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SINGLE AND MULTI-USER CAPACITY OF COMMUNICATION BY SILENCE IN TERAHERTZ BAND

Master of Science thesis

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ABSTRACT

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Nanotechnology utilizes the operation of nano-sensors also called nano-machines. Nano-machines are very small in size, about a few hundreds of nanometers. At the nanoscale, single nano-machine has very limited functionalities so it is able to perform only a simple task. However, the group of nano-machine can perform complex tasks when they communicate among themselves. The tasks performed by those machines have applications in the field of biomedical, environmental, and military. There are various models of communication among nano machines, like electromagnetic wireless communication, molecular communication, acoustic communication, nano-mechanical communication model. In this studies, electromagnetic wireless communication model is used with the latest advancement in graphene based electronic. Graphene and its derivatives points that the frequency range of operation of future electronic nano-machines is terahertz band (0.1 – 10.0 THz). This band of frequency is still unlicensed and it can theoretically support a very large transmission speed.

Nano-machines, due to its small size have resource constrain. Nano-machines with nano-batteries are typically characterized by a limited energy supply. Hence, to overcome the power limitation, there is a need of an energy-efficient communication paradigm. Such an energy-efficient communication paradigm is *communication through silence* (CtS) strategy. This strategy enables energy-efficient information transfer within the nano-machines. In CtS, information is transmitted using silence period which makes this strategy energy-efficient. This thesis is focused in this new communication paradigm, CtS. The performance from this strategy is evaluated in terms of channel capacity for both single and multiple user cases in terahertz band. A propagation model for terahertz band based on radiative transfer theory is used to calculate the total path loss and the molecular absorption noise that a travelling wave suffers. Chanel capacity was formulated in this studies using those parameters. Analytical result in this studies shows that the performance is very high for both lower distance like, 1 meter and lower number of water vapour (H_2O) molecules.

PREFACE

This thesis has been written for the completion of Master of Science (Technology) Degree in Electrical Engineering 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.

First and foremost, I would like to express my sincere gratitude to my examiner Prof. Evgeny Kucheryavy. I would like to thank my supervisor Senior Research Fellow, Dr. Dmitri Moltchanov for guiding me throughout the thesis period. I am grateful to my supervisor Dmitri Moltchanov for providing an opportunity to work under his supervision, for various ideas he presented during the thesis work and showing the correct way in the writing phase of the thesis.

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Tampere, March 2016

Rohit Karki

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LIST OF ABBREVIATIONS AND SYMBOLS

ATP	Adenosine triphosphate
CNT	Carbon nanotubes
CtS	Communication through silence
DNA	Deoxyribonucleic acid
EbT	Energy based transmission
EM	Electromagnetic
FET	Field effect transistor
GNR	Graphene nano-ribbons
HITRAN	High resolution transmission
LPSR	Localized surface Plasmon resonance
NEMS	Nano-electromechanical system
PSD	Power spectral density
TEM-STM	Transmission electron microscope – scanning tunneling microscope
THz	Terahertz
UHF	Ultra high frequency
WNSN	Wireless nano-sensor network

p	System pressure
p_0	Reference pressure
T	System temperature
T_0	Reference temperature
T_{STP}	Temperature at Standard Pressure
V	Volume
n	Total number of moles
q^g	Mixing ratio of gas g
$q^{i,g}$	Mixing ratio of isotopologue i of gas g
Q^g	Number of molecules per volume unit of gas g
$Q^{i,g}$	Number of molecules per volume unit of isotopologue i of gas g
$k^{i,g}$	Absorption coefficient for isotopologue i of gas g
$\sigma^{i,g}$	Absorption cross section of isotopologue i of gas g
$S^{i,g}$	Absorption peak amplitude of isotopologue i of gas g
$G^{i,g}$	Spectral lines shape of isotopologue i of gas g
$F^{i,g}$	Van Vleck-Weisskopf line shape for isotopologue i of gas g
$f_c^{i,g}$	Resonant frequency of isotopologue i of gas g
$f_{c0}^{i,g}$	Resonant frequency of isotopologue i of gas g at reference pressure
$\delta^{i,g}$	Linear pressure shift of isotopologue i of gas g
$a_L^{i,g}$	Lorentz half-width for isotopologue i of gas g
a_Q^{air}	Broadening coefficient of air
$a_0^{i,g}$	Broadening coefficient of isotopologue i of gas g
γ	Temperature broadening coefficient
h	Planck constant
k_B	Boltzmann constant
c	Speed of light in the vacuum
R	Gas constant
N_A	Avogadro constant

1. INTRODUCTION

Nanotechnology is the manipulation of matter directly on an individual level at atomic, molecular, and super molecular scale. Nano-networking is the branch of research field where nano-machines are deployed into the field of digital communication. Nano-network refers to the connection and coordination of nano-machines. Nano-machines are very small in size. Nano-network has a potential application in a very large range of areas. So, scientists are carrying out the research works focusing on this unexplored research topic.

Nanotechnology furnish challenging path for the design and manufacture of nano-machines (electronic components), whose sizes are few cubic nanometer [1]. These nano-machines are devices capable of performing only a few tasks of computation, sensing, and actuation [2]. However, the nano-machines can also perform complex tasks when they are interconnected via nanoscale communication links. The interconnected nano-machines communicate to perform tasks such as nano-scale computing, collaborative drug delivery, health monitoring, and biological or chemical attack detection in nanoscale environments. However, the connection strategy among nano-machines through nanoscale communication links are yet to be solved.

Basically, there are four main approaches for nanoscale communication links, they are nano-mechanical, acoustic, molecular, and electromagnetic (EM) [20]. In a nano-mechanical communication system, a mechanical contact between transmitter and receiver transmits the message signal. Whereas, in acoustic communication, acoustic energy like pressure variation is used to transmit the message signal between transmitter and receiver. Similarly, in molecular communication, molecules are used as the message carrier between transmitter and receiver. Similarly, in EM communication, the message signal is transmitted from the transmitter to the receiver through EM waves [21]. Among the four approaches, EM communication is the most appropriate technique for the realization of nanoscale communication. Due to the availability of many micro and nano-scale devices, wireless EM based nanoscale communication links are the most suitable for data transmission within the nano-network. The integration of nano-machines and communication technologies is necessary to develop frontier nano-networks applications.

Due to the recent advancement in nanomaterials, the small sized nano-machines communicate in terahertz band frequency. This is the least explored frequency band. The overall goal of this thesis work is to analyze the channel capacity using communication through silence (CtS) strategy in the terahertz (THz) band for both single and multi-user case in order to compute the throughput of the system.

1.1 Motivation

Communication between the nano-machines is an interesting topic to study on. Two facts about the tiny machines motivates to contribute on its study. Firstly, nano-machines are assumed to be so small that they are not visible to our naked eyes. Secondly, but more amazing is that such small machines are still capable of performing the tasks like computation, sensing, actuation and many more. Manufacture, as well as communication between nano-machines, is still in the phase of research. That means for the time being, it is still unclear how nano-machines will communicate. So, they have not yet been implemented in the real time environment.

All over the world research work is proceeding in this field. Scientists and researchers are proposing various theories that can be possibly implemented for the communication of nano-machines. Among these, CtS is also one of the proposals that can possibly be implemented in the future. However, a lot of research work has to be performed before it can be implemented. It is believed that analyzing the channel capacity of CtS in terahertz band for both single and multi-users case has not ever been performed. Hence, the result of this thesis work can be one of the footsteps or contributions for implementing communication among nano-machines in terahertz band.

1.2 Research objectives

Nano-machine as a single device has only a basic functionality. However, when they are inter-connected with each other, they can perform complex tasks. Inter-connecting nano-machines is a great challenge. These machines are not inter-connected practically up to date. Scientists are in the path to realize feasible techniques which will assist nano-machines to communicate among themselves. CtS is one of the proposed techniques for connecting nano-machines.

CtS is a new technique in which message signal is transmitted using two 1's. First and the last bit of the message frame is each 1 and 0's are in between these 1's. Energy is only required to transmit 1's. During the transmission of 0's the transmitter stays silent, so there is no energy consumption. Energy consumption is one of the main limitations in nano-machines communication. Nano-machine has nano-battery as energy backup whose volumetric capacity is in the order of 45 µAh-1cm-2µm-1 [1]. CtS strategy consumes very low amount of energy. So it is very suitable for nano-scale communication. The performance of CtS strategy is evaluated in terms of channel capacity for both single user and multi-user case in terahertz band frequency. Moreover, it is known that nano-machines communicate in terahertz band of frequency and this band of frequency has peculiar behavior towards the noise. In order to calculate and observe the parameters like path loss, molecular absorption noise, and absorption coefficient, a terahertz propagation model proposed in [17] for different channel molecular composition is used. The parameters are further applied in the calculation of both single and multi-user channel capacity.

1.3 Structure of thesis

This thesis work consists of six chapters. Chapter 2 provides the theoretical background related to nano-machines. Here, the discussion is based on the development, manufacturing as well as application field of nano-machines. Chapter 3 is focused on the terahertz band communication. In this chapter the properties of the terahertz channel are reviewed. Similarly, terahertz propagation model based on previous study is discussed here. The propagation model is used in the calculation of total path loss, absorption coefficient, molecular absorption noise. Likewise, chapter 4 is based on the discussion CtS strategy and analytical process for calculating channel capacity for both single and multi-user cases. Similarly, chapter 5 presents the illustrated results along with the numerical results which are produced using MATLAB algorithms. The results are based on the equations provided in the above chapters. Finally, chapter 6 concludes the overall thesis work suggesting some future works related to the thesis work.

2. THEORITICAL BACKGROUND

This chapter is the layout of theoretical background for nano-machines and nanotechnology. It presents the history of nanotechnology along with the development process and architecture of nano-machines. The uses of nano-machines and the mode of communication between these machines are also described in this chapter. The primary objectives of this chapter can be summarized as follows:

- General information on nano-machines,
- Historical background on nano-machines and nano-technology,
- Communication modes in nano-networks,
- Development and manufacturing process of nano-machines, and
- General applications of nano-machines.

The chapter consists of five sections. Section 2.1 gives the general description on history of nano-technology. Section 2.2 describes the development techniques of artificial and biological nano-machines. Section 2.3 gives the general idea on manufacturing process of nano-machines. Section 2.4 gives the general idea about communication model in nano-networks. The final section describes the general applications of nano-networks.

2.1 History of nanotechnology

The word nano is derived from a latin word nānus which means dwarf and also from Greek work nanos. Scientifically, in SI unit nano means one-billionth or 10^{-9}. That means one nanometer is a single fraction of one-billionth of a meter [3]. The concept of nanotechnology was first set by Richard Feynman. He is also 1965 Nobel laureate physicist. In December 1959, his speech entitled, "There's Plenty of Room at the Bottom" at an American Physical Society meeting at Caltech, sets the pillar for the concept of nanotechnology. This speech was based on the scaling issue i.e. minimizing the sizes of devices in future contemporary with the increase in its output. In 1974, the Japanese scientist Norio Taniguchi from the Tokyo University of Science, first defined the term nanotechnology in an International Conference on Production Engineering. He defined the term nanotechnology as, "Nanotechnology mainly consists of the processing of, separation, consolidation and deformation of materials by one atom or by one molecule". However, research on nanotechnology started after K. Eric Drexler explored nanotechnology in his famous book "Engines of Creation: The Coming Era of Nanotechnology" in 1986. He explored nanotechnology taking into consideration Feynman's concept and put forward the idea of nano-assembler which could build complex devices. [4]

2.2 Nano-machine development techniques

Nano-machine is a very tiny device which is in the range of 1 to 100 nanometers. Individually these machines can perform very simple tasks at nano-scale as communicating, computing, data storing, sensing and or actuation. These nano-machines can be used for the development of complex systems like nano-robots and computing devices like nano-processors, nano-memory when used in a group. Based on the current research, nano-machines can be developed from two different aspects:

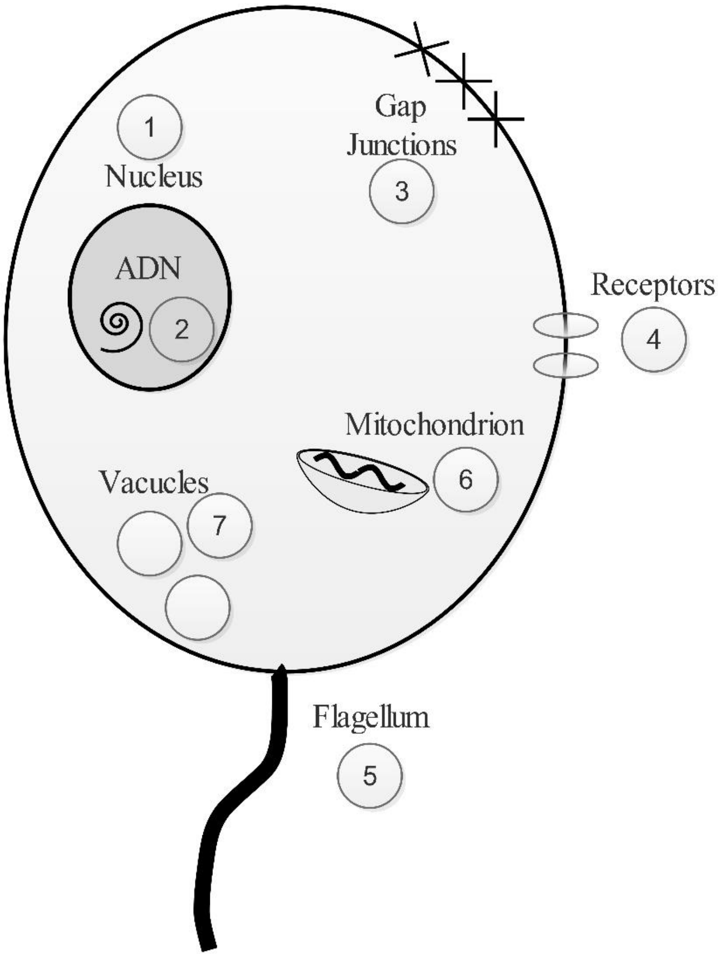

Figure 2.1. *Architecture of a biological cells representing nano-machines units [4].*

2.2.1 Biological nano-machine

Biological nano-machines are nano-scale machines which either exist in a biological world or these are manufactured artificially from biological materials. The examples of nano-machines that exists in the biological world is biological cells, molecular motors and any biological molecules. A molecular motor is a protein which transforms chemical energy to change the position or structure of a molecule [2]. Whereas, the examples of nano-machines that are artificially manufactured or developed from biological materials are artificial molecular machines and genetically engineered biological cells. These types of machines can be programmed as per our requirements [5].

Biological nano-machine architecture

The components that are in included in the biological nano-machines are a control unit, a communication unit, a reproduction unit, power unit and actuators. However, at this stage, it is very difficult to build such nano-machines. But based on [4], the existing biological cells' architecture’s units are described below. This special features of biological cells will lead to the development of a nano-machine that can be used for specific purposes.

