reach destination is 0.5, half of the total transmitted packets are successfully received at the receiver.

5. PERFORMANCE EVALUATION

5.1 Introduction

To study the RADAR model, simulations are performed without implementing RADAR model and with implementing RADAR model. By comparing the results of the simulation experiments we can evaluate the performance of RADAR model.

The response of nanonetwork can be different with changing network parameters. There are several parameters that can be changed and response of the network can be analyzed accordingly. Some of the network parameters that can be changed are:

a. The number of nanonodes may vary.
b. The message generation time may vary.
c. The angle of rotation in RADAR model may vary.

To analyze the network behavior in different situations, simulation run is performed. The simulation is performed using Nano-Sim which is add-on to the ns-3 simulator. The Simulation parameters that are common to all the simulations are shown in table 5.1 below.

Table 5.1: *Common Simulation parameters*

Number of interface	1
Initial TTL value	100
Packet size	100 bits
Pulse energy	100e-12J
Pulse duration	100 Femto second
Pulse inter-arrival time	10 Pico second
Transmission range of Nano nodes	0.001m
Radius of circle	0.01m
Position of Nano-interface	On center of circle of radius 0.01m

Similarly simulation parameters that are different for different applications are shown in table 5.2 below:

Table 5.2: *Additional simulation parameters which varies between different simulation*

Message generation time	Number of nodes
0.1 micro second	200, 500, 1000
0.5 micro second	200, 500, 1000
1 micro second	200, 500, 1000
5 micro second	200,500,1000

10 micro second	200,500,1000
100 micro second	200,500,1000

This chapter starts with the description of various tests performed without using the RADAR model. This is followed by description of tests performed by implementing RADAR model. Both of these sections include tables having probability of a message to reach its destination for different message generation time and corresponding plots. This chapter concludes with the conclusion.

5.2 Tests performed without implementing RADAR model

Using the parameters from table 1 and table 2, nine simulations run are performed without implementing the RADAR model. These can be classified in three groups as:

5.2.1 Number of nodes is 200

The probability of a packet to reach its destination successfully for different message generation time is shown in table 5.3 as below:

Table 5.3: *ppd values for different message generation time when number of nodes is 200*

Message generation time	Probability of a message to reach its destination
0.1 micro second	0.45
0.5 micro second	0.78
1 micro second	0.94
5 micro second	0.96
10 micro second	0.99
100 microsecond	0.99

The results above shows that probability of correct packet reception increases with increase in message generation time. The simulation data obtained as above in table 5.3 are used to plot histogram using gnu plot. The histogram plot obtained is represented as below:

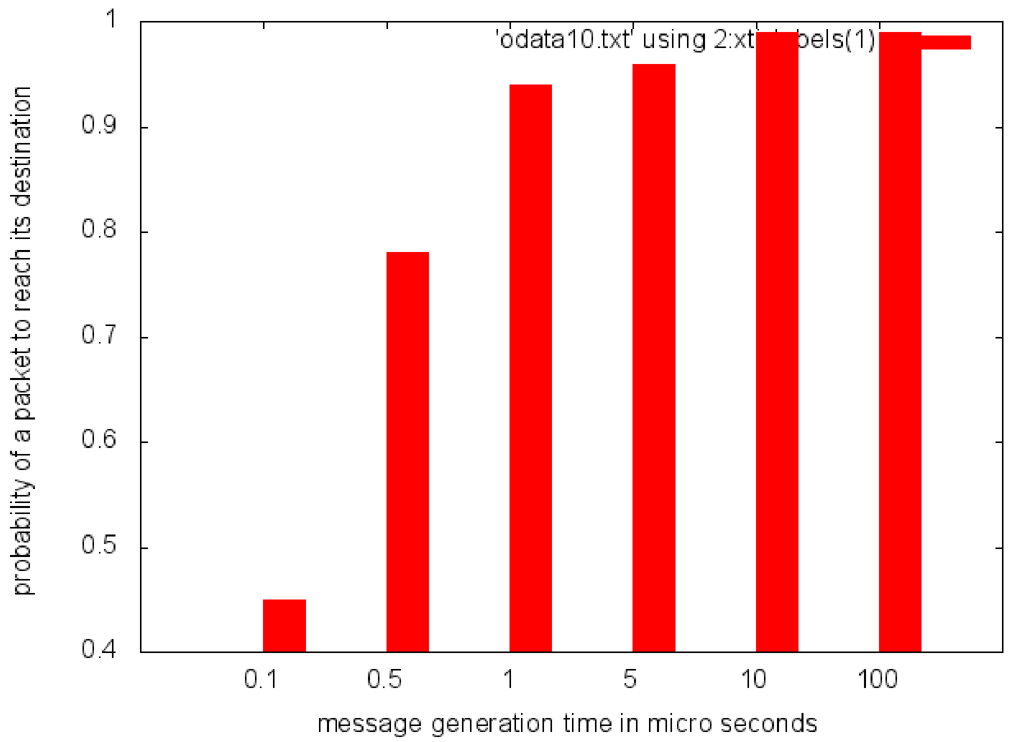

Figure 5.1: *Histogram plot showing ppd for different message generation time when number of nodes is 200*

5.2.2 Number of nodes is 500

The probability of a packet to reach its destination successfully for different message generation time is shown in table 5.4 as below:

Table 5.4*: ppd values for different message generation time when number of nodes is 500*

Message generation time	Probability of a message to reach its destination
0.1 micro second	0.21
0.5 micro second	0.64
1 micro second	0.87
5 micro second	0.94
10 micro second	0.98
100 micro second	0.99

The simulation data above demonstrates that probability of packet reception increases with increase in message generation time. This trend is similar as in the case when the number of nodes is 200. But the probability value is decreasing with the increase in number of nodes when compared with the case when the number of nodes is 200.

These simulation data are used to plot histogram using gnu plot. The histogram obtained is as below:

