

A Thesis for the Degree of Ph.D. in Engineering

Equalization Schemes for Distortion Caused in Propagation Medium

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access points: AP	12
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bit error rate: BER	90
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Abstract

Wireless communication is by far the swiftly developing area of the communication engineering industry. Signal propagation in wireless communication largely depends on the characteristics of propagation medium and propagation environments. In electrical magnetic wave propagation, the received signal attenuates due to absorption by interfering objects when it passes through obstacles like glass, wood, concrete and metal surfaces. On the other hand, in molecular communications (MCs) the characteristics of a diffusion channel play an important role in propagating the data molecules. Some of these molecules hit the receiver while few remain in the medium which may reach later or lost. Inter-symbol interference (ISI) is a major problem that is caused by diffusion. The objective of this thesis is to study the effect of materials on signal propagation in radio communication as well as in MC and proposes solutions for suppressing distortions caused in the propagation medium and the propagation environments.

The chapter one introduces the visualization of wireless communication systems and technical issues related to it including radio communication (RF) and MC. Different types and potential application areas of wireless communications are explained. The characteristics of a channel and issues faced in radio and MC environment are explained. In the preceding sections the types of equalizers have been discussed. The research motivation, research objectives and contribution of this thesis is discussed at the end of this chapter.

The chapter two introduces indoor propagation of wireless local area network (WLAN) across different materials. The first section introduces the WLAN while WLAN standards are discussed in the second section. Understanding of propagation radio signals is necessary for coming up with appropriate design, deployment, and management strategies for wireless local area networks. For that reason, the effect of materials on WLAN has been discussed in the fourth section. In the preceding sections the performance of Wi-Fi signal strength between practical measurements and theoretical model are analysed.

The chapter three introduces the implementation of frequency domain equalization at the receiver side in the MC systems. The first section introduces the inter symbol interference (ISI) cancelation. The second section introduces the types of MC receiver. The third section illustrates the system design while fourth discusses the proposed technique. At the end the simulation results are presented with the discussion over them.

The chapter four introduces frequency domain precoding at the transmitter side of MC system. The second section describes the RC equivalent circuit of MC transmitter while third section illustrates the zero-forcing precoding. The implementation of threshold and approximation of equalized signal have been discussed in section four. In the preceding sections the performance of approximated signal with the conventional approach are analysed.

The chapter five summarizes the results of each chapter and presents an overall conclusion of this dissertation.

Chapter # 1

General Introduction

1.1 Introduction

Wireless communication is without any doubt a expeditiously developing area of the communication engineering industry. By the way, it needs to apprehend the consideration of the media and the creativeness of the community. Wireless systems are presently dignified to complement, or substitute wired data networks in lots of industries and sites. Several new lineups, along with wireless sensor networks, autonomous vehicles and industrial units, smart cities to smart homes tele-medicines and connecting appliances, are evolving from research designs to real implementations [1]. The quick-tempered flourishing of wireless communicating systems attached by way of the spread of laptops and computer systems suggests a vivid destiny for radiocommunication data networks, simultaneously as single connecting system and as sharing portion of the bigger networking and interacting set-up [2].

1.1.1 Wireless Vision and Technical Issues:

The visualization of wireless communications assisting information interchange among individuals or devices is the communication frontline for the future times. This idea resolves individuals to function a cybernetic workplace everywhere in the world by means of a trivial handheld entity - with unified desktop computers, palmtop and laptop, and everywhere inside a workplace, building or an educational campus as well as customers in a nearby coffee shops. These systems will permit a fresh class of smart home electronics that are able to interrelate with each one other by the Internet by adding to offer integration among computers, phones, and safety/observing arrangements inside the home. These smart households can similarly support the senior citizens and disabled by supported living life style, round the clock monitoring patients, and urgent situation response [3].

While evolving from conventional landline phone systems to mobile cellular networks and reforming traditional wired local-area networks towards radiocommunication networks i.e. Wi-Fi, the purpose was to provide following to the users [4]:

- Comfort
- Mobilization
- Expandable
- Productive
- Significant decrease of prices

As shown in the Fig. 1.1, initially there were wired networks all around that were complex and not agile in nature. So, there was a need of mobility, expandability and cost reduction which led the users to evolve to the wireless communication that are more convenient and practical then wired networks.

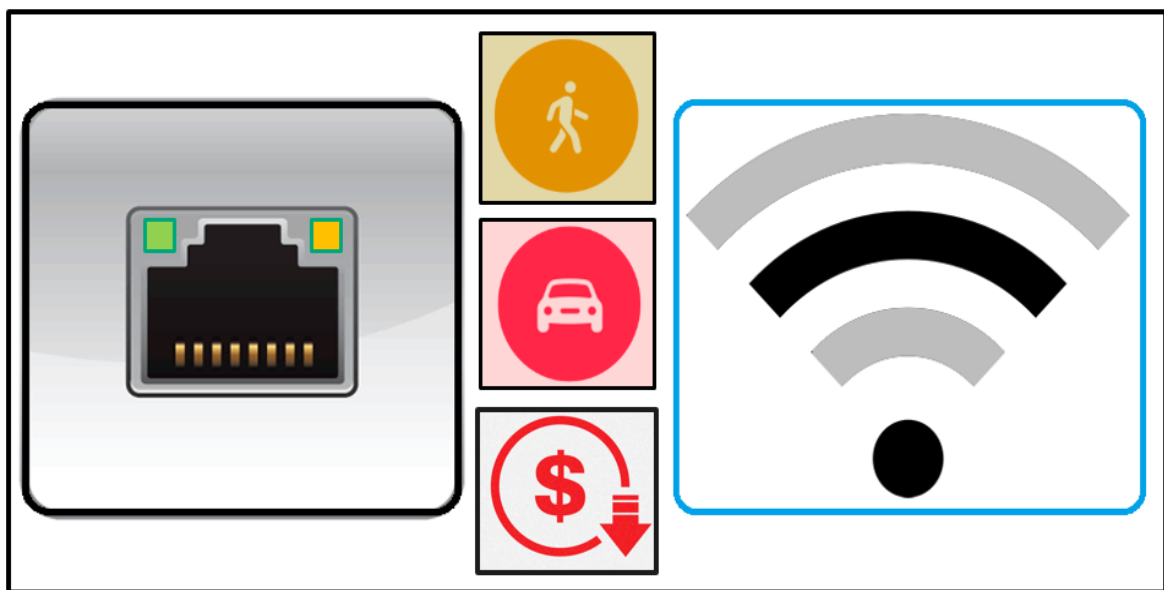


Figure 1.1 Need for wired to wireless communications.

Wireless correspondence systems have pervaded all through current society, however existing frameworks are compelled where customary wireless frequency technologies be able to carried out. There are increasing approaches where radiocommunication correspondence may possibly be an essential communication system, although traditional applications would be perilous or unreasonable. An elective methodology that got expanding consideration inside the community of engineering research throughout the

most recent period is molecular communication (MC), wherein particles have being utilized in the same way as the data carriers. MC systems were firstly anticipated for the plan of engineered correspondence organizes in [5]. The theme has gotten enduring development since the original review on nano-networks in [6], which was a system network that included nanoscale applied segments. An appealing component of MC is its pervasive sending in regular biochemical and biophysical frameworks, which allows acceptability to its potential for natural applications, for example, focusing on substances, profound medicine conveyance, and planning laboratory-on-a-small-chip frameworks [5]. Besides this, MC systems may possibly be sent in modern manufacturing situations, involving the observation of chemical vessels and miniature scale fabricating, or for bigger exercises, for example, checking the outflow of poisons or the conveyance of oil.

Nowadays, amongst the additional auspicious research areas, nano-technology is supporting operation of organic substance at molecular or atomic scale, which ranges from single to hundreds of nanometers. One objective of nanotechnology is to obtain practical procedures grounded on the exclusive occurrences and the proprietorships of matters at a nano-scale [6]. Presently, excessive research efforts are being made for developing comprehend nano-scale machines, which are also known as molecular machines or nano-machines, and is said to be “mechanical devices that perform useful functions using components of nanometer-scale and defined molecular structure” [7]. In particular, nano-machines have being anticipated to require capability to get, calculate, stimulate, cope up with their energy, and interconnect in network systems, termed as nano-networks, to trounce their specific constraints and get benefit from collective efforts [8].

The interchange of information data among nano-machines, and their interconnection into nano-networks, is important to cover-up their distinctive limits in size, energy as well as computational abilities, and get benefit from cooperative efforts. In nano-networks, the operability of conventional communication tools are restricted through some limitations. Specifically, the precise restricted dimension of the nano-machines and particularities of surroundings where they being projected to communicate in biotic situations, there is a call for innovative resolutions from the perspective of communication medium and

learning of appropriate communication procedures. Though a conceivable answer to the difficulty of communication amongst artificial nano-machines has been proposed by latest research [8] on nano-structures and nano-electronics. The availability of biological nano-machines around near future inspires to study in the nature by means of biochemical procedures, is predictable to remain particularly attractive since its characteristic practicability in a bio-compatible environment [3, 5].

The numerous submissions labelled above are entirely the constituents of the wireless vision. Thus, the question arises that what precisely is wireless communication? There are several diverse methods to divide this multifaceted matter into altered applications, systems, or coverage areas. Radiocommunication uses comprise of internet browsing, speech i.e. voice, paging, file transference, audiovisual tele-conferencing, detecting, and disseminated control unit. The wireless communication arrangements comprise of current wireless LANs, cellular telephone procedures, and satellite communication systems. The exposure regions of these radiocommunication signals comprise of biological bodies, buildings, metropolitan, nation-wide, and worldwide [9].

In the quest of, what to portray wireless communications alongside these many sections has led to in substantial disintegration in the communication industry, which is proven by the development of several diverse wireless entities, their operational standards, and facilities being presented or suggested. One motive of this disintegration is that diverse wireless applications have dissimilar needs. For example, the voice communicating systems have comparatively requirements of little data-rate of few Kbps and they be able to endure a reasonably high probability of bit error but the total delay essentially be fewer than 100 milliseconds or else it turn out to be evident to the user at far end. While conversely towards other side, information systems usually need significantly greater data-rates (i.e. 20-500 Mbps) with very small BERs [2].

As a signal spreads from one side to another side in a wireless network, it faces unsystematic variations in an interval if the source or sink is not stationary, owing to substituting of reflection points and the variations of attenuation amounts. Likewise, the security of the data is also more problematic to carry out in wireless communication

systems as the air waves are vulnerable to the interfering signals which originates from anybody having a radio frequency (RF) antenna. The analog wireless systems do not get hold of safety measures and able to clearly be listened during communication exchanges by skimming the equivalent wireless frequency. Altogether almost every digital radiocommunication system applies roughly the same scale of encryption techniques. Though, with sufficient understanding and intention majority of these information security procedures can be ruptured and, undeniably, some systems have to compromise over the extent of wireless communication. To aid current famous applications like shopping through internet i.e. online credit card transactions and E-commerce, these wireless networks needs to have more security for fraudsters to stay away[9].