Control unit

Each cell contains the nucleus. The nucleus can be thought as the control unit of the cell which is pointed as "1" in Figure 2.1. It is the brain of the nano-machine which is supposed to execute the instructions for performing the specified tasks.

Communication unit

The communication unit is pointed as "3" in Figure 2.1. The gap junction between hormonal and pheromonal receptors behaves like a transceiver between the cells for communication purpose. These transceivers have to be able to send and receive the messages.

Reproduction unit

Centrosome and molecular motors existing in a cell are responsible for the reproduction of a new machine. Before the cell division, the cells are duplicated and these duplicated cells contain an original copy of the Deoxyribonucleic acid (DNA) sequence. The basic function of reproduction unit is to create new nano-machines having the characteristics of the old machines.

Power unit

Biological cells contain 'mitochondrion' and 'chloroplast' which generates chemical substances as energy for cells and converts sunlight to chemical fuel respectively. This is pointed as "6" in Figure 2.1. The main function of this unit is to supply power to all the other units in the nano-machine.

Sensors and actuators

Biological cells that have transient receptor potential can behave as a sensor for taste. Also, the flagellum of bacteria acts as a locomotion mechanism. This unit is pointed as "5" in Figure 2.1. The main function of this unit is to behave like a bridge between the environment and the nano-machines.

2.2.2 Artificial nano-machine

Artificial nano-machines are based on the manufacture of nano-devices using the electronic components. The miniaturization of the present EM transceivers to the nano-size is not feasible. It is because of the limitation of its size, complexity, energy consumption and feasibility of EM communication within nano-machines. However, the recent findings of novel nano-materials have set up the foundation for the development of nano-machines manufacture. Novel nano-materials are graphene and its derivatives, such as Carbon Nanotubes (CNT) and Graphene Nanoribbons (GNR). [6]

Artificial nano-machine architecture

Nano-machines are a very tiny device with limited functionality. The building architecture of artificial nano-machines is as shown in Figure 2.2. The architecture of nano-machines is similar to micro and macro scale machines. However, there are many differences in terms of manufacture complexity, the materials used to build it, the way they communicate with each other, its capacity, applications and so on. Each unit of artificial nano-machines are described based on [1] as follows.

Sensing unit

CNT and GNR are a very good sensing element as they have outstanding sensing capability. Sensing unit can be further sub-divided as follows:

Physical nano-sensors

These type of sensors can be used to measure physical magnitudes like force, pressure, mass, and displacement. The working principle of physical nano-sensors is that when CNT and GNR are bent or deformed, there is a change in electronic properties. Pressure nano-sensors, force nano-sensors or displacement nano-sensors are proposed based on this principle.

Chemical nano-sensors

These type of nano-sensors can be used to measure chemical properties of the concentration of a gas, occurrence of unwanted molecules and so on. The working principle of these nano-sensors is that when CNT or GNR are exposed to chemicals, then they absorb molecules which in return changes the electronic properties of CNT or GNR.

Biological nano-sensors

These type of nano-sensors can be used to observe biomolecular process like antibody interaction, DNA interactions, cellular communication processes. Biological nano-sensors can be further divided into electro-chemical biological nano-sensors and photometric biological nano-sensors based on its working principle. The working principle of electro-chemical biological nano-sensors is similar to the chemical nano-sensors. When electro-chemical biological nano-sensors are exposed to protein or specific antigen then they absorb molecules which in return changes the electronic properties of the nano-sensors. Whereas, photometric biological nano-sensors' working principle is based on Localized Surface Plasmon Resonance (LPSR).

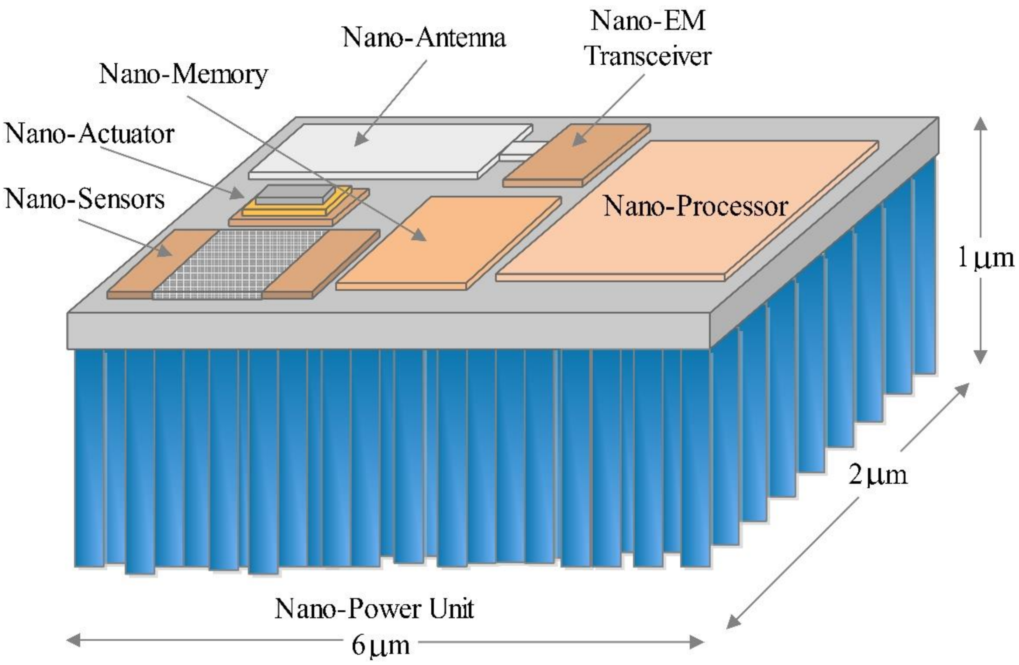

Figure 2.2. *Architecture of an artificial nano-sensor device [1].*

Actuation unit

This unit is the interface between nano-machines and environment. Actuation unit can be subdivided into the following category:

Physical nano-actuators

This type of nano-actuators is based on nano-electromechanical system (NEMS). Nano-tweezer is an example of physical nano-actuators which closes by applying a specific voltage and opens by means of some external macro-actuators. Such nano-actuators will be inbuilt in the future nano-machines.

Chemical and biological nano-actuators

These type of nano-actuators are based on the interaction among nano-particles and nano-materials, EM fields, and heat. Examples of such nano-actuators are nano-heaters which can be used to damage or burn the specific cancer cells by heating them. When these nano-particles and biological agents like antibodies work together, it will be possible to deliver the drugs to the targeted cells.

Power unit

This unit supplies power to the nano-machine. It is one of the most important units. Nano-batteries are already invented. The measured volumetric capacity for each nano-battery is $45\mu Ah^{-1}cm^{-2}\mu m^{-1}$. Such nano-battery has to be frequently recharged in order to operate nano-machines. This limitation of frequently charging the battery limits its use in the nano-machine. In order to get rid of the limitation, it is necessary to manufacture nano-machines that can be self-powered. This can be done by means of conversation of mechanical energy, vibration energy, hydraulic energy, and EM waves into electrical energy.

Processing unit

The size of the processing unit in nano-machines is very tiny whose size is in the scale of the nanometer. Nano-materials like CNTs and GNRs can be used in building a nano-scale transistor for the development of nano-processor. Such nano-scale processors are already experimentally developed whose dimension is less than 1 nm. The processor is based on a thin GNR and its performance is predictably faster. Some silicon-based transistors are also being developed whose active channel is composed of a single phosphorous atom in silicon. This type of transistor can be alternative to GNR based transistor. Although, these nano-transistors are experimentally developed but the main challenge is to integrate them to give a complete shape of a processor.

Storage unit

Nano-memory unit which can store a single bit in a single atom is being enabled by nano-materials and new manufacturing processes. This concept of storage was introduced by Richard Feynman in 1959. Based on the concept, several atomic memories are proposed. A memory has been developed which can store a bit by the presence or absence of one silicon atom. This type of memory has silicon surface with deposited mono-layers of gold defining the tracks. Recently, ensuing the concept of Feynman, IBM Corporation has developed magnetic atomic memories. In these memories, single atoms which can be used to store a bit information is placed on a surface by means of magnetic forces.

Communication unit

This unit is responsible for communication purpose among the nano-sensors. By the development of nano-antennas and EM nano-transceivers, EM communication among the nano-sensors will be enabled.

Nano-antennas

When the size of an antenna of a classical sensor is decreased to a very low size in nanometers, there is the need of an extremely high frequency for its operation. Operating in such extremely high frequency is not feasible. The limitation of extremely high frequency can be accomplished by the use of graphene-based nano-antenna. The resonant frequency of graphene-based nano-antennas can be two orders of magnitude below that of nano-antennas based on non-carbon elements. Such nano-antenna based on graphene has already been proposed.

Electromagnetic nano-transceivers

The EM transceiver in nano-sensors has the circuit components which will be able to perform baseband processing, frequency conversion, filtering, and power amplification of signals which are received or transmitted by nano-sensors through nano-antennas.

2.3 Nano-machine manufacturing approach

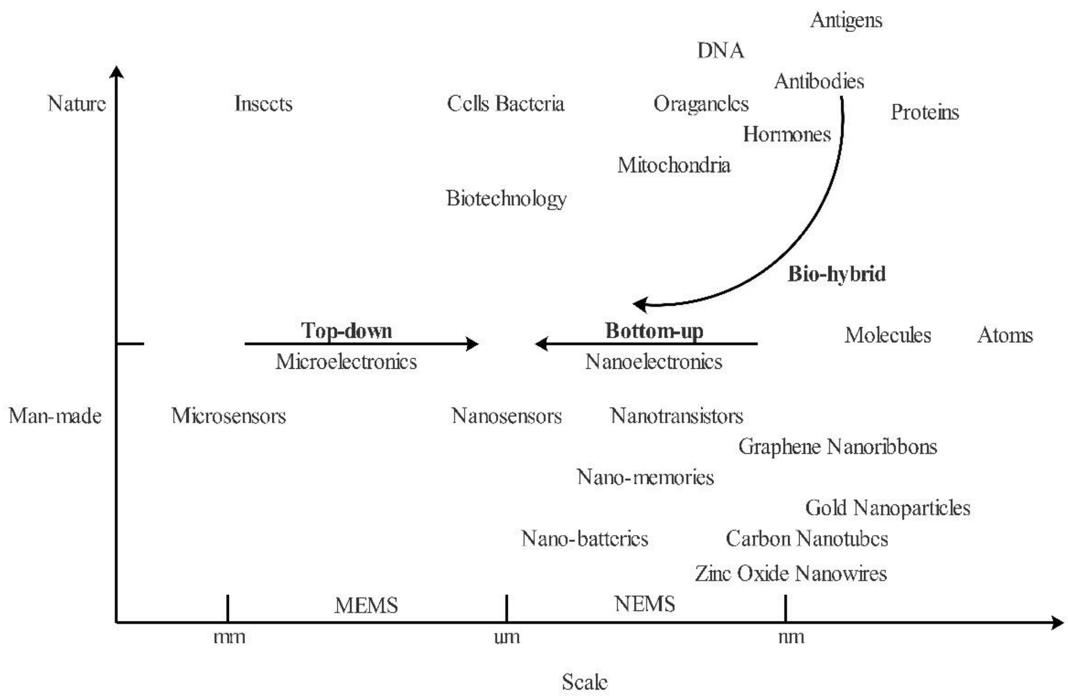

Figure 2.3. *Approaches for the manufacturing of nano-sensors [1].*

Nano-components can be integrated to build up a complete nano-machine through different approaches. There are mainly three approaches to build up a nano-machine. They are top-down, bottom-up and bio-hybrid approach. These manufacturing approaches are described below based on [1].

Top-down approach

In this approach, nano-machines are manufactured by down scaling the micro-scale electronic components. The nano-fabrication techniques that are currently being used to fabricate components are micro-contact printing, imprint lithography or direct-write dip-pen nano-lithography. For example, GNR can be used to build field effect transistor (FET), similarly, graphene-based nano-antenna or sensor can be obtained with an integrated Transmission Electron Microscope - Scanning Tunneling Microscope (TEM-STM) system.

Bottom-up approach

In this approach, nano-machines are manufactured by assembling very small molecular components. Techniques used in this approach are DNA scaffolding and molecular manufacturing. Molecular manufacturing is the process of assembling nano-devices molecule by molecule.

Bio-hybrid approach

In this approach, existing biological components like biosensors, nano-actuators found in living organisms are used to manufacture nano-machines. For example, an adenosine triphosphate (ATP) battery can be manufactured as an alternative energy sources for bio-nano-devices.

2.4 Nano-network communication

Nano-machines are tiny devices whose sizes are a few hundred nanometers. Although such type of nano-machines has not been developed up to date, however, the research is focused in its development. Individually these machines can only perform a very simple task like computing, sensing, data storage, and actuation. In order to gain a complex work done by nano-machines, it is necessary to build a network of such nano-machines. This type of network is also known as nano-networks. In the nano-network millions of nano-machines can get connected to each other where they share the information through communicating with each other. The capability of individual nano-machine in nano-network can be improved both in terms of complexity and the range of operation. [7]

In order to enable networking capabilities among the nano-machines, communication should be adapted. Communication between these machines can be realized through nano-mechanical, acoustic, biologically-inspired approach (e.g. molecular, bacterial, neuronal communication), and ultra-high frequency (UHF) EM communication [8]. These approaches of communication are described below. Among these approaches, UHF EM communication is the promising techniques. Hence, the overall thesis work is based on the UHF EM communication.

In the EM nano-networking research, the focus is on increasing the capacity and achievable data rates that utilize ultra-broadband signals occupying entire THz Band. Moreover, one of the main limitations in the nano-machine is the energy provided by nano-batteries. Taking this limitation into consideration a new digital communication scheme called CtS is implemented in order to obtain the capacity of the channel. Nano-machines consumes less energy when CtS scheme is followed.

2.4.1 Nano-mechanical communication

In this communication mechanism, information is transmitted through mechanical contact between the transmitter and the receiver. Transmitter and receiver should be in direct contact in order to communicate [22]. This is the main drawback of this type of communication system. As the nano-machines are deployed over large areas without having direct contact, this method of communication is not suitable.

2.4.2 Acoustic communication

Sound can be used in an effective communication modality. When a physical object vibrates rapidly, sound is produced. Such vibration disturbs nearby air molecules and hence it generates compression wave. Compression wave travels in all direction away from the source. The wave can be used to carry the information from transmitter to receiver [23]. Extremely wide and complex range of signals can be created by varying frequency, amplitude, and periodicity of sound. Ultrasonic wave is used in the acoustic communication system for transmission and reception of information. Nano-machines are integrated with ultrasonic transducers. Such transducers sense the variation of pressure produced by ultrasonic waves [4]. Manufacturing such nano-acoustic transducers is still a major challenge.