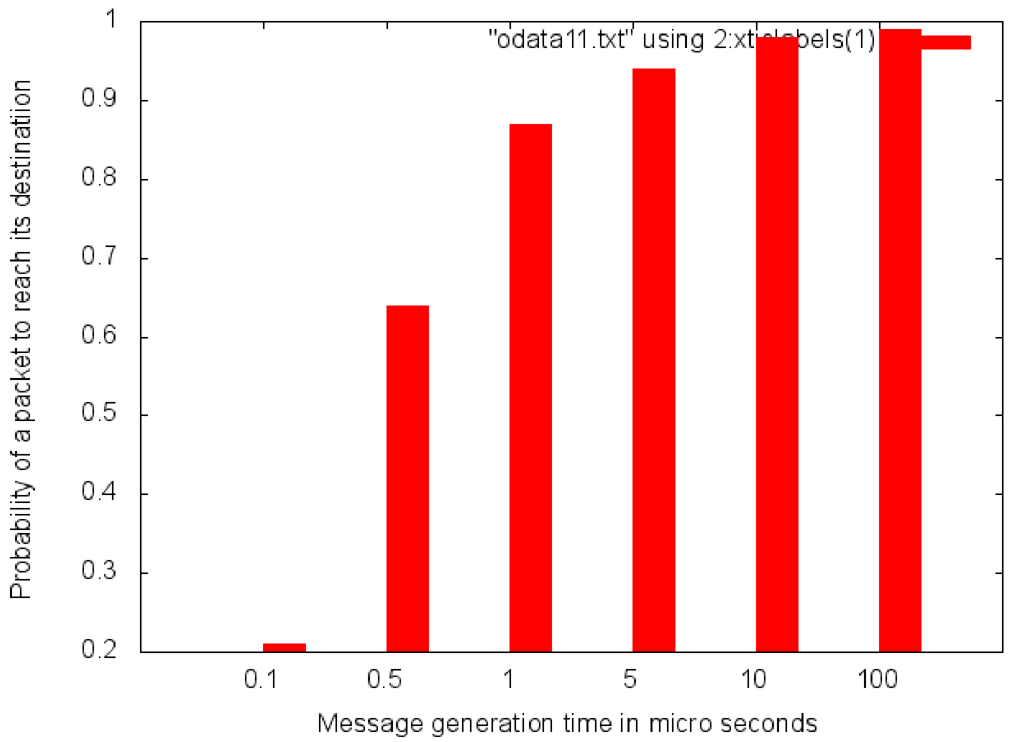

Figure 5.2: *Histogram plot showing ppd for different message generation time when number of nodes is 500*

5.2.3 Number of nodes is 1000

The probability of a packet to reach its destination successfully for different message generation time is shown in table 5.5 as below:

Table 5.5: *ppd values for different message generation time when number of nodes is 1000*

Message generation time	Probability of a message to reach its destination
0.1 micro second	0.11
0.5 micro second	0.42
1 micro second	0.78
5 micro second	0.91
10 micro second	0.97
100 micro second	0.99

The simulation data above shows increase in probability of a message to reach destination with increase in message generation time. The trend is similar as seen in the cases when number of nodes is 200 and 500. Similarly the probability value is decreasing with increase in number of nodes as compared with the cases when number of nodes is 200 and 500.These simulation data are used to plot histogram using gnu plot. The histogram obtained is as below:

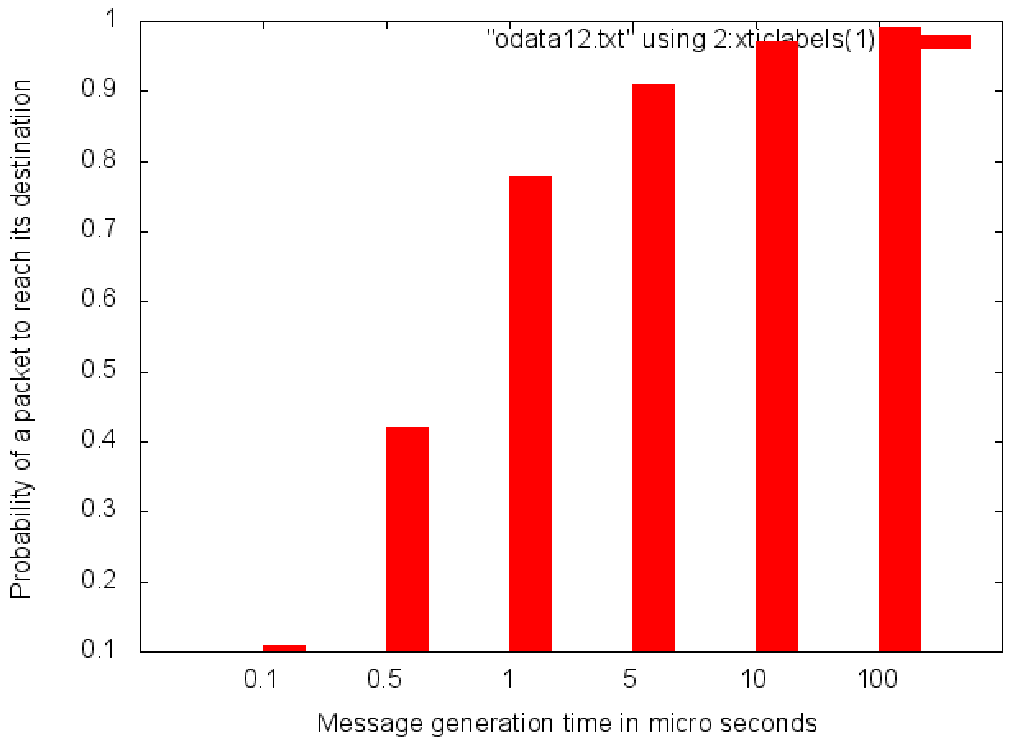

Figure 5.3: *Histogram plot showing ppd for different message generation time when number of nodes is 1000*

5.3 Tests performed implementing RADAR model

The simulation parameters are taken from table 5.1 and table 5.2. In addition to these parameters the angle of rotation is taken as 30, 60 and 90 degree. For each angle of rotation, experiments are done with six message generation time of 0.1, 0.5, 1, 5, 10 and 100 micro seconds. Ten experiments are performed for each case scenario. Then the probability of a packet to reach the destination is calculated for every case. The average value of these ten probabilities is calculated. The number of nodes is taken as 200 and 500.

5.3.1 Number of nodes is 200

Simulation is performed by taking number of nodes as 200 and angle of rotation as 90, 60 and 30 degree. Similarly different message generation time are taken for the experiment. Ten experiments are performed for each case scenario. This gives ten values of probability to reach destination for each case scenario. The average value of ten probabilities is calculated. The ten probability values for each case scenario are tabulated in *appendix A*. The average probability values corresponding to each message generation time for different angle of rotation are shown in table 5.6, 5.7 and 5.8 as below:

Table 5.6: *ppd values for different message generation time when angle of rotation is 90 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)

0.1	0.79
0.5	0.94
1	0.97
5	0.99
10	0.99
100	1

Table 5.7: *ppd values for different message generation time when angle of rotation is 60 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)
0.1	0.88
0.5	0.96
1	0.98
5	0.99
10	0.99
100	1

Table 5.8: *ppd values for different message generation time when angle of rotation is 30 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)
0.1	0.92
0.5	0.99
1	0.99
5	0.99
10	1
100	1

The simulation data as represented above in table 5.6, 5.7 and 5.8 shows increase in probability of a packet to reach destination with increase in message generation time. The probability value is increased by implementing RADAR model as compared to data obtained without implementing RADAR model in all cases. Similarly the probability value is increased with decrease in angle of rotation. This shows that RADAR model works better and increases the probability of correct packet reception.

