TAMPEREEN TEKNILLINEN YLIOPISTO
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UNIFICATION OF SYSTEM EQUIPMENT FOR NANOSENSOR NODES

Master of Science Thesis

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and Dr. Dmitri Moltchanov

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ABSTRACT

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Nanotechnology is aiming to design nanocomponents where unique phenomena empower novel applications at nanoscale level. By integrating these nanocomponents into a single entity will enable the development of nano-machines. Nanonetwork is an interconnection among nano-machines that makes use of novel nanomaterials and nanoparticles to detect and measure with new functionalities stemming in a scale ranging from one to few hundred nanometers. Up to date, it is still on research and challenging issues to define how nano-machines will communicate. Existing communication technology are not appropriate due to their size and power consumption of transceivers, receivers and other apparatuses which demand us novel solution regarding channel modelling or protocols for nanonetwork.

In this thesis work we mainly focused on electromagnetic communication among nanosensors by explaining the details of architecture, their individual components and development process. In communication perspective we focused on terahertz (0.1-10.0THz) channel propagation model for and The EM properties of novel nanomaterials *graphene* based nano-antennas which will define the communication capabilities of nanosensor devices.

Based on composition of medium, different bandwidth is suitable for different transmission distances. If we are going to choose best available bandwidth we can greatly decrease the density of nanosensor nodes we need. We simulate based on HITRAN database of molecular absorption for different medias e.g. air, Ozone (O_3), Ammonia (NH3), Nitrogen (isotopologue $^{14}N^{14}N$ for N_2) and Water (H_2O). To determine optimal frequency band that minimizes the path loss and maximizes the transmission distance at nanoscale network for example in open environment, we would like to have coverage as huge as possible and probability of connectivity of the network to estimate how many sensors we require to be placed. The density of the nodes must be really huge if the communication range is lower. Our simulation result shows for different radius of disk field to keep the probability of 1-connetivity the required nodes decreases hugely when communication range increases from 1mm to 2mm which is nearly 9times.

PREFACE

This Mater of Science Thesis has been done as a part of project in “Nano Communication Center” Dept. of Electronics and Communications Engineering and financial support by “Industrial Research Fund” of Tampere University of Technology, Tampere, Finland during 2014 and 2015.

First of all, my all over gratitude to my Creator, to my Almighty ALLAH (s.w.t) who has given me such strength and intellectuality to demonstrate this work.

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Tampere, 2015

Sk Md Shahedul Karim

LIST OF ABBREVIATIONS

IoNT	Internet of Nano-Things
NBC	Nuclear, biological and chemical
NEMS	Nano-electromechanical systems
MEMS	Micro- elctro-mechanical system
FET	Field effect transistors
BW	Bandwidth
THz	Terahertz
CNT	Carbon nanotube
GNR	Graphene nanoribbon
EM	Electro magnetic
RF	Radio Frequency
SWNCT	Single Walled Carbon nanotube
MWNCT	Multi-walled carbon nanotube
HITRAN	High resolution transmission
MAC	Media Access Control
WNSN	Wireless Nano Sensor Network

Chapter 1

In this chapter we will get introduce with the nanotechnology and nanoscale in size. The Internet of Nano-Things (IoNT) and network architecture has been illustrated. In the following we go through overview of nanonetwork and their different application areas.

1.Introduction

"I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously. The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

— Richard Feynman (1959), Nobel Prize winner in physics

Based on Richard Feynman concept about the advanced future technology he envisioned miniaturization of human-designed nano-devices with more functionabilities by taking advantage of unique properties of nanomaterials and nano-particles. After more than 50years, nanotechnology figuring out a new set of techniques and tools to deal at atomic and molecular scales which devices are conceived.

1.1 Nanotechnology

Nanotechnology is enables the control of matter at an atomic and molecular scale. Nobel nano-materials like graphene, nanotubes & nanoribbons create new properties which can't possible to observe at microscopic level. Nanotechnology objects how to exploits of these new nano-material properties and invent new devices. Nanotechnology covers broad multidisciplinary field encompassing all diverse science, engineering and technological areas of knowledge such as computer science and engineering, physics, chemistry, material science and molecular biology and many other disciplines. Most challenging issues for nanotechnology related with components, structures and systems are in a size regime.

The most important requirement to understand nanotechnology is that the nano-structure has special properties that are exclusively due to its nanoscale proportions. A nanometer is 1-billionth of a meter. It's very difficult to notice or understand how small that is the dimensions between approximately 1 and 100 nanometers are known as the nanoscale. Some examples are following below [21]:

- There are 25,400,000 nanometers in one inch
- A human hair is approximately 80,000-100,000 nm wide
- A sheet of paper is about 100,000 nm thickness
- A single gold atom is about a third of a nanometer in diameter
- 1nm is about as long as fingernail grown in 1 second.

In Fig 1.1 the illustration examples of the size and scale of nanotechnology where we can visualize how small things at nanoscale area.

Figure 1.1 *Nanoscale things [21]*

1.2 The Inter of Nano-Things (IoNT)

As nanotechnology is enabling nano-devices in the range between one to few hundred nanometers, at this scale, these integrated nanocomponent can able to perform simple task like sensing or actuation. The interconnection of nanoscale devices with existing communication networks with thanks to the Internet open a new networking paradigm that is further referred to as the *Internet of Nano-Things (IoNT).*

1.2.1 Network Architecture

The interconnections of nano-machines with traditional network coordinate with internet which requires the enhanced development of new network architecture. In Fig 1.2 is one type of model [2].

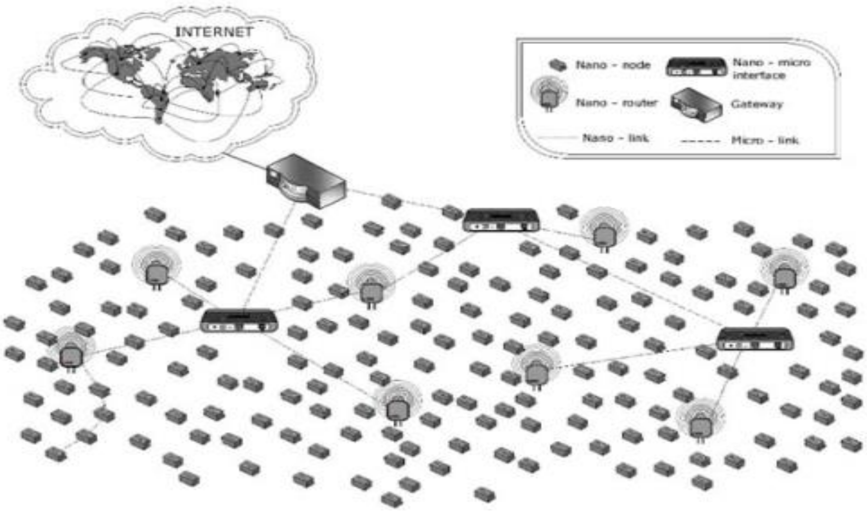


Figure 1.2 *Architecure of wireless nanosensor network*

Components in the network architecture of the Internet of Nano-Things:

Nano-nodes	To perform simple computation by using limited memory and can able to transmit in shorter distance.
Nano-routers	Suitable for aggregating information coming from limited nano-machines. Also, by exchanging control commands can control the behavior of nano-nodes.
Nano-micro interface devices	Hybrid device which able to aggregate information from nano-routers then to microscale and vice versa. These are able to aggregate the information coming from nano- routers, to convey it to the microscale, and vice versa.
Gateway	Just like modem router which enables the remote control of the entire system over the internet.

The Internet of Nano-Thing in two different application, intrabody nanonetworks for remote healthcare, and the future interconnected office:

In intra-body networks

Nanosensors and nano-actuators deployed inside the human body such as molecules, DNA, proteins, organelles and major component of cells are remotely controlled from the macro scale and over the Internet by an external user such as a healthcare provider.

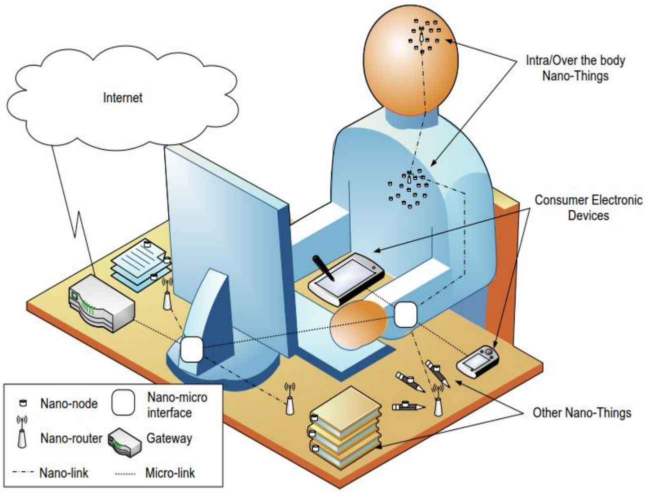


Figure 1.3 *The Internet of Nano-Things.*

In the interconnected office

In Fig 1.3 , we can see that every single element can be provided of a nanosensor device which will keep track of the location and status of objects and components are using in an office and even its internal components are provided of a nano-transceiver which allows them to be permanently connected to the Internet.

1.3 Nanonetwork

Nanonetwork is one of the advanced applications of nanotechnology scientific research areas like environmental, biomedical, industrial and military fields. It's enabling the enhanced of nano-devices in a scale between one to few hundred nanometers in size. At this scale, by exploiting the properties of novel nanomaterials e.g., crack healing and nanoparticles e.g., data storage, super capacitors for its manufacture and design just not means of developing miniaturized typical machines, moreover to operate complex tasks by integrating novel electronic nano-components of advanced nano-devices.

In terms of functionality and performance of today's internet the major exception that at nanoscale communication network nanosensor nodes and channels are measured and separated up to hundred nanometer. Nanonetwork is defined as the communication network between nano-machine. At this scale, as a functional unit nano-machine can be considered to perform tasks like simple computation, sensing and/or actuation. To execute these task nano- machines can be interconnected. To define complex task, nano-machines such as chemical sensors, nano-valves, nano-switches by exchanging information and commands between networked nano-machines enable them to work. For having tiny size nanomachine capability is very limited individually but if interconnected nano-machines and dense of deployment will allow by the nanonetwork. The resulting nanonetwork will be able to increase coverage, capability and application large areas of nano-machines more significantly.

The intra communication between nano-machines throughout several methods: nanomechanical, acoustic, electromagnetic and chemical or molecular communication;

Nanomechanical communication

Its required mechanical contact between transmitter and receiver, more specifically information through the hard junctions between linked devices**.** When nano-devices distributed in large areas this is not much effective method because of without direct contact.

Acoustic communication

In this communication technique mainly based on ultrasonic waves. When message encoded in ultrasonic waves by meaning of variation of pressure move at sound speed which emits the acoustic signals. Ultrasonic transducers are integrated in nano-machines. Traditional acoustic transducers are not feasible due to their size and principles which is challenging task to manufacture at nano-scale level.

Electromagnetic communication

EM communication system information is transmitted through modulated EM wave. The transmission and reception of EM radiation from nano-electro component such as *nanobatteries, nano-memories, nano logical circuitry and nano-antennas* based of novel nanomaterials and their unique properties will decide the bandwidth (BW), the time lag of the emission, or magnitude for the emitted power for a given input energy [3][36]. For the time being, nanoscale communications have been envisioned two alternatives for EM communication;

(i) an electromechanically resonating carbon nanotube(CNTs) which is able to decode an amplitude or frequency modulated wave [11]

(ii) Graphene based nano-antennas for EM radiation in terahertz (THz) band [6].

Molecular communication

It's defined as the transmission and reception of molecules. Based on type of molecule propagation, several communication techniques can be classified; walkway-based where molecules propagate through pre-defined pathways by carrier substance, flow-based molecules propagate through diffusion in a fluidic medium whose flow predictable and diffusion-based molecules propagate through spontaneous diffusion in a fluidic medium. To create molecular communication system need to be account existing biological communication mechanism e.g. intra-cell and inter-cell communication of exchanging molecules for short range (nm to mm) and intra-spice communication which ranging from mm to few km for long range communication.

1.4 Application areas of Nanonetwork

Application of nanonetworks can be classified into four groups as: biomedical, environmental, industrial and military applications [1].

1.4.1 Biomedical application

The advantages of nanonetworks due to tiny size, biocompatibility and bio-stability which can applicable for using in intra-body (e.g. tissues, organs etc.) Fig 1.3 application enabled control system at molecular level. Some examples are below

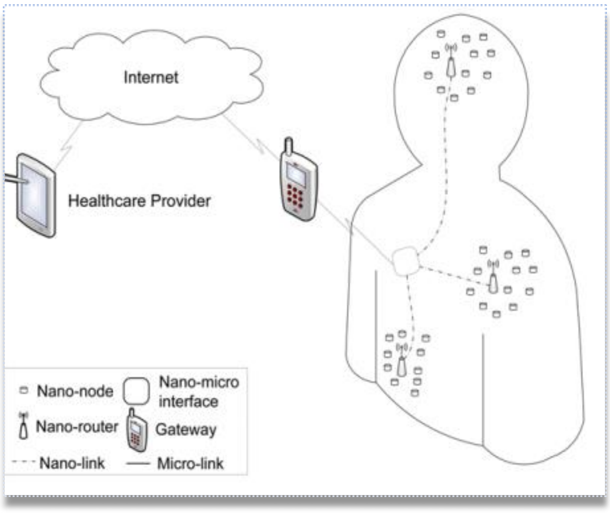


Figure 1.4 *Network architecture for WNSNs in healthcare applications*

Immune system support

It can be used to detect infected cell in-body such as cancer cell which is less aggressive treatment compared to traditional. This immune system work will consist of several nano-machines by co-ordination of nanosensor and actuators to identify and protect pathogen elements. Nano-machines can also use to help elimination procedures.