2.4.3 Molecular communication

Molecular communication is a new platform for nano-machines to communicate over a short range of distance. In this platform, carrier molecules are used to send and receive information. Information to be transmitted or received are encoded to and decoded from molecules respectively [5]. Existing biological nano-scale communication mechanisms and communication components are used in molecular communication. Such biological nano-scale communication mechanisms are intracellular, and intercellular communication mechanisms of exchanging molecules [2]. Likewise, nano-scale communication components are molecular motors, cells with receptors. In intracellular communication, there is communication between components within a single biological cell. Similarly, in intercellular communication, there is communication through cell-cell channels gap junctions [2].

Molecular communication prototype consists of carrier, sender, and receiver as in the existing EM communication system. Carriers molecules are proteins or ions which carry information to be transmitted. Sender nano-machines transmit the carrier molecules, whereas, the receiver nano-machines receives the carrier molecules. [2]

There are many advantages of molecular communication compared to the others existing communication models. Molecular communication uses biological components for communication purpose. So, the communication method can be very suitable in such applications which are sensitive to artificial materials. Energy efficiency is the other advantage of using biological components in molecular communication. Existing biological system are highly energy efficient. As the system consumes very less energy, it can perform more computation with less energy. There is less heat dissipation in this system, so molecular communication can be used to transmit information over longer ranges with the same amount of power. Moreover, usage of biological systems in molecular communication addresses the drawbacks of nano-scale communication that the existing electrical and optical wave based communication system my encounter. [2]

2.4.4 Electromagnetic communication

In nano communication, EM communication can be defined as the transmission and reception of EM radiations among the nano-machines. The nano-machines are made up of novel nanomaterials. In EM communication, EM waves are modulated to transmit information from the transmitter to receiver.

Major steps have been taken to minimize the size of the current EM transceiver to nanoscale. However, the size, complexity and energy consumption of nano-machines are the major limitation regarding the feasibility of EM communication in nano-scale. Due to the recent advancements in carbon electronics, several nano-components have been invented. Such nano-components are nano-batteries, nano-memories, logical circuitry in nanoscale, and nano-antennas [1]. These components are the backbone for EM communication. For the communication prospective, the properties distinguished in the carbon materials will decide on the specific bandwidths for emission of EM radiation as well as the operating frequency of such system. It is necessary to characterize the radiation properties of carbon (graphene) in order to anticipate the operating frequency band. Studies conducted on this has shown that terahertz band (0.1 - 1.0 THz) is the frequency range of operation for future nano-electromagnetic transceivers [17].

2.5 Applications of nano-machine networks

The application of a single nano-machine is extremely very limited. However, larger application scenarios can be enabled when interconnected nano-machines are densely deployed in a nano-network. Precisely, nano-network application can be classified in four main groups. They are in the field of biomedical, environmental, industrial, and military applications. These application fields are described below.

2.5.1 Biomedical application

Wireless nano-networks have large number of application in biomedical field. Molecular nano-machines can be bridge or interface to connect biological phenomenon with electronic devices. Such biomedical applications are briefly described in this sub-section based on [1].

Health monitoring system

Nano-machines can be used to monitor the level or status of ions in blood, cancer biomarkers and other infectious agents in the human body. For example, glucose level in the blood can be monitored by deploying the nano-machines into the body. Nano-machines can be placed in different parts of the human body. These machines regularly monitor the status of the organ that it is placed in. They can communicate the dates regarding the status of the organ to some special micro-devices or specialized medical equipment. The micro-devices act as a sink and they are placed outside the human body. The data provided by the system can be used by healthcare providers.

Drug delivery system

Application of nano-network has a great importance in drug delivery system. Nano-sensors with the coordination of nano-actuators can be used to deliver drugs into the unreachable location of human body. The amount of drugs that a nano-actuators have to drop into the human organs can be remotely decided. For example, this system can be used to compensate glucose deficiency in disease like diabetes. All these data can be collected and monitored by a healthcare provider remotely.

2.5.2 Environmental application

Nano-machines have a huge application in environmental aspects which cannot be fulfilled by the current technologies. Some of these applications are briefly described based on [1] below.

Plant monitoring system

Plants release various kind of chemical compositions to the environment. Such chemical compositions can be detected by the chemical nano-machines. Chemical nano-machines can be deployed in agriculture fields in order to monitor the ongoing chemical changes in the plants.

Air pollution control

Large amount of nano-machines is connected through nano-networks and they are deployed in the environment. They give the data about the harmful gas scattered in the air.

Such harmful gas can be controlled using appropriate air filters which helps in increasing fresh air quality

Animals and biodiversity control

Some animals produce pheromones that affects the behavior or physiology of other species. Nano-machines can sense such pheromones and transmit the data remotely. So, presence of animals which can be affected by pheromones can be controlled in that area.

2.5.3 Industrial application

Nano-networks have many applications that are already proposed in the field of industry. It can facilitate in the manufacturing process along with the development of new materials. Some of the application of nano-networks in industrial field are briefly described based on [4] below.

Food and water quality control

Nano-network can be used in food and water quality control. The nano-network can be used to detect small bacteria and toxic components from food and fluid. Such bacteria and toxic components can affect quality of the product. They cannot be detected using the traditional sensing technology. Nano-network can be used to detect chemical or biological components from the water supplies which helps to supply the pure water to the households.

Functionalized materials and fabrics

New and improved functionalities can be acquired from advanced fabrics and materials with the use of nano-networks. Airflow can be maintained by the nano-actuators in smart fabrics. Nano-actuators communicate through nano-networks to control the proper reaction based on the external condition.

2.5.4 Military application

Nano-networks have range of realistic application in military field. It can be used from soldier performance monitoring to battlefield monitoring. Some of its application in military field are briefly described based on [4] below.

Nuclear, biological, and chemical defenses

Nano-machines can be scattered on the battle field or the place of interest. They can detect the dangerous chemical and biological agents that can cause harm to the defensive forces. Some defensive response can be carried out after the detection of such dangerous agents.

Nano-machines can also be used to detect unauthorized chemical, biological or radiological agents from cargo that can be brought into the territory.

Nano-functionalized equipment

The equipment used by the soldiers can feature inbuilt nano-machines. For example, the uniform of armies which consist of nano-machines can give the information about the temperature and the condition nearby. They can also detect if the soldiers are injured. Nano-machines can also be used to detect damages in soldiers' armor as well.

3. COMMUNICATION IN TERAHERTZ BAND

This chapter is the layout of theoretical background for terahertz band communication among nano-machines. It presents the theoretical approaches for communication model among nano-machines. Moreover, this chapter deals with channel parameters like absorption coefficient, overall path loss, and molecular noise. The primary objectives of this chapter can be summarized as follows:

- General information on communication in THz band,
- Channel model for THz band.
- Parameters implemented in channel model, and
- Uses High resolution transmission (HITRAN) database for calculation of parameters.

The chapter consists of three sections. Section 3.1 gives the general description on electromagnetic communication in terahertz band. Section 3.2 describes the channel model implemented for computing parameters like noise, path loss, molecular absorption in terahertz frequency band. The final section introduces general idea on HITRAN database.

3.1 Nano-electromagnetic communication in THz band

Terahertz (THz) band exists between traditional microwave and visible light. Its frequency band is defined from 0.1 to 10.0 THz (1 THz = 1012 Hz). Compared to the other bands of frequency, THz band is the least explored band of frequency. Due to the latest advancement and research in the field of nano-technology, especially nano-machines, tremendous effort has been made to explore the THz band. THz communication uses the higher frequency and broader information bandwidth compared to microwave, so it can take benefit of high-bit-rate wireless technology [9].

Nano-machine, that the scientists are developing in the size ranging from one to few hundred nanometers. It consists of only basic functional unit which is able to perform very simple tasks. Communication among these nano-machines will increase the capabilities and application of individual nano-machines in terms of complexity and range of operation [10]. The communication capability among these nano-machines enables 'wireless nano-sensor networks' (WNSNs) which will boost the applications of nano-technology in the biomedical field, environmental research and in military technology.

One of the applications of these nano-machines are in the field of nano-sensing, where the nano-machines behave as nano-sensors [1]. Nano-sensor takes into consideration the properties of novel nano-materials to identify and measure new types of events in the nano-scale. The outcome or the results from such nano-sensor are limited to a very close environment about a few micrometers. Moreover, these nano-sensors should also be linked to some other micro or bigger devices (sinks) in order to process its output. It is only by the means of communication; these sensors can transmit the sensed data in a multi-hop fashion to a sink.

Till the current date, it is still unknown about how to enable communication among nano-machines. Existing communication system like EM communication or optical communication needs to undergo a vast change in order to enable communication among nano-machines. There are limitations in terms of size, complexity, and energy consumption within nano-machines to implement the existing radio communication system. Because of these limitations, a new novel nano-material 'graphene' is used for the purpose of nano-machine generation instead of existing silicon materials. Graphene is pure carbon in the form of a very thin, about one-atom-thick planar sheet which is packed in a honeycomb crystal lattice. [11]

Graphene and its derivatives GNRs and CNTs are used these days to develop the elements of nano-machines like nano-battery, nano-processor, nano-memory, and nano-antenna [11]. The electromagnetic properties developed in graphene and its derivatives based nano-antennas determine the specific frequency bands for emission of EM radiation. According to the well know antenna theory, we know that when the size of an antenna is reduced to few hundred nanometers then high resonant frequencies is to be imposed. But the propagation of EM wave in graphene is different from the normal elements like silicon. In graphene the resonant frequency of nano-antennas can be up to two orders of magnitude below the predicted values. This means that for the normal antenna material, operation frequency would be larger than THz if the size of the antenna would be in few hundred nanometers, whereas, its decreased to THz in the case of graphene-based antennas. According to the study made on [12], both nano-dipole and nano-patch antenna which are in the size of few hundred nanometers will be able to radiate EM waves in the terahertz band frequency.

3.2 Channel model for EM wireless nano-networks

Nano-machines have nano-antennas for transmission and reception of signals. These antennas are not the nano version of the antennas used in the classical wireless devices. Reducing classical antennas to nano size would require the use of extremely high operating frequency beyond terahertz band [18]. The limitation of building the nano-antenna is overcome by the use of graphene to fabricate nano-antenna. The resonant frequency of graphene based nano-antennas is in the range of terahertz. So it can be said that the nano-electromagnetic network operates in terahertz band. Characterizing a terahertz channel model is obligatory. There are already a few terahertz channel models existing. But these models characterize the communication between devices which are several meters apart from each other. While, nano-scale communication occurs in a distance below 1 meter, hence a channel model in terahertz band for communicating much below 1 meter is necessary [18]. Such channel model in terahertz band is reviewed below based on [11], [17] and [18]. The channel model uses a new propagation model based on radiative transfer theory and data is retrieved from HITRAN database.

3.2.1 Molecular absorption

Several molecules are present in the path between transmitter nano-machines and receiver nano-machines. During the transmission of a signal, the molecules get excited by EM waves at a specific frequency in the terahertz band. The excited molecules begin to vibrate internally. When vibration occurs, some part of the energy of the propagating wave is converted into kinetic energy. Production of kinetic energy means a loss in terms of communication. Losses are caused when the molecules absorb the EM wave. The absorption of EM waves in the molecules can be determined through the absorption coefficient of the molecules. Molecular absorption causes attenuation to a wave traveling a few meter distance. Attenuation encountered by the traveling wave can be calculated by using radiative transfer theory along with the data from HITRAN web portal.

Resonant frequency varies among the molecules hence, the absorption at each resonance is not confided to a single center frequency. Absorption loss accounts the total attenuation an EM wave experiences when travelling a distance with certain frequency. Absorption loss is given as,

$$A_{abs}(f,d) = \frac{1}{\tau(f,d)} \tag{3.1}$$

where, f is the wave frequency, d is the total path length and τ is the medium's transmittance. Transmittance measures the fraction of incident wave transmitted from the medium. Transmittance can be further calculated using Beer-Lambert Law as,

$$\tau(f,d) = e^{-k(f)d} \tag{3.2}$$

where, f is the wave frequency, d is the total path length and k is the absorption coefficient of the medium. Absorption coefficient depends on the composition of molecules that form a medium. It can be given as,

$$k(f) = \sum_{ig} k^{i,g}(f) \tag{3.3}$$

where, $k^{i,g}$ is the individual absorption coefficient for the isotopologue i of gas g. Isotopologue refers to a molecule which differs in its isotopic composition [13]. For eg. CH4, CH3D, CH2D2.

Now, the absorption coefficient of isotopologue i of gas g in per meter for a molecular volumetric density $Q^{i,g}$ in molecules per cubic meter at pressure p and temperature T can be written as,

$$k^{i,g}(f) = \frac{p}{p_0}\frac{T_{STP}}{T}Q^{i,g}\sigma^{i,g}(f) \quad (3.4)$$

where, p_0 and T_{STP} are the standard-pressure-temperature and $\sigma^{i,g}$ is the absorption cross section of the isotopologue i of gas g in square meter per molecule. It can be said that the total absorption depends upon the number of molecules of gas present in the medium. From the Ideal Gas Law, we can obtain the total number of molecules of the isotopologue i of gas g in per volume unit $Q^{i,g}$ at pressure p and temperature T for a given gas mixture as,

$$Q^{i,g} = \frac{n}{V}q^{i,g}N_A = \frac{p}{RT}q^{i,g}N_A \quad (3.5)$$

where, n is the total number of moles of the gas mixture, V is the volume, $q^{i,g}$ is the mixing ration for the isotopologue i of gas g, N_A is the Avogadro constant, whereas, R is the gas constant.

The absorption cross section $\sigma^{i,g}$ can be further defragment into the spectral line shape $G^{i,g}$ and line intensity $S^{i,g}$ for the absorption of the isotopologue i of gas g, which is given as

$$\sigma^{i,g}(f) = S^{i,g}G^{i,g}(f) \quad (3.6)$$

From the HITRAN database, line intensity $S^{i,g}$ can be obtained, whereas, spectral line shape $G^{i,g}$ can be obtained by first determining the position of the resonant frequency $f_c^{i,g}$ for an isotopologue i of gas g as,

$$f_c^{i,g} = f_{c0}^{i,g} + \delta^{i,g}\, {}^{p}\!/_{p_0} \quad (3.7)$$

where, $f_{c0}^{i,g}$ is the zero-pressure of the resonance, p_0 is the reference pressure and $\delta^{i,g}$ is the linear pressure shift. We can find all those parameters at HITRAN. When the pressure is above 0.1 atm then the spreading occurs mainly due to the collisions between molecules of the same gas. That means the absorption from any molecule differs over a range of frequencies. Lorentz half-width $\alpha_L^{i,g}$ is the amount of broadening depending on the molecules that involves in the collision. It can be obtained as a function of the air α_0^{air} and self-broadened half widths $\alpha_0^{i,g}$ as,

$$\alpha_L^{i,g} = \left[(1-q^g)\alpha_0^{air} + q_g\alpha_0^{i,g}\right]\left(\frac{p}{p_0}\right)\left(\frac{T_0}{T}\right)^{\gamma} \tag{3.8}$$

where, γ is temperature broadening coefficient. All the data for α_0^{air} , $\alpha_0^{i,g}$ and γ can be obtained from HITRAN database.