While concluding, technological advancements in the subsequent sectors are required to implement the wireless vision outlined above:

- A secure architecture to attach the numerous wireless networks together and at the backend with the wired network.
- Distinctive models, analysis, and measurements for wireless channels.
- Equipment for power efficient hand-held user equipment's.
- Methods to diminish channel deficiencies.
- Designing efficient protocols for routing and agility managing which support the moving users.

Assumed these desires, currently wireless communications attract innovations from many ranges of proficiency, that includes analog and digital processing of signal, network design and communications engineering[10].

1.1.2 Wireless Communication System

A communication system in a wireless domain includes a transmitter, propagating medium, and a receiver. A standard transmitter comprises of four main sub parts: information bits, encoder, modulator and emitter afterwards the signal is transmitted with a help of an antenna. The signal then propagates through a medium known as channel.

Channel might be in the form of air, water or any aqueous medium. In the propagation process, spread through the atmosphere complying the considerable attributes of the channel. A standard receiver comprises of a receptor, decoder, demodulator, and deciding the output in the form of destination bits as shown in Fig. 1.2.

Encoder converts the information bits onto a physical property of the signal. Emitter releases the information in the form of signal into the surrounding environment. When signal reaches the receiver, they are detected and riveted by the receiver, which is baptized as the receiving progression. The characteristics of this collected signal constitute the accepted signal which is then interpreted corresponding to the transmitter encoding method.

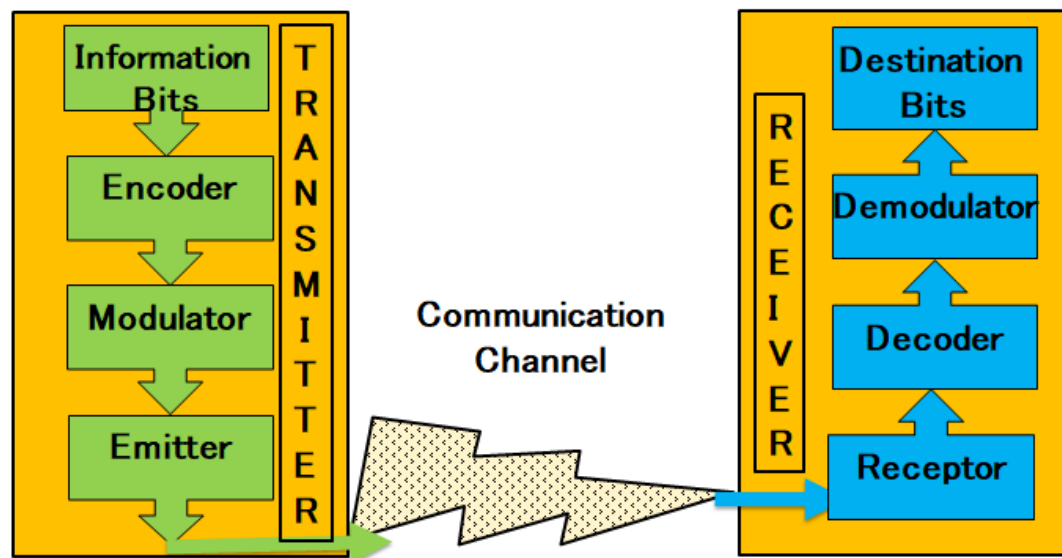


Figure 1.2 Block diagram of wireless communication system.

1.2 Types of Wireless Communication Networks:

It should be worth considering that modern civilization is dependent upon communication and in particularly communication among many users at one time i.e. having a proper networking among devices and users. A communication network can be organized according to range and area that it covers. As shown in Fig. 1.3, following are the types of wireless communication network from wider geographical area network WAN to restricted small area body area network (BAN) that just ranges within 1m range.

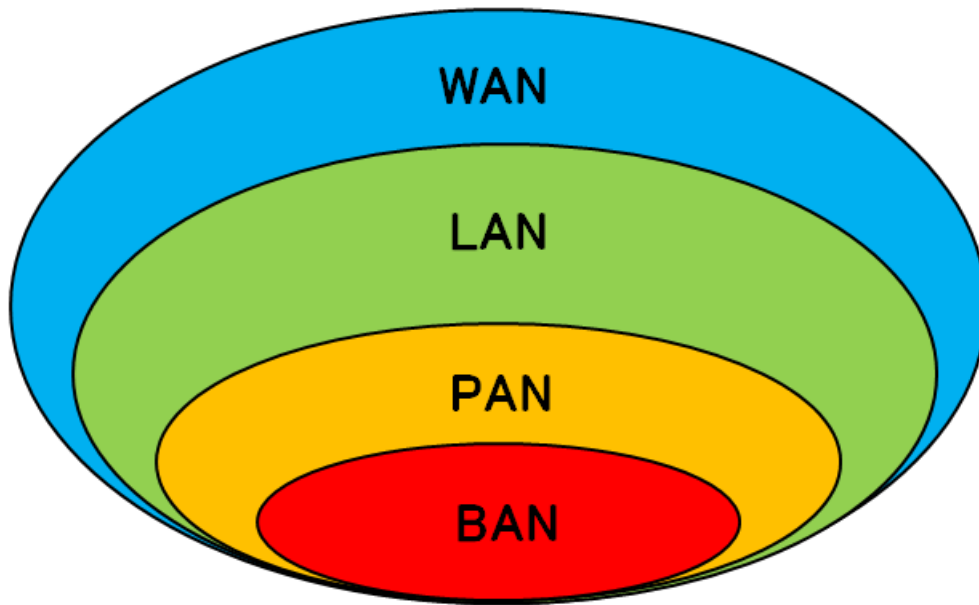


Figure 1.3 Types of wireless networks.

1.2.1 Body Area Network

The technology of BAN is the use of small, low power wireless devices that can be tried to carry or implanted inside or embedded on the human body.

It usually involves:

- Tracking fitness and wellbeing
- Physical training (e.g. performance measurement);
- Personalized regenerative medicine (e.g., cardiac monitoring)
- Personal safety (for example, fall detection)

A variety of BAN wireless networking technologies, based on existing radio technologies, have been introduced. That being said, if BAN technology is to maximize its potential, a more precise and dedicated technology, optimized for BAN, is needed. For example, solutions to people monitoring one or two hours a day of activity, several days a week, might not be optimal for 24/7 surveillance in the context of Internet of Things (IoT). The smart BAN technology provides lightweight low power devices, including medical, health, personal security and fitness, sports and leisure to handle varied applications.

However, numerous challenges which foster the implementation of BAN communication have been established. For instance, as shown in Fig. 1.4, BAN can be utilized for solutions that are ideal for monitoring people one or two hours a day, a few days a week, do not follow the criteria of the IoT 24/7 monitoring framework. It includes monitoring of heart rate, breathing rate, muscular activity, blood oxygen level and facial expressions during an athlete's physical activity with the help of smart glasses, smart garments and smart watch. A number of BAN technological innovations have been deployed in the field of wireless communication, based on existing standards but a more advanced technology is required to optimize BAN [11].

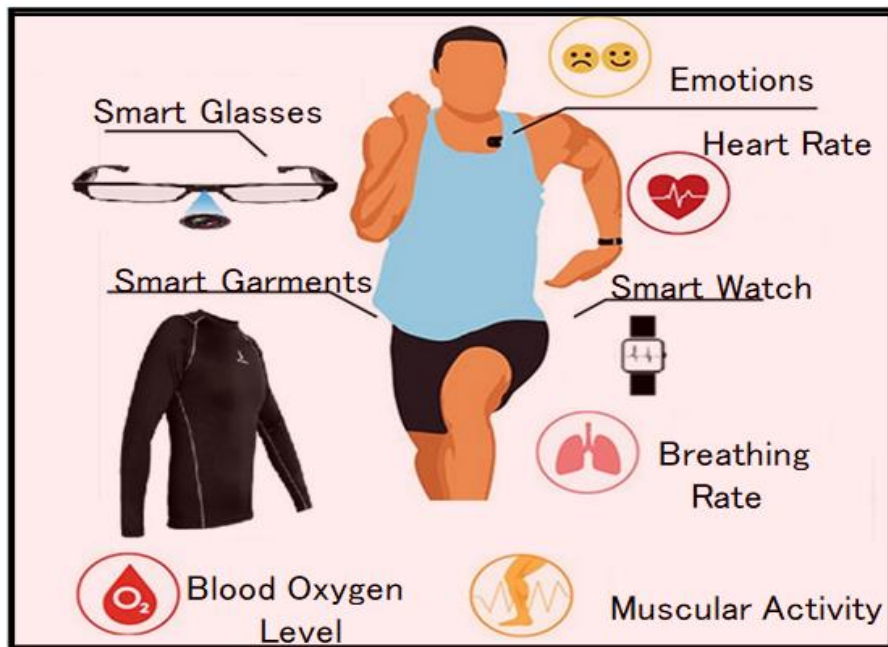


Figure 1.4 Body area network.

It will include the introduction of features such as ultra-low power radio, with a lower sophistication of medium access control (MAC) protocol for increased flexibility, improved interference robustness, and interoperability when interacting over heterogeneous IoT networks. Some key issues to address entail security and service quality [12].

1.2.2 Personal Area Network

A network that is dedicated to the sharing of information within 10-12 meters in an individual's vicinity is known as a personal area network (PAN). These systems typically operate in wireless and require data transmission between devices like mobile phones, computers, laptop computers and other portable computing devices also known as wireless PAN (WPANs). The objective of such a network is typically either to allow data or information to be transmitted between such devices or to act as the network that allows connections to the internet to proceed further. The IEEE working group 802.15 primarily manages innovations in the field of PANs [13].

As shown in Fig. 1.5 Bluetooth has been utilized to connect the devices for example cell phone to the wireless headphone, personal computer (PC) to the wireless keyboard, mouse and a tablet can be connected to the printer remotely as well.



Figure 1. 5 Personal Area Network.

1.2.3 Local Area Networks

The next popular form of network is the local area networks (LAN). When there are two or more personal computers (PC) linked collectively, they create a computer network. A LAN is able to be arranged of simply a limited to a number of hundred computers attached by a physical Ethernet wires from anyplace. In the 1970s, the impetus for LAN growth intended to allow for the sharing of costly resources such as printers and other commonly

used devices in the office. Through linking all the PC stations in an indoor environment by LAN and then attaching printing machines and other common resources. LANs can be linked to other LANs and allow to access to resources remotely[13].