Drug delivery system

This system could support to restore metabolism diseases inside the body such as diabetes. Nano-sensor and smart glucose cooperatively support to regulate such mechanism. It can deliver neurotransmitters or other drugs to mitigate the effects of neurodegenerative diseases [24].

Health monitoring system

By deploying Nanosensor around the body, it can be possible to monitor sodium, glucose level in blood [25], cancer cell [26], cholesterol [27] or the infected agents in-body. *Health monitoring* system in-body nanosensor network can able to monitor like oxygen and cholesterol level, hormonal disorders. After monitoring and collecting these data by integrating wireless interface between nano-sensor and micro device could be utilize to send health care centers for further diagnostic.

Bio-hybrid implants

Nanonetwork can make interfaces between implant and the environment which will support as well as by replacing components such as organs, nervous tracks or lost tissues.

In [8] are some other possible application in this field has been propose.

1.4.2 Industrial and consumer goods applications

Nanonetworks can support by developing new materials, manufacturing process and quality control of the product in industrial sectors. For example,

Food and water quality control

Nanonetworks helps to provide safety in food and keep control the quality of water Nanosensor can detect very small bacteria and toxic element; it's very much similar to health monitoring system which is not possible for existing sensing technologies.

Functionalized materials and fabrics

Consumer goods like functionalized fabric can make by embedding nano-machines, nano-actuators can develop airflow in smart fabrics, motorcycles helmets or racing car equipped with nanosensor to get more security on the road[28].

1.4.3 Military applications

In battlefield, communication among nanosensors deploying over large areas to monitor and actuation, over smaller areas, i.e., human body to monitor soldier performance.

Nuclear, biological and chemical (NBC) defenses

Nanosensor and nanoactuator in nanomachine can placed in battlefields and targeted areas to detect aggressive biological and chemical agents. As like as, by deploying nanosensor in cargo container to detect biological, chemical and radiological materials.

Nano functionalized equipment

These type of equipment can be manufactured army uniforms by containing advanced materials nanonetwork that self-regulate the temperature and also can detect the soldier has been injured.

1.4.4 Environmental applications

As nanonetworks are inspired in biological system found in nature, environmental application can help to achieve several goals which deny existing solution.

Biodegradation

Globally garbage handling is a problematic procedure in current systems. By increasing the amounts it becomes more challenging day by day. Nanonetworks can provide solution by sensing and tagging different sort of materials that can be later located and processed by the support of nano-actuators.

Animals and biodiversity control

Nanonetworks using pheromones as messages can trigger certain behaviors on animals for interaction with them and control presence in particular areas.

Air pollution control

Nano-filters can use to remove harmful substances to monitor and control the quality of air.

1.5 Objective

In nanonetwork, nanosensor nodes are low-power and multiple functional tiny sensing nodes. These nodes are basically used to sense as well as to process data and communication components correspondingly these sensors can directly communicate with each other and also able to communicate .Any wireless sensing network can contain thousands and even millions of similar operational nodes. These nodes are responsible for sensing the environments and its information about temperature, humidity, air speed/pressure, light, dust category, constraints and so on.

Different bandwidth is suitable for in different transmission distances based on composition of medium. To determine optimal frequency band that minimizes the path loss and maximizes the transmission radius at nanoscale network. We would like to have this coverage as huge as possible, because at the end it effects how many sensors we need to be placed. For certain dimension of network area to enable connectivity which depends on the coverage radius of one node. The density of the nodes must be really huge. If we are going to choose best available bandwidth we can greatly decrease the density we need.

For example, if we set nanosensor network in open environment we might have natural affect like rain as its change humidity or some other effect which changes the absorption loss, that's why they should adaptive somehow. Thus, enable such kind of adaptivity to the environment unified system needed.

The system should be unified for any environment (oil, water, humidity or air any type of) doesn't matter really for us. Only thing we should care is which channel is the best one for a time being. To encounter this challenge, we introduced millimeter scale novel nanomaterials graphene based Carbon nano tubes (CNTs) antenna for electromagnetic waves propagate in THz BW (0.1-10.0Thz). Homogenous is perfect example for adaptive algorithm because nodes are similar in this environment. But the problem in heterogeneous environment and one of main problem is that nodes are different as a result the effect on the choice of suitable bandwidth.

The implementation part has been done by using MATLAB software for our simulation to see the behavior of connectivity of a network if nodes are uniformly randomly distributed. We analyze that how many nodes we required to keep the connectivity in randomly deployed sensor nodes. Thus, the number of require nodes will check the probability of connectivity to achieve that all network is at least 1-connected.

Chapter 2

In this chapter we explain in details about the architectural overview of the nano-machines and every component involve with their functionalities. After that we focus on the development approaches *top-down, bottom-up and bio-hybrid* of nano-machines.

2. Nano-machine

A nano-machine is defined as ‘‘an artificial eutectic mechanical device that relies on nanoscale components” [7]. In recent time development in nanotechnology has enabled the manufacturing of devices at nanoscale which are basically low power and low cost called nano-machines. The capabilities of these nano-machines with limited functioning, sensing, actuating and computing due to their size and structure. But by interconnecting them and build nanonetwork, it can able to perform complex task and provide solution for different application areas in biomedical, industry and military fields.

2.1 Nanosensor device architecture

An integrated nanosensor device capable to perform simple sensing, computation and actuation. Abstract model has present in Fig 2.1.

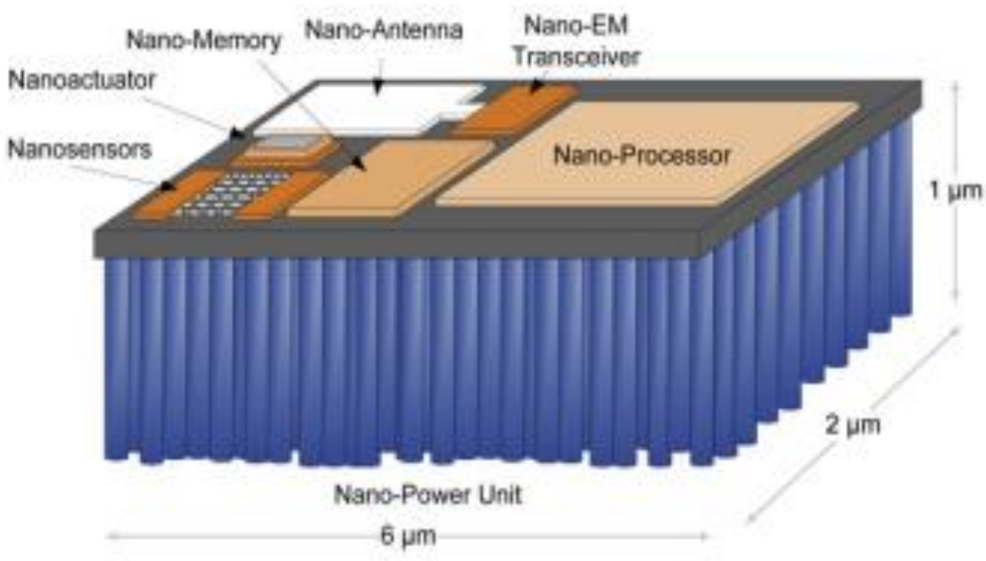


Figure 2.1 *an integrated nanosensor device. [3]*

In the following, we will see different solution technique to implement each feature integrating a nanosensor.

Nanosensors

The functionality of nanosensor is able to sense physical and environmental condition at very small and gaseous level. Nanosensor has special sensation capability which can detect data and information. Based on novel nanomaterials Graphene, Graphene Nanoribbons (GNRs) and Carbon Nanotubes (CNTs) provide tremendous sensing capabilities and concept of many type of sensors[29].

To follow the nature of the measured magnitude, nanosensors can be classified as follows

Physical nanosensors: these are used to measure magnitudes such as mass, pressure, force, or displacement. The methodology is when nanotubes and nanoribbons are bent or deformed change of both the electronic properties. Based on this simple principle, different types of nano-electromechanical systems (NEMSs) have been proposed several applications such as pressure nanosensors, force nanosensors or displacement nanosensors [30].

Chemical nanosensors: to measures magnitude such as concentration of a given gas, presence of specific type of molecules and composition of a substance. Similar principle like physical nanosensors, the electronic properties of CNTs and GNRs change when molecules absorbs on top of them. Using this principle, numerous chemical nanosensors have been manufactured.

Biological nanosensors: to monitor bio-molecular process such as interaction of antibody, DNA, enzymatic or cellular communication process. These sensors combined of *bioreceptor* such as antibody, enzyme, protein or DNA strain and *transduction mechanism* such as electrochemical detector, optical transducer, and magnetic detector. Electrochemical and photometric biological nanosensors are two subtypes of biological nanosensors. The electrochemical biological nanosensors follow similar way to chemical nanosensor but protein, antigen or DNA are blinds/glued or attached to CNTs.

Nano-Power unit

By using nanomaterials it can be possible to manufactured nanobatteries with high power density, reasonable lifetime and contained charge/discharge rate. These limitations to overcome self-powered nano-device has been introduced in which nano-devices energy such as mechanical, vibrational and hydraulic conversion (by means of the piezoelectric effect seen in zinc oxide (ZnO) nanowires) o electrical energy [31][32].

Nano-Processor

Different types of tinier field effect transistors (FET) can be used to develop nanoscale processors. Nanomaterial such as CNTs and specially GNRs can be used to build this transistor at nanoscale. Graphene-based transistors are smaller and faster as electron can travel larger distance in grapheme. Due to small size of nanosensor devices will limit the capability of nanoscale processors to perform complex task but not the speed. But the switching frequency of Graphene based transistors which is faster for the time being which are in the order up to a few hundreds of terahertz.

Nano-memory

Nano-memories utilizing a single atom to store single bit that can be used as a nano-memory. Out of several types of atomic memories has been proposed so far. One developed method was that memory stores a bit by the presence or absence of one silicon atom based on a silicon surface with deposited monolayers of gold defining the tracks. The writing process done by removing silicon atoms from the gold lattice and reading the memory was performed by means of a nano-tip able to detect the presence/absence of silicon atoms. In recent times, IBM Corporation has demonstrated the concept of magnetic atomic memories.

Electromagnetic (EM) communication among nanoscale devices is enabled by using of nanomaterials such as *graphene* in terms of radio frequency (RF) nano-transceiver and corresponding EM antennas.

Nano-antennas: Graphene based nano-antennas are open a new door for communication among nanosensor devices for its unique properties. The EM investigated novel nanomaterial such as CNTs and GNRs will define the specific frequency range for emission of EM radiation, the time lag of the communication or the magnitude of the emitted power for a given input energy [6]. Till now, Nano-patch antennas based on GNRs and nano-dipole antennas based on CNTs is proposed, modeled and analyzed. There are several research challenge need to be overcome to develop nano-antennas accurately by providing details on their specific band of operation, radiation bandwidth and radiation efficiency and by exploiting the properties of nanomaterials and new manufacturing techniques.

Nano EM-transceivers: EM transceivers are subject to perform baseband processing, frequency conversion, filtering and power amplification of both transmitted and received signals from free space through the nano-antenna. The nano-antennas would resonate at THz band, Radio Frequency Field Effect Transistors (RF FET) able to operate at these very high frequencies are necessary. Recently, IBM corp. has announced the first ever grapheme based RF transistor which able to switch at 100GHz [10]. Moreover, electronic and thermal noise should be modeled as this noise limiting the range of nano-devices by reducing signal to noise ratio (SNR) at receiver. In addition, new communication and information modulation techniques need to be developed

2.2 Approaches for development of nanomachine

To develop nano-machine following three approaches Fig 2.1 will be obtained in future for fabrication and manufacturing [1]:

2.2.1 Top-down approach

Miniaturized to a nanometric scale, development of nano-machine mechanism by means of downscaling current existing micro-scale device into nano-scale device with involvement of microelectronics and micro-elctro-mechanical system (MEMS) such as *electro beam lithography* [33] and *micro contact printing* [34], using such kind of advanced manufacturing techniques where devices integrate mechanical component with electrical circuitry. Based on this concept, nano-machines like nano-clectromechanical systems (NEMS) are being developed even though fabrication and manufacturing process of these nano-components are still now in very early stage.