Van Vleck-Weisskopf asymmetric line shape is the most suitable line shape which represents molecular absorption in the terahertz frequency band. It is given as,

$$F^{i,g}(f) = \frac{\alpha_L^{i,g}}{\pi}\frac{f}{f_c^{i,g}} \cdot \left[\frac{1}{\left(f-f_c^{i,g}\right)^2 + \left(\alpha_L^{i,g}\right)^2} + \frac{1}{\left(f+f_c^{i,g}\right)^2 + \left(\alpha_L^{i,g}\right)^2}\right] \tag{3.9}$$

To take into consideration for the continuum absorption some adjustments to the far ends of the line shape can be done as,

$$G^{i,g}(f) = \frac{f}{f_c^{i,g}}\frac{tanh\left(\frac{hcf}{2k_BT}\right)}{tanh\left(\frac{hcf_c^{i,g}}{2k_BT}\right)}F^{i,g}(f) \tag{3.10}$$

where, h is the Planck Constant, c is the speed of the light in vacuum, k_B is the Boltzmann Constant and T is the temperature of the system.

Taking into account all the equations derived above and obtaining the values from the HITRAN database, we can calculate the molecular absorption loss from each isotopologue i of gas g. As the absorption of the signal from each isotopologue i of gas g varies with the resonant frequency, we can say that terahertz channel is highly frequency selective.

Figure 3.1 is the absorption coefficient (k) of pure water vapor molecules at temperature 296 K, pressure 1 atm and for 0.1 - 10 THz frequency. Data required for this plot was acquired from [19]. Water vapor dominates the absorption in standard medium conditions. That means water vapor molecules have the major contribution to the total absorption in a medium. The figure shows that molecular absorption at some frequency is high, whereas, at some frequency it is low. Molecular absorption is highly frequency selective. When the absorption coefficient is high, it diminishes the communication range. Hence, the molecular absorption significantly affects the performance of the channel.

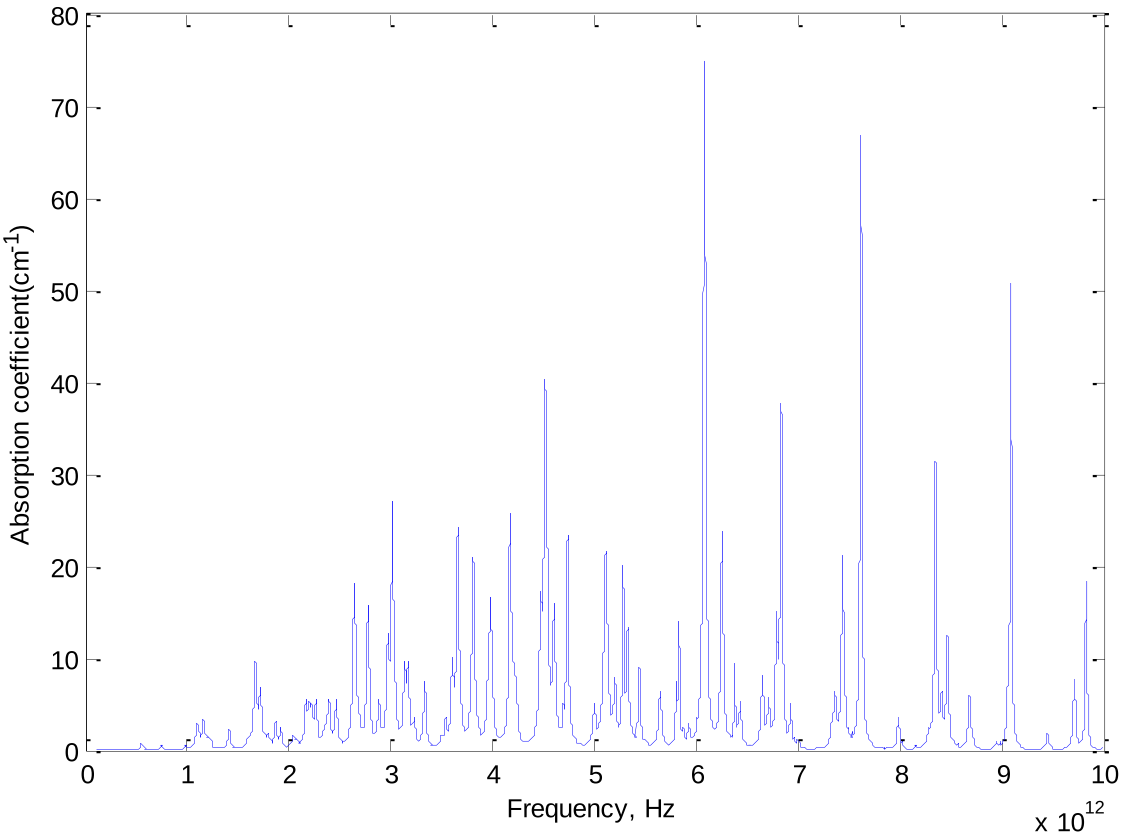

Figure 3.1. *Molecular absorption coefficient (k) for pure water vapour molecules (H_2O) as a function of frequency.*

3.2.2 Path loss

For a travelling wave in the terahertz band, the total path loss (A) is the addition of spreading loss (A_{spread}) in dB and molecular absorption loss (A_{abs}) in dB. It can be given as,

$$A(f,d)\ [dB] = A_{spread}(f,d)\ [dB] + A_{abs}(f,d)\ [dB] \tag{3.11}$$

where, f is the wave frequency and d is the total path length between transmitter and receiver. The spreading loss accounts for the attenuation due to the expansion of the wave as it propagates through the medium. It depends on the signal frequency and transmission distance. Spreading loss is given as,

$$A_{spread}(f,d)\ [dB] = 20\ log_{10}\left(\frac{4\pi f d}{c}\right) \tag{3.12}$$

where, f is the wave frequency, d is the total path length between transmitter and receiver and c is the speed of the light in vacuum. The increase in the frequency increases the spreading loss. So, spreading loss is large in terahertz band which limits transmission range. Similarly, absorption loss in equation (3.1) can be converted in dB as,

$$A_{abs}(f,d)\ [dB] = 10\ log_{10}\left(\frac{1}{\tau(f,d)}\right) \tag{3.13}$$

3.2.3 Noise

When the signals are transmitted in terahertz frequency through any medium, it strikes the molecules of the medium. Hence, the molecules in the medium begin to vibrate. Vibrated molecules emit EM radiation at the same frequency that the incident is propagating at. This creates an ambient noise in the terahertz channel. Ambient noise is created only when the transmitting signal has some power. That means no noise is created when transmitting 0's, whereas, noise is created when transmitting 1's of a signal. Such absorption by molecules in the medium attenuates the signal as well as creates molecular noise. This phenomenon can be measured by the emissivity of the channel ε, as

$$\varepsilon(f,d) = 1 - \tau\ (f,d) \tag{3.14}$$

where, f is the frequency of the signal, d is the total path length, while τ is the transmissivity of the medium. The equivalent noise temperature in Kelvin which an omnidirectional antenna detects from the medium due to molecular absorption T_{mol} is given as,

$$T_{mol}(f,d) = T_0\varepsilon(f,d) \tag{3.15}$$

where, T_0 is the reference temperature.

Now, to evaluate the noise power at the receiver, we have to first define the transmission bandwidth. Bandwidth depends on the transmission distance and the medium's composition. The total equivalent noise power P_n at the receiver for given bandwidth can be computed as,

$$P_n(f,d) = k_B B(T_{mol}(f,d) + T_{other}(f)) \tag{3.16}$$

where, f stands for the wave frequency, d stands for the total path length, k_B as Boltzmann constant, B is the system bandwidth, T_{mol} is the molecular noise temperature and T_{other} is the additional noise source from another medium. Hence, we can compute the total noise power at the receivers' side.

3.2.4 Bandwidth and channel capacity

Molecular composition of terahertz channel, as well as the transmission distance, may vary. Molecular absorption also varies along with the variation of molecular composition distance in terahertz channel. Usable bandwidth in terahertz channel can be determined by molecular absorption. In nano-networks, the available bandwidth is almost the entire band (0.1 to 10 THz). As the bandwidth is high, the channel capacity in wireless nano-network is also very high in the range of few terabits per seconds. [18]

3.3 High resolution transmission (HITRAN) database

HITRAN is an acronym for HIgh resolution TRANsmission [11] molecular absorption database. In HITRAN, a variety of spectroscopic parameters is compiled. These parameters are used in computer programming to predict and simulate the transmission of light in the atmosphere [24]. The parameters compiled in HITRAN database comes from the observations, theoretical calculations, and semi-empirical values. The calculations are based on the result of various quantum-mechanical solutions. However, as this database is very large, it will be very difficult and time-consuming to find the required parameters in the calculation. So, to ease the calculation, these parameters are available on the web having an access via the internet. An example of HITRAN web portal can be seen at [19].

4. COMMUNICATION THROUGH SILENCE

This chapter deals with the concept of communication through silence scheme. Additionally, this chapter presents the system model for CtS paradigm which is extensively covered in this studies. Moreover, chapter defines the optimization strategy used in CtS and then formulates the channel capacity for both single and multiple users. The primary objectives of this chapter can be summarized as follows:

- Better understanding of CtS scheme.
- To define system model for CtS
- General information on throughput optimization in CtS
- Energy consumption in CtS is lower than convectional communication - EbT
- To formulate single user and multiple user channel capacity.

The chapter consists of six sections. Section 4.1 introduces CtS strategy in general. Section 4.2 presents the mathematical model of CtS strategy. Section 4.3 deals with approaches used to optimize the throughput in CtS strategy. Section 4.4 compares the energy consumption between CtS strategy and convectional communication – EbT. Section 4.5 formulates the channel capacity for a single user under CtS strategy in terahertz band. The final section deals with formulating channel capacity for multiple users in terahertz band using CtS strategy.

4.1 Introduction to communication through silence strategy

A nano-sensor network is a network of many spatially distributed devices which monitors and relays the data [14]. In such network, a nano-sensor known as node collects the information and communicates it to the central processor. These nano-sensors are very small in size and the size of the battery used in it is also very small. Hence, a communication protocol that conserves their energy is the most important in order to gain a continuous wireless connectivity among the nano-sensors. Energy efficiency is one of the biggest challenges in the context of a nano-sensor network. It helps the wireless device to reduce the cycle of recharging which finally plays a vital role in the continuous connectivity of the nano-machines. The energy consumption can be minimized with the implementation of CtS scheme for communication. Silence is an important part of any conversation in CtS. Silence itself is a value less but it is the context and timing that conveys the message [14]. Silence can be utilized in the wireless communication for data transfer.

CtS strategy utilizes silent periods to convey information from the transmitter to the receiver. It uses silent periods in between start and stop bits along with the clock pulse to convey any messages. If we assume that start and the stop bits are one-bit transmissions each, the total energy consumption for transmission of any message in CtS is always $2 *$

e_b, given e_b as the energy required to transmit each bit. However, some extra energy is also consumed for counting the clock cycle. [16]

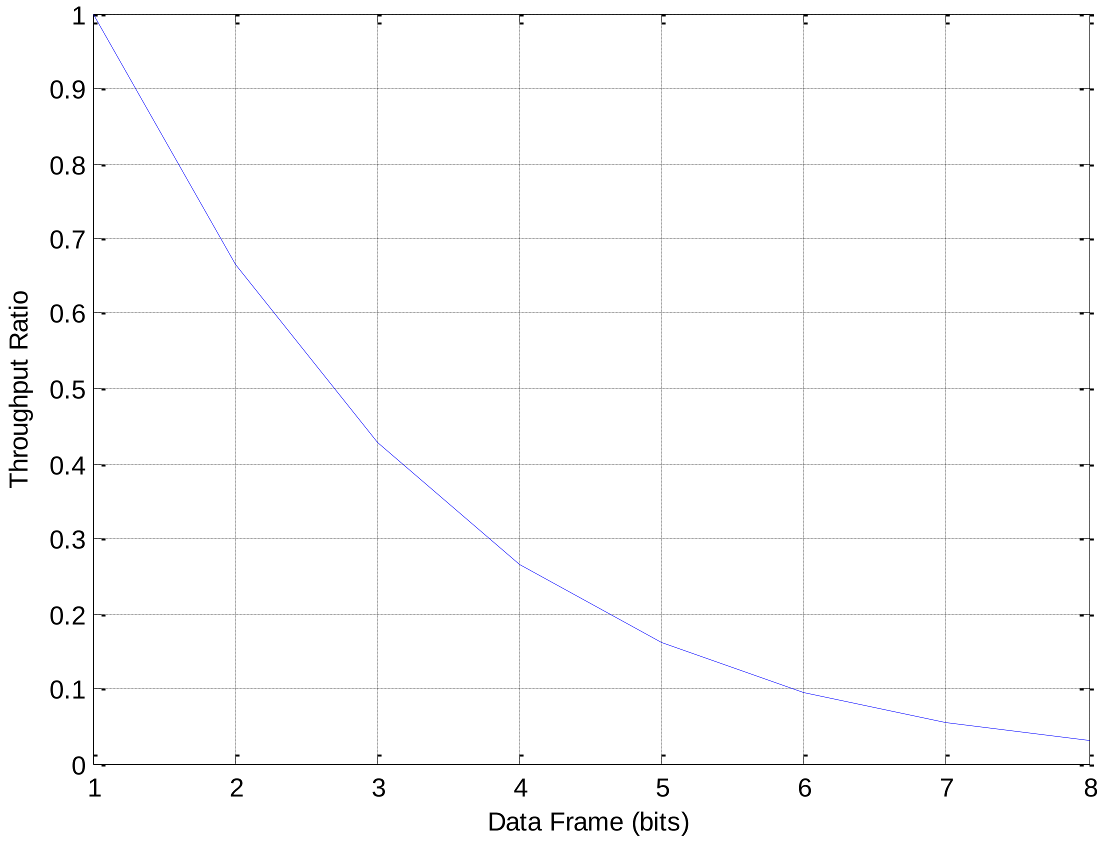

Figure 4.1. *CtS Vs EbT throughput*

In the CtS strategy, to send a binary packet of size k and form $n_{k-1} \dots n_1 n_0$ (where $n_i = 0{,}1$ for all $i = 1, 2, \dots\ k-1$), sender interprets the bit stream as a value N as given in [16] as,

$$N = 2^{k-1} * n_{k-1} + 2^{k-2} * n_{k-2} + \ \dots\dots + 2 * n_1 + n_0 \tag{4.1}$$

and N is transmitted using only start and stop signals. The time between the start and the stop signal is the time taken by the receiver to count up to the value N from zero. The receiver knows N and k that is the standard frame length in bits, infers the bit stream $n_{k-1} \dots n_1 n_0$. For example, a transmitter wants to transmit a binary packet 01011111 which has a size of $k = 8$ bits. This packet is not transmitted in the binary format but is converted into the decimal. The exact value the transmitter sends in decimal number is as,

$$N = 2^{8-1} * 0_{8-1} + 2^{8-2} * 1_{8-2} + 2^{8-3} * 0_{8-3} + 2^{8-4} * 1_{8-4} + 2^{8-5} * 1_{8-5} + 2^{8-6} * 1_{8-6} \quad + 2^{8-7} * 1_{8-7} + 2^{8-8} * 1_{8-8}$$

$\therefore N = 95.$

The example shows that the transmitter conveys any piece of information using delays. The transmitter first sends the start bit to the receiver and then waits for 95 clock pulses before sending the stop bit. Here, the receiver has to wait for 95 clock pulses between the start and stop bit to receive the message from the transmitter. It indicates that the throughput of the basic CtS strategy is substantially low. Figure 4.1 shows that the throughput of transmitting each frame decreases exponentially with increase in a number of bits in the frame size. The throughput in basic CtS decreases by $\frac{s}{2^s}$, where s is a size of the frame. Optimization of throughput in basic CtS is discussed in the succeeding section. There is a tradeoff between energy consumption and throughput in CtS strategy. There are also challenges associated with the realization of the CtS strategy in terms of functionalities such as framing, addressing, sequencing, error control, and contentation.