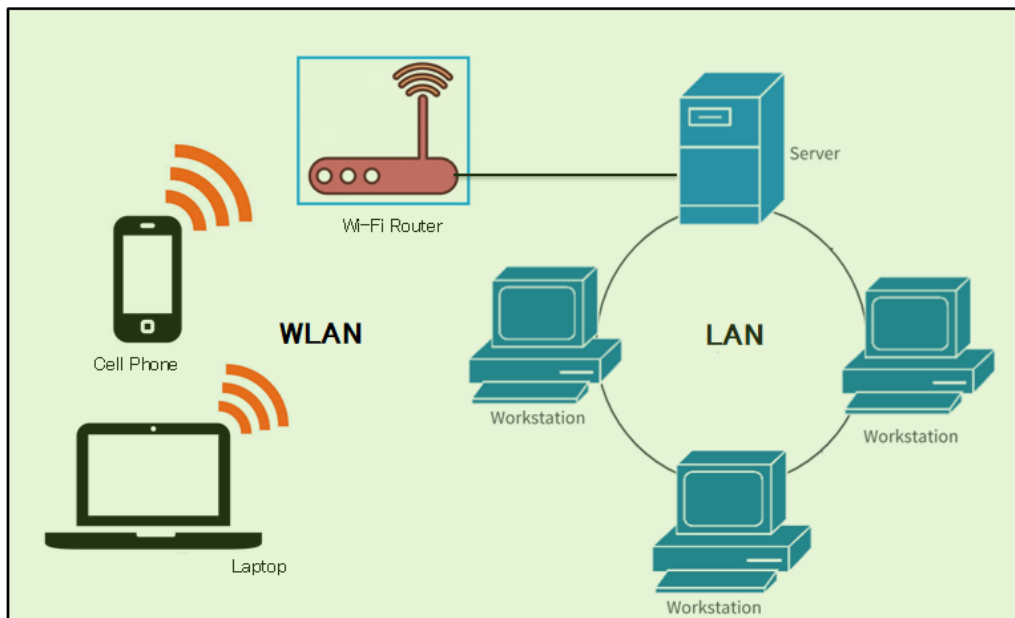


Figure 1.6 Local Area Network.

A network in which wireless medium is utilized for linking PCs and hand held devices is known as wireless LAN (WLAN). When converting conventional wired telephone networks into wireless networks and remodeling a modern LAN to a WLAN (Wi-Fi), the primary motivation was to provide end-users with comfort, mobility, expandability, and efficiency. The mobile cellular networks happened to be resulting from the popular introduction of WLANs, however their data rate, average throughput, frequency range control & distribution method to consumers are the difference between these. The novelty in either of these technologies is that a physical wire does not need to connect devices on the network by utilizing radio signals [14].

Access points (AP), also known as Wi-Fi router and cell phones, personal digital assistant (PDA) and laptops also known as mobile clients, are the basic components of WLAN as shown in Fig. 1.6. Ethernet cables are installed in the building to establish wired network infrastructure and then these buildings connect within and outside world by employing fiber-optic cables. For WLAN, APs are installed at different spots in the indoors, and even

in the open air, to establish the network infrastructure. Specific mobile customers then connect with each other by first contacting these access points [14].

The basic drive behind these networks to implement was to bring down costs and the challenges involved in wiring design. There is one specific advantage to consider when setting up a network in a historic house. The physical effect of constructing a network in such building is reduced by not needing to spread LAN cables. The advantages also remain in its compatibility because it is possible to connect the multitude of devices to WLANs that include conventional PCs, laptops, PDAs, and devices such as television sets or stereos [15].

1.2.4 Wide Area Network

The geographically dispersed LAN networks are similarly recognized as wide area networks (WANs). A most prominent WAN is PC's and LAN's connecting all over the world through internet. A WAN remains a networking framework that extends to a broad geographic region, including cities or countries. A WAN consists of several LANs and is not restricted to a specific location, though it covers a large geographical region via a, fiber-optic cable, satellite connections or simply a phone line. The Web is one of the world's largest WANs. Data is consolidated in a central position in a WAN arrangement. Generally, a router or other multi-function devices are used to link a LAN to a WAN as shown in Fig. 1.7. An organizational WANs let users gain access to computer software system, essential services and other assets in a specific centralized location. That minimizes the need for multiple locations to install the identical firewall, application server, or other resources [16] e.g. incorporating software defined networks (SDN) in 5G networks.

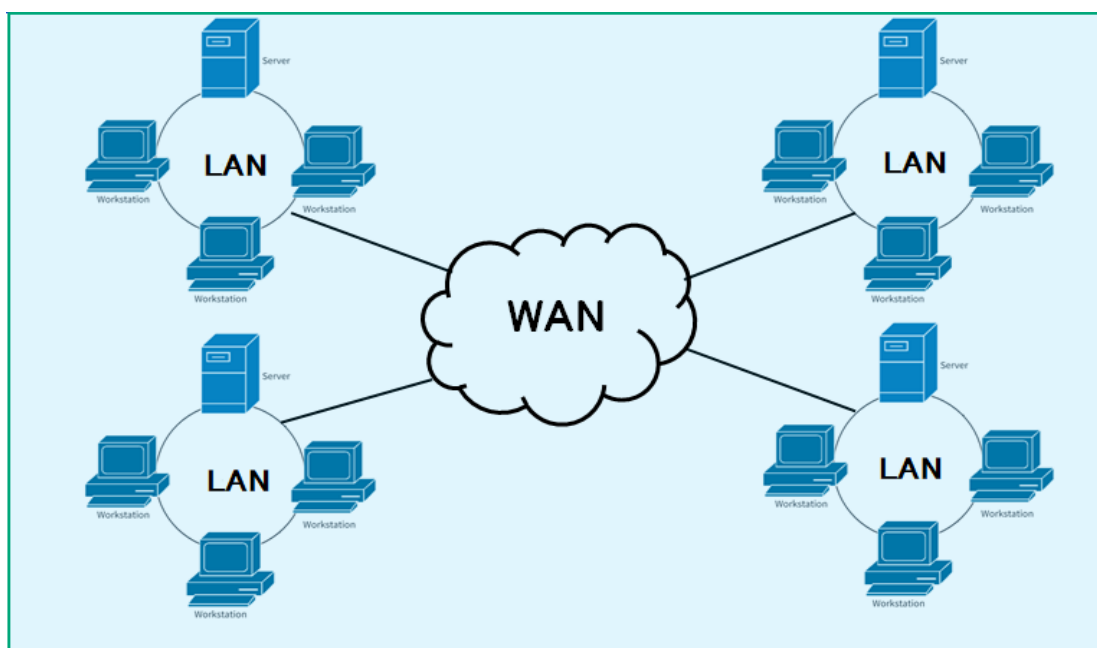


Figure 1.7 Wide area network.

1.3 Types of Molecular Communications

MC is the system of communication with particulate matters in a scale of one to thousand nano-meters. At this minute size, the most common operating unit can be used for a nano-machines [5]. These are relatively tiny modules encompassing of an organized set of bits of minute particles, that can carry out very reasonable tasks of computation, identification, and activation [6]. This can be connected to create a nano-size network where data and knowledge can be shared, transmitted and retrieved. Electromagnetic (EM) wave communications at this minute scale are difficult due to real-time executions constraints such as the capacity of the EM wave antenna to disseminate the RF signals [7]. Molecular communication is a revolutionary area of information technologies suitable for nanoparticle networking, where thin, small particle structures known as molecules are employed to handover information from an origin to a target despite the EM waves or electric currents [17].

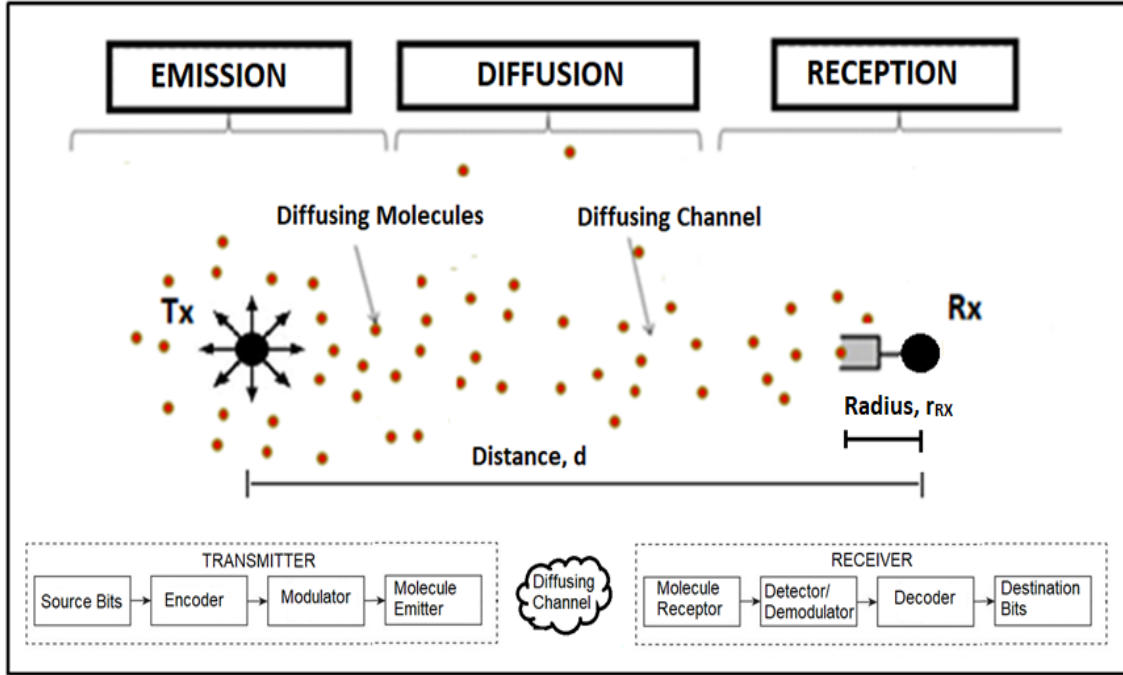


Figure 1.8 Molecular communication system.

Fig. 1.8 represents a standard MC device model. The transmitter produces and transmits particles into the media. The transmitter i.e. source passes the information bits through a method and modulates them into a chemical signal that then releases the molecules into the surrounding channel. The sensor counts these molecules on the receiver's side and accumulates the amount of particles involved in each slot [18]. The molecules absorbed is calculated against a pre-specified demodulation threshold. In a microcontroller the de-modulator and decoder block is designed according to the nature of molecules [19]. In the literature, numerous MC systems, such as MC via diffusion (MCvD), microtubules, pheromone implying, calcium indicating, and microorganisms-based transmission are recommended [18]. They are discussed as below.

1.3.1 Free Diffusion-based Molecular Communication

A MC system where molecules are discharged into surrounding natural environment and follows a disorganized motion is known as free diffusion-based MC as shown in Fig. 1.9. A transmitter releases the particles and diffuses into the channel according to the

Brownian motion, these particles propagate freely through medium and reach receiver where it is processed to get the information that is being sent by the transmitter [6].