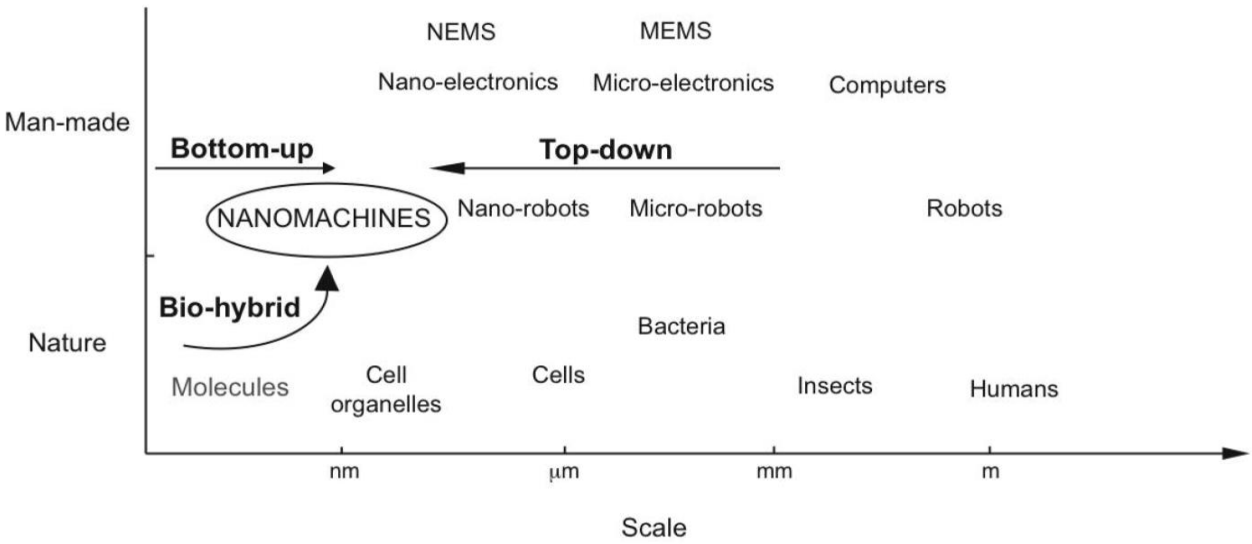


Figure 2.1 *Approaches for the fabrication and integration of nano-machine [1]*

2.2.2 Bottom-up approach

This approach is a promising way to create nano-machines as here. By using chemical and physical forces individual atoms or molecules build up larger structures in an assembled way. The idea that atoms could construct such a way and can applicable at nano-scale machine Feynman was the first person who claims it, "The principles of physics do not speak against the possibility of maneuvering things atom-by-atom". In this bottom-up approach still in theoretical process as well as some challenging task regarding assembling such as atoms would be too fat to have control, too sticky and also continual shaking because of collision with surrounding molecules. Currently this approach has been followed to create molecular switches and molecular shuttles based on self-assembly molecular properties for developing nano-machines.

2.2.3 Bio-hybrid approach

This bio-hybrid approach has inspired by nature based on the use of existing biological nano-machines, such as molecular motors. Different biological structures found in cells include nano-biosensors, nano-actuators, biological data storing components, tools and control units of living organisms are considered as nano-machines. These nano-machines can be interconnected and forming the network structure which can capable to perform more complex task such as *cell division*. This kind of molecular signaling technique also used for inter-cell communication. In this approach, by using these biological nano-machines as model to invent new nano-machine and integrating them into more complex system such as *nano-robots*.

The components we have describes at the section 2.1 it has followed top-down approach. Currently, the most important challenge is to define how to assemble these nanocomponents and their different unit integrated into a single nanosensor device as well as the manufacturing process also still open issue.

In future technology, these three approaches will be obtained following any of these approaches to create nano-machine. In term of architecture, power consumption and communication the biological nano-machine is highly optimized which is really promising and will motivate to new development as model or building block.

Chapter 3

3.Theoretical background

In this chapter we will go through terahertz BW(0.1-10.0THz) in electromagnetic spectrum then review of propagation mechanism of terahertz as well as their perspectives and related issues of molecular absorption, how to compute path loss that a signal suffers while travelling through a medium, how molecular absorption does effect on the total system noise and capacity analysis.

3.1 Terahertz radiation

Terahertz (THz) radiation also known as submillimeter radiation or tremendously high frequency based on EM waves, wavelength ranging from 1milimeter to100 micrometer and frequency range is 300GHz or 0.3 THz to 3.0THz. In Fig 3.1 electromagnetic spectrum scale Terahertz radiation occupies a ground between microwave and infrared region also called "THz Gap" where the frequency of electromagnetic radiation becomes to high digitally. Therefore, there frequency must be measured by proxy to be measure used the properties of wavelength and energy. Similarly the generation and modulation of coherent EM signal in this frequency range becomes harder by the conventional electronic devices use radio waves and micro waves. In other word we can say that is meeting point of electronics and optics[39].

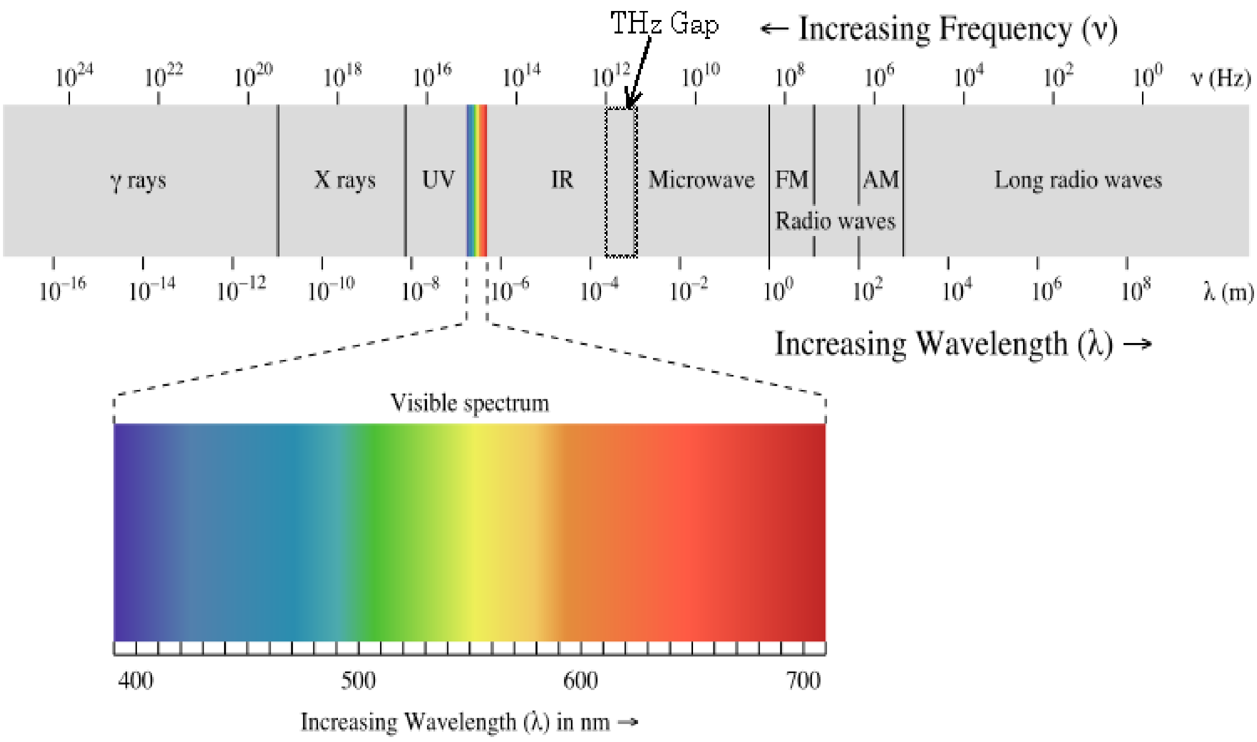


Figure 3.1 *Overview of frequency region [15]*

As example,

Frequency: v = 1 THz

Angular frequency: $\omega = 2\pi v$= 6.28 THz

Period: τ = $1/_{v}$ = 1ps

Wavelength: $\lambda = {}^{c}/_{v}$= 0.3 mm = 300μm

Wavenumber: $\bar{k} = {}^{k}/_{2\pi} = {}^{1}/_{\lambda} =$ 33.3 cm^{-1}

Photon energy: $hv = \hbar\omega = 4.14\ meV$

Temperature: $T = {}^{hv}/_{k_B} = 48\ K$

This THz gap arises in fact from the source of the nature and detectors used in spectroscopy both at high frequency and low frequency side of the gap. As above we see that 1.0THz corresponds to photon energy 4meV which is less than the electronic transition of atoms and molecules but corresponds to the resonance of rotational frequencies of small molecules and vibrational modes of large molecules.

3.2 Properties of Terahertz band

- Terahertz band has a huge bandwidth
    - A bandwidth of length 10GHz to several THz that is unused by any other technologies. As a comparison current Wi-Fi system utilize bandwidth only 10MHz or 20MHz.
    - Consequently the THz band and THz signaling offers extremely high data rate but this benefit not come without drawbacks and limitations.

- Very high path loss.

    - Being physically very small THz waves are greatly affected by metal obstacles or even water molecules. As a result it does suffer with very high path loss. These losses become much more limiting especially when the transmission range is higher than 1.0 meter.

- Noise sources
    - In addition, the noise sources affecting the THz signals. Molecular absorption noise is shown non-white.
    - And another noise type is receiver noise which is high in this frequency range

3.3 Terahertz propagation model

Out of several communications technology among nano-machine is still challenging task due to size, complexity and energy consumption. But good sign that it's motivated to investigate of novel nanomaterials for electromagnetic communication among nano-machines. Among others the most extraordinary nanomaterials is *graphene* for its crystalline allotrope of carbon with 2-dimensional properties which derivatives Graphene Nanoribbons or Carbon nanotubes (CNTs).

To develop graphene-based nano-transceivers it's necessitates to define radiation properties of graphene in order to select operating frequency. So far, two approaches have been done to characterize radiation properties based on RF and Optical perspective. Both approach conclude that it enable to electromagnetic communication in terahertz band ranges from 0.1-10.0THz [5].

RF perspective, from classical antenna theory, we know that if decreasing the size of antenna down to few hundred of nanometer will increase resonant frequency highly which reduced the performance of antenna. However, propagation of graphene based EM waves influenced by two quantum effects, i) the quantum capacitance ii) the kinetic inductance. And the resonant frequency of this nano-antenna can be up to two orders of magnitude below the predicted values. The feasibility to design nano-antenna with atomic precision working at low resonant frequencies opens a new door to EM communication for nanonetworks [5, 6].

Optical perspective, the emission of photos from nano-structure due to interaction between electrons and ions inside the material, inspired the study of nanotubes and nanoribbons as optical emitters and detectors. Based on this, the EM radiation is produced by collision of electron when they are travelling through the edge of material or with other particles, releasing photons. So, as a result carbon nano-tubes (CNTs) have been recently proposed as a potential optical antennas operating in the THz band (0.1-10.0 THz).

3.3.1 Molecular Absorption

In THz band when electromagnetic waves travel through in a medium, molecules gets excited and vibrated internally at specific frequencies. Due to constant translational and rotational motions, part of energy propagation wave converted to kinetic energy or in terms of communication, simply lost. By solving Schrödinger equation for internal form of molecules will provide the vibration frequencies at which a given molecules resonates [38].

To predict molecular absorption several methods for a given medium exist in both microwave and infrared regions. The infrared perspective and for frequencies above 1THz only available option to rely HITRAN (High resolution Transmission molecular absorption database) for the computation of the attenuation due to molecular absorption or similar databases. Due to molecular absorption the attenuation that a wave suffers while travelling up to a few meters. So, to define the transmittance of medium we should count the fraction of electromagnetic radiation at a given frequency that is able to pass through the medium. By using Beer-Lambert law as:

$$\tau\,(f,d) = \frac{p_0}{p_i}e^{-k(f)d}$$

where f is the frequency of the electromagnetic wave, d stands for the total path length, P_i incident power, P_0 radiated powers and k is the medium absorption coefficient depends upon the concentration and the particular mixture of molecules encountered along the path.

The resulting [5] expression of total attenuation that a signal suffers due to molecular absorption can be expressed as:

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

or in dB scale we can write:

$$A_{abs}(f,d)[dB] = k(f)d10log_{10}e$$

Different types of molecules have different resonant frequencies and, in addition, the absorption at each resonance is not confided to a single center frequency, but spread over a range of frequencies. As a result, the terahertz channel is very frequency-selective.

3.3.2 Path Loss

The total path loss for transmitting wave in THz band is obtained by summation of spreading loss A_{spread} (The spreading loss depends only on the signal frequency and the transmission distance) and molecular absorption attenuation A_{abs} as the addition in dB

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

Where d is the total path length and f stands for the wave frequency.

The spreading loss accounts for the attenuation due to the expansion of a wave as it propagates through the medium, i.e., the free-space loss. This is defined in dB as

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

where d is the total path length, f is the frequency of the EM wave and c stands for the speed of light in the vacuum. The spreading loss within Terahertz Band is large due to limiting the maximum transmission range, to apply classical communication which is a major inconvenience.

3.3.3 Molecular absorption noise temperature

So far we understand that molecules presents in the medium only affect due to attenuation. In addition, when electromagnetic wave propagate through the medium, the emission of electromagnetic radiation by vibration of the molecules at the same frequency that provoked motion consider as a noise factor affect [37].

At receiver, the equivalent noise temperature will to compute this affect by introducing emissivity of the channel which defined as,

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

where ε is the transmissivity of the medium, f is the frequency of EM wave and d is the path length.

An omnidirectional antenna will detect from the transmission medium due to molecular absorption the equivalent noise temperature T_{mol} in Kelvin can be expressed as:

$$T_{mol}(f,d) = T_o \varepsilon(f,d)$$

where T_0 is the reference temperature. This type of noise will only be present around the frequencies in which the molecular absorption is considerably high.