4.2 System model for communication through silence

Under the scheme of CtS, the signal transmitted by a user, $S_T(t)$ is given by,

$$S_T(t) = \sum_{j=0}^{J-1} p(t - j\tau) + p(t - j\tau - Ta_j) \tag{4.2}$$

where, $p(t)$ stands for a pulse with duration T_p, j is the total number of message frames to be transmitted, τ is the update time interval between two frames, T is the clock resolution and a is the message to be transmitted (e.g. any decimal number). This is the purposed equation for signal transmission in CtS. Illustration of transmitting signal is as shown in Figure 4.2.

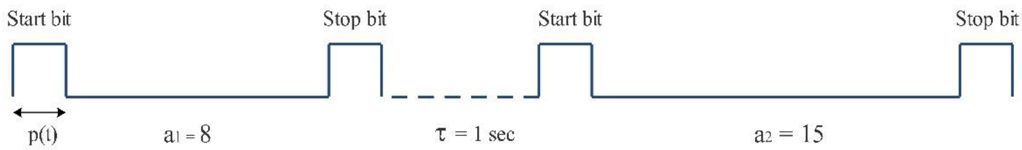

Figure 4.2. *Illustration of transmission in CtS strategy*

The signal received by a nano-sensor can be written as,

$$\boldsymbol{S_R(t) = \sum_{j=0}^{J-1} \left[p(t - j\tau) + p\left(t - j\tau - Ta_j\right)\right] * h(t) + w(t)} \tag{4.3}$$

where, $h(t)$ is the terahertz channel impulse response between the transmitter and the receiver and $w(t)$ is the molecular absorption noise created between the transmitter and the receiver. Both impulse response and molecular absorption noise depend on the medium conditions and the transmission distance. The dependency on medium conditions and transmission distance are already described in chapter 3 and further numerical results are presented in chapter 5. Hence, it can be said that the capacity for CtS strategy depends on the terahertz channel impulse response and the molecular absorption noise.

In Figure 4.2, 8 and 15 are the messages to be delivered. It can be seen that only two bits are required to transmit each value. The transmitter is totally silent between the start and the stop bit. There is no any energy emitted by the transmitter during the silent period. Energy is emitted only during the transmission of start and stop signals. We know that if there is no transmission then there will be no any path loss as well as the molecular absorption noise. That means in the context of CtS strategy it is only the start bit and stop bit that creates molecular absorption noise and hence it is only the signal bit that suffers from path loss as well. So during the calculation of channel capacity, we can consider only those bits.

4.3 Optimization approach in CtS

It is straightforward from the discussion in the above section that the CtS suffers a lot in terms of throughput when the values to be transmitted increases. However, the performance of the basic CtS strategy can be increased concerning throughput while preserving the same benefits in energy consumption. The approaches for the optimization of performance of CtS strategy are discussed below with examples based on [16].

4.3.1 Multiplexing

Let us consider that there are four sensors s_1, s_2, s_3 and s_4. There are two contending links L_{12} and L_{34}. The first link connects sensors s_1 and s_2, whereas, the second link connects sensors s_3 and s_4.

Now, let us first take a look at the EbT scheme. In EbT scheme, data cannot be transmitted through these two links simultaneously. That means one of the links has to wait until the other link totally transmits the data. For example, senor s_1 has to transmit a value 13 to sensor s_2 through contending link L_{12} and in the same way senor s_3 has to transmit a value 19 to sensor s_4 through contending link L_{34}. As both of these links are contending links, so L_{12} has to completely transmit the value 13 before L_{34} can start the transmission of the value 19. The example shows that the information transmission has to be sequentialized.

Let us use the same scenario of data transmission in the case of CtS strategy. In order to transmit the value 13 from sensor s_1 to sensor s_2 through contending link L_{12}, sensor s_1 has to send the start signal in bit time slot t_i and stop signal in bit time slot t_{i+13}. Simultaneously, senor s_3 can transmit the value 19 to sensor s_4 through contending link L_{34} by sending a start signal at bit time slot t_{i+1} and stop signal at bit time slot t_{i+20}. It shows that the information can be transmitted in parallel even if the links are contending by multiplexing the start and the stop bit appropriately. Without multiplexing in CtS strategy the total bit time slot consumed to transmit the two values 13 and 19 are 32(13+19), whereas, both of these values can be transmitted only consuming 21-bit time slot applying multiplexing approach. Hence, multiplexing assists to improve the throughput of the basic CtS strategy.

4.3.2 Cascading

Let us consider sensor s_1 has to transmit CtS frame with values 8, 14, 20, 29, 11, 7, 8, 22 to nearby sensor s_2. In basic CtS strategy to transmit all those values, it requires 119-bit time slots (which is simply the addition of the values). Whereas, in EbT if we assume that each value are 5-bit data frames then it only requires 8*5=40 bits to transmit all those values. This example reflects that basic CtS strategy only utilizes 33.61% (40/119) throughput.

Cascading can be one of the important methods to improve the throughput suffered by the basic CtS strategy. In this method, CtS is augmented with an intermediate signal in addition to the basic start and stop signals. When the intermediate signal is received by the receiver, the receiver records the values it has currently counted up to. Then it continues to count for the next value rather than resetting the counter to zero. Let us take an example of the scenario that best describes the cascading approach. When sensor s_1 has to transmit the CtS frame, it first sends a start signal at time slot t_i, intermediate signals at t_{i+8}, t_{i+14}, t_{i+20} and stop signal at t_{i+29}. There are still four more frames to be transmitted, however, it has to send stop signal at t_{i+29} since the next value to be transmitted is 11, which is less than 29. Here the first four values can be transmitted in 29-bit time slots, the fifth value in 11-bit time slots and the last three values in 22-bit time slots. The example shows that the cascading approach in CtS improves the throughput efficiency to 64.51% (40/62) from 33.61%. The improvement in the throughput efficiency described is based on considering the example. The throughput efficiency improvement varies with the number of values to be transmitted. Overall, it can be said that cascading in basic CtS strategy assists to improve the throughput of the basic CtS strategy.

4.3.3 Fast-forwarding

Let us consider a sensor s_m has to transmit a value 15 to the sink. There are other sensors s_{j1}, s_{j2}, s_{j3} respectively in the path between sensor s_m and the sink. Data packets are transmitted hop-by-hop from the s_m to the sink. The process of transmitting the values from sensor s_m to sink is such that, sensor s_m first transmit it to the s_{j1} which is on the way to the sink. After receiving the complete values from sensor s_m, senor s_{j1} forwards it to s_{j2}. Similarly, sensor s_{j2} forwards the value to sensor s_{j3} and finally sensor s_{j3} forwards it to the sink. If we assume that there are no other transmission contending for the channel, then in basic CtS strategy the total duration of the process is 4*15=60-bit time slot. Whereas, the total bit time slot required in EbT strategy is only 4*5=20-bit time slot if we assume 5-bit data frame. This shows that basic CtS has highly suffered in the data throughput. The approach of fast-forwarding can increase the efficiency of throughput in CtS strategy.

In the fast-forwarding method, neither sensor s_{j1} nor the remaining others have to receive the complete values before the values can be forwarded to succeeding sensors and finally to the sink. So, end-to-end delay of delivering a data packet is much lower in CtS implementing the fast-forwarding approach. Here, when the sensor s_m sends the start signal at time slot t_i, then sensor s_{j1} receives it. After the reception of start signal at $t_{i,}$ sensor s_{j1} can immediately send its own start signal to s_{j2} at time t_{i+1}. Similarly, sensor s_{j2} and s_{j3} can send their respective start signal to the succeeding sensors at $t_{i+2,}$ t_{i+3} after the reception of their respective start signal from the preceding sensors. After the complete transmission of the value 15 from the sensor s_m, it sends the stop signal to s_{j1} at time slot t_{i+15}. Similarly, sensors s_{j1}, s_{j2} and s_{j3} sends their respective stop signal at time slots t_{i+16}, t_{i+17} and t_{i+18} respectively. Finally, the sink receives the stop signal at time slot t_{i+18}, this shows that only 18-bit time slots are consumed to transmit the given value. But it can be seen that 60-bit time slots were consumed to transmit the same value in CtS without implementing the fast-forwarding method. Here, throughput has increased by 333% (60/18) after the implementation of the fast-forwarding method in basic CtS strategy. Not only increase the throughput but also saves the energy as no nodes remain idle while transmitting the values from the source to the sink.

4.4 Comparison of CtS and EbT based on energy consumption

Up to date, almost all forms of communication in wireless sensor network use a common strategy called EbT for the communication purpose. They utilize the non-zero voltage levels for both 0 and 1 to distinguish between silent and busy channel [15]. It requires energy to transmit each bit of information from transmitter to the receiver. Moreover, both the transmitters and receivers are switched on for the whole duration of transmission of a data frame. If the length of the message to be transmitted spans k-bit then the energy consumption is $k * e_b$. For example, in order to transmit a byte of value 105, sensor s_1 sends bit sequence <1101001> to sensor s_2. Sensor s_1 consumes energy to send each bit of value. Now, if the energy required to send each bit is e_b, then the total energy consumed to send the value 105 will be 7*e_b [16].

A very high energy in consumed to transmit a value in EbT according to the above example. However, the consumption of energy can be minimized in CtS strategy. In CtS strategy information is transmitted through the nano-sensors using silent periods between the start and the stop bits. The following example clarifies the consumption of energy in CtS. Let us again transmit a byte of value 105 from sensor s_1 to sensor s_2. Sensor s_1 sends a start signal to sensor s_2, then immediately the counter is started from zero. Sensor s_1 knows the rate at which sensor s_2 is counting, so after s_1 knows that s_2 has counted up to

105, sensor s_1 sends a stop signal to sensor s_2, thus the value 105 is transmitted to sensor s_2. In this method only two bits (start and stop) consumes energy. If each start and stop bit takes the same energy as e_b, it requires only 2*eb energy irrespective the values to be sent.

The given examples for energy consumption in CtS and EbT shows that the energy efficiency is better by a factor of over 3 in CtS than EbT. The efficiency may vary with the length of the message to be delivered. Additionally, CtS strategy also requires energy for counting the clock cycle beside energy for start and stop bits. However, counting clock cycle should also be active in convectional communication - EbT. So, energy consumption for counting clock in CtS is not incurring any additional overheads. Comparatively, CtS strategy is better than EbT strategy in terms of energy consumption. This gives a valid reason for further research focused on CtS strategy for the purpose of information transformation in the nano-networks.

4.5 Analytical model of single user channel capacity

In order to account the channel capacity of CtS in THz band, properties like path-loss, noise, bandwidth is to be investigated. The calculation of these factors is already discussed in chapter 3. Information theory is used to calculate the single user channel of communication by silence in THz band as discussed in [10].

In a discrete valued input and continuous valued output, the capacity of a discrete-time channel can be defined as a maximum average mutual information ${}^{max}_{x}I(X,Y)$ over the input (X) probability distribution and the noise level. Hence, the capacity of a communication channel can be calculated as,

$$C = {}^{max}_{x}I(X,Y)$$

$$= {}^{max}_{X}\{H(X) - H(X|Y)\} \quad \text{bit/symbol} \tag{4.4}$$

The mutual information depends on the probability distribution of the input as well as the transition probabilities. Transition probabilities are dependent on the channel conditions. In the above equation information of X is obtained by observing Y. Here, X is the source of information which takes its values from $\Omega_X = x_1, x_2, \ldots\ldots, x_n$, Y is the output of the channel, *H (X)* is the entropy of the source *X*, and *H (X|Y)* is the conditional entropy of *X* given *Y*.

In CtS, we can generate source as a random variable with constant 1's at the beginning and the end time slot and varying 0's in between them. Entropy $H(X)$ of such source is as,

$$H(X) = -\sum_{m=0}^{1} pX(x_m) \log_2 px(x_m) \tag{4.5}$$

$$= -\left\{\frac{n}{n+2} log_2\left(\frac{n}{n+2}\right) + \frac{2}{n+2} log_2\left(\frac{2}{n+2}\right)\right\} \tag{4.6}$$

here, $pX(x_m)$ is the probability of transmitting the symbol m = {0, 1} and n is the total number of zeros transmitting. A pulse is transmitted for 1's and the transmitter stays silent during 0's transmission.

The terahertz channel consists of molecular absorption noise. The noise distorts (gets added to) the input signal, so the output of the channel (Y) is a continuous random variable regardless of the input being discrete random variable. So, the equivocation of the channel *H(X|Y)* is given as,

$$H(X|Y) = \int pY(y) H(X|Y = y) dy$$

$$= -\int pY(y) \sum_{m=0}^{1} pX(x_m|Y = y) \; \log_2 px(x_m|Y = y)\, dy \tag{4.7}$$

here, the term $pX(x_m|Y = y)$ denotes the probability of having transmitted x_m for the given output y.

The values of *y* in the above equation is still unknown. *y* it is the result of x_m added with the molecular absorption noise but we know the input random variable x_m. So, Mixed Bayes Rule and the Total Probability Theorem can be implemented to calculate the equivocation $H(X|Y)$ which can be written in terms of the probability of the channel output *Y* given the input x_m as,

$$H(X|Y) = \int \sum_{m=0}^{1} pY(Y|X = x_m) pX(x_m). \log_2 \left(\frac{\sum_{i=0}^{1} pY(Y|X = x_i) pX(x_i)}{pY(Y|X = x_m) pX(x_m)}\right) dy \tag{4.8}$$

We have already calculated the molecular absorption noise at the receiver which is created by the vibration of molecules present in the atmosphere. Hence, the noise power spectral density (PSD) can be utilized to further calculate probability density function of the output Y for given input $X = x_m$ as,

$$pY(Y|X = x_m) = \frac{1}{\sqrt{2\pi N_m}} e^{-1/2 \frac{(y-a_m)^2}{N_m}} \tag{4.9}$$

Here N_m is total noise PSD at the receiver which is created by the transmission of symbol $x_{m=1}$, and a_m refers to the amplitude of received symbol.