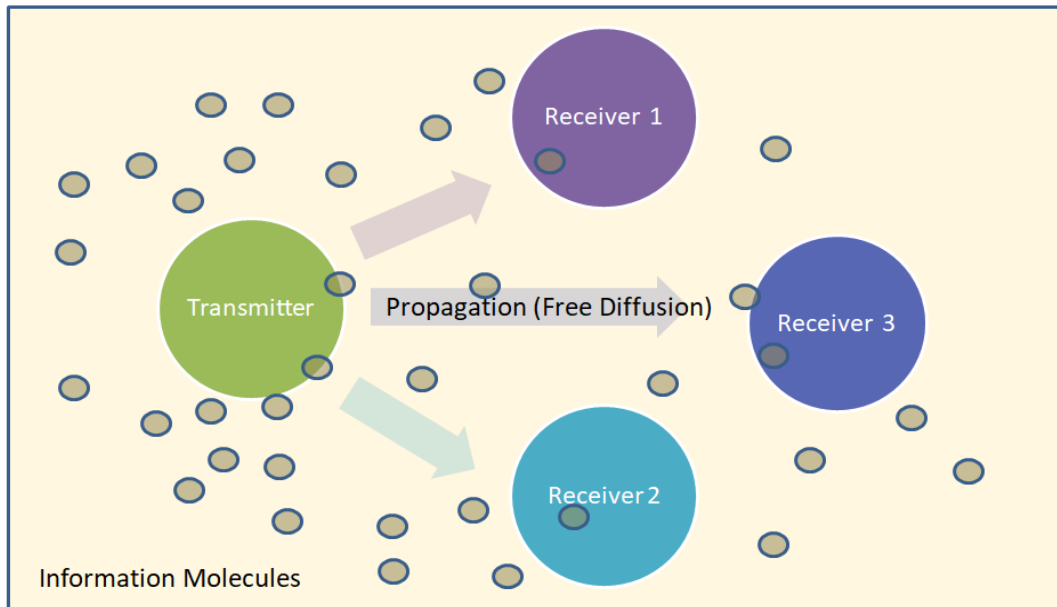


Figure 1.9 Free Diffusion molecular communication.

1.3.2 Gap Junction-based Molecular Communication

Signal data particles can also be driven all the way into a communication channels creating a direct link between transmitter and receivers by filling up the gaps between them. Gap-junction channels allow self-contained linked cells to connect, allowing synchronized activities amongst neighboring cells, such as synchronized heart beating via cardiomyocytes [7]. While routing between various gaps and reaching the destination might require additional features of switching and amplification of the data.

As revealed in Fig. 1.10, in this type of MC system, particles must fill various gaps to develop a communication link among transmitter and receiver. For that reason, the MC indicator might distort along with a particular amplification needs to be acquired at the gap junction. Similarly, routing of particles among different gaps for the eventual communication requires a tedious job of switching as well.

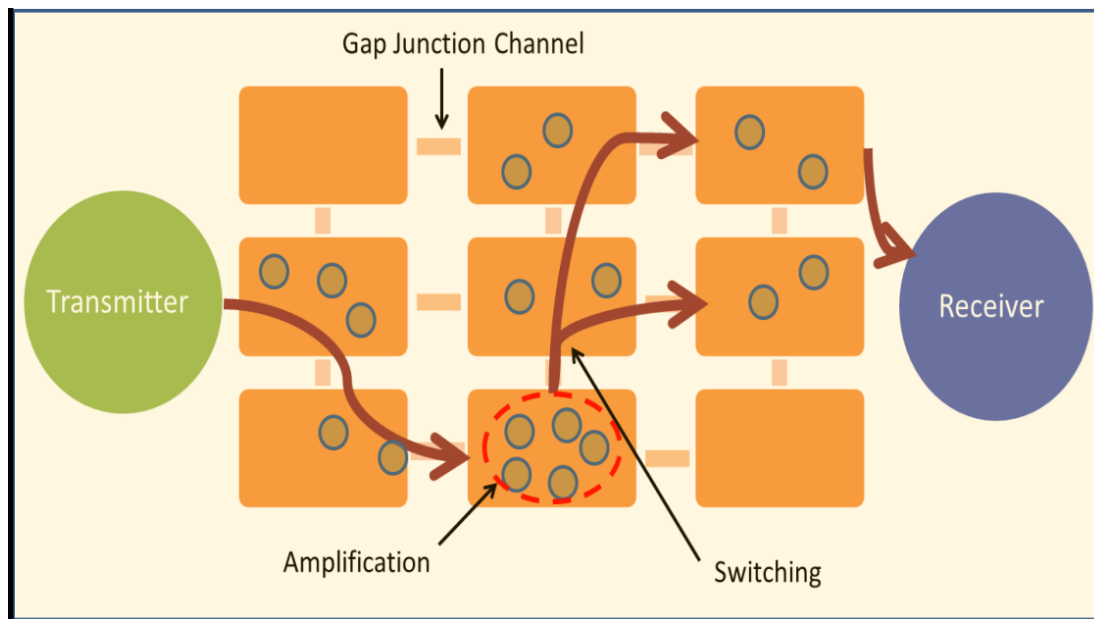


Figure 1.10 Gap junction molecular communication.

1.3.3 Diffusion-reaction-based Molecular Communication

Diffusion of signal particles comprises of chemical reactions to attain a different method of communication that lets dissemination of impulses, the signal molecules seems to be as impulse that transmits in the atmosphere are due to the rapid upsurge and drop of signal molecules concentrations. For example, inside human body, neurons likewise produces signals that proliferate throughout the extent of the neuron.

In effective transport, a directional transmission mechanism to specific locations is provided. It can disseminate molecule signal over elongated areas (up to several meters) as matched with passive communication of diffusion-based. It includes following two foremost types of active molecular communication [20].

1.3.4 Molecular Motor-based Molecular Communication

In the living cell with molecular motors for the transport of signal molecules, this type of MC system is found. A protein compound is known as molecular motor that transforms biochemical vitality into biological cellular mechanical energy [21].

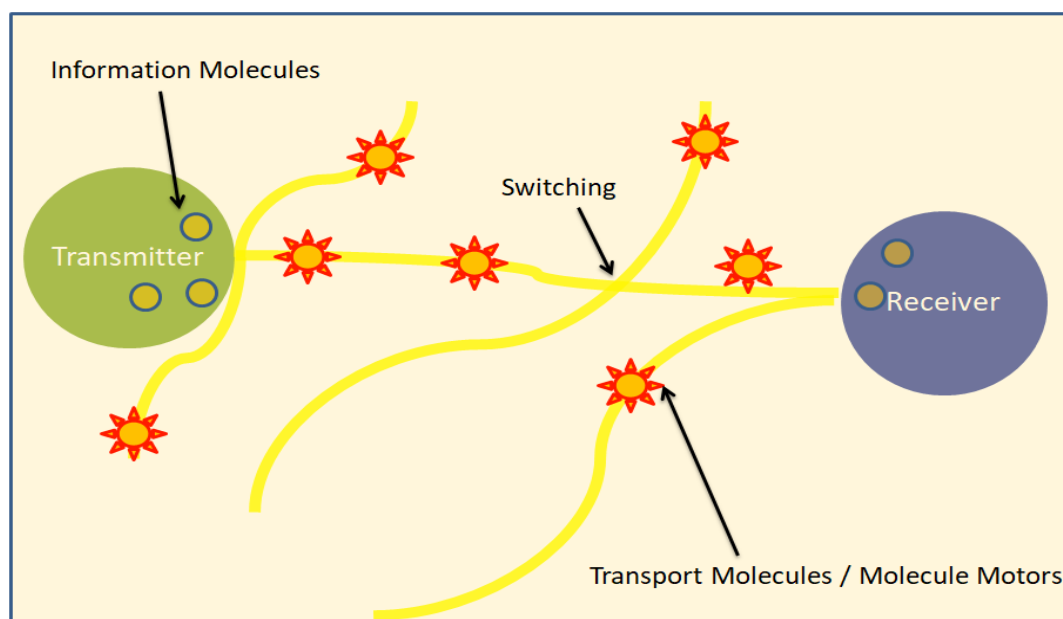


Figure 1.11 Molecular communication based on molecular motors.

As shown in the Fig. 1.11, the information is encapsulated in a transport molecule also known as molecular motors which follows a certain path and delivers the information to the receiver. The communication path is established after a proper switching technique for efficient end to end communication.

1.3.5 Bacterial Motor-based Molecular Communication

A living organism e.g. bacteria is being incorporated for the correspondence of information in this sort of MC system. Bacteria travels directionally which be influenced by the concentration of chemicals in the atmosphere. They also interchange DNA by the progression of conjugation. Handover of DNA amongst bacteria might permit the receiver bacterium to obtain DNA which harvests valuable functionality of a living cells (e.g., antibiotic challenge, protein fabrication,). Fundamentally, bacteria transports DNA to other microorganisms in the natural environment [22].

As shown in the Fig. 1.12, the living organisms are used as a receiver of information, take it from transmitting entity and then carry to guided location with the help of Bacteria tail.

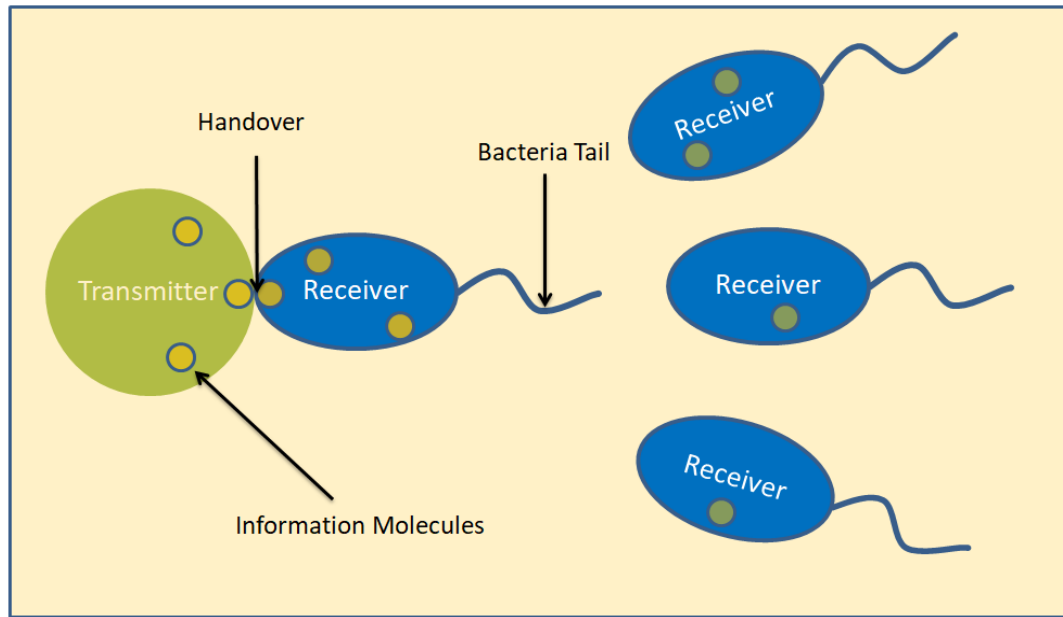


Figure 1.12 Bacterial motor based molecular communication.