3.3.4 Total system noise power

To compute total system noise power T_{noise} is the combination of nano-electronic noise temperature [40]and the antenna noise temperature from several sources such as created by surrounding nano-devices, the noise introduce by the receiver calculated as:

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

where T_{sys} represent the system electronic noise temperature, T_{ant} is the total antenna noise temperature, T_{mol} is the molecular absorption noise, and T_{other} accounts for any other additional noise source.

If we want to compute the equivalent noise power at the receiver, we have to define the transmission bandwidth, which will on its turn depend on the transmission distance and the composition of the medium. For a given bandwidth, the total noise power $p_n$can be calculated as

$$p_n(f,d) = \int_B N(f,d)df = k_B \int_B T_{noise}(f,d)df$$

Where f stands for frequency, d is the transmission distance, N refers to the noise power spectral density (p.s.d.), k_B is the Boltzmann constant and T_{noise} refers to the equivalent noise temperature.

3.3.5 Channel capacity

According to the Shannon's formula, for considering the capacity C_{ij} of a link from transmitter *j* to receiver *i*,

$$C_{ij} = BW \ ln(1 + (S/N)_{ij})$$

Where *BW* is the channel bandwidth, $(S/N)_{ij}$is the signal-to-noise ratio (SNR) which measures the ratio between noise and arbitrary signal on the channel. In [17], result shows that the channel capacity by assuming SNR = ½, rises as the scale is reduced towards 0 using Shannon's formula.

The capacity in bit per second is obtained by multiplying the capacity in bit per symbol for single user can be expressed as:

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

at which signals are transmitted, if $\beta = T_s/T_p$ (where T_s is the time between symbol, T_p is the pulse length) is increased then single-user capacity is reduced, but advantage is that to create nano-transceiver the requirements get significantly relaxed. To assume $BT_p \approx 1$, B is the term of BW, the capacity:

$$C_u = \frac{B}{\beta} C_{u-sym} \qquad \text{[bit/second]}$$

In [18], statistical model of molecular absorption has been developed for both single and multi-user capacity. Noted, if the silence is transmitted than molecular absorption noise is nonexistent. The maximum capacity per user can be can be achieved, If all symbols by means pulses or silences are transmitted in burst.

As we have analyzed the THz signaling and THz propagation model we can be sure that it has strong dependency on transmission range and molecular composition of the medium. The key factor affecting absorption by water vapor molecules in this frequency range, which attenuates the transmitted signal as well as introduces colored noise. The high channel capacity can able to support transmits high bit rates, also enables new coding schemes and networking protocols which more suited for resource-limited nano-devices. All we have discussed still in proposal level and still challenging.

Chapter 4

4.Approach and Design

Towards our approach we review the basic ad-hoc network routing protocol and communication distance between nodes and how to increase it. After that we consider five different medias such as air, ammonia (NH_3), water (H_2O), nitrogen (N_2), ozone (O_3) and implement their absorption spectrum in THz band (0.1-10.0THz) with the help of HITRAN database. In the last part of this chapter, we reviewed the graphene based carbon nanotube antennas (CNTs) are used that supports the electromagnetic communication for the choice of operating frequency.

4.1 Metrics

4.1.1 Ad-hoc network

Ad-hoc network is infrastructureless mobile network without having fixed routers; all nodes capable to move and connected dynamically in an arbitrary manner. Nodes of these networks function as routers which discover and maintain routes to other nodes in the network. Example applications of ad hoc networks are emergency search-and-rescue operations, meetings or conventions in which persons wish to quickly share information.

Numerous protocols have been developed for ad hoc mobile networks. Such protocols must deal with the typical limitations of these networks, which include high power consumption, low bandwidth, and high error rates. As shown in Fig 4.1routing protocols may generally be categorized as:

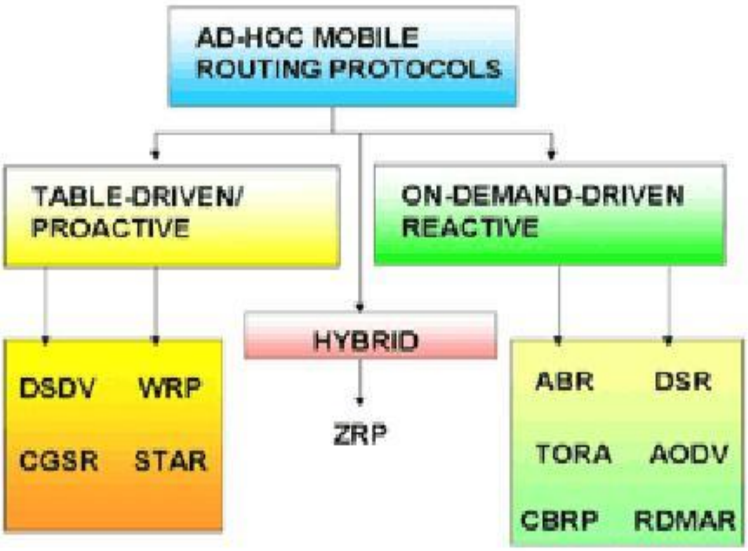


Figure 4.1 *Categorization of ad hoc routing protocols* [12]

Table-driven or proactive protocols require each node to maintain one or more tables to store routing information and they respond to changes in network topology by propagating updates throughout the network in order to maintain a consistent network view.

On demand-driven or reactive protocol this type of routing creates routes only when desired by the source node. When a node requires a route to a destination, it initiates a route discovery process within the network

Hybrid routing protocols is the combination of both table driven protocols with on demand routing protocols. To define the best path, this protocol use distance vector. Each node has its own routing zone and size is defined by number of hops.

According to above protocol and some other existing routing protocols, important factors are needed such as store routing information means memory, route update regularly, huge memory etc. But Communication networking between two or even several nanosensors nodes at nanoscale is still challenging task. The transmission range of nano-machines are very limited, multi hop communication would be the best possible way to communicate between sender and receiver. Even we are not assuming nano-nodes are transmitting packet directly to its nearest nano-router. To allow bidirectional and multi hop communication, the packet should include about its source and destination but how to include still undefined. Moreover, due to lack of resources and high proneness to failure of nano-machines, it's not guaranteed that route information can be stored between transmissions.

4.1.2 Communication distance

Communication distance between two nodes is a problem simply because if it's small then density of nodes must be huge. To consider one-dimensional random network comprises *n* (communication) nodes which are placed independently on the interval [0, 1] according to some probability distribution F. Two nodes are communicated with each other if their distance is less than some transmission range $\tau > 0$.

For a typical scheme, graph connectivity as *n* becomes large and the transmission range T is scaled appropriately with *n*. This is achieved by means of scaling or range functions $\tau : \mathbb{N}_0 \rightarrow \mathbb{R}_+ : \rightarrow \ \tau_n$, and mostly results in zero-one laws according to which the graph is connected (resp. not connected) with a very high probability (as *n* becomes large) the scaling depending on how deviates from a critical scaling T*. Such critical thresholds are probably to be distribution dependent and serve as rough indicators of the smallest communication distance needed to defined network connectivity [22][23].

So, for short communication distance density of nodes must be really huge and costly. For example, sparse network graph where networks are connected and with short distances. But such a kind of topology is too expensive to install. And for large communication diction it requires different densities to coverage to same area. , increasing by some percentage decreases the density big time. Density to cover in certain are for communication distance is the direct function.

4.1.3 Reliability

In wireless nanosensor network, end-to-end reliability has to be ensured in both case for messages going from command center to the nanosensor devices and packets coming from the nano-machines to a common sink. Nanosensor device failure (unknown robustness against environmental and chemical phenomena) and Transient molecular interference (sudden burst of molecules can occur temporal disconnection for single nanosensor devices) can affect the network reliability.

By increasing the number of nano-machines into certain area is a solution but complex to cope up from these affect. Network reliability should be investigated by considering random communication features.

4.1.4 Cost

The price of installation as its directly related with number of sensors installed that means price increase linearly as number of sensors required. It greatly depends on the coverage and correspondingly coverage depends on the environment sensors currently located. In Fig 4.2 illustrate the procedure. That's why we would like to enable adaptivity up to some extend. If this adaptivity would cost us lot in terms of implementation become challenging.

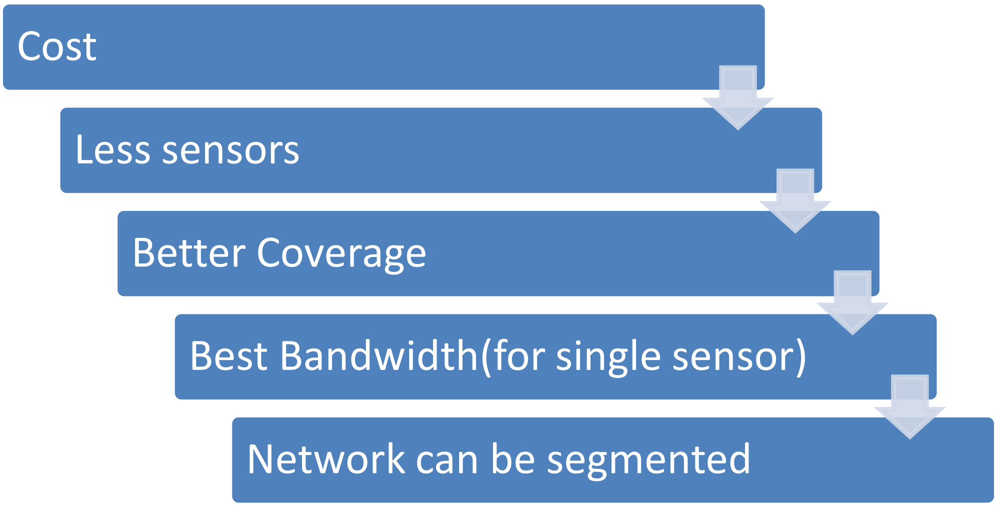


Figure 4.2 *Illustration of cost*

4.2 Description of possible environments

Reducing the antenna of a classical wireless device down to a few hundreds of nanometers would require the use of extremely high operating frequencies, compromising the feasibility of electromagnetic wireless communication among nano-devices. However, the usage of graphene to fabricate nano-antennas can overcome this limitation. Indeed, the wave propagation velocity in carbon nanotubes (CNTs) and graphene nanoribbons (GNRs) can be up to one hundred times below the speed of light in vacuum depending on the structure geometry, temperature and Fermi energy.

4.2.1 Details of different media

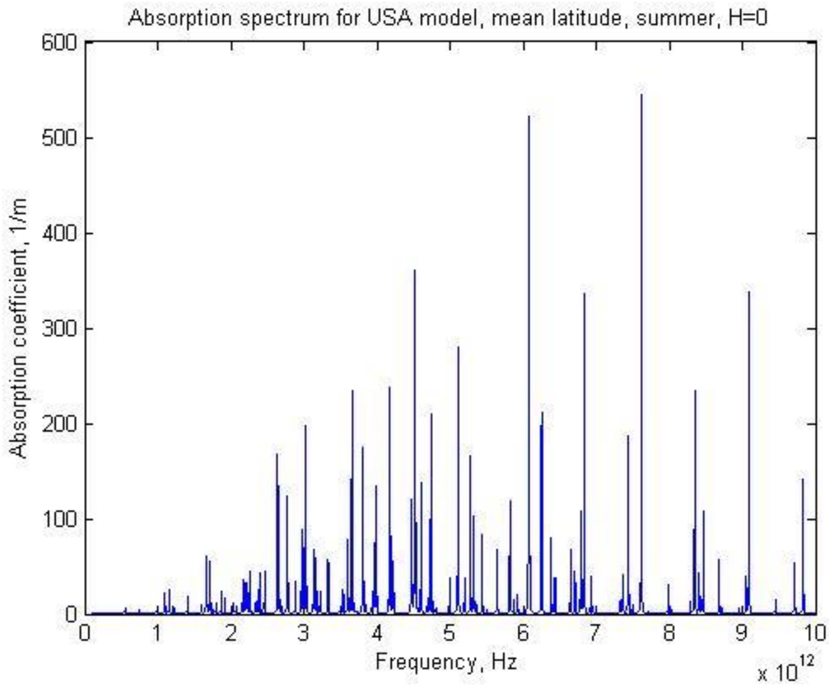
The effect of each chemical species on the individual radio signal is characterized by its molecular absorption coefficient of specie at THz frequency. The molecular absorption coefficients of many chemical species are available from the HITRAN database [2]. For every media we plot the Molecular absorption over the frequency band 0.1-10.1 THz in the *HITRAN on the web* platform for both room and standard temperature at Pressure, 1.0atm. The molecular absorption varies across the frequency band.