By inserting the values of noise, equations (4.5), (4.8) and (4.9) in equation (4.4), we can calculate the capacity of the channel in bits/symbol for a single user by CtS scheme in THz band as given below. However, it is not feasible to solve the channel capacity given by equation (4.10) analytically, so it is numerically solved in chapter 5.

$$C_{u-sym} = \max_X \{-\sum_{m=0}^{1} pX(x_m)\log_2 px(x_m) - \int \sum_{m=0}^{1} \frac{1}{\sqrt{2\pi N_m}} e^{-1/2\frac{(y-a_m)^2}{N_m}} \mathrm{pX}(x_m). \log_2(\sum_{n=0}^{1} \frac{pX(x_i)}{pX(x_m)} \sqrt{\frac{N_m}{N_i}} e^{-1/2\frac{(y-a_i)^2}{N_m}+1/2\frac{(y-a_m)^2}{N_m}}) dy\} \text{ bit/symbol} \tag{4.10}$$

4.6 Multiple user channel capacity

In this section, a new statistical model for interference in CtS is formulated. Additionally, the model is investigated analytically to formulate the channel capacity for multiple user scenario in CtS based on [10].

4.6.1 A statistical model of interference

Interference in multi-user case occurs when symbols from different nano-machines reach to the receiver at the same time overlapping the amplitude and shape of the received pulses. The interference during the process of detection at the receiver *j* due to the symbols transmitted by nano-machine 1 is given as,

$$I = \sum_{u=2}^{U} A^u (p * h)^{u,j}(\gamma_1^u) + \omega^{u,j}(\gamma_1^u) \tag{4.11}$$

here, U is the total number of nano-machines, A^u is the amplitude of the symbol that each nano-machine transmits, $(p * h)^{u,j}(t)$ is the convolution of transmitted pulse and channel impulse response between nano- machine u and j. Similarly, γ_1^u is the time difference that machines 1 and u transmits, and, $\omega^{u,j}(t)$ is the absorption noise experienced at receiver due to the transmission from user u.

The following assumptions are considered to investigate statistical characterization of interference from individual nano-machine [10].

- A central entity controls nano-machines, however, they communicate in as ad-hoc fashion.

- Independent transmissions from different nano-machines with the same source probability distribution X are considered.
- Uniformly distributed transmissions from different nano-machine is achieved by waiting a random time before starting the transmission of a packet.
- Uniform distribution in space among nano-machine is considered, thus, the propagation delay between any pair of users is also uniformly distributed in time.

4.6.2 Analytical study of multiple users channel capacity

The multiple user channel capacity is the maximum throughput in the multiple user scenarios. It can be given by,

$$C_{mul} = \max_X (UC^I_{u-bits}) \tag{4.12}$$

here, U is the total number of interfering users, X is the source of information for every single nano-machines which takes its values from $\Omega_X = x_1, x_2, \dots \dots, x_n$, and, C^I_{u-bits} is the capacity for individual nano-machines. However, the capacity for individual machines is not exactly the same as in single user case. It is because of the multiple user interferences experienced by each nano-machines. So, in order to calculate capacity for individual nano-machines we need to add interference into the probability of the output Y for given input $X = x_m$. The noise model introduced at (4.9) becomes as below in multiple user scenarios,

$$pY(Y|X = x_m) = \frac{1}{\sqrt{2\pi(N_m + N_I)}} e^{-1/2 \frac{(y - \mathrm{E}[\mathrm{I}] - a_m)^2}{N_m + N_I}} \tag{4.13}$$

N_I is the variance of the interferences, and, E [I] is the mean value of the interference and calculated as in equations (4.14, 15), respectively.

$$N_I = \sum_{u=2}^{U} \left(\frac{(a^{u,j})^2 + N^{u,j}}{\beta} \right) p_X(x_1) + 2 * \sum_{u=2<v}^{U} (\frac{p_X(x_1)}{\beta})^2 a^{u,j} a^{v,j} - (\sum_{u=2}^{U} \frac{a^{u,j}}{\beta})^2 p_X(x_1) \tag{4.14}$$

and,

$$E[I] = E \left[\sum_{u=2}^{U} A^u (p * h)^{u,j} (\gamma_1^u) + \omega^{u,j} (\gamma_1^u) \right] \tag{4.15}$$

where, $a^{u,j}$ is the amplitude of the pulse transmitted by nano-machine *u* at the receiver *j*, $N^{u,j}$ is the noise power created from the transmission of *u* to *j*.

Now, combining equations (4.13, 8, 5, 4), C^{I}_{u-bits} can be achieved and capacity for multiple users in bits/symbol is formulated as in equation (4.16),

$$C_{mul} = \max_{X}\{\mathrm{U} - \sum_{m=0}^{1} pX(x_m)\log_2 px(x_m) - \int \sum_{\mathrm{m=0}}^{1} \frac{1}{\sqrt{2\pi(N_m+N_I)}} e^{-1/2\frac{(y-\mathrm{E[I]}-a_m)^2}{N_m+N_I}}\,\mathrm{pX}(x_m).$$

$$\log_2(\sum_{n=0}^{1} \frac{pX(x_i)}{pX(x_m)} \sqrt{\frac{N_m+N_I}{N_i+N_I}}\, e^{-1/2\frac{(y-E[I]-a_i)^2}{N_m+N_I}+1/2\frac{(y-\mathrm{E[I]}-a_m)^2}{N_m+N_I}})dy\} \tag{4.16}$$

5. NUMERICAL RESULTS

This chapter describes single and multiple user channel capacity of CtS in terahertz frequency under various test scenarios. Results under those scenarios are presented on following sections. In test scenario, two mediums are considered with 1% and 6% water vapor molecules, respectively. Additionally, various distance parameters have been considered for test results. Specifically, research conducted on this thesis considers HITRAN database to extract absorption coefficient for different mediums [19]. Specifically, chapter presents the numerical results illustration for molecular absorption coefficient, path-loss, molecular noise temperature based on the previous studies. Finally, the numerical results on channel capacity for both single and multiple users are presented based on the MATLAB algorithm developed.

The chapter consists of two sections. Section 5.1 illustrates the results based on channel model studies in terahertz band. Section 5.2 presents the analytical results for channel capacity for both single and multiple users.

5.1 Illustration of results

In this section results based on previous studies on channel model for terahertz band is considered. Results presented in following sub-sections is based on previous studies, however, different scenario is considered in accordance to our studies.

5.1.1 Molecular absorption coefficient

The overall capacity of the channel is dependent in the noise created in the channel. The noise in the channel is mainly due to the molecular absorption noise. This type of noise varies within different medium. Mediums have different molecular composition and each variety of molecules have different absorption coefficient. So, two different types of homogenous mediums are created here in the test scenario. The mediums were created with the help of [19]. The abundancy of molecules in the mediums are as shown in the table below.

Table 5.1. *Abundancy of molecules in % for two test scenario mediums.*

	Medium 1	Medium 2
H_2O	1.0%	6.0%
CO_2	0.032701%	0.032701%
O_3	0.000003%	0.000003%
N_2O	0.000032%	0.000032%
CO	0.000015%	0.000015%
CH_4	0.000168%	0.000168%
O_2	20.710864%	20.710864%
N_2	78.256217%	73.256217%

The absorption coefficients for both the mediums are obtained from the simulation result at [19]. In this simulation the numerical values of parameters are defined as, minimum wave number (WN_{min}) = 3.33 cm^{-1}, maximum wave number (WN_{max}) = 333.33 cm^{-1}, temperature (T) = 296 K, pressure (P) = 1atm, intensity cutoff (I_{cut}) = 1x 10^{-28} cm/mol.

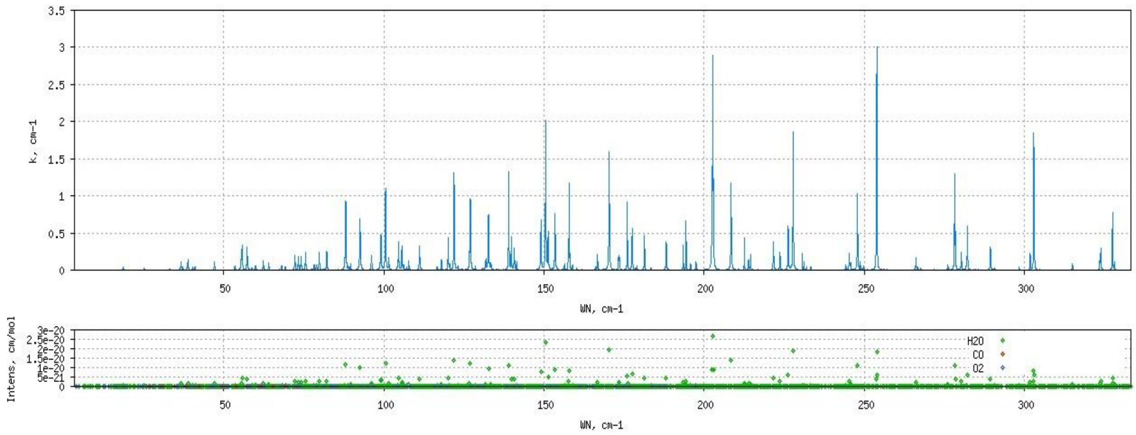

Figure 5.1. *Molecular absorption of the medium 1 containing 1% molecules of water vapour for wave number between 3.33 to 333.33 obtained directly from [19].*

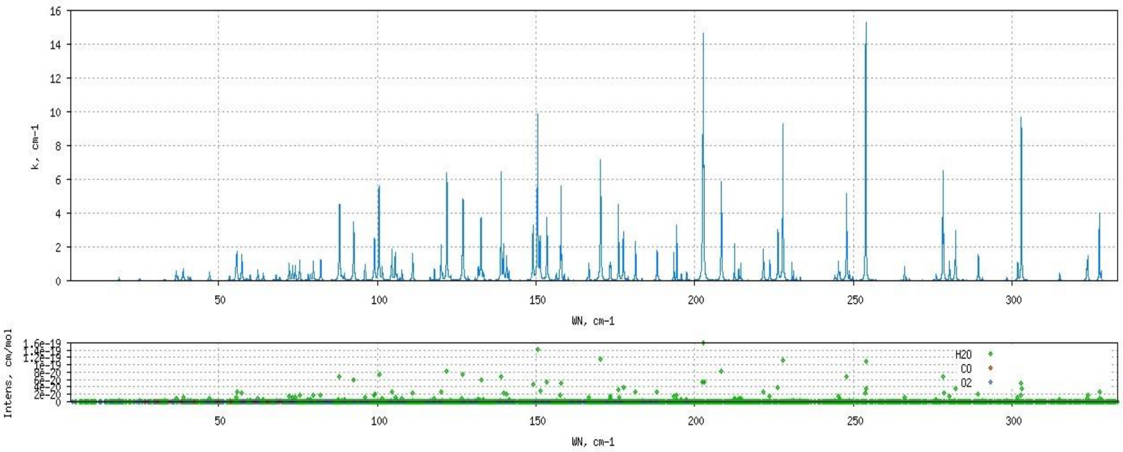

Figure 5.2. *Molecular absorption of the medium 2 containing 6% molecules of water vapour for wave number between 3.33 to 333.33 obtained directly from [19].*

Both the Figures 5.1 and 5.2 are simulated result from [19]. These figures show the absorption coefficient with respect to wave number. The raw data obtained from the simulation is processed into MATLAB. After processing the data, absorption coefficients for each medium are obtained with respect to frequency which are shown below.

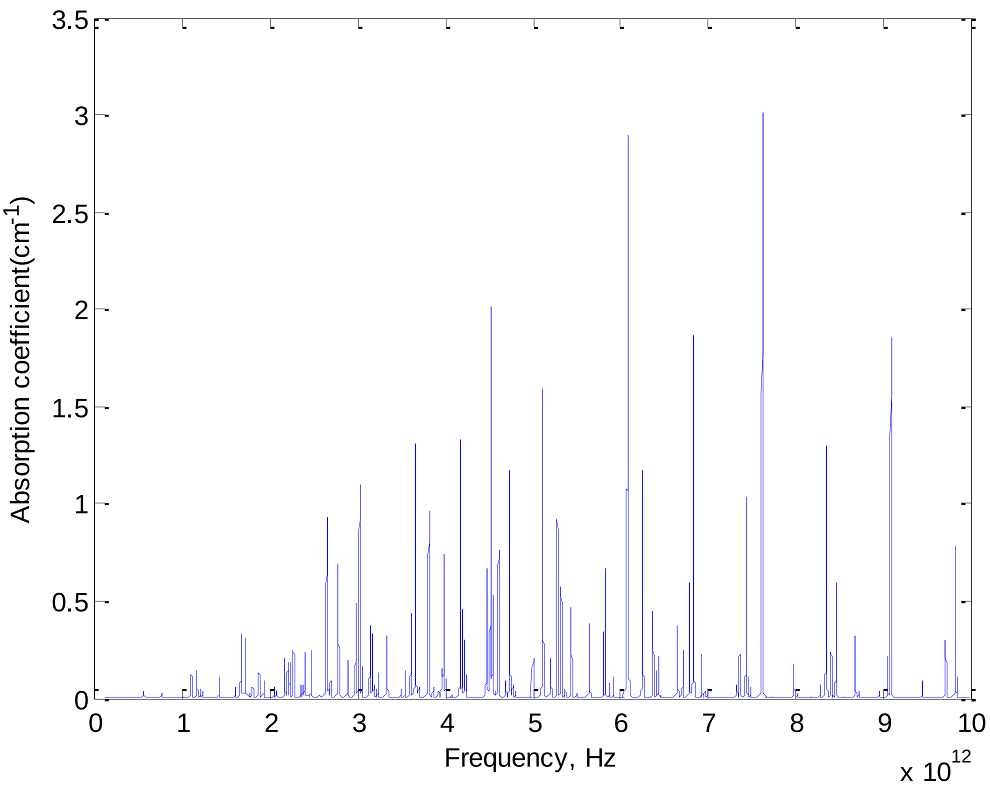

Figure 5.3. *Molecular absorption coefficient of the medium 1 containing 1% molecules of water vapour [8,11,17].*

Figures 5.3 and 5.4 are the illustration of result based on previous study. However, absorption coefficients are numerically presented for the two mediums taken in test scenario. Both figures show the molecular absorption coefficient with respect to frequency for medium 1 and medium 2 respectively. It shows that the absorption coefficient is higher at transparency window between 6 THz to 8 THz. More interestingly, it can be seen that molecular absorption coefficient is higher for medium 2 compared to medium 1. Hence, the increase in water vapour molecules in the atmosphere also increases molecular absorption coefficient. Water vapour molecules or H2O has the major contribution in total absorption of the medium. Absorption coefficient of a medium is given by the total absorption of the medium. Path loss is directly proportional with the absorption coefficient. So, as the absorption coefficient of a medium is high then the path loss at the medium is also high. Thus, analyzing Figure 5.3 and 5.4, it can be said that transparency window between 6 to 8 THz is less suitable for transmitting a single through. It can also be noticed that the medium with higher abundancy of water vapour molecules in not suitable for transmitting a signal through. So, it can be said that a propagating wave suffers from higher path loss as it travels through the medium with higher water vapour molecules and also when it travels between 6 to 8 THz band of frequency.