1.4 Wireless Signal Interference

In communications systems, interference is that which modifies a signal in a disorderly manner, as it moves all through a medium. The term is frequently used to state to the accumulation of undesirable signals to a desirable signal.

1.4.1 Electromagnetic Wave Signal Interference

As it is known that electronic devices release a definite quantity of electromagnetic radiation their processing operation might be corrupted when receive unintended electric interference which is known as electromagnetic interference (EMI). This EMI is also known as **radio frequency** interference (RFI). Therefore, when inside a car while listening to a radio, an incoming cell phone signal creates an irritating noise in the speakers. Furthermore, not all RFI and EMI is man-made natural incidents, like lightning from clouds and solar flickers, can also cause disorder in electronic devices operation. RFI can cause substantial problems in an occurrence wherever a communicating system

receives an erroneous signal, causing reception signal interruptions followed by complete signal loss [24].

Some probable causes of RFI comprise of:

- Concentration of communicating devices in a frequency spectrum lies in the same band
- System design faults

Wi-Fi routers and Wi-Fi enabled devices may face RFI from other devices which communicates in the same frequency band, e.g. microwave oven, Bluetooth and baby monitors.

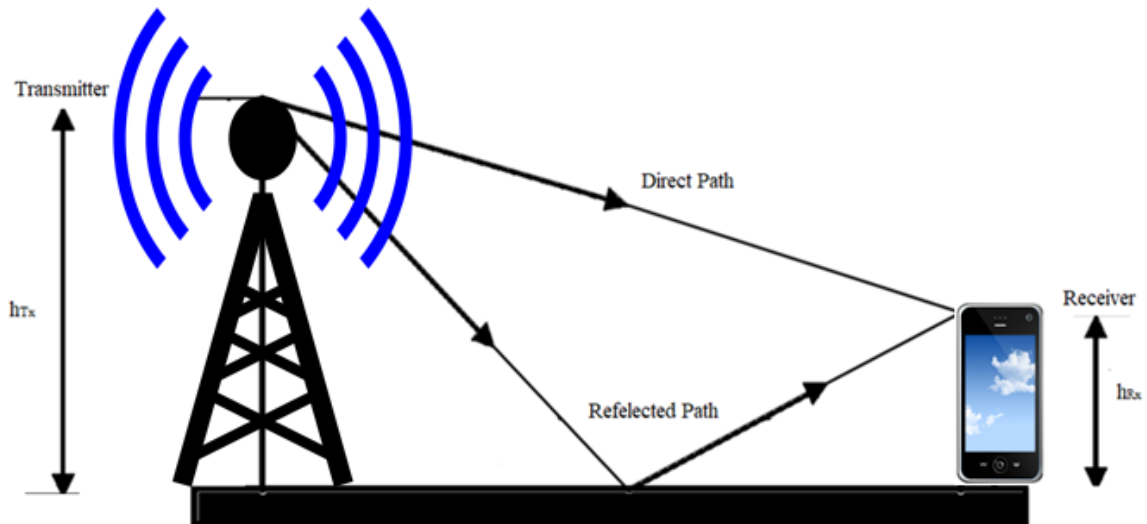


Figure 1.13 EM wave signal interference scenario.

A cellular communication interference scenario has been shown in Fig. 1.13 where a receiver receives a direct signal and a reflected path signal from the transmitter creates an interference scenario at the receiver side [25].

1.4.2 Molecular Signal Interference

The evolution of modulation methods in the communication systems permitted noteworthy developments in wireless communications by the transmission of symbols carrying an enormous volume of information data from source to the target. However, there is a common problem in such systems: the inter-symbol interference (ISI). In a

impeccable communication arrangement (ideal situation), the communicated signal reaches the receiver without any loss or interference [26]. However, in an actual situation the communicated signals are affected in diverse ways according to the propagation environment. The delayed signal reaches via many routes known as multipath with dissimilar delays known as delay spread (DS) [27].

In MC, the receiver detects the positive interaction of molecules emitted by various transmitters in earlier symbol intervals. This adds to other undesirable effects. Firstly, many theories focus on both constructive and disruptive superposition of the signal in conventional wireless communications as shown in Fig. 1.14 [28]. This means that beam forming, and transverse (orthogonal) sequences do not occur in MC. The impulse response of the MC channels demonstrates the low-pass filter with an intense-tailed pattern. Thirdly, as molecules are continuously released, the signal molecules' intensity is increasing over the time, contaminating the environment with additional residual molecules [29].

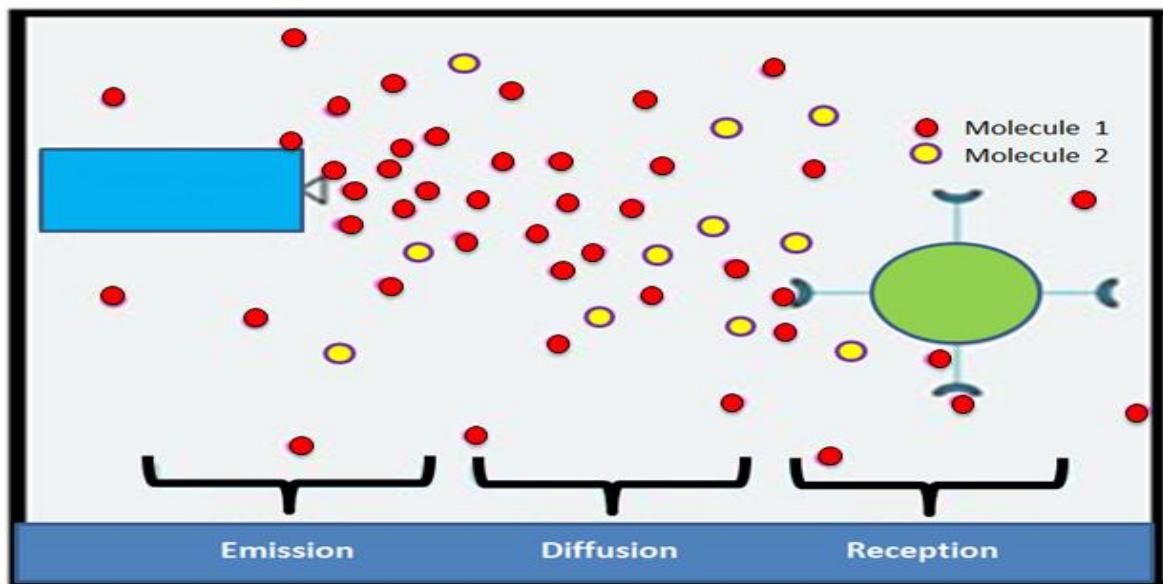


Figure 1.14 MC signal interference scenario.

1.4.3 Inter symbol Interference

As a pulse spreads out in such a way that it overlaps with adjacent symbol at the same symbol duration so that ISI occurs. As shown in the Fig. 1.15 below the symbol duration

is 1.0 second, while there are four pulses of same symbol period which gather at the receive at the same symbol duration with different information creating ISI scenario.

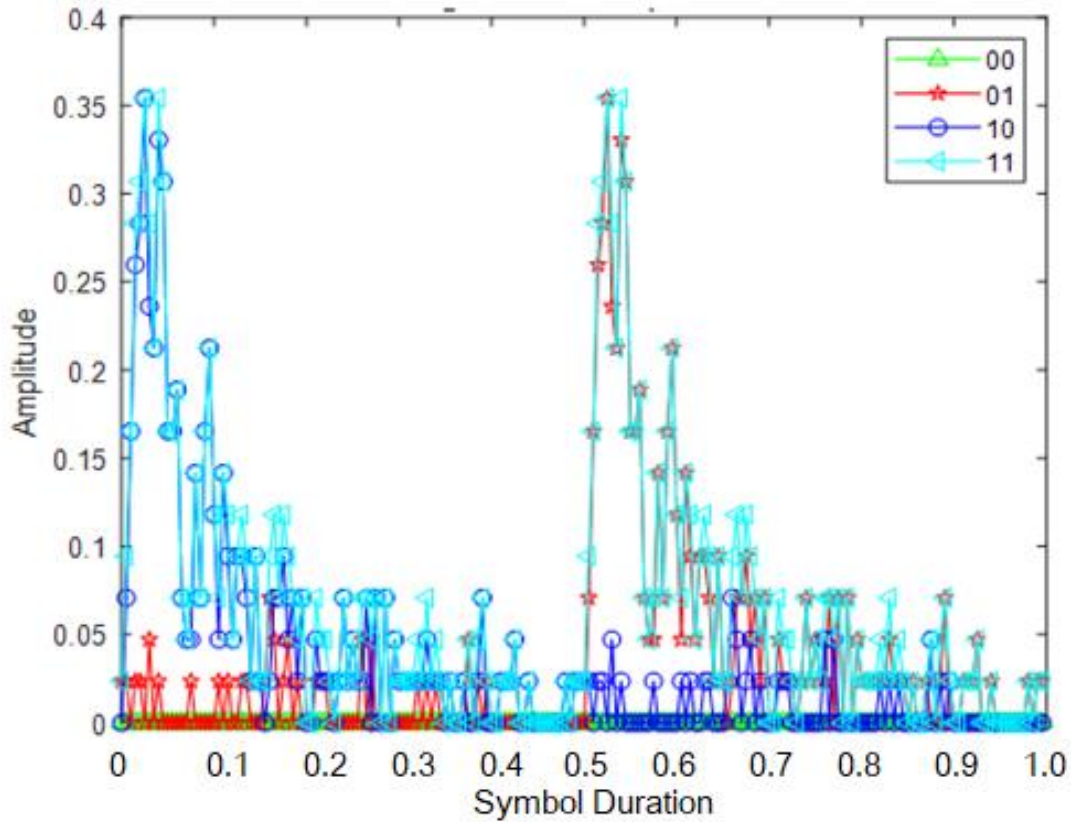


Figure 1.15 Inter-symbol interference scenario.

1.4.4 Causes of Noise in Wireless Communications

Noise is an unwelcome sign that is experienced by a received signal after experiencing other channel related distortions, at the receiver side that cause serious problems to a communication system.

1.4.4.1 EM Wave Communication

There are numerous causes of noise in radio communication that comprises of [25]:

- ✓ Avalanche noise
- ✓ Thermal noise

- ✓ Flicker noise
- ✓ Shot noise
- ✓ Phase noise

1.4.4.2 Molecular Communication

The sources of molecular noise include [26]:

- ✓ Uncertainty of Brownian motion, i.e., an undesirable distress on the acknowledged signal also known as diffusion noise.
- ✓ Particle counting noise like shot noise
- ✓ Noise due to MC receiver hardware
- ✓ Random diffusion of signal
- ✓ Environmental noise i.e. degradation or reaction

1.5 Characteristics of Channel

A communication channel is the medium used to transport information data from one place to another. The representation of all communication schemes is ultimately stanchied by the medium that has been exploited between a transmitter and receiver. This medium, that might be a wireless air link, a fiber optics, or water, is indicated as a communication channel. There are good ranges of channels that might be distributed mainly into two sets. If there exists a firm concrete connection amid sender and collector, then the channel is named a wired medium. If this firm linking is absent, then this linkage is called a wireless channel [30]

The physical characteristics of wireless signal that begins from the transmitter changes as it travels towards the receiver. The distance and direction to reach the receiver, and the atmosphere around the direction depend on these features. If there is a specific medium pattern among source and destination, the outline of collected information be able to be obtained from the transmitted signal [31].