We assume the radio channels are in different media; here we consider

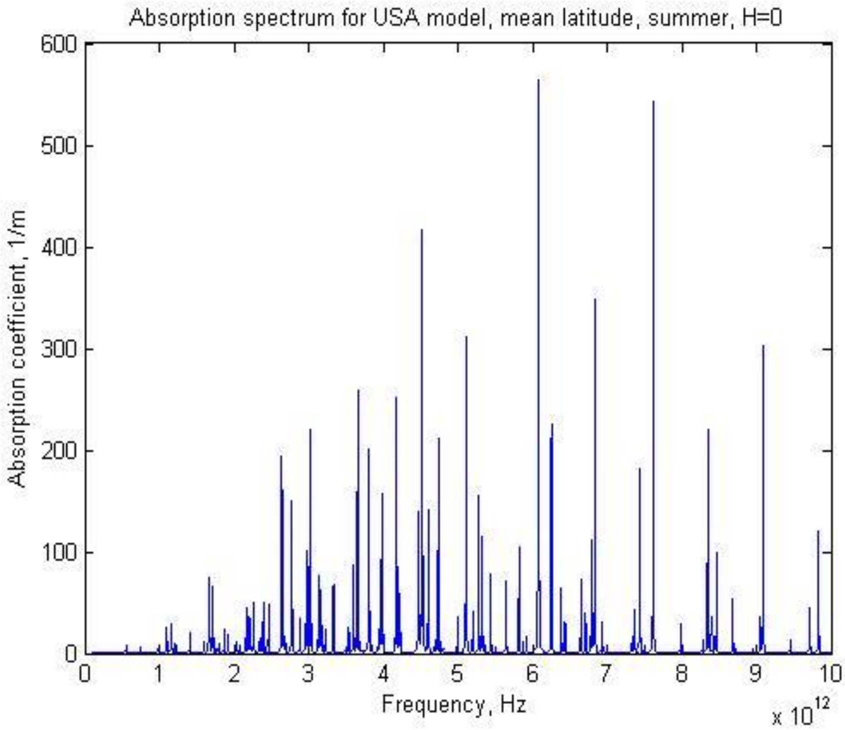
- Air
- Ozone (O_3)
- Ammonia (NH3)
- Nitrogen (isotopologue $^{14}N^{14}N$ for N_2) and
- Water (H_2O).

In Fig 4.3 molecular absorption spectrum *for USA model, mean latitude, summer* for both a) room temperature and b) standard temperature shows that the total absorption in a regular medium comes from the air with resonances within the entire band. At room temperature highest peak reach 7.6 THz and then decreasing slightly compare to standard temperature where highest peak at 6.1THz.

In Fig 4.4 molecular absorption spectrum *in comparison for USA model, mean latitude, Winter, H=0* at room temperature highest peak 7.7 THz and absorption coefficient is $130m^{-1}$ absorption coefficient. And at standard temperature 6.1THz with $140m^{-1}$ absorption coefficient, after that decreasing in slower rate compare to room temperature.

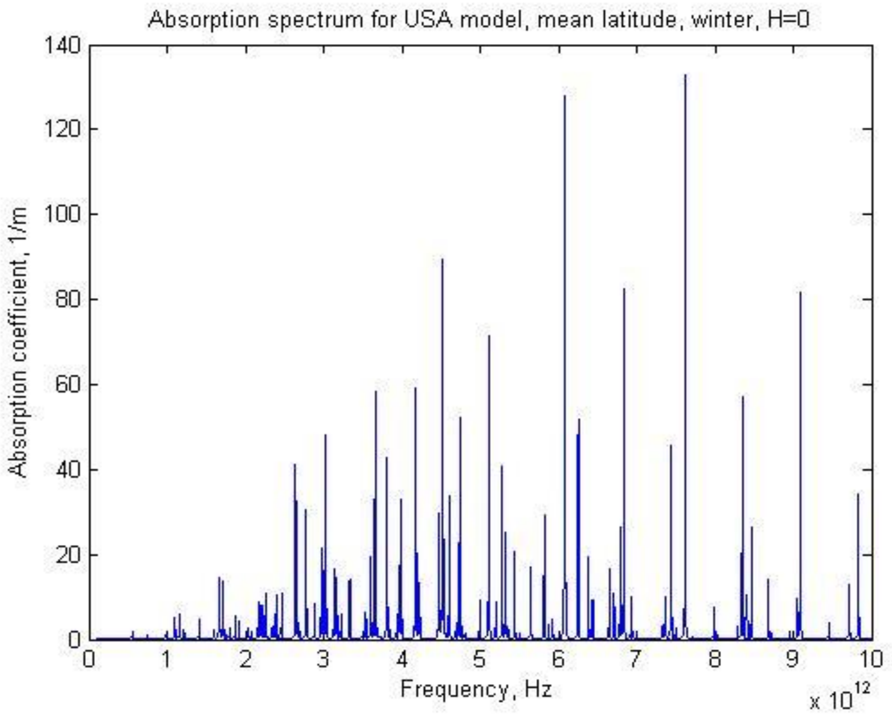


a) Room Temperature, 296K

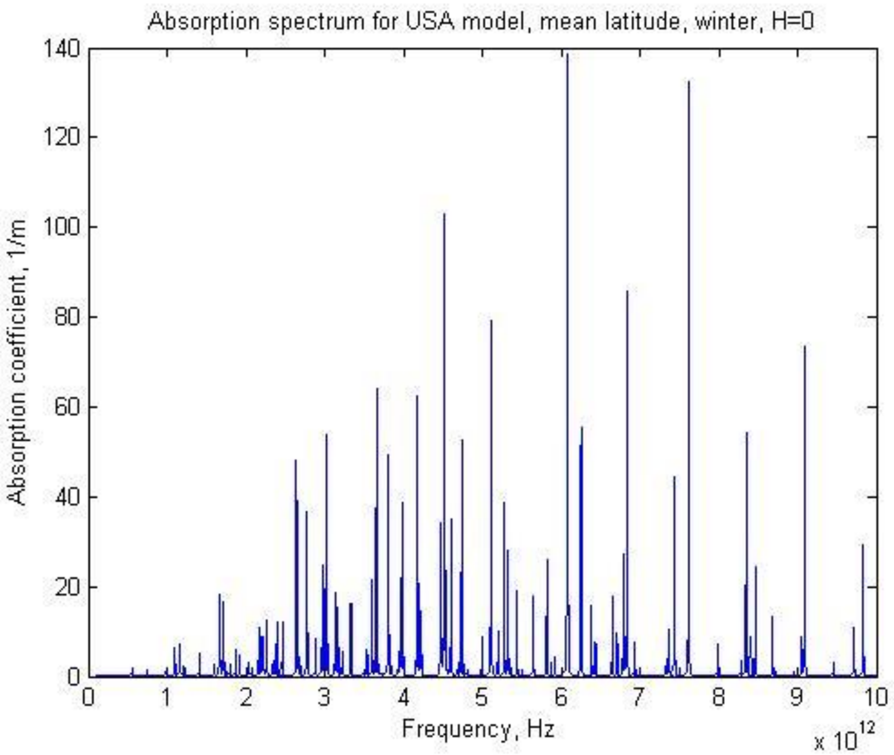


b) Standard Temperature, 273K

Figure 4.3 *Comparison of molecular absorption coefficient in m-1 for USA model, mean latitude, Summer, H=0 atmosphere consisting of oxygen (O2) 20.71%, nitrogen (N2) 77.39% and water vapor (H2O) 1.86% as a function of frequency a) Room Temperature, 296K, b) Standard Temperature, 273K*

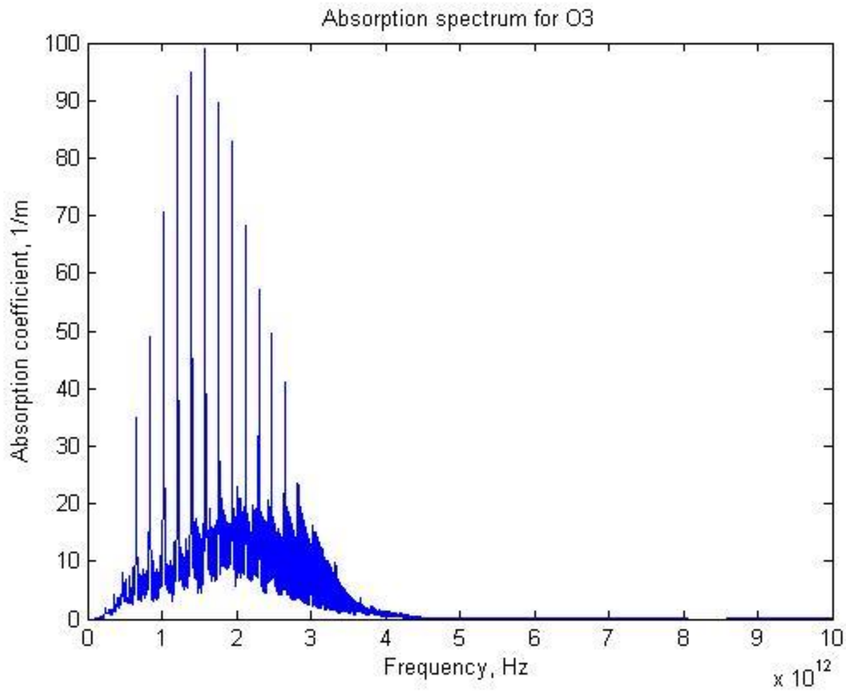


a) Room Temperature, 296K

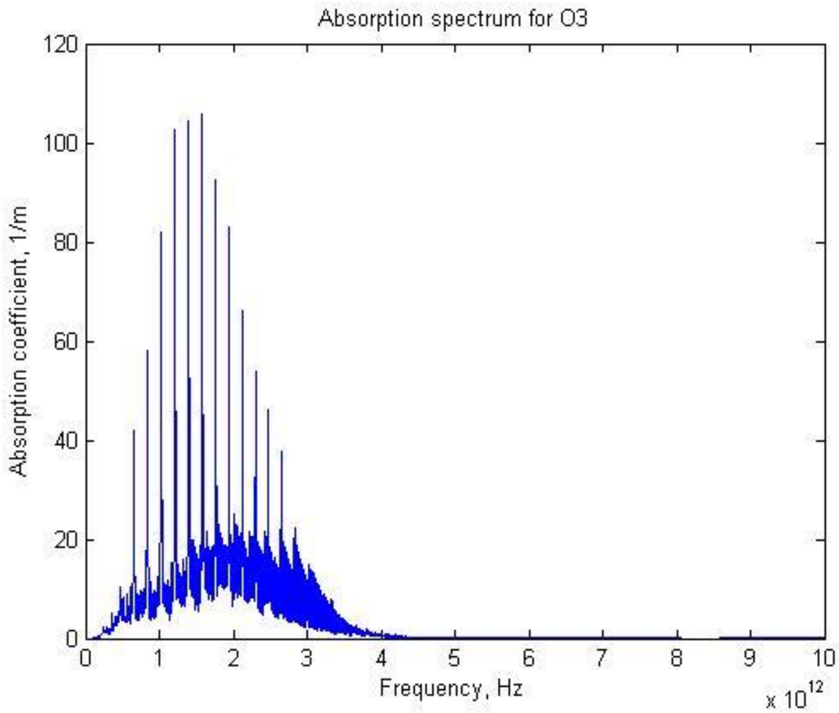


b) Standard Temperature, 273K

Figure 4.4 *Comparison of molecular absorption coefficient in comparison for USA model, mean latitude, Winter, H=0 atmosphere consisting of oxygen (O_2) 20.90%, nitrogen (N_2) 78.10% and water vapor (H_2O) 1.86% as a function of frequency a) Room Temperature, 296K, b) Standard Temperature, 273K.*



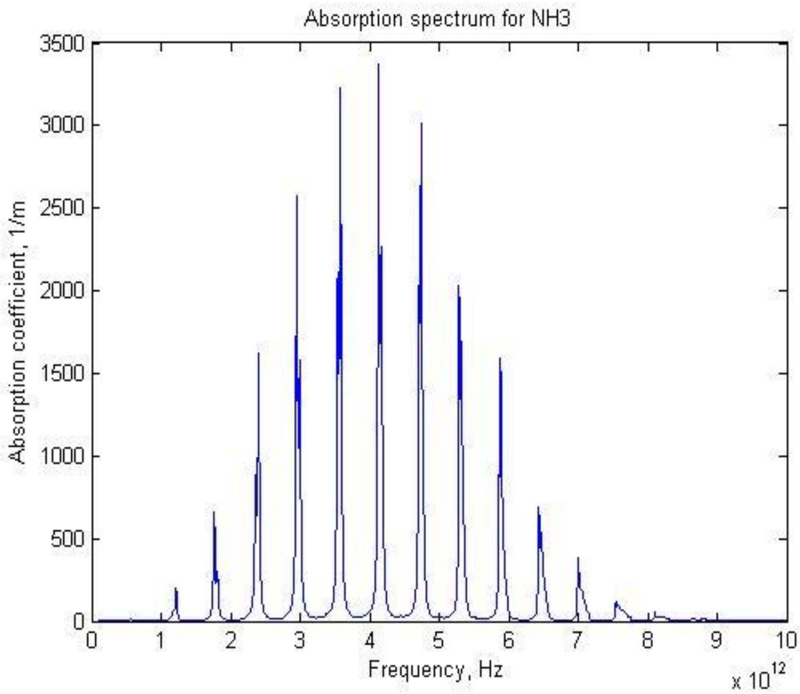
a) Room Temperature, 296K



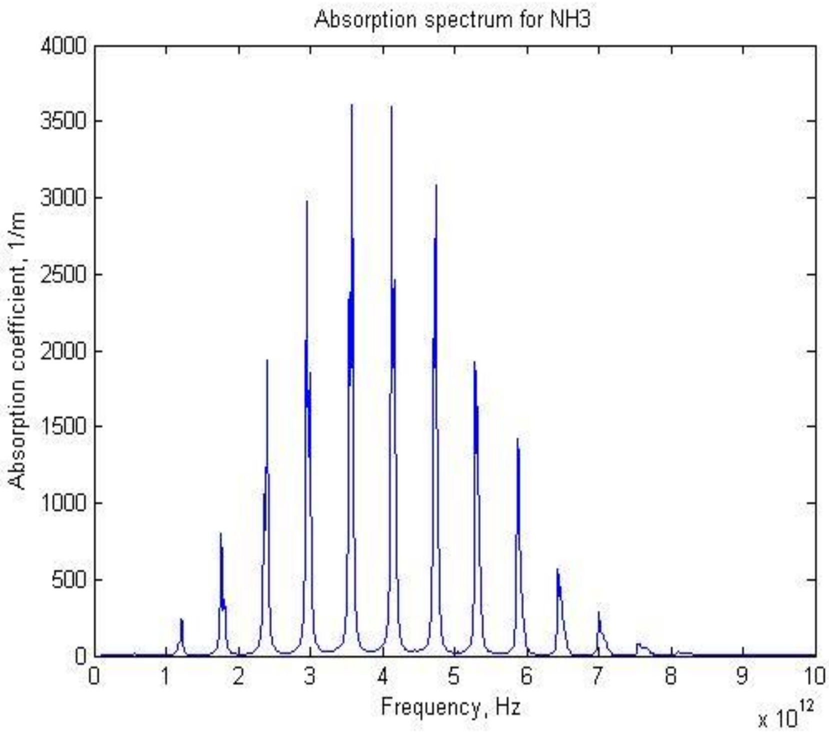
b) Standard Temperature, 273K

Figure 4.5 *Comparison of the absorption spectrum for Ozone (0_3) plotted on a frequency scale 0.1-10 THz and absorption coefficient m-^{1} a) Room Temperature, 296K, b) Standard Temperature, 273K*