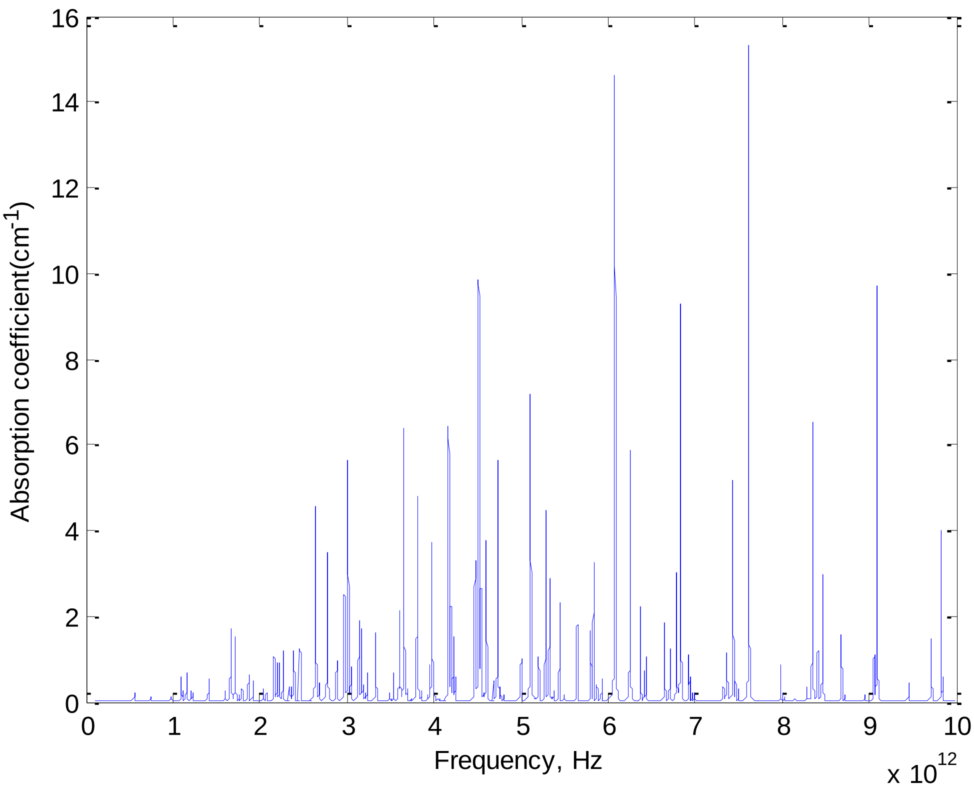

Figure 5.4. *Molecular absorption coefficient of the medium 2 containing 6% molecules of water vapour [8,11,17].*

5.1.2 Path loss

The total path loss in terahertz band is the summation of spreading loss and molecular absorption loss. It depends on EM wave frequency *f*, the transmission distance *d* as well as the composition of the medium that the wave passes through. Figures 5.5 and 5.6 shows the path loss for the created test mediums which are illustrated from the previous studies. Figure 5.5 shows the overall path loss in the medium where the content of water vapour molecules is 1%, whereas, Figure 5.6 is for the medium containing 6% water vapor molecules abundancy. The path losses in Figure 5.5 and 5.6 is the result from adding spreading loss and molecular absorption loss in dB scale. For both the mediums path loss is calculated for four different distances d = 0.001 m, 0.01 m, 0.1 m and 1 m. In this calculation reference temperature T = 296 K, frequency band from 0.1 to 10 THz was considered.

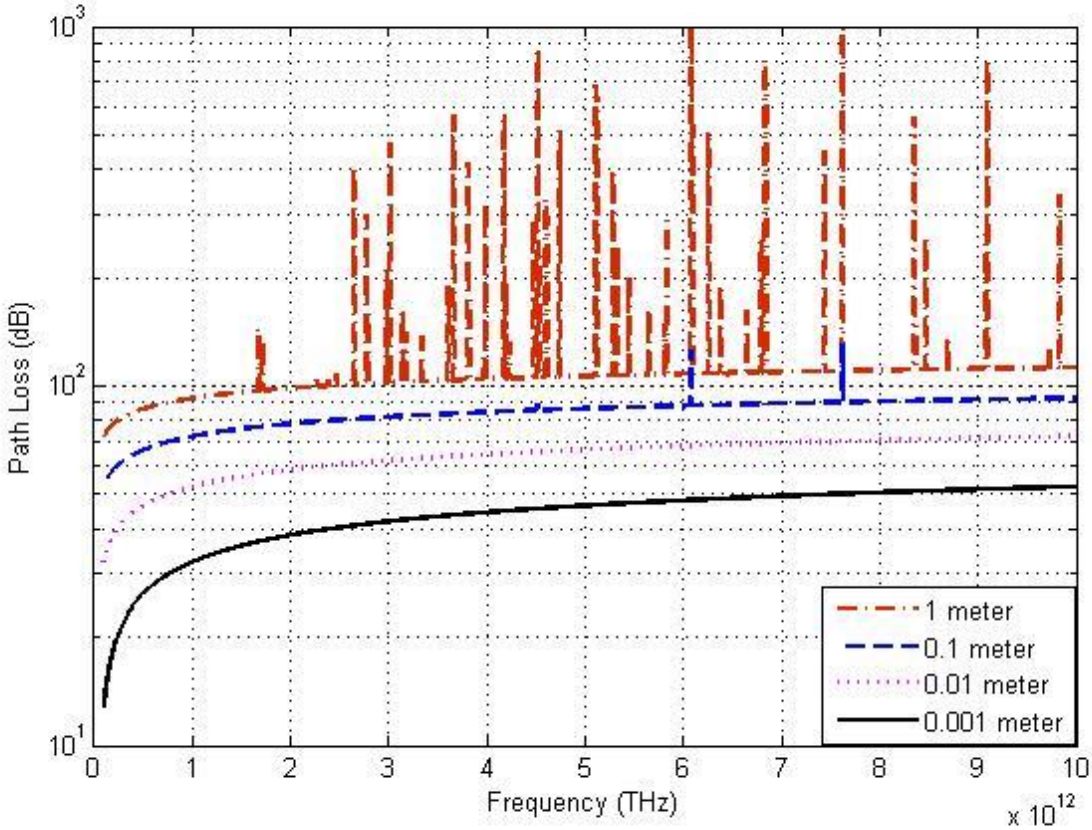

Figure 5.5. *Total path loss (addition of spreading loss in dB and molecular absorption loss in dB) in dB for four different distances in a medium with 1% water vapour molecules abundancy [8,11,17].*

Figures 5.5 and 5.6 show the interrelationship between path loss, distance, frequency and the composition of the medium. The total path loss in dB scale is shown in the y-axis against frequency in x-axis. Overall path loss in Figure 5.6 is more and has more peaks compared to Figure 5.5. Path loss in a medium depends on the composition of the medium. The abundancy of water vapour molecules for Figure 5.5 is 1%, whereas, for Figure

5.6 is 6%. The molecular absorption coefficient for medium with 6% water vapour abundancy is higher than that for 1%. So, the path loss in Figure 5.6 is higher compared to Figure 5.5. If we do not take into consideration the composition of the medium, however, the path loss still increases with the increase in the distance and frequency. It is due to the spreading loss that a propagating EM wave encounters. In the overall path loss figures, we can observe several peaks of attenuation which is caused due to the molecular absorption loss.

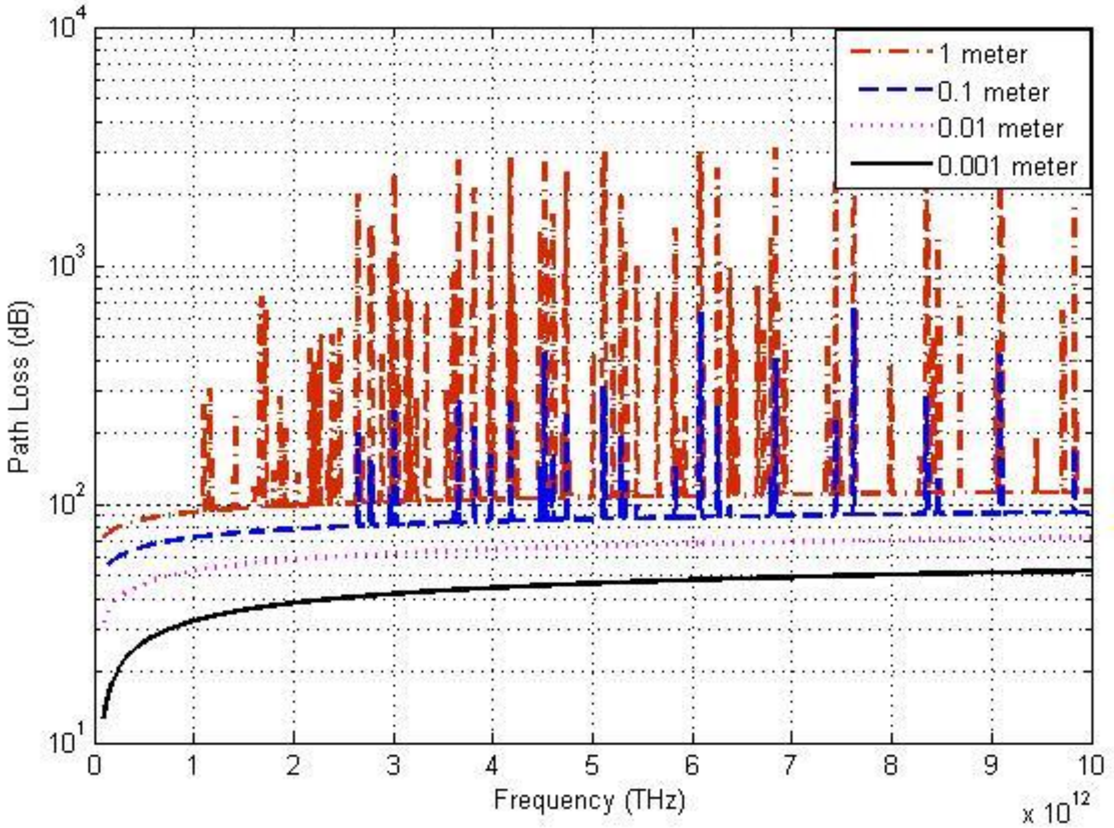

Figure 5.6. *Total path loss (addition of spreading loss in dB and molecular absorption loss in dB) in dB for four different distances in a medium with 6% water vapour molecules abundancy [8,11,17].*

5.1.3 Molecular absorption noise temperature

As shown in equation (3.16), the total noise power in the terahertz system depends on the molecular absorption noise temperature and electronic thermal noise in the receiver. However, the electronic thermal noise due to the graphene in the system is considered to be very low. So, such noise is not taken into consideration in the calculation of total noise power. Hence, it can be said that molecular absorption noise introduced by the channel is the main source of noise in the terahertz band. In Figure 5.7 and 5.8, PSD of molecular absorption noise is plotted for 1% and 6% water vapour molecules concentration respectively. These figures for noise are illustrated based on the previous studies. During the calculation, the reference temperature T_0 = 296 K and frequency band between 0.1 to 10

THz is considered. These figures are plotted for transmission distance d = 0.001, 0.01, 0.1, 1.0 m.

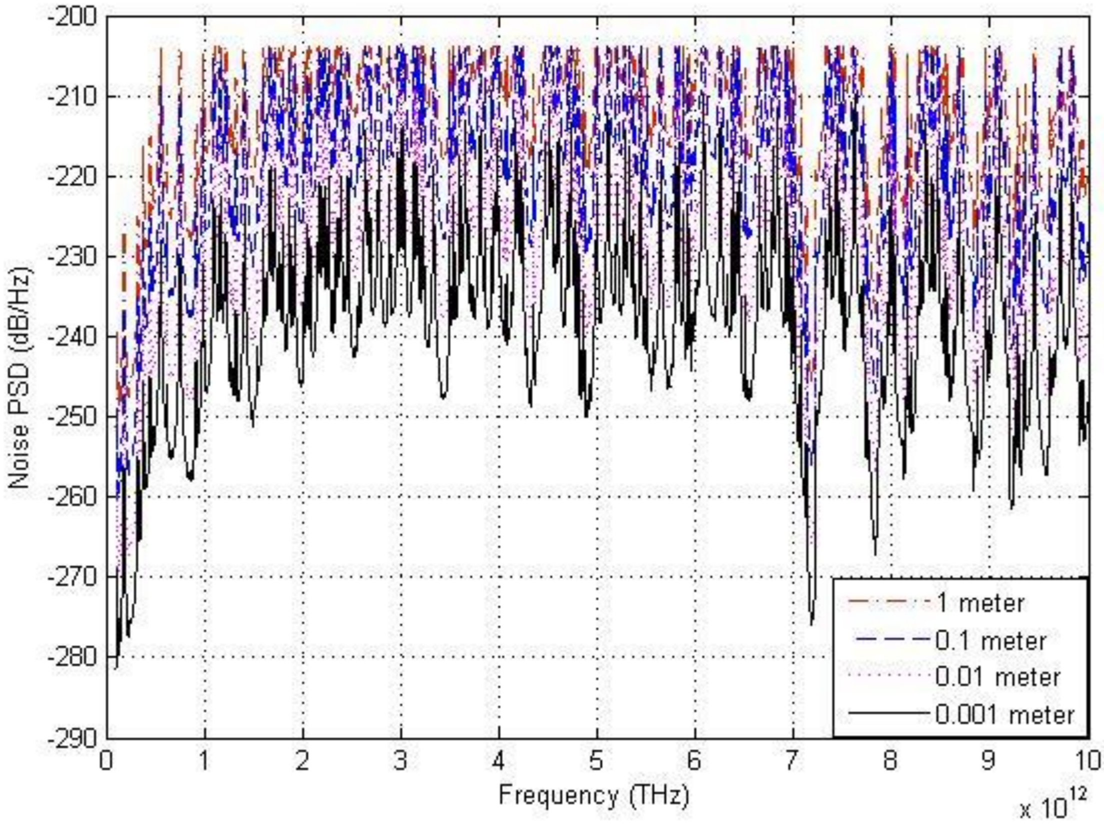

Figure 5.7. *The PSD of molecular absorption noise for four different distances in a medium with 1% water vapour molecules abundancy [8,11,17].*

In the Figures 5.7 and 5.8, it can be seen that for a short distance transmission, the noise temperature is low. Likewise, with the increase in the transmission distance, the noise temperature increases. Noise temperature occurs due to the highly absorbent molecules in the transmission medium. As the probability of such absorbent molecules is higher in long distance transmission than in the short distance transmission, so the noise temperature in long distance transmission is high. It can be noticed in the figure that there are several peaks in the total noise temperature. This is caused when propagating signal encounters, the increasing amount of absorbent molecules in the medium. So, there are more peaks in the medium with 6% water vapour molecules than the medium with 1% water vapour molecules.