Comparison of the data obtained from simulation using RADAR model and without RADAR model

We have obtained probability of a packet to reach its destination using RADAR model and without using RADAR model. Now these values for different message generation times are shown in table 5.9 - 5.13 as below:

Table 5.9: *ppd values without RADAR model and with RADAR model when message generation time is 0.1 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.45	0.92	0.88	0.79

Table 5.10*: ppd values without RADAR model and with RADAR model when message generation time is 0.5 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.78	0.99	0.96	0.94

Table 5.11: *ppd values without RADAR model and with RADAR model when message generation time is 1 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.94	0.99	0.98	0.97

Table 5.12: *ppd values without RADAR model and with RADAR model when message generation time is 10 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.96	0.99	0.99	0.99

Table 5.13: *ppd values without RADAR model and with RADAR model when message generation time is 10 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.99	1.0	0.99	0.99

Table 5.14: *ppd values without RADAR model and with RADAR model when message generation time is 100 micro second*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.99	1.0	1.0	1.0

Plot for different case scenarios

Gnuplot is used to plot probability of a packet to reach the destination (ppd) corresponding to different case scenarios. The y-axis will designate probability values and x-axis will designate normal routing and RADAR routing with specific angle of rotation. The different plots are represented below:

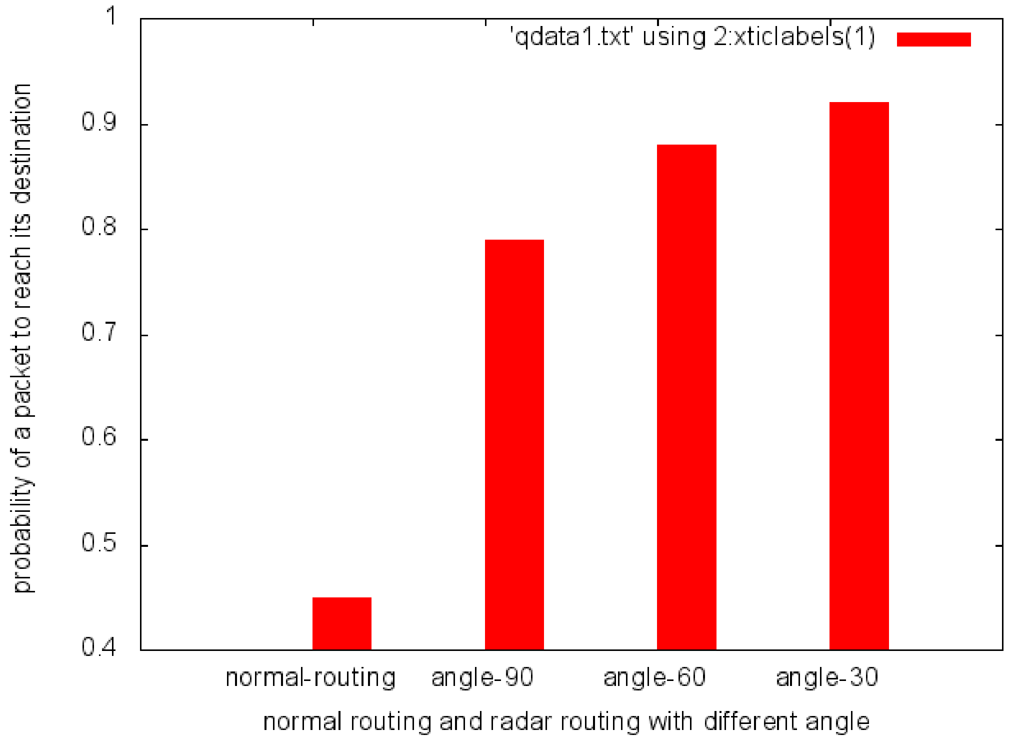

Figure 5.4: *Comparison of ppd between normal routing and RADAR routing when message generation time is 0.1 micro second and number of nodes is 200*

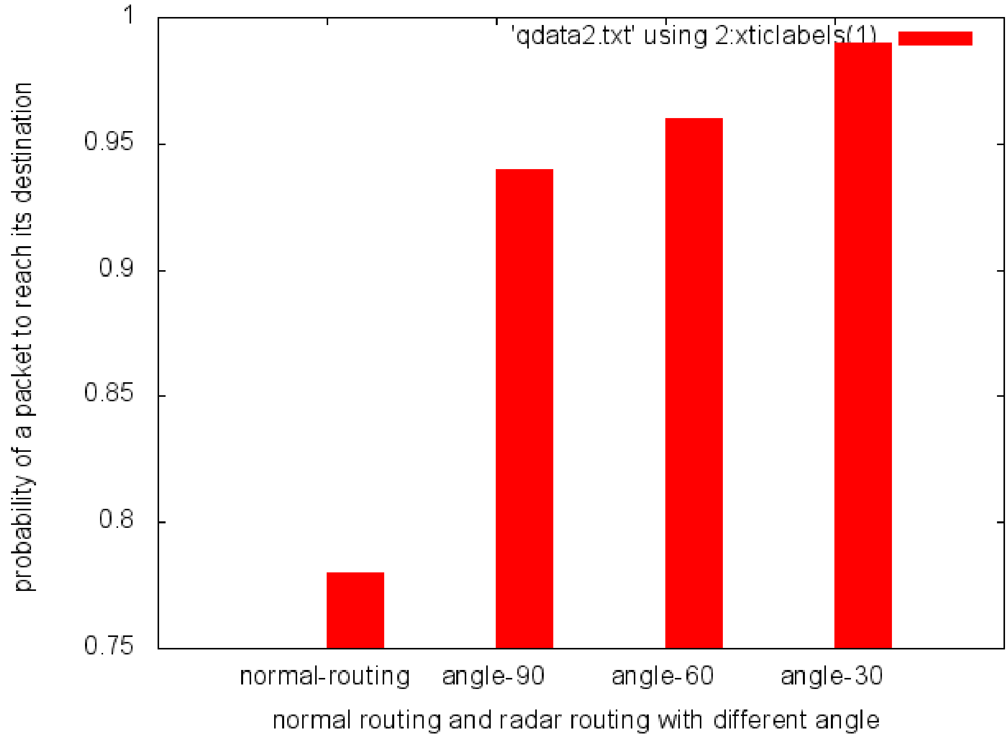

Figure 5.5: *Comparison of ppd between normal routing and RADAR routing when message generation time is 0.5 micro second and number of nodes is 200*

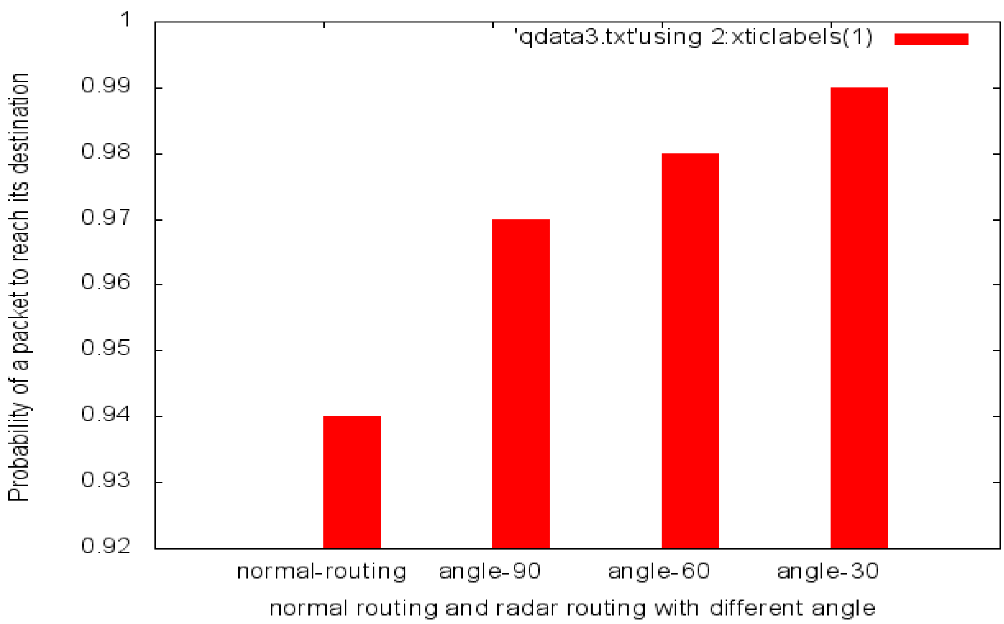

Figure 5.6: *Comparison of ppd between normal routing and RADAR routing when message generation time is 1 micro second and number of nodes is 200*