In Fig 4.5 we can observe that the absorptions happens between 0.1-5.0 THz range in both temperature where at room temperature 100m^{-1} and at room temperature over 100m^{-1}. In the next media Fig 4.6 shows that at room temperature NH_3 molecule starts absorbing periodically



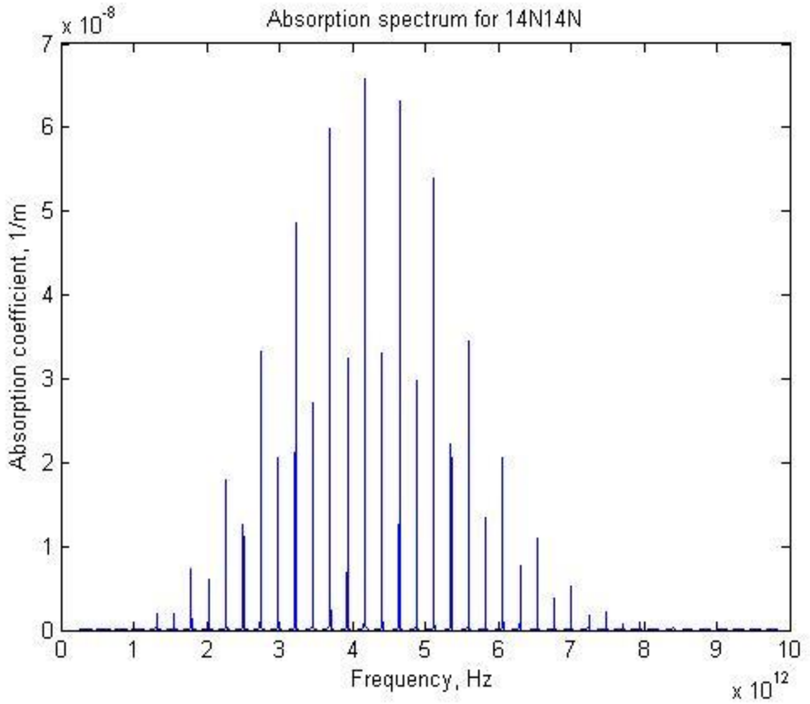
a) Room Temperature, 296K



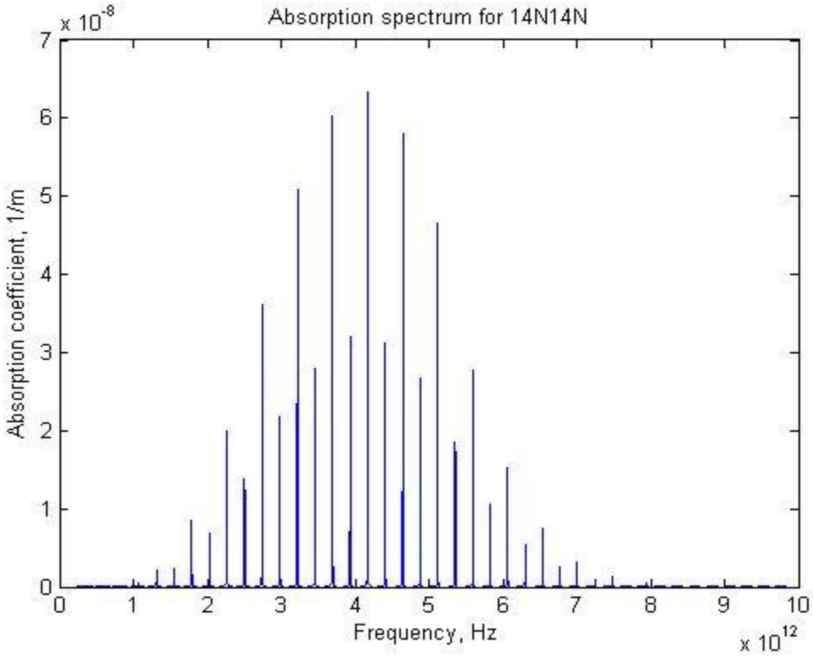
b) Standard Temperature, 273K

Figure 4.6 *Comparison of the absorption spectrum for NH_3 plotted on a frequency scale 0.1-10 THz and absorption coefficient m^{-1}. a) Room Temperature, 296K, b) Standard Temperature, 273K*

from 1.0-9.0THz and reach the highest peak at 4.1 THz where the absorption coefficient 3400m^{-1} and at standard temperature highest peak over 3500m^{-1} in the range of 1.0-8.0 THz.

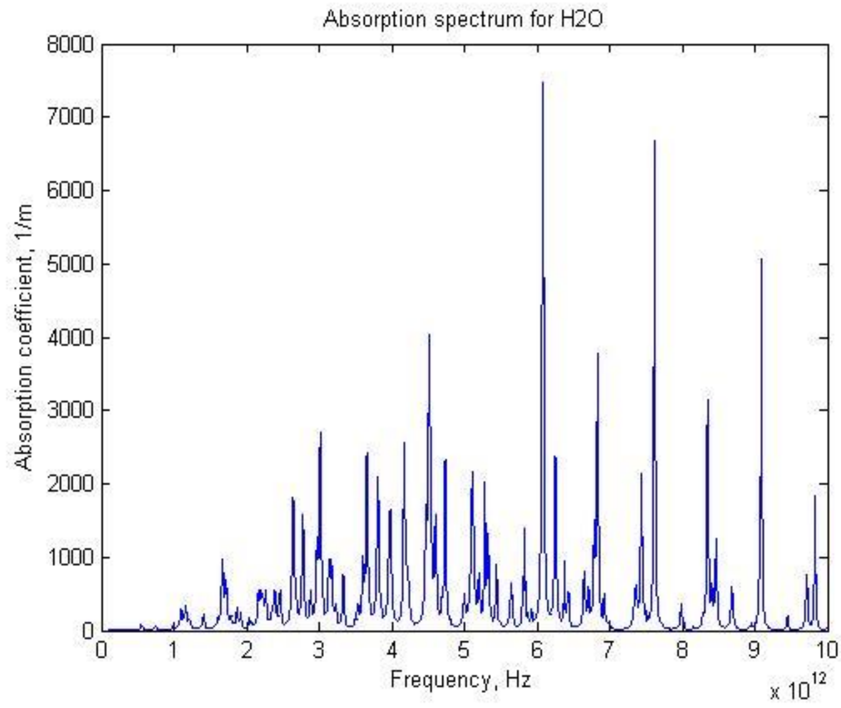


a) Room Temperature, 296K

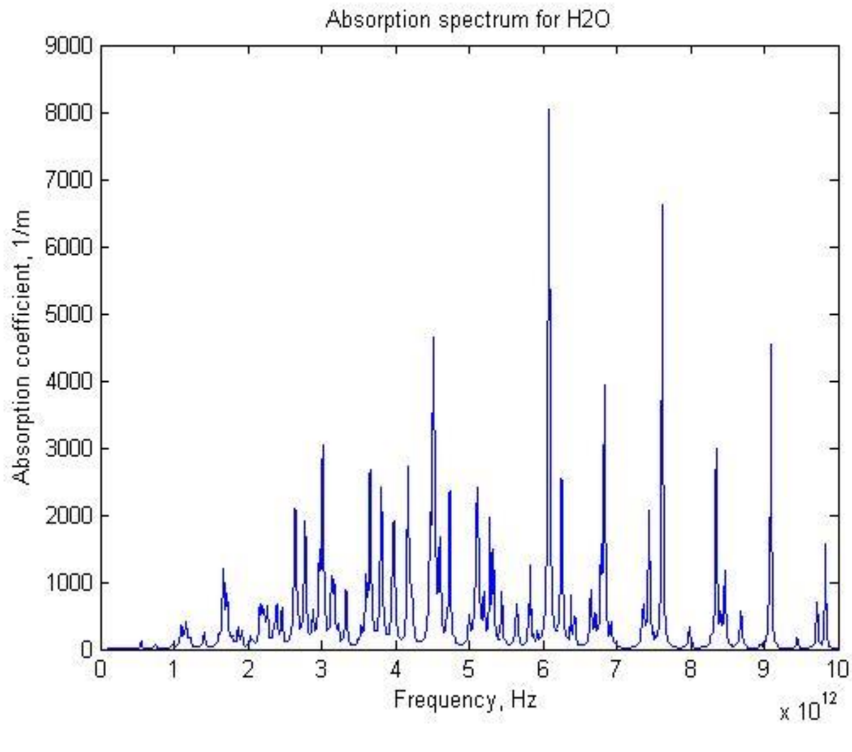


b) Standard Temperature, 273K

Figure 4.7 *Comparison of the absorption spectrum for isotopologue of nitrogen ($^{14}N^{14}N$) plotted on a frequency scale 0.1-10 THz and absorption coefficient m^{-1} a) Room Temperature, 296K, b) Standard Temperature, 273K*



a) Room Temperature, 296K



b) Standard Temperature, 273K

Figure 4.8 *Comparison of the absorption spectrum for water (H_20) plotted on a frequency scale 0.1-10 THz and absorption coefficient m-^{1} a) Room Temperature, 296K, b) Standard Temperature, 273K*

For the isotopologue of nitrogen ($^{14}N^{14}N$) in Fig 4.7 absorption occurs within the range of 1.0-8.0THz at room temperature and at standard temperature 1.0-7.5THz region. In Fig 4.8 for water (H_20) the resonant peaks within the entire band in both temperatures, at room temperature the most absorption coefficient in 6.0THz with more than 7000m^{-1} and at standard temperature 8000m^{-1}, after that decreasing absorption compare to room temperature.

According to our simulation we can observe that in different medias molecular absorption coefficient varies in different frequency range in terahertz BW (0.1-10.0THz). Out of our analysis we can understand that molecular absorption is highly frequency selective process. At some frequencies absorption coefficient are extremely high or small, at some frequencies there is null absorption coefficient.

4.3 Operating frequency by carbon nanotube

The EM properties of novel nanomaterials will define the communication capabilities of nanosensor devices, such as the frequency band of operation or the magnitude of the emitted power for a given input energy. Novel nanomaterial Graphene is a one-atom-thick planar sheet in a honeycomb crystal lattice of bonded carbon. Carbon is capable to form allotropes due to its valency. Carbon nano tubes are allotropes of carbon with cylindrical nanostructure where nanotubes are built with the internal cylinder diameter of 1 to 50nm and length of about 100nm up to several micrometers or even longer [35].

CNTs is a folded strip of graphene (1991) Fig 4.9, they can be single layered of graphene sheet and by folding constructed tube called Single walled nanotubes(SWNTs) with a diameter of close to 1nm and the tube length can be many thousands of times longer. When there are multiple layers then it's called multiple walled nanotubes (MWNTs) with a diameter in the range 5nm to 50nm. Graphene nanoribbons are a thin trip of graphene (2004).