The medium concept is defined as the model of the channel. Frequency domain (FD) multiplication is equivalent to the time domain (TD) convolution. Thus, after propagation across channel H , the signal x is transmitted and it becomes y to be the received signal:

$$y(f) = H(f)x(f) + \sigma(f) \quad (1.1)$$

where $H(f)$ is the channel impulse response CIR, and $\sigma(f)$ is the noise at the receiver side. Realizing that x , y , H , and σ are the signals in frequency domain. Path loss, shadowing and multipath are the three key components of the channel response.

The three independent phenomena can be roughly described as radiation propagation because of these mechanisms of EM wave propagation as shown in the following Fig. 1.16 in the form of channel modelling.

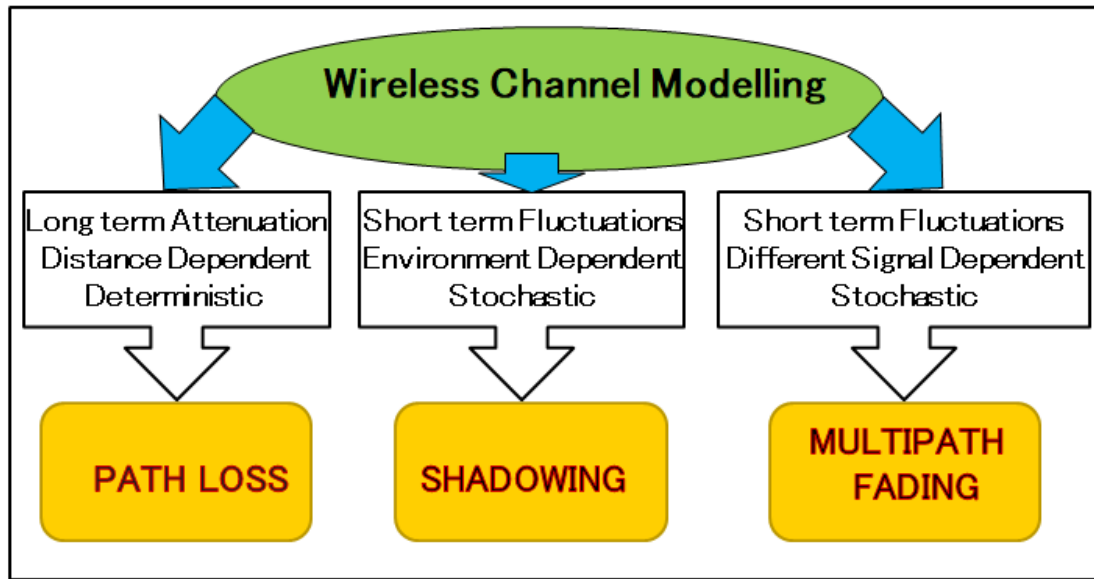


Figure 1.16 Wireless channel modelling.

1.5.1 Path Loss

The properties of data transmission wirelessly (with whether electromagnetic or molecular) will be treated and expressions will be presented for the loss in power that relies on the distance and the frequency. This phenomenon is called path loss. It is a deterministic outcome subject to the gap in the middle of Tx & Rx. It shows a vital part on larger time units i.e. seconds or minutes, as the space between source and destination

in many circumstances do not variate significantly on lower time measures [32]. For a specific time, t , distance d and diffusion D , the equation defines the contact aspects of the channel. The models of path loss are concerned more about the decreasing level of energy over time and distance. The estimation of models are vital in the communication channel's link budget. In [33] the path loss mechanism for both molecular and EM waves has been investigated in an infinite free-specific environment. Assuming that the EM signals release from a definite transmitter, then the path loss by distance d will be,

$$d = \frac{1}{\left(\frac{4\pi f d}{c}\right)^2} = \left(\frac{c}{4\pi f d}\right)^2 \quad (1.2)$$

where c is the speed of light and f is the operating frequency.

There are two measures of loss in the molecular communication where molecules dispersed from a point source into an open area:

- Peak molecular response: The max of a pulse amplitude signal is sensed at $t = d^2 / 6D$, which produces a peak hitting amplitude, P_{ha}

$$P_{ha} \propto \frac{D}{d^{-3}} \quad (1.3)$$

with a peak absorbing amplitude P_{aa} at the receiver with a radius r_r [33]:

$$P_{aa} \propto \frac{r_r D}{(r_r + d) d^2} \quad (1.4)$$

- Total molecular response: It is known as counting the total number of molecules slamming destination for a certain time to be $\frac{1}{(4\pi D d)}$ and captivated by the receiver to be $\frac{r_r}{(r_r + d)}$. Consequently, when relating Molecular Diffusion with EM wave, path loss in free space has following relations [31]:

$$\Psi_{MC-FS}(D, d, t) = \left[\frac{1}{(4\pi D t)^\rho} \exp\left(\frac{-d^2}{4Dt}\right) \right], \quad (1.5)$$

The value ρ varies along with the dimensions of area in which MC is being performed, i.e. for one-dimensional (1D) space $\rho = 1/2$, two-dimensional (2D) space $\rho = 1$ and three-dimensional (3D) space $\rho = 3/2$. Currently, MC research is being conducted until 3D.

$$\Psi_{EM-FS}(d, f) = \left[\left(\frac{4d\pi f}{c} \right)^2 \right] . \quad (1.6)$$

For Electromagnetic: the path loss is $\propto d^{-2}$ while time-of-arrival is $\propto d$.

Molecular Diffusion: the overall path loss is $\propto d^{-1}$, the maximum path loss is $\propto d^{-3}$, while time-of-arrival molecules is $\propto d^2$.

In relation to EM wave propagation of MC diffusion, it should be noted that:

- (i) The EM wave power gain is inversely quadratically proportional to the wavelength, f and distance, d . The molecular power gain is inversely proportional to d and size of the diffusion coefficient, D ;
- (ii) The time of arrival of the EM wavelengths does not depend on the frequency of the carrier, f , and increase linearly, d . As soon as molecules arrive, D depends on the diffusion coefficient and decreases with quadratically distance d .

1.5.2 Shadowing

Shadowing replicates alterations in the signal power at the receiver side that is calculated relative to the theoretic value measured by path loss formulations. The received signal power is averaged for the similar distance, that determines the precise value specified by path loss. Shadowing can be revealed from beforehand. The path loss causes fluctuations in the power of signal transmitted with the same wavelength as the source, on the same time scale. The cumulative mean of these points does, however, show the transmitted signal strength of the path loss [34].

It should be noted that shadowing is generalization that replicates the consequence of some diffusion phenomena which happens once a MC or EM signal wave spreads in an environment: echoes (from surroundings and ground), diffraction (caused by sharp edges), refraction (e.g. through medium or materials), scattering (e.g. ground or obstructions), and absorption (e.g. by the environment). The exact calculation of the properties of each of these occurrences intended for respective points is not possible (occasionally difficult) equally due to complication and time limitations. Hence, shadowing is used to labeled as the combined effects of altogether these occurrences in the communication systems.

1.5.3 Multipath Fading

Fading is even stochastic in character; in short time frames such as milliseconds or even microseconds it contributes to major deterioration of signal. Fading is often induced by an atmosphere that spreads multipaths, which reflects the received EM waves that interact with the receiving antenna with several versions of the transmitted signal. Fading is the intrusion of multiple dispersed signals reaching the received antenna. It is accountable for the quickest and most aggressive changes in terms of its received power. Such rapid fluctuation is often experienced in limited time scale, i.e. a fraction of a second or less depending on the mobility of the destination entity, i.e. a receiver. As depicted in Fig. 1.17 a signal may experience multipath fading due to reflection, diffraction across edges, or even scattering from uneven surfaces [35].

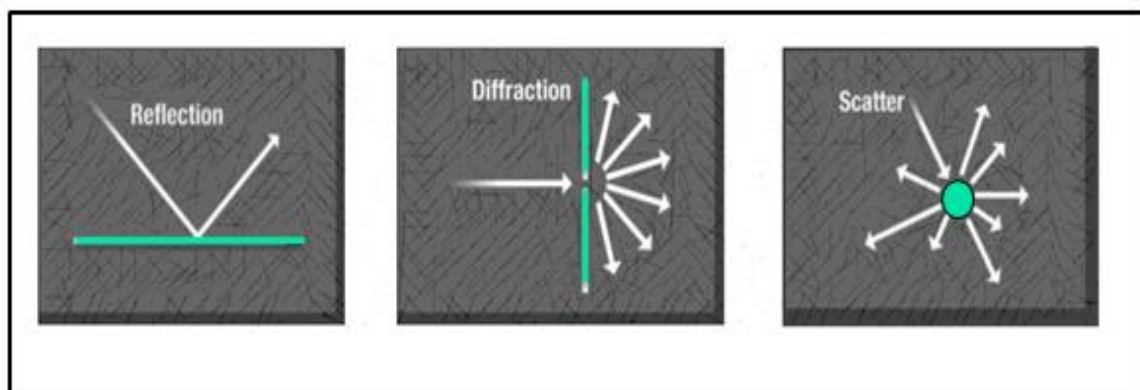


Figure 1.17 Different Multipath Wave Propagation phenomena.

The following transmission advantages were noticed in MC as a comparison to the EM-wave signals:

1. **No diffraction loss:** In the presence of objects it is not subject to diffraction loss.
2. **Not sensitive to obstacle-size:** not limited to cut-off in confined surroundings
3. **Predomination of shortest route:** only a small gap between transmitters and receivers defines a molecular path loss [9].

These transmission benefits for molecular communications can be subjugated in definite communication situations. There are numerous limitations to molecular communications i.e. along with the evident sluggish nature of diffusion and its dependency on changes in the surrounding environment i.e. temperature and drift of molecules. Molecular communication is likewise having threat either from the proliferations of other chemical reactions or consuming of bio-molecules by bacteria. In a free space, the energy of MC diminishes in lesser amount as compared to EM wave signals. [10].

1.5.4 Propagation Models

Earlier study on developments of transmission schemes in the existing frequency range, that also considered a propagation environment, focused primarily on the analysis of propagation features in relation to major factors like path losses, propagation delay and angular dissipation.

However, in view of the mobility of the surrounding environment, current spread models show great predictive errors when predicting spreading, and the signal strength of heterogeneous and physical networks can hardly be compared with these propagation schemes. In general, beforehand information should be obtained on the signal and noise power, in order to design a receiver that can provide wireless signal communication with a certain level of quality. During propagation estimation, it is necessary to consider the propagating environment and agility.