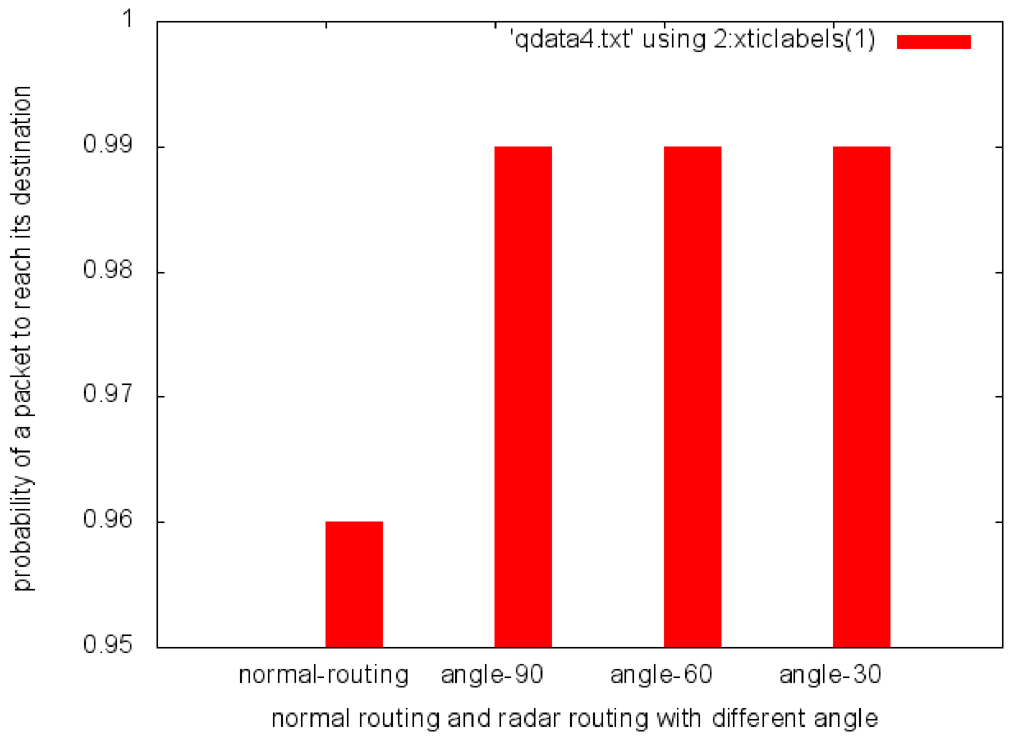

Figure 5.7: *Comparison of ppd between normal routing and RADAR routing when message generation time is 5 micro second and number of nodes is 200*

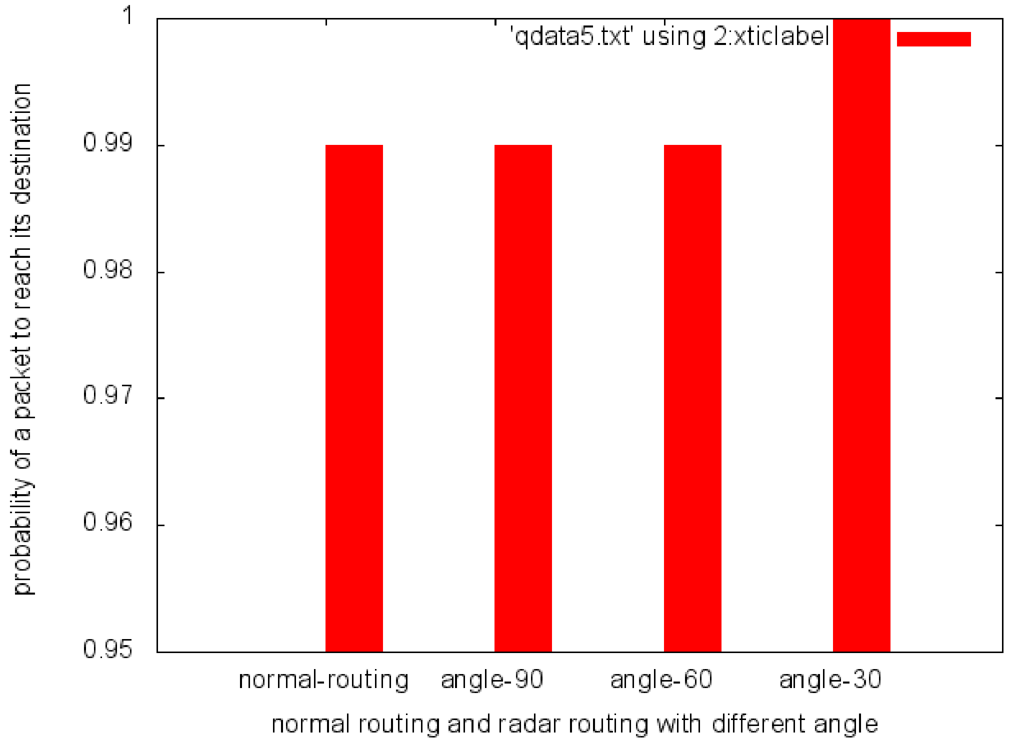

Figure 5.8: *Comparison of ppd between normal routing and RADAR routing when message generation time is 10 micro second and number of nodes is 200*

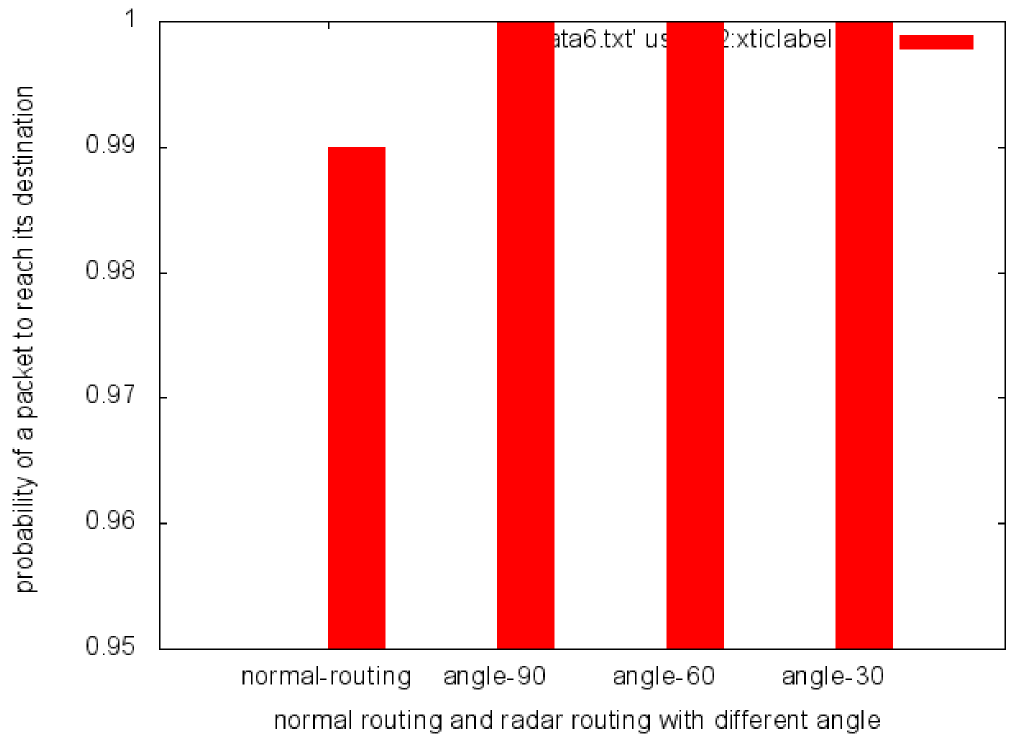

Figure 5.9: *Comparison of ppd between normal routing and RADAR routing when message generation time is 100 micro second and number of nodes is 200*