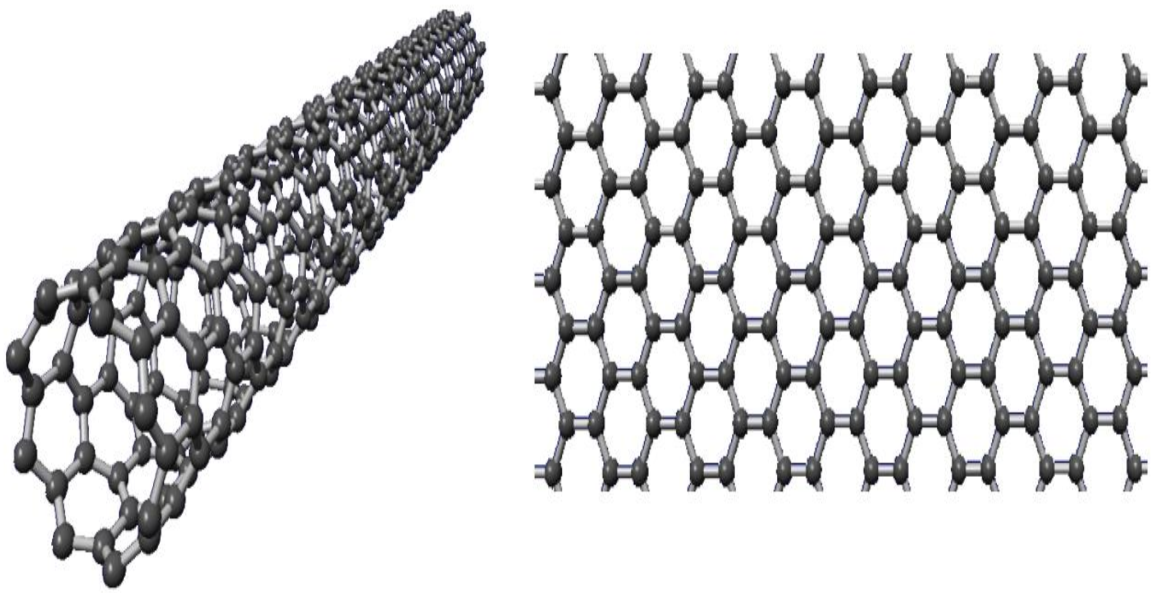


Figure 4.9 *folded and thin strip of Graphene.*

In graphene, all their atoms are exposed as a result very high sensitivity. Some tremendous natural properties are high current capacity and thermal conductivity which is good for energy efficiency. The atomic structure of CNTs makes them high robustness that means extremely high mechanical strength. In addition, atoms in graphene are exposed which results very high sensitivity. Due to their small size nanotubes can reach deep into their environment without affecting their natural behavior and individual nanotubes can be used to construct a network sensing elements.

Reducing the antenna of a typical sensor device downgrading to nanometer scale ($\sim 100nm$) needs extremely high operating frequency which compromising with the feasibility of EM wireless communication as nanomaterials such graphene to fabricate nano-antennas can meet the limitation. The resonant frequency of graphene based nano-antennas can be up two orders of magnitude due to geometrical structure, temperature and Fermi energy.

In [6], two types of nano-antennas GNRs based nano-patch antenna and CNTs based nano dipole antenna Fig 4.10 have been compared by involving tight binding model based on quantum mechanical structure, with the transmission line properties of nano-dipole antenna as a function of CNT dimension, edge geometry, Fermi energy and parameters such as the fundamental resonant frequency, input impedance with compare similar dimension of GNRs based nano-patch antenna. The outcome was that both antennas capable to radiate EM wave in the THz band (0.1-10.0THz) for maximum antenna size.

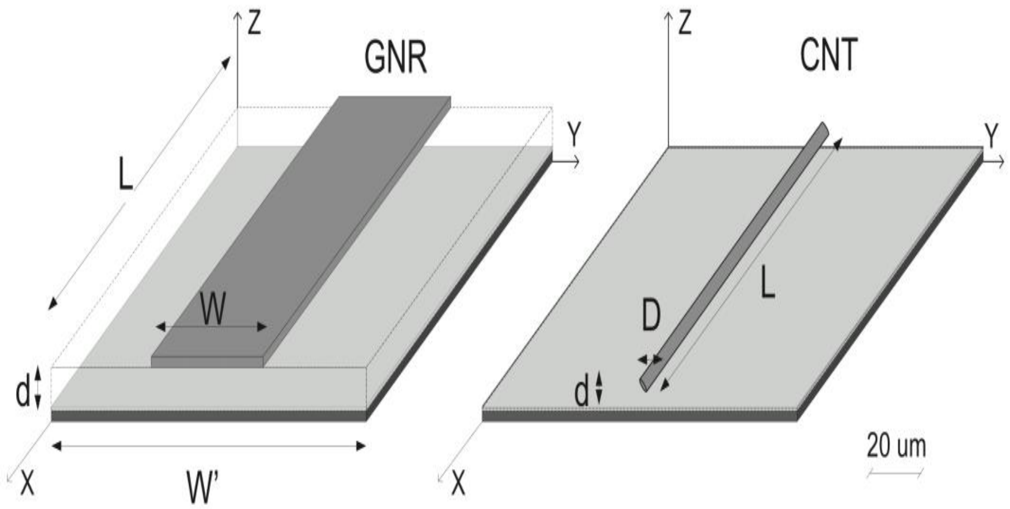


Figure 4.10 *A nano-patch antenna based on a GNR (left) and a nano-dipole based on a CNT (right) [3].*

Due to well defined atomic structure graphene shows ballistic transport of electrons for relatively large lengths. The total *quantum resistance or contact resistance* of ballistic conductors, nanotube with more than one conducting band, defined as

$\mathcal{R}_Q^T \approx h/2e^2M$

where *M* refers to the number of conducting bands which increases with the diameter of the nanotube as the separation band reduced.

In *Kinetic Inductance* , the resistance to current change due to Faraday's law and energy stored in the magnetic field generated by a current going through the device. Nanotube with *M* conducting, the total kinetic inductance $\mathcal{L}_k^T$ per unit length is:

$$\mathcal{L}_k^T = \left(\sum_{n=1}^{M} (\mathcal{L}_k^n)^{-1}\right)^{-1}$$

So, we can see that by increasing the diameter of the nanotube conducting bands becomes larger, and the total kinetic inductance is decreased. A similar effect is shown when the Fermi energy is increased.

And for *Line Impedance*, as the quantum capacitance increases with width and energy and much smaller electrostatic capacitance C_E will dominate the parallel equivalent circuit of both capacitors, in a way the total capacitance of the system increases with the width and energy of the nanotube. So, the magnetic inductance per unit length,

$$\frac{1}{\sqrt{\mathcal{L}_m C_E}} = \frac{c}{\sqrt{\varepsilon_r}}$$

where ε_r is the relative permittivity of the material between the nanotube and the ground plane and total inductance

$$\mathcal{L} = \mathcal{L}_m + \mathcal{L}_k^T$$

As we know, the kinetic inductance of a nano-structure decreases with its width and the system energy. So, the total inductance of the system decreases with the width and the energy of the nanotube.

Wave Propagation Speed inside the CNT depends on the nanotube dimensions, its edge pattern and the Fermi energy of the structure can be obtained in a transmission line:

$$\upsilon_{\boldsymbol{p}} = \frac{\mathbf{1}}{\sqrt{\mathcal{L}C}}$$

where $\upsilon_{\boldsymbol{p}}$ is the propagation velocity. According to [6], [19] the first resonant frequency of a CNT-based antenna is:

$$f = {}^{\upsilon_{\boldsymbol{p}}}/_{2L}$$

where *L* is stands for carbon nano tube length. The result shows that the nanotube length kept constant for different energies. For a very thin nanotube, 4nm diameter resonant frequency will be below 1.17THz. And by increasing diameter resonant frequency will increase non-linearly. But the resonant frequencies of GNR lower rather than CNT.

Another issue show to taken into account that nanomaterials are high contact resistance but it can be reduced by applying voltage to the nano-antennas or changing diameter or width.

At nanoscale, graphene based EM propagation wave is governed mainly with the quantum capacitance and kinetic inductance. The resonant frequency of these graphene enabled nano-antennas can be up two orders of magnitude below the expected values. To define such a kind of antenna with atomic accuracy structured opens the path to EM communication for nanonetwork.

Chapter 5

5.Implementation & analysis

In this chapter we implement our approach to keep the probability of connectivity in randomly uniformly deployed nanosensor nodes in an open environment and estimate how many nodes we required.

5.1 Connectivity

Basically connectivity deals with possibility to transfer information between two nodes by ignoring all capacity and traffic related issues as well as most importantly interference effect. If a set of nodes have an equal transmission range, the connectivity problem reduces to determining the distribution of the threshold range for connectivity, in [20]Penrose shows that for uniformly randomly distributed nodes placed in unit square the threshold range for connectivity has asymptotically the same.

5.2 Scenario

We assumed random disk field or random graph where nodes distributed randomly. If the communication distances between two nodes less than a certain value then the graph is fully connected. If not then is not connected. Because basically this is a distance between coverage areas.so if this distance is longer than the coverage radius this two nodes cannot communicate with each other. But if it's less will communicate. There is a value so called quantile, by means 95% all the probability mass, so if this value for a certain intensity is less than our radius than we could use such kind of communication strategy, if not then we cannot really use. We are trying to find intensity of nodes λ for which intensity of nodes the network is fully connected for a given

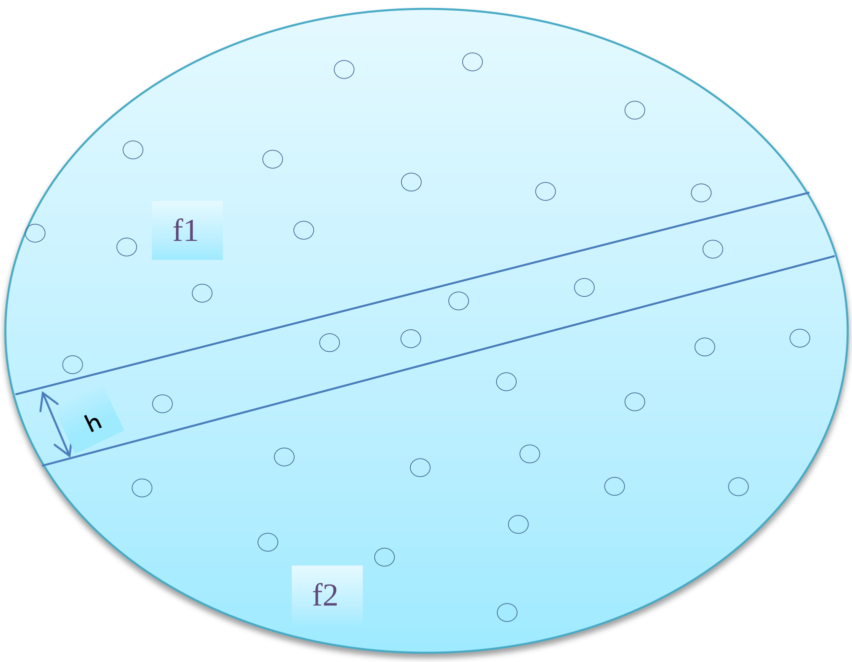


Figure 5.1 *randomly distributed nodes in disk field with two different medias.*

probability. This basically quantile says that this probability 0.95, the network is fully connected and probability with 0.05, the network is not connected fully-this called 1-connectivity.

In case of two different medias Fig 5.1, we presume that nodes randomly distributed in a network area with communication range r among medias f1 and f2, between them a kind of cross border that has a certain range h, depends on the concentration of both medias, then some of the nodes are going to choose f1 media bandwidth and some of them choose f2 medias bandwidth. In added to avoid difficulties in our analysis we neglect border affect nodes are residing in border choose their nearest band that means all the nodes between border either using f1 or f2 probability 0.5 %. We are aiming to define nodes connected with 1-connectivity, to ensure that nodes are in border that decided to go with this band or with other band are connected and actual density for us is λ/2 because in here half of the nodes are using band f1 and half of the nodes using band f2.so, this derives density of nodes between in here that could be connected in a network λ/2and we need to ensure that the probability of connectivity of these nodes to get fully connected network. We need to estimate quantile as a function of λ and for which λ the network is fully connected.

5.3 Approximation for probability of connectivity

In this part we compute based on stochastic-based algorithm number of nodes for analysis the connectivity. Approximation for probability of connectivity method analyzed based on Random Waypoint Mobility (RWP) model. Analytical approximations have been given calculating the probability is *k*-connected in certain network consisting *n* nodes.

With the RWP model in the unit disk field the probability density that a node is at a distance from the center equals *2πr f(r).* The probability that an arbitrary node has at least k-neighbors is given by [20]

$$Q_{n.k}(d) = 2\pi \int_0^1 rf(r)\left(1 - \sum_{i=0}^{k-1} \binom{n-1}{i} . p(r,d)^{\,i} . (1 - p(r,d))^{\,n-1-i}\right) dr \quad (5.1)$$

p(r, d) denote the probability for *n* node in given area , this probability depends only on the distance *r*= |r| from the center. For details, an algorithm to compute *p(r, d)* numerically has been given in the Appendix.