1.5.4.1 Electromagnetic Wave Signal Propagation Models

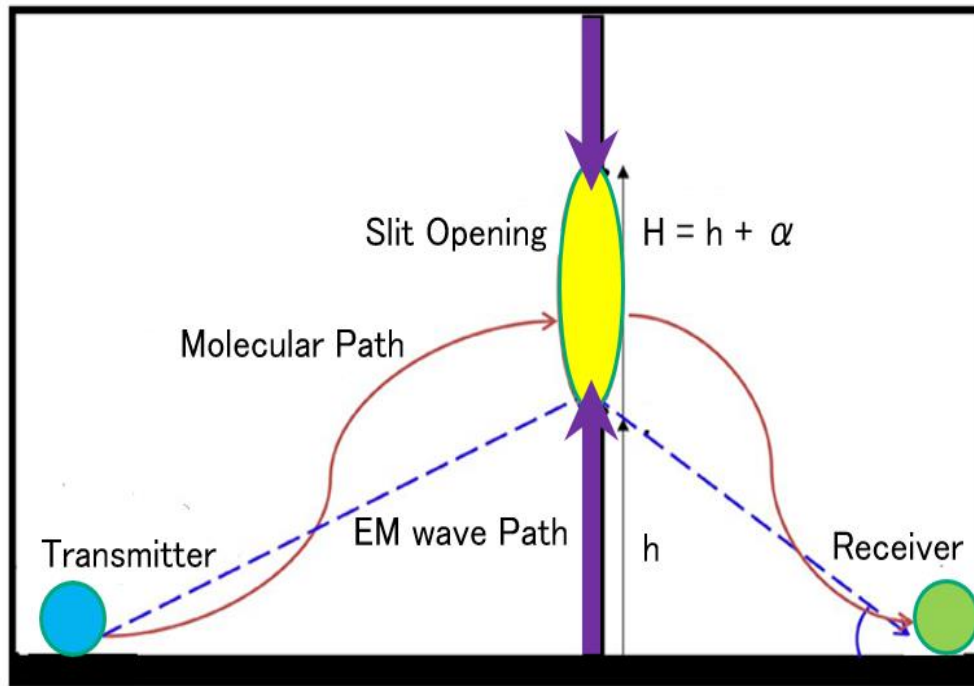


Figure 1.18 Comparison of EM wave & MC signal paths.

In the literature there is no reference which treats the degradation of molecule propagation due to diffraction or sharp edge. The knife sharp edge obstacle medium channel is employed as a modest estimated prototype for manipulating RF signal transmission across mountain peaks as well as construction structures corners and edges. The knife-edge types of entities have been frequently found in rural as well as in urban locations. As illustrated in Fig. 1.18, an only point- transmitter (Tx) and a point-receiver (Rx) have been considered that are blocked by a spliced, captivating partition with a height H , and gap of α that is greater than the wavelength of EM signal.

For molecular diffusion through the opening that has sharp edges, random walk has been considered amid two static points [31]:

- one is on the leftwards of the hindrance having d_1 distance to the hurdle from transmitter,
- is on the rightwards of the blockage having d_2 distance from the hindrance to the receiver.

The transitional power density function (PDF) $p_{T1}(d_1, h, D, t)$ for the left-hand side arbitrary move from the point $(-d_1, 0)$ to the point $(0, h)$, and similarly the transitional PDF $p_{T2}(d_2, h, D, t)$ towards the other side i.e. right side random walk which starts from point $(0, h)$ to the receiver $(d_2, 0)$. The provisional PDF's are half-planar hitting pdfs with $(d = d_1)$ for the transmitter side T1 and $(d = d_2)$ for receiver side:

$$\rho_T(d, h, D, t) = \frac{1}{2\pi Dt} \exp\left(-\frac{d^2+h^2}{4Dt}\right) \quad (1.5)$$

Taking the convolution of ρ_{T1} & ρ_{T2} for the effective range of $(h \geq H)$ the overall hitting PDF for the sharp edge can be given as:

$$\rho_{Sharp,MC}(d_1, d_2, H, t) = \left(\frac{\exp\left(-\frac{d^2+h^2}{4Dt}\right)}{4\pi Dt}\right) * \left(\text{erfc}\left(\frac{H}{\sqrt{8Dt}}\right)\right)^2 \quad (1.6)$$

The hitting PDF in the above equation has two main elements, first is the 2-dimensional planar hitting pdf and second is the complementary error gain function (CEGF). The two-dimensional hitting PDF ranges as a function of the smallest gap within the hindrance i.e. d_1 being the distance from transmitter to the obstacle while d_2 being distance from the obstacle to the receiver and height of obstacle H [33]. Henceforth,

$$\Psi_{MC-Sharp}(H, d_1, d_2) = \lim_{T \rightarrow \infty} \int_0^T (\rho_{Sharp,MC}(d_1, d_2, H, t) dt) \quad (1.7)$$

Regarding the EM wave, the diffraction through a slit is given by [24]:

$$\Psi_{EM-Sharp}(H, d, f) = \Psi_{EM-FS} |\mathfrak{D}|^2 \quad (1.8)$$

Where \mathfrak{D} is the sharp edge diffraction loss.

As shown in the Fig. 1.19 below, in an indoor environment there are various blockages that a signal receives during its travel from a transmitter to the receiver. It is clearly depicted that there are 7 Wi-Fi AP's. With respect to the received power of Wi-Fi signals at the recipient experiencing a variety of Wi-Fi signal power from the transmitter according to the distance that a transmitted signal travels with -10 dBm being the highest

power while -90dBm being the lowest power. It is said that the signal strength between -30 to -40 dBm is very good for Wi-Fi receivers [36].

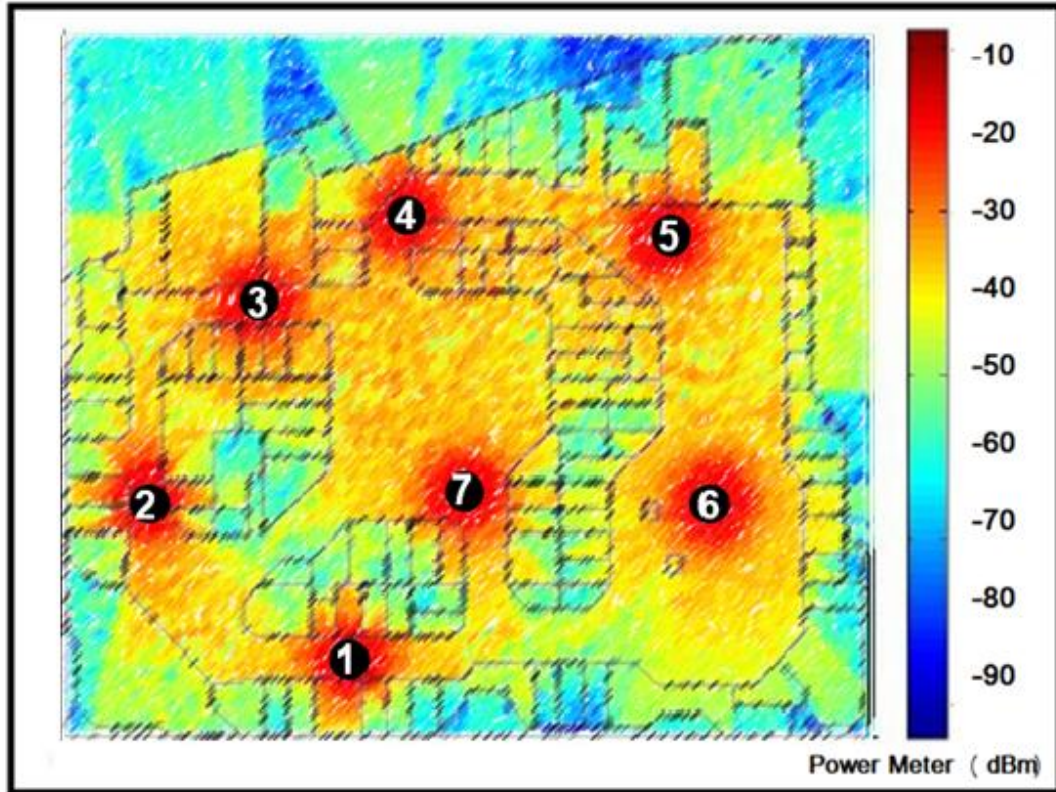


Figure 1.19 Indoor received power map for Wi-Fi signals.

1.5.4.2 Molecular Communication Channel Model

As stated above, the EM signal may follow a straight path to reach a receiver whether it is at line of sight (LOS) or at non line of sight (NLOS) [37]. As far as MC molecule is concerned it diffuses into the environment arbitrarily and follows a Brownian motion as shown in the Fig. 1.20 below .

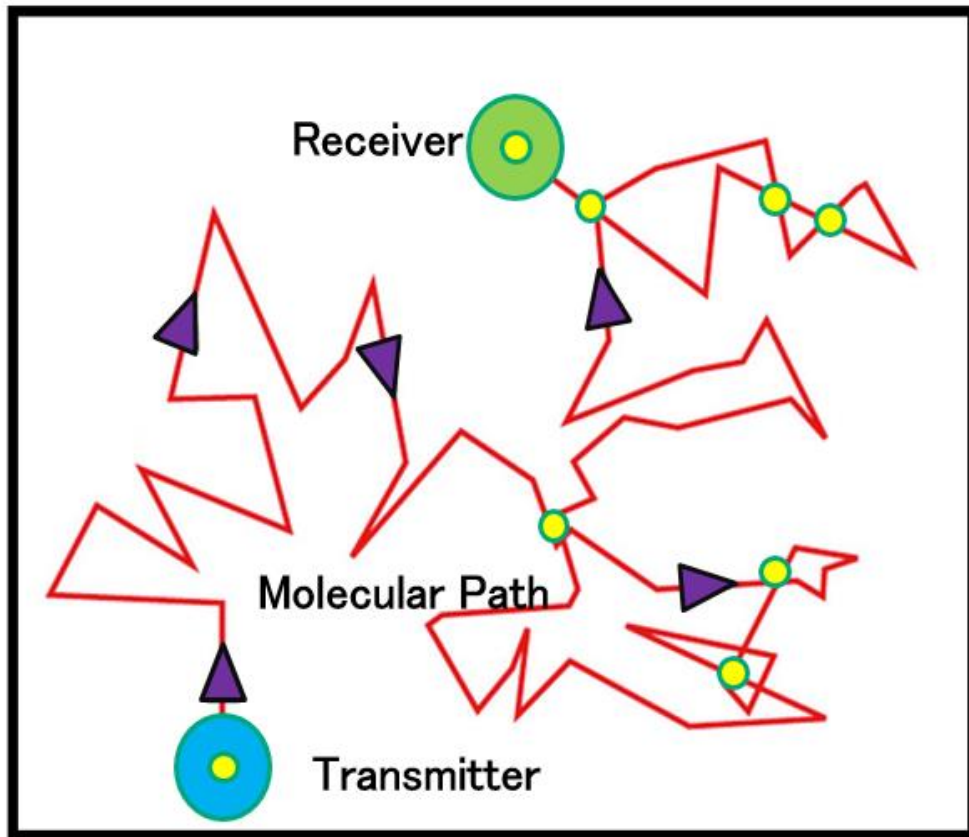


Figure 1.20 Brownian motion for a SISO arrangement.