5.3.2 Number of nodes is 500

Simulation is performed by taking number of nodes as 500. Similarly angle of rotation is taken as 90, 60 and 30 degree and different message generation time are taken for the experiment. Ten experiments are performed for each case scenario which gives ten values of probability to reach destination for each case scenario. These ten probability values for each case scenario are tabulated in *appendix B*. The average value of ten probabilities is calculated. The average probability values corresponding to each message generation time for different angle of rotation are shown in table 5.15, 5.16 and 5.17 as below:

Table 5.15*: ppd values for different message generation time when angle of rotation is 90 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)
0.1	0.58
0.5	0.90
1	0.93
5	0.98
10	0.99
100	1

Table 5.16: *ppd values for different message generation time when angle of rotation is 60 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)
0.1	0.66
0.5	0.91
1	0.94
5	0.98
10	0.99
100	1

Table 5.17 *ppd values for different message generation time when angle of rotation is 30 degree*

Message generation time(In microsecond)	Probability to reach destination(ppd)
0.1	0.81
0.5	0.96
1	0.96
5	1
10	1
100	1

The simulation data as shown above in table 5.15, 5.16 and 5.17 shows that probability of a packet to reach destination increases with increase in message generation time. Similarly probability value is increased with decrease in angle of rotation. The probability value is increased as compared to data obtained without implementing RADAR model in all cases. The trends are similar as with the case when number of nodes is 200. This shows that RADAR model works better independent of number of nodes when compared with data obtained without implementing RADAR model.

Comparison of the data obtained from simulation using RADAR model and without RADAR model

We have obtained probability of a packet to reach its destination using RADAR model and without using RADAR model. Now these values for different message generation times are shown in table 5.18-5.23 as below:

Table 5.18: *ppd values without RADAR model and with RADAR model when message generation time is 0.1 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.21	0.81	0.66	0.58

Table 5.19: *ppd values without RADAR model and with RADAR model when message generation time is 0.5 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.64	0.96	0.91	0.90

Table 5.20*: ppd values without RADAR model and with RADAR model when message generation time is 1 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.87	0.96	0.94	0.93

Table 5.21: *ppd values without RADAR model and with RADAR model when message generation time is 5 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.94	1	0.98	0.98

Table 5.22: *ppd values without RADAR model and with RADAR model when message generation time is 10 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.98	1.0	0.99	0.99

Table 5.23: *ppd values without RADAR model and with RADAR model when message generation time is 100 micro second and number of nodes is 500*

Without radar model	With radar model(angle=30)	With radar model(angle=60)	With radar model(angle=90)
0.99	1.0	1.0	1.0

Plots obtained for different case scenarios

Gnuplot is used to plot probability of a packet to reach the destination (ppd) corresponding to different case scenarios. The y-axis will designate probability values and x-axis will designate normal routing and RADAR routing with specific angle of rotation. The different plots are represented as below:

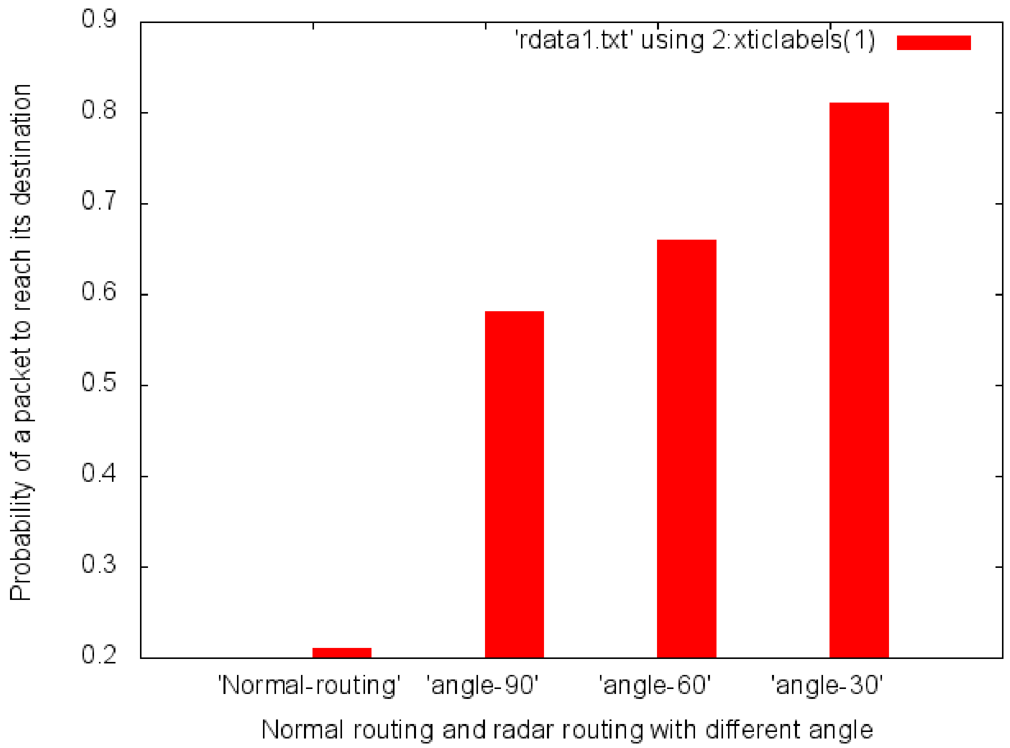

Figure 5.10: *Comparison of ppd between normal routing and RADAR routing when message generation time is 0.1 micro second and number of nodes is 500*