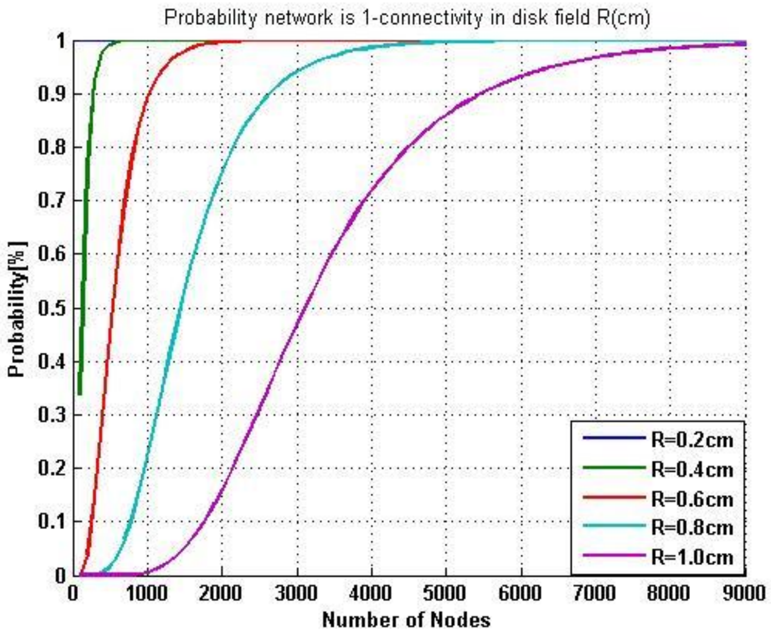
The probability that a network with n nodes is k-connected at an arbitrary point of time is given by

$$C_{n,k}(d) = \mathrm{P}\{n\ nodes\ are\ k - connected\} \approx \left(Q_{n,d}(d)\right)^{\,n} \quad (5.2)$$

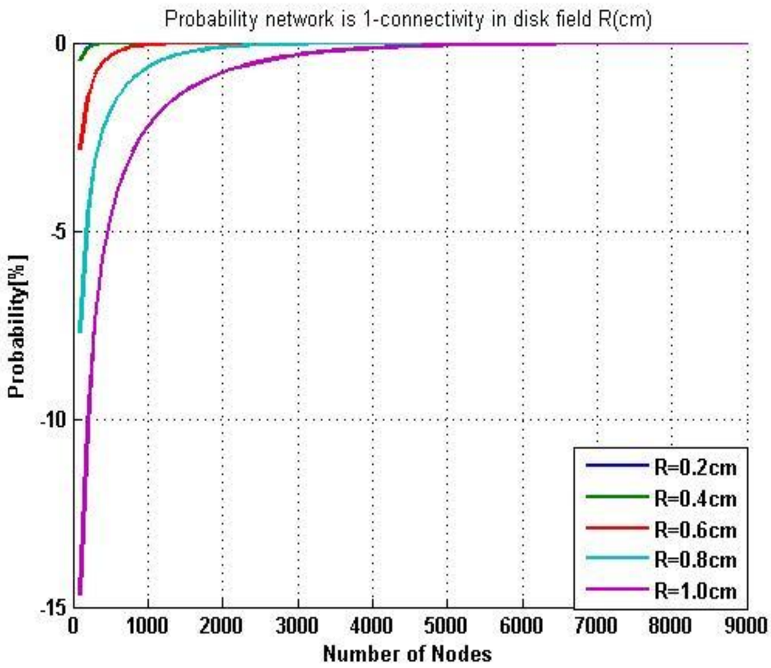
d is the communication range of sensors, *k* is number of neighbors of arbitrary node.

5.4 Simulation results and analysis

The probability of WNSN is 1-connected with *n* (100-9000) nodes on disk field with radius R (0.2-1.0cm) in linear scale and log scale for the fixed 1mm communication range.



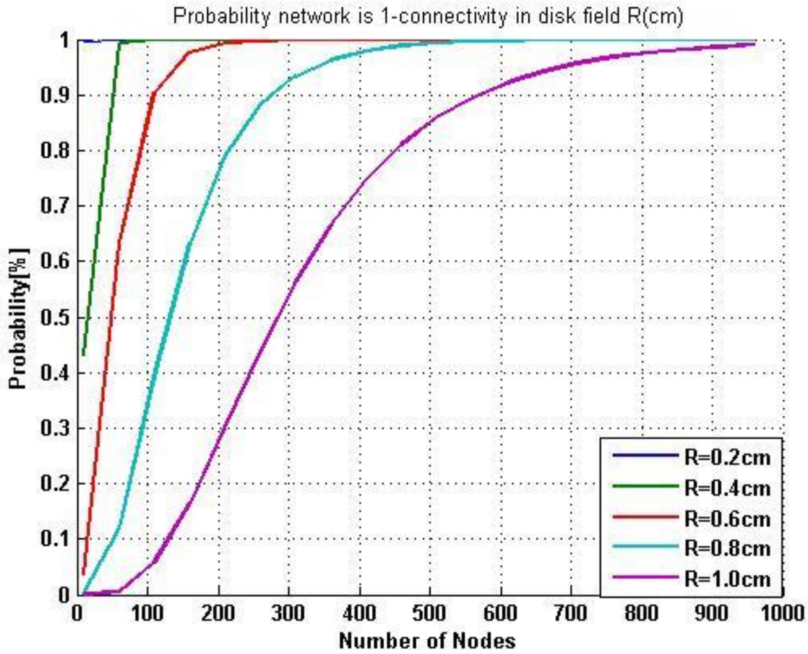
a) Linear scale for fixed 1mm



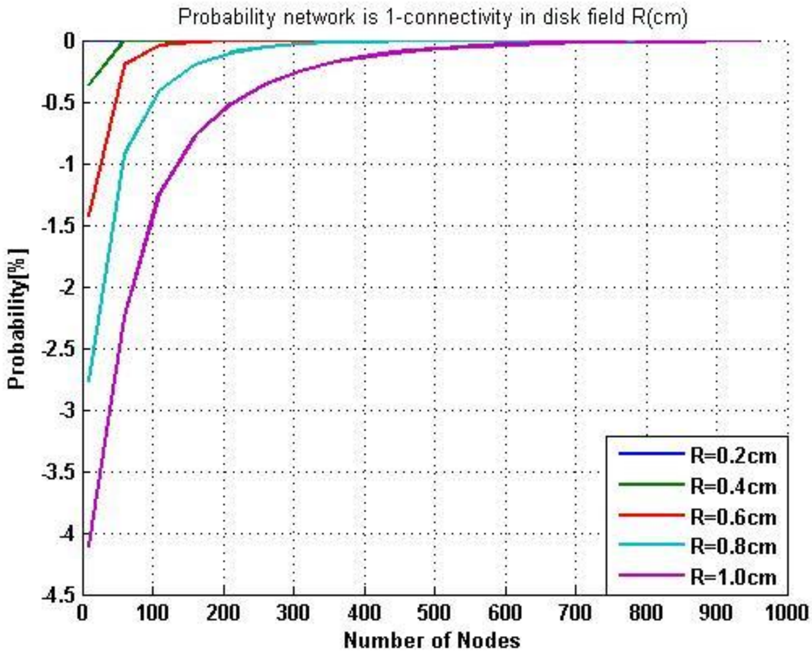
b) Log scale for fixed 1mm

Figure 5.2 *Probability of WNSN is 1-connected in disk field R (cm) and communication distance 1mm.*

The probability of WNSN is 1-connected with *n* (10-1000) nodes on disk field with radius R (0.2-1.0cm) in linear scale and log scale for the fixed 2mm communication range.



a) Linear scale for fixed 2mm



a) Log scale for fixed 2mm

Figure 5.3 *Probability of WNSN is 1-connected in disk field R (cm) and communication distance 2mm.*

In Fig 5.2 shows that when communication range 1mm, for the radius of disk field 0.2cm to keep the 95% probability at least its needed 6500nodes and for 99% probability of 1-connetivity its need 200nodes where the density of nodes $\approx 66\, nodes/cm^2$. Accordingly for the maximum 1.0cm radius of disk field to achieve 1-connected 99% probability we must have 9000nodes and the density of nodes$\approx 2864\, nodes/cm^2$.

In another approximation Fig 5.3 we observe that for the fixed communication range 2mm, when the minimum radius of disk field 0.2cm, to keep the 99% probability of 1-connectivity we required 10nodes and the density of nodes is $\approx 3\, nodes/cm^2$and for the maximum 1.0cm radius of disk field we have to have nearby 960 nodes where the density of nodes is $\approx 305\, nodes/cm^2$

So, based on our both simulation result, we can see that when we increase the communication range from 1mm to 2mm, to keep the probability of 1-connetivity the required nodes decreases hugely, for the radius 1.0cm disk field for 2mm communication range $\approx 305\, nodes/cm^2$ and for 1mm $\approx 2864\, nodes/cm^2$ which is over 9 times.

Chapter 6

6.Future Challenges in Nanonetwork and Conclusion

Nanonetworks will boost numerous application in many areas related to our day to day life and to do more flexible and secured our society starting from healthcare facilities accurately and safely, to protect our environment, industrial development. Up to date, existing communication network technology is not suitable enough for nanonetworks due to their different features. The requirement for nanonetwork system needs innovative ideas & network techniques according to communication characteristics of channel properties, processes and equipment to operate.

To overcome such kind of difficulties several factors must be focus on such as:

- How to enable the communication among nanosensors by using novel nanomaterials.
- How to design optimal and quasi-optimal encoding/decoding information by using short pulses at nanoscale.
- To manage the structure of the network as well as other parameters of the network , efficient MAC protocol, routing techniques and algorithm is required among several nanosensors devices.
- How to guarantee the end-to-end reliability in nanosensor network.
- Due to limited size nanosensor devices has limited energy; in the way energy harvesting and consumption need to be taken in account.

This thesis work provides general theoretical views of nanonetwork in terms of architecture of nano-machines and approaches for development. Also we reviewed deeply propagation model in THz bandwidth taken account of molecular absorption and molecular noise does effect in transmission medium.

We simulate absorption spectrum in (0.1-10.0) THz band for different medias Air, Ozone (O_3), Ammonia (NH3), Nitrogen (N_2 for isotopologue $^{14}N^{14}N$) and Water (H_2O) to investigate that for which bandwidth molecular absorption behavior both in room temperature, 296k and standard temperature 273k which will help us to calculate path loss and maximizes the transmission radius at nanoscale network.

WNSN can contain thousands and even millions of similar operational nodes which responsibility for sensing the environments and its information about temperature, humidity, air etc. To build nanonetwork topology in open environment, if deployed them randomly uniformly, the density of nodes must be really huge. If we are going to choose best available bandwidth we can greatly decrease the density off nodes as well as maximize the transmission radius for better coverage as well as to maintain the connectivity in network and reduce cost of sensors. To enable connectivity such kind of topology which it's hugely depends on communication range between nodes as we can see in our implementation part, probability of connectivity for number of nodes reduces by increasing of communication range of nodes. The result shows that for the radius 1.0cm disk field for 2mm communication range $\approx 305\ \mathrm{nodes/cm^2}$ and for 1mm $\approx 2864\ \mathrm{nodes/cm^2}$ which is over 9 times to keep the probability of 1-connectivity in nanonetwork. In addition, by analyzing connectivity to achieve connected nanonetwork we can capable to reduce the cost for implementing nanonetwork.

We understand that to implement fully functional nano-machines and nanonetwork are still in very early stage to introduce. Information and Communication Technologies (ICT) are a key role which can contribute network architectures, nanoscale channel models, nano-machines, nano-antenna design, medium access control and routing protocols to introduce a new network paradigm. Many research group and scientist are currently involving to solve these issues.

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APPENDIX A

PROBABILITY OF FINDING A NODE INSIDE A GIVEN AREA

An algorithm for computing *p(r, d)*, the probability of finding a node inside a disk field with a radius *d* at the distance of r from the origin, is given in Algorithm 1 an 2 and Figure 1 and Figure 2.

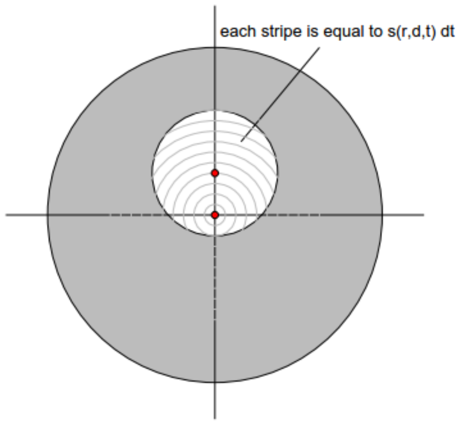

Figure 1: Partitioning the $B_d(r)$ into circular "stripes" results in a one directional integral.

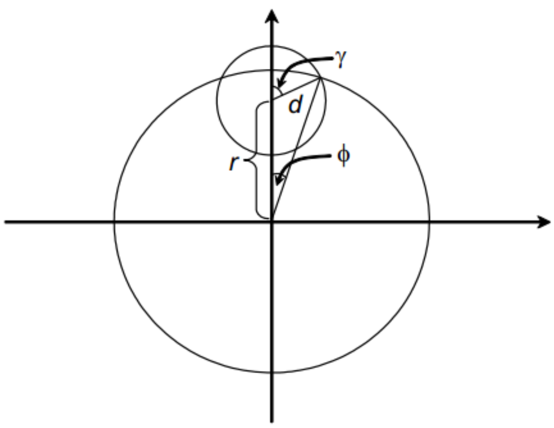

Figure 2: Notation for used in *A(r,d)* for unit disk

Algorithm 1 Function *s(r, d, t)*

if $t \leq 0\ or\ t \leq d - r$ **then**

$\theta = 2\pi$

else

A= d/t

B=r/t

$\theta = 2(\frac{\pi}{2} - arcsin((1 + B^2 - A^2)/(2B))\,)$

else if

return (1/C). θ.t. h (t)

Algorithm 2 Function *p(r, d)*

$t_0 = max\{0. r - d\}$

$t_1 = min\{1. r + d\}$

if $d > r$ **then**

$$x = \int_{t_0}^{d-r} s(r, d, t)dt + \int_{d-r}^{t_1} s(r, d, t)dt$$

else

$$x = \int_{t_0}^{t_1} s(r, d, t)dt$$

end if

return x