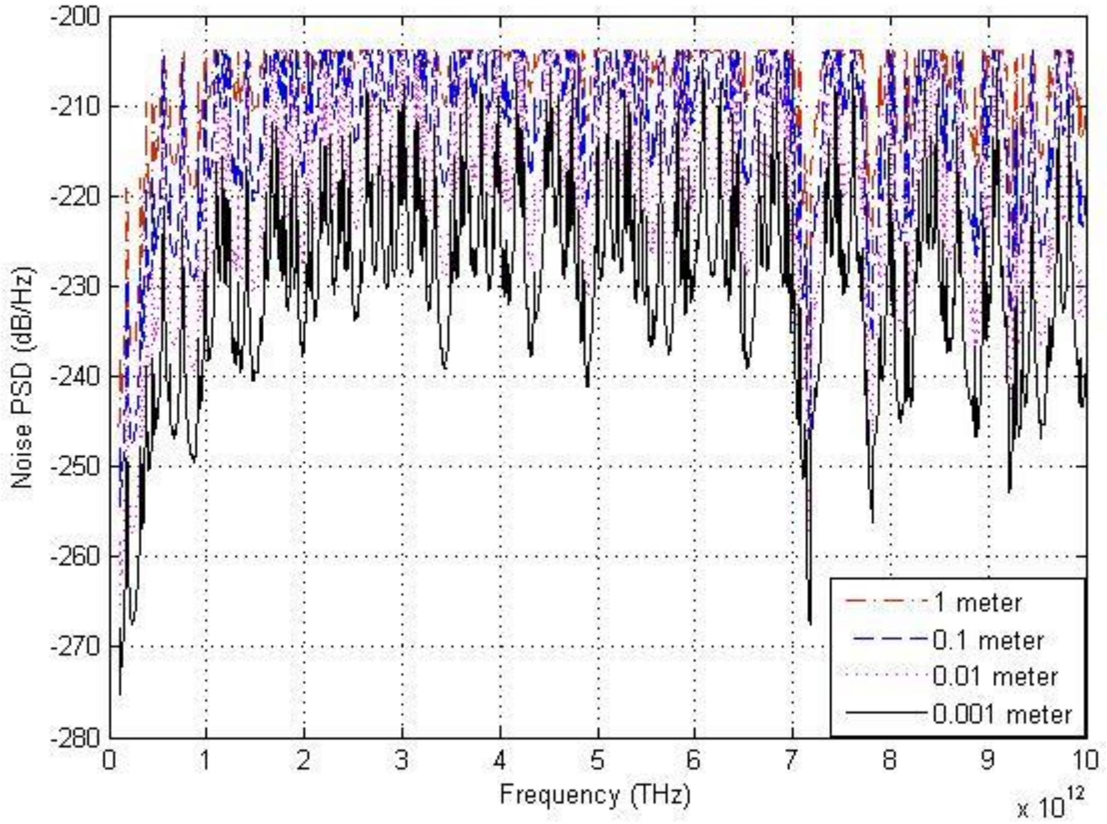

Figure 5.8. *The PSD of molecular absorption noise for four different distances in a medium with 6% water vapour molecules abundancy [8,11,17].*

5.2 Simulation results for channel capacity

The numerical results of channel capacity are presented in this section. In test scenario, 1% and 6% H_2O vapor molecules were considered. For test condition, 0.001 m, 0.01 m, 0.1 m, and 1.0 m were considered. Frequency band of 0.1 to 10 THz were considered. Terahertz propagation model discussed in Chapter 3 is used for the computation of the total path-loss and molecular absorption noise temperature. The numerical results presented in the above sections are used for the calculation of channel capacity. The transmitted pulses were modeled as the first-order time-derivative of a 100-femtosecondlong Gaussian pulse. In an intent to keep the numbers realistic, and in light of the state of the art in molecular-electronics, we keep the total pulse energy constant and equal to 1 picoJoule. For the transmission distance, path lengths ranging from 0.001 meter to 1 meter are considered.

5.2.1 Channel capacity for single user

Channel capacity for single user is presented in this section. Figure 5.9 shows the channel capacity for both 1% and 6% water vapor molecules. As depicted in figure below, channel capacity for both conditions over distances is presented. With increase in distance the channel capacity decreases gradually. In Terahertz band communication, channel capacity is greatly affected by the distances. Figure shows, increase in water vapor concentration in medium adversely affect the channel capacity.

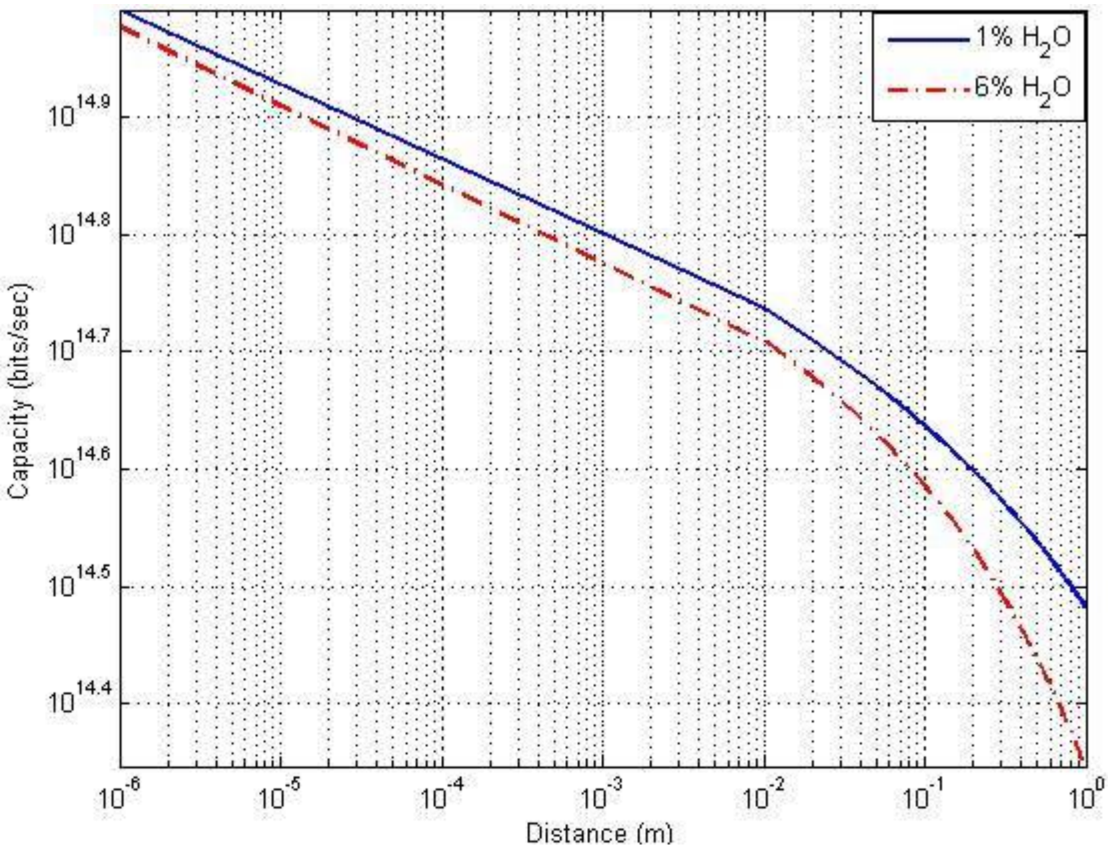

Figure 5.9. *Channel capacity for single user case in the medium with 1% and 6% water vapor molecules abundancy.*

5.2.2 Channel capacity for multiple user

Channel capacity for multiple user is presented in this section. While computing channel capacity for multiple user, the signal from other users is behaved as noise for the interested user. The test is carried out for two users case (multiple user). Figure 5.10 shows the channel capacity for both 1% and 6% water vapor molecules for multiple users. As depicted in figure below, channel capacity for both conditions over distances for multiple user in terahertz communication is presented. With increase in distance the channel capacity decreases gradually. In Terahertz band communication, channel capacity is greatly affected by the distances. Figure shows, increase in water vapor concentration in medium adversely affect the channel capacity. On comparison, channel capacity for multiple user is lower compared to that of single user channel capacity.

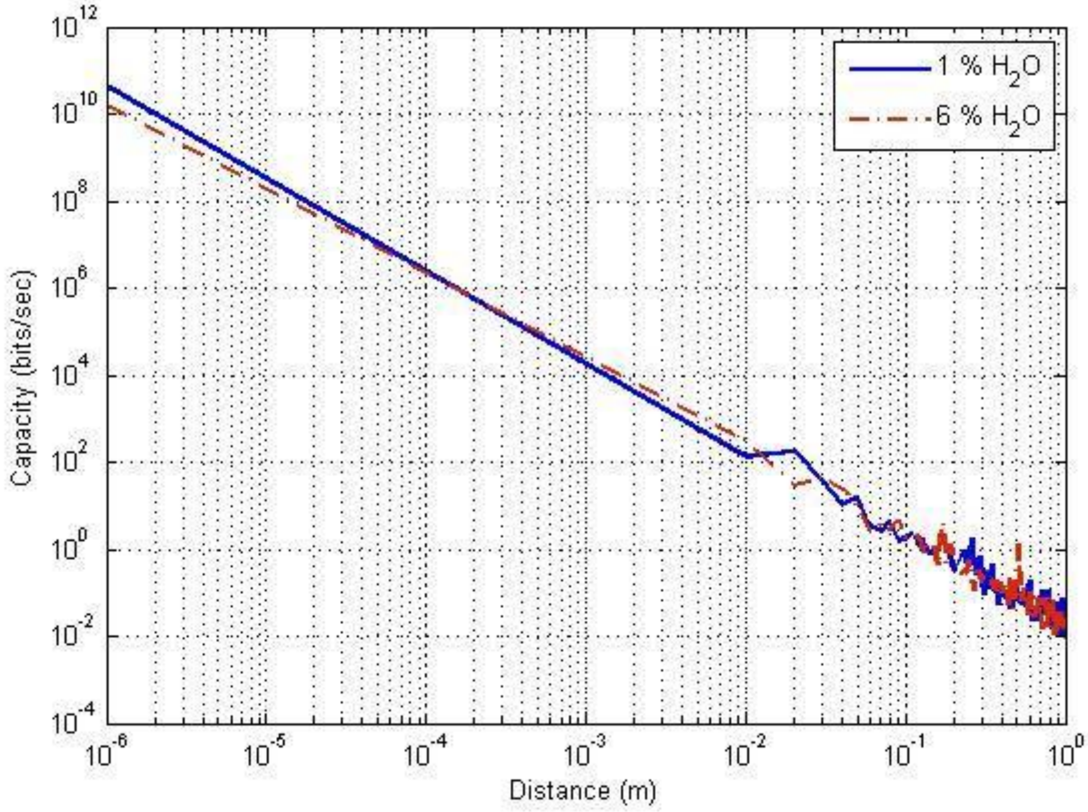

Figure 5.10. *Channel capacity for multiple user case in the medium with 1% and 6% water vapor molecules abundancy.*

6. CONCLUSION AND FUTURE WORKS

In this chapter conclusion of this studies along with future works on this studies is presented.

6.1 Conclusion

The study in this thesis is principally focused in computing channel capacity for both single user and multiple user. A single nano-machine has very limited functionality, whereas, a group of interconnected nano-machines have various application in our day to day life, like, biomedical, environmental, industrial, military and other applications. Communication among nano-machines is essential to achieve utmost benefit from them. Communication is focused in terahertz frequency band. A new communication paradigm called – CtS is discussed for communicating in terahertz frequency band. This technique is used to derive single and multiple user channel capacity in terahertz frequency band. The contributions of this studies are shortly summarized below.

Chapter 2 covered the history of nano-technology. It showed that the technology was first discussed in 1959 AD. Nano-machines is the main component in the nanotechnology. Nano-machines can be developed from two aspects, i.e. biological and artificial. Biological nano-machines either exist in biological environment or they are manufactured from biological materials. Similarly, artificial nano-machines are manufactured from electronic components. However, the architecture of both types of nano-machines are similar which consists of control unit, power unit, sensors, and so on. There are different modes of communication among nano-machines some of them are nano-mechanical, acoustic, molecular and electromagnetic communication. This studies in this thesis work is focused in electromagnetic communication.

Chapter 3 contributes on better understanding of terahertz channel propagation model and material used for nano-machine generation. Graphene is used in the generation of nano-machine and replaces exiting silicon materials. The terahertz channel propagation model discussed in the chapter which is based on the radiative transfer theory. The model is utilized to characterize the terahertz channel in terms of total path loss and system noise. The overall path loss and the system noise is dependent on the medium through which the signal propagates. Molecular absorption coefficient of the medium is the main factor that affects the both path loss and system noise. Water vapor molecules present in the medium is also the factor which also affects the path loss including system noise.

Chapter 4 contributes the general therein on the novel paradigm, the CtS strategy. CtS strategy primarily uses a radio silence to deliver information between nano-machines, so energy consumption is greatly reduced. Although this strategy consumes less energy, it has tradeoff in overall throughput. However, various strategy like multiplexing, cascading, fast-forwarding can be utilized to overcome throughput tradeoff in CtS. CtS strategy is used in analytical study of single user and multiple user channel capacity. Whereas, the numerical solutions to such capacities are performed in succeeding chapter.

Chapter 5 covered the analytical results that are formulated based on chapter 3 and chapter 4. Illustration of results for path loss, molecular absorption noise temperature in terahertz band based on previous studies are presented. These results are presented for four different transmission distances as well as two different mediums having different abundancy of water vapour molecules. The result showed that the terahertz channel is highly dependent on molecular composition and transmission distance. The main factor that affects the behavior in the terahertz channel comes from the availability of water vapour molecules. The absorption of the transmitted signal by water vapour molecules attenuates the transmitted signal. Additionally, both the path loss and molecular absorption noise temperature is lower when the transmitting distance is short. Whereas, they are increased with increase in transmitting distance. Taking into consideration these factors, single user and multiple user capacity by communication through silence is presented numerically. Channel capacity in both cases, is higher when the abundancy of water vapour molecules in the medium is lower.

The overall contribution of the thesis can be summarized as better understanding about the terahertz frequency band communication and CtS paradigm. The studies in this thesis determines the channel capacity for the both single and multiple user. Contributions in these studies are expected to have a good impact in the development and implementation of nanotechnology in future.

6.2 Future works

For future studies, capacity formulated in this studies can be compared with the capacity based on time spread on-off keying (TS-OOK). Study could be extended to find out the exact amount of energy consumption reduction in CtS compared to other traditional studies.

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