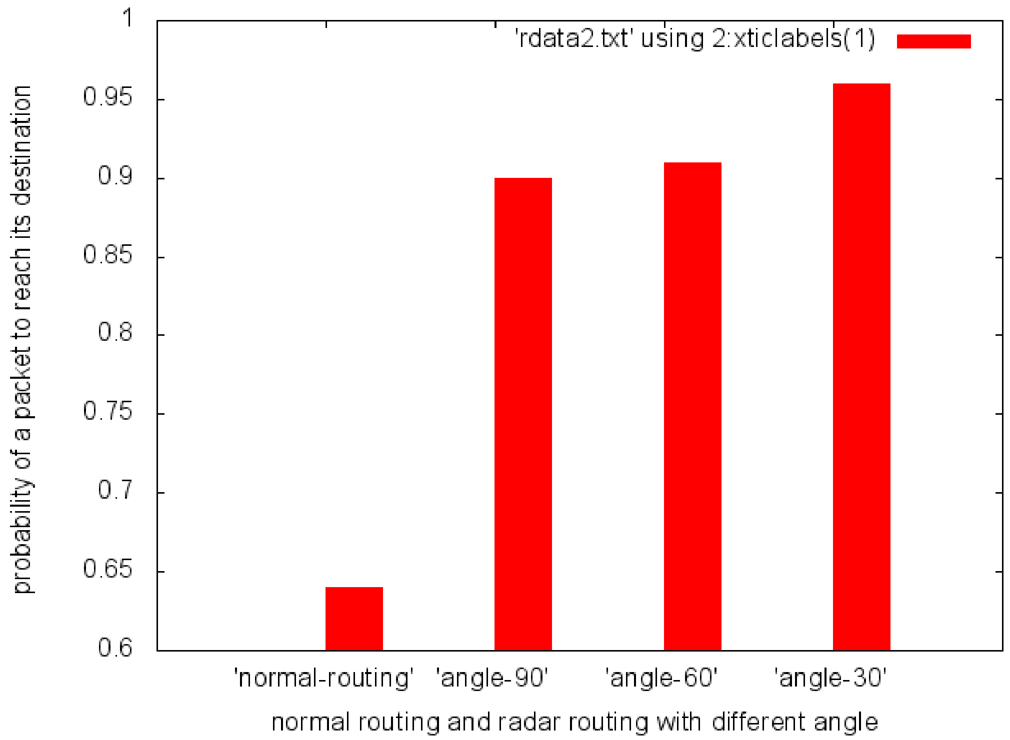

Figure 5.11: *Comparison of ppd between normal routing and RADAR routing when message generation time is 0.5 micro second and number of nodes is 500*

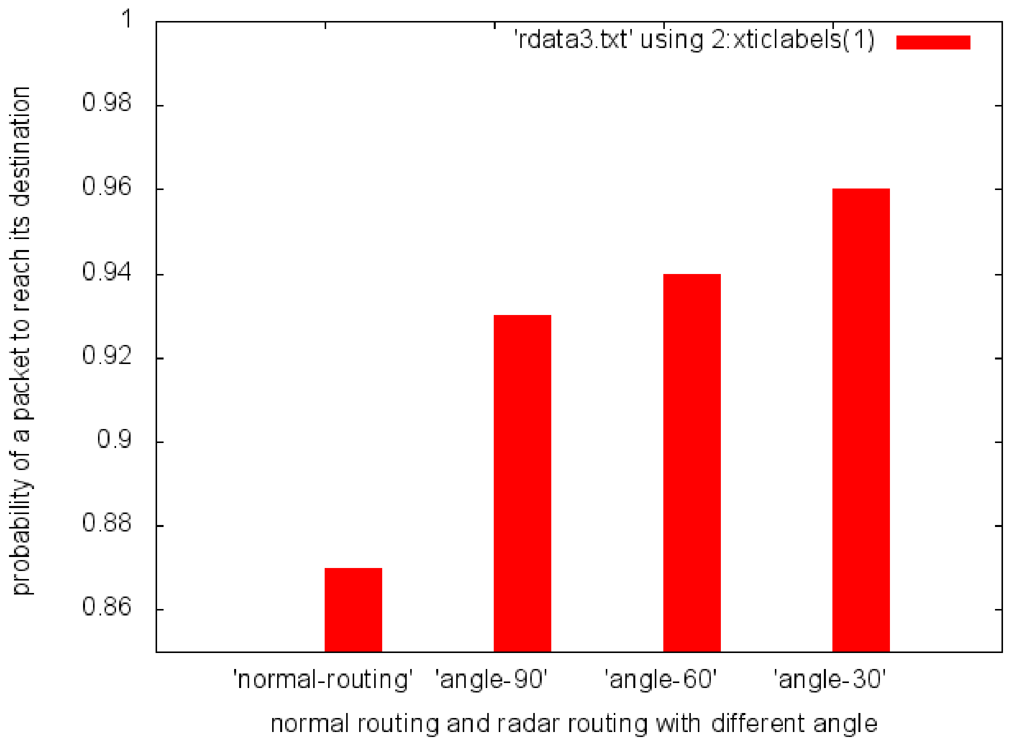

Figure 5.12: *Comparison of ppd between normal routing and RADAR routing when message generation time is 1 micro second and number of nodes is 500*

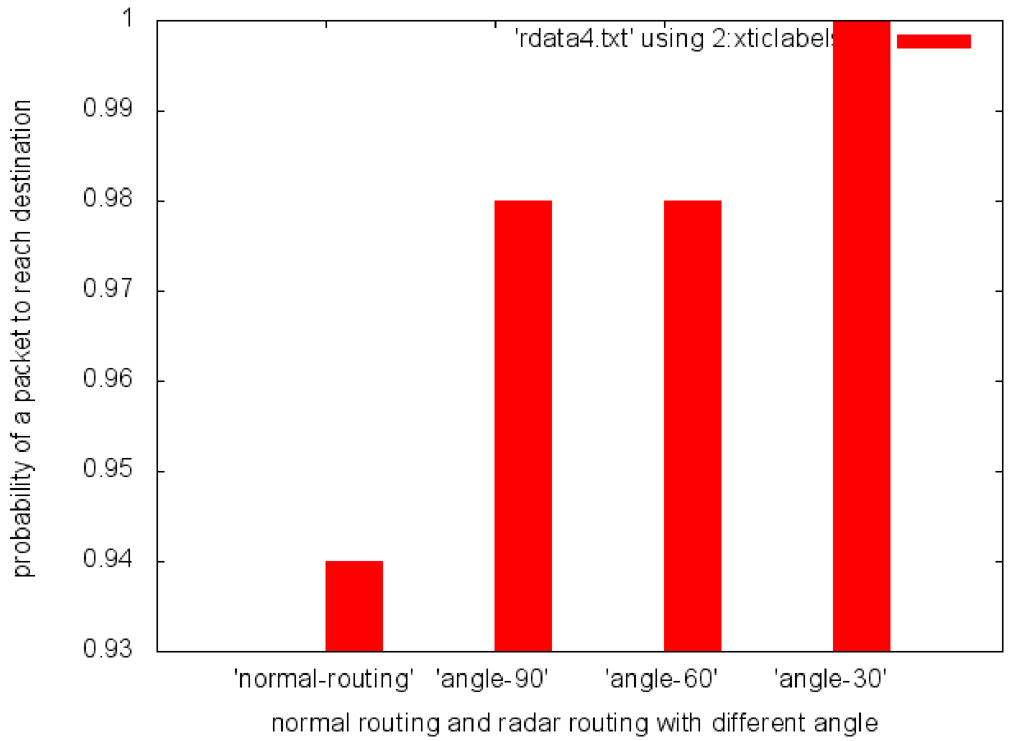

Figure 5.13: *Comparison of ppd between normal routing and RADAR routing when message generation time is 5 micro second and number of nodes is 500*

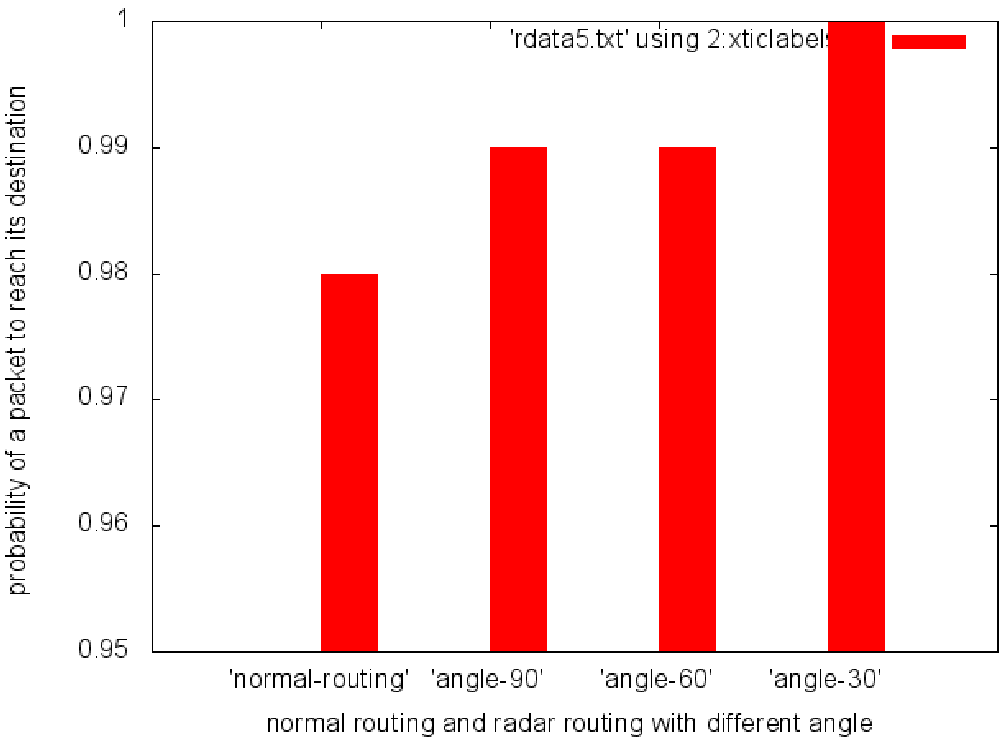

Figure 5.14: *Comparison of ppd between normal routing and RADAR routing when message generation time is 10 micro second and number of nodes is 500*

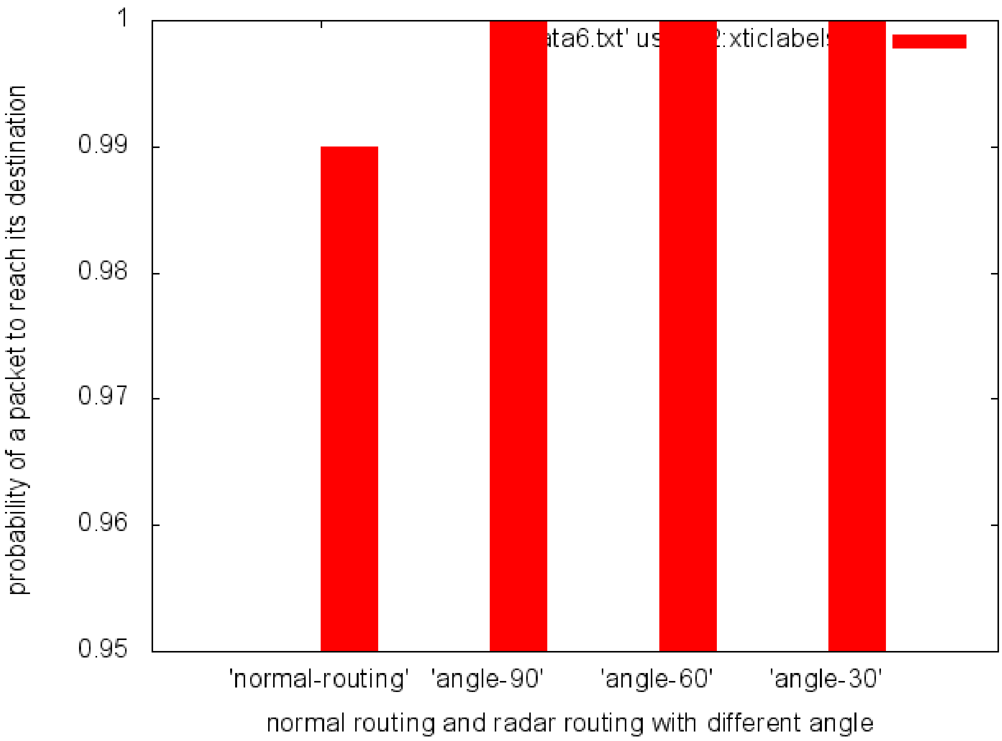

Figure 5.15: *Comparison of ppd between normal routing and RADAR routing when message generation time is 100 micro second and number of nodes is 500*

5.4 Conclusion

Simulation experiments are performed with number of nodes 200, 500 and 1000 without using RADAR model. Similarly simulations are performed with number of nodes 200 and 500 with implementing RADAR model. Different message generation time and different angle of rotation in RADAR routing are taken for the simulation. Probability of a packet to reach the destination is calculated for each simulation. The value of probability increases when RADAR routing is implemented. Similarly, the value of probability increases with decrease in angle of rotation in RADAR routing. This increase of probability value in different cases is shown in table 5.24 and 5.25 as below:

***Table 5.24*:** Increases in ppd value in RADAR routing with different angle of rotation as compared to without RADAR routing when number of node is 200

Message generation time	Angle=30 degree (increase in %)	Angle=60 degree (increase in %)	Angle=90 degree (increase in %)
0.1	47	43	34
0.5	21	18	16
1	5	4	3
5	3	3	3
10	1	0	0
100	1	1	1

Table 5.25: Increases in ppd value in RADAR routing with different angle of rotation as compared to without RADAR routing when number of node is 500

Message generation time	Angle=30 degree (increase in %)	Angle=60 degree (increase in %)	Angle=90 degree (increase in %)
0.1	60	45	37
0.5	32	27	26
1	9	7	6
5	6	4	4
10	2	1	1
100	1	1	1

Increase in probability value signifies that less number of packet are lost in collision. These shows improve in the performance of system by implementing RADAR routing. Therefore we can conclude that RADAR routing is suitable as a routing technique for nano communication network.

6. CONCLUSION

Simulation experiments were performed by implementing the RADAR model and without implementing the RADAR model. The number of nodes is taken as 200, 500 and 1000 without implementing RADAR model and 200 and 500 with implementing RADAR model. The angle of rotation is taken as 30, 60 and 90 degree. The message generation time is taken as 0.1, 0.5, 1, 5, 10 and100 micro seconds and simulations are performed considering all these scenarios. Probability of a packet to reach the destination is evaluated in both the cases for varying conditions. The conclusions can be summarized as below:

1. The probability of a packet to reach the destination decreases as the number of nodes increases. This holds true for both RADAR model implementation and without RADAR model implementation. The increase in number of nodes results in increase in number of packets. This results in increase in collisions leading to increase in packet loss. Hence the probability of a packet to reach the destination decreases as the number of nodes increases and increases as the number of nodes decreases.
2. The probability of a packet to reach the destination increases as the message generation time increases. This holds true for both RADAR model implementation and without RADAR model implementation. Message generation time is related with the packet collision. When message generation time is decreased, there will be more collisions and when message generation time is increased there will be less collisions. Increase in collision will reduce the probability of a packet to reach the destination. Hence, the probability of a packet to reach destination increases with increase in message generation time and decreases with decrease in message generation time.
3. With RADAR model, the probability of a packet to reach the destination increases with decrease in angle of rotation. With lower angle of rotation, there will be less number of nodes in ON stage. Less number of nodes results in less number of packets and less collisions. This will increase the probability of a packet to reach the destination. Hence the probability of a packet to reach the destination increases with decrease in angle of rotation and decreases with increase in angle of rotation.
4. The probability of a packet to reach the destination increases with the implementation of the RADAR model. With RADAR model there will be less number of nodes in ON stage as compared to implementation without RADAR model keeping other parameters same. Less number of nodes will produce less packets resulting in less collision. This leads to lowering in number of packet loss. Hence the probability of a packet to reach the destination increases with the implementa-

tion of RADAR model and decreases without the implementation of RADAR model.

5. The RADAR model works better when we compare the probability of a packet to reach destination. RADAR model is better in terms of energy conservation as well. Since some of the nodes will be in ON stage at a given time, battery power will be saved. The nodes that are in OFF stage will not consume battery power. Since energy is one of constraint factor in nano world, energy saving is important factor while choosing any model.

Hence we can conclude that RADAR model makes nanonetwork more reliable and energy friendly.

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APPENDIX

APPENDIX A

Simulations is performed by taking number of nodes as 200 and three angle of rotation of 90, 60 and 30 degree with different message generation time.

Angle of rotation =90 degree

Simulation run is performed by taking angle of rotation as 90 degree for different values of message generation time.

Case 1: Message generation time=0.1 micro second

Simulation run is performed by taking message generation time as 0.1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.79	0.81	0.76	0.76	0.81	0.76	0.76	0.88	0.83	0.79

The average value obtained from the above table is 0.79.

Case 2: Message generation time=0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.95	0.93	0.97	0.93	0.93	0.97	0.97	0.98	0.85	1

The average value obtained from the above table is 0.94.

Case3: Message generation time =1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.95	0.95	0.95	1	0.97	1	0.97	1	1	1

The average value obtained from the above table is 0.97.

Case 4: When Message generation time=5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.97	1	0.97	1	1	1	0.97	1	1	1

The average value obtained from the above table is 0.99.

Case 5: When Message generation time=10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	0.97	0.97	1	1	1

The average value obtained from the above table is 0.99.

Case 6: When Message generation time=100 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

Angle of rotation =60 degree

Case 1: When Message generation time=0.1 micro second

Simulation run is performed by taking message generation time as 0.1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.82	0.82	0.89	0.86	0.96	0.89	0.89	0.93	0.89	0.86

The average value obtained from the above table is 0.88.

Case 2: When Message generation time=0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	0.93	0.93	0.93	0.96	0.96	0.96	0.96	1	1

The average value obtained from the above table is 0.96.

Case3: When Message generation time =1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	0.96	0.96	1	1	1	0.96	1	0.96	0.96

The average value obtained from the above table is 0.98.

Case 4: When Message generation time=5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.96	1	1	1	1	1	1	0.96	1	1

The average value obtained from the above table is 0.99.

Case 5: When Message generation time=10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	0.96	1	1	1	1

The average value obtained from the above table is 0.99.

Case 6: When Message generation time=100 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	0.96	1	1	1	1

The average value obtained from the above table is 0.99

For angle of rotation =30 degree

Case 1: When Message generation time= 0.1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	0.93	0.86	0.93	0.8	0.93	0.93	0.93	1	0.93

The average value obtained from the above table is 0.92

Case 2: When Message generation time= 0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	0.93	1	1	1	1	1	1	1	1

The average value obtained from the above table is 0.99

Case 3: When Message generation time=1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	0.93	1	1	1

The average value obtained from the above table is 0.99

Case 4: When Message generation time= 5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	0.93	1	1	1

The average value obtained from the above table is 0.99

Case 5: When Message generation time= 10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

Case 6: When Message generation time= 100 micro second

Simulation run is performed by taking message generation time as 100 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

APPENDIX B

Simulation is performed by taking number of nodes as 500 and different angle of rotation.

Angle of rotation =90 degree

Case1: When Message generation time =0.1 micro second

Simulation run is performed by taking message generation time as 0.1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.58	0.59	0.57	0.52	0.60	0.60	0.62	0.59	0.62	0.59

The average value obtained from the above table is 0.58.

Case 2: When Message generation time=0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.88	0.89	0.93	0.91	0.88	0.93	0.88	0.90	0.92	0.93

The average value obtained from the above table is 0.90.

Case 3: When Message generation time=1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.95	0.93	0.94	0.98	0.93	0.94	0.94	0.94	0.91	0.93

The average value obtained from the above table is 0.93.

Case 4: When Message generation time=5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.98	1	0.98	0.99	0.98	1	1	1	0.98	0.99

The average value obtained from the above table is 0.98.

Case 5: When Message generation time=10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	0.98	0.99	0.99	1	0.99	0.99	1	1	0.99

The average value obtained from the above table is 0.99.

Case 6: When Message generation time=100 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

Angle of rotation =60 degree

Case1: When Message generation time =0.1 micro second

Simulation run is performed by taking message generation time as 0.1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.63	0.63	0.60	0.69	0.67	0.68	0.69	0.70	0.74	0.62

The average value obtained from the above table is 0.66.

Case 2: When Message generation time=0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.92	0.87	0.91	0.92	0.95	0.91	0.89	0.87	0.92	0.96

The average value obtained from the above table is 0.91.

Case 3: When Message generation time=1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.96	0.93	0.95	0.97	0.95	0.96	0.92	0.97	0.92	0.96

The average value obtained from the above table is 0.94.

Case 4: When Message generation time=5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	0.98	0.97	1	1	0.97	0.98	0.97	0.97

The average value obtained from the above table is 0.98.

Case 5: When Message generation time=10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	0.98	1	1	1	1	1

The average value obtained from the above table is 0.99.

Case 6: When Message generation time=100 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

Angle of rotation =30 degree

Case 1: When Message generation time=0.1 micro second

Simulation run is performed by taking message generation time as 0.1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.80	0.83	0.71	0.76	0.85	0.85	0.80	0.80	0.85	0.85

The average value obtained from the above table is 0.81

Case 2: When Message generation time= 0.5 micro second

Simulation run is performed by taking message generation time as 0.5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.97	0.97	0.97	1	0.95	0.92	0.95	0.95	0.97	0.97

The average value obtained from the above table is 0.96

Case 3: When Message generation time= 1 micro second

Simulation run is performed by taking message generation time as 1 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

0.97	0.95	1	0.95	0.97	0.95	0.97	0.97	0.92	0.92

The average value obtained from the above table is 0.96

Case 4: When Message generation time= 5 micro second

Simulation run is performed by taking message generation time as 5 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1

Case 5: When Message generation time= 10 micro second

Simulation run is performed by taking message generation time as 10 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.

Case 6: When Message generation time= 100 micro second

Simulation run is performed by taking message generation time as 100 micro second. The probability to reach the destination is calculated corresponding to 10 experiments. These probability values are listed as below:

1	1	1	1	1	1	1	1	1	1

The average value obtained from the above table is 1.