The multiple-input-multiple-output (MIMO) scenario in which multiple transmitters and receivers interact with each other can be arranged as follows. A typical MIMO scenario in MC follows a gap junction arrangement where a dedicated path is being followed by transmitted signal to reach to target. It forms a grid scenario as signals from multiple transmitters travel to multiple receivers at the same instant as shown in Fig. 1.21. There are multiple nodes (junctions) on the way of a signal that have to fill the gaps to reach their respective destinations. These nodes have equivalent distance d , from each other in a grid type architecture for end-to-end molecular communication [38].

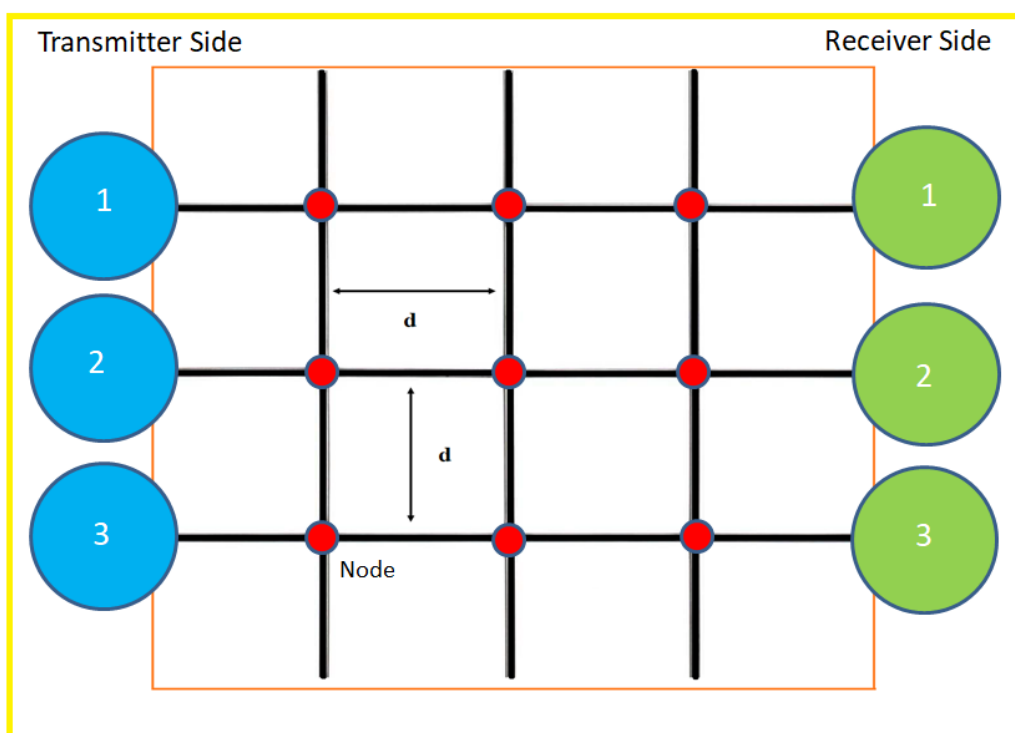


Figure 1.21 Gap junction based MIMO arrangement.

In the human body as a MC channel drug is been targeted in to body and it is making that place as a transmitter while reaching to a target place at the body as shown in Fig. 1.22. For an efficient end to end MC system, a drug delivery rate is equivalent to the rate of drug being given as a drug molecule.

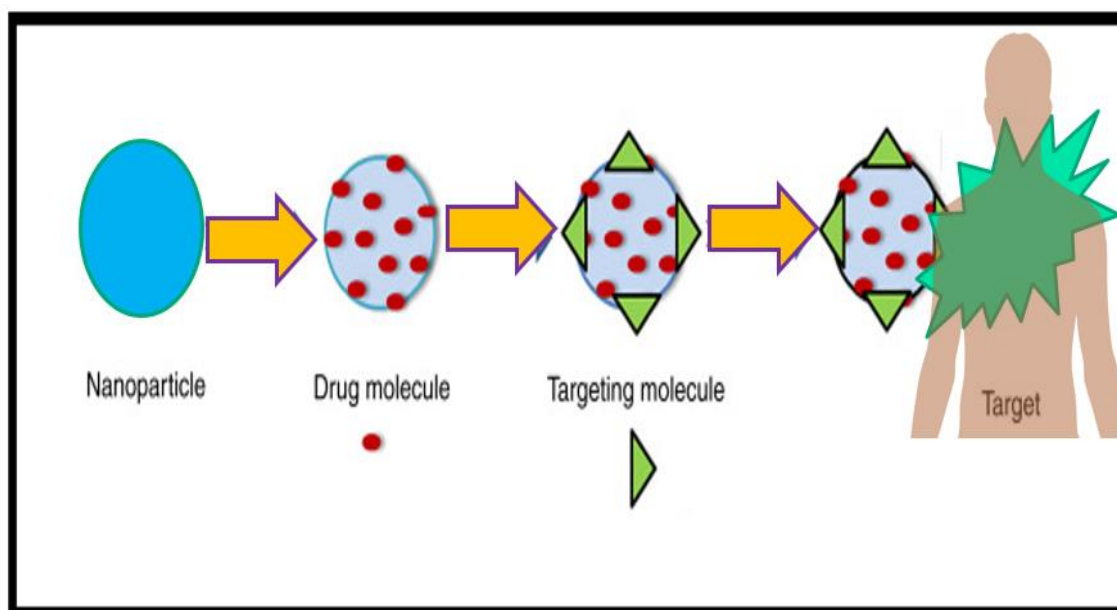


Figure 1.22 Human based targeted delivery scenario.

1.5.5 Propagation through Channel Materials

1.5.5.1 Electromagnetic Wave Channel Materials

There are different factors such as radio operating frequency, distance, geographic characteristics and transmitting power affect the propagation of an EM wave. Subsequently, signal strength and spectral efficiency cannot be accurately estimated. Multiple factors such as path loss, signal interference, and multi-path propagation have influence on signal strength and radio propagation [39]. The 2.4 GHz industrial scientific medical (ISM) frequency band poses a severe problem of artificial noise. There are multiple commercial products, medical instruments and domestic appliances that are in operation at the 2.4 GHz ISM band, such as the microwave oven or Bluetooth. If too many ISM devices operate in a small area, there might be interference created among those and thus their performance degrades. In fact, interference not only triggers an increased amount of error, but also an increased rate of re-transmission [40].

Signal strength decreases as it passes through different types of material like

- ✓ Brick
- ✓ Concrete
- ✓ Glass
- ✓ Steel
- ✓ Wood
- ✓ Cloth
- ✓ Tiles
- etc.

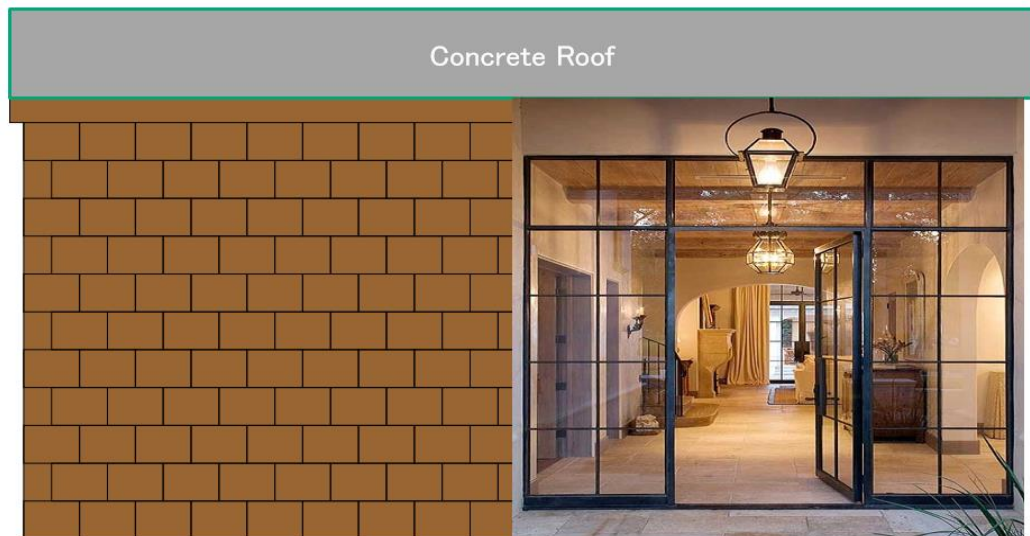


Figure 1.23 EM wave channel materials.

Fig. 1.23 represents a typical indoor environment of a house that comprises of all the materials that include concrete roof, brick and wooden walls, glass and metal framed doors, glass chandeliers, tiles, furniture, and curtains. EM wave can travel across various mediums, whether gases, liquids or solids, the interference level of EM waves tends to change for different materials. As shown in the table below, the interference level is low for air, wood and plastic while medium interference is provided by glass, water and bricks. On the hand, marble and concrete have high interference level and metals (steel, aluminum) and mirror offers very high interference for EM wave signal [41].

As mentioned in Table 1-1, the intensity of EM wave decreases as it travels across different materials that interfere with the radio signal. As mentioned, air, wood and plastic offer less obstruction. Glass, water, and bricks offer medium interference. Marble and concrete offer high level of hindrance while very high reduction of radio signals is observed across metal and mirror.

Table 1-1 Interference level of EM wave signal across various materials

Type of Material	Interference Level			
	Low	Medium	High	Very High
Air				
Wood				
Plastic				
Glass				
Water				
Bricks				
Marble				
Concrete				
Metal				
Mirror				

1.5.5.2 Molecular Communication Channel Materials

MC is a Molecule-based communication which is a common and pervasive scheme by which biological Nano-machines interconnect. There are many manners and techniques of molecular communication found inside and among cells. There are different methods and processes of MC are considered focused on propagation i.e. whether molecules merely diffuse into the atmosphere known as passive transport-based molecular communication or they directionally emit and propagate via environment by consuming chemical energy known as lively transport-based molecular communication [42].

In passive communication, signal particles arbitrarily diffuse in all clear directions, creating a predominantly suitable environment that is extremely vibrant and random. It is similarly appropriate to circumstances in which arrangement intended for communications is not reasonable. It includes following main types of passive molecular communication [43].

- Air
- Aqueous medium

- Conduit pipes
- Blood vessels inside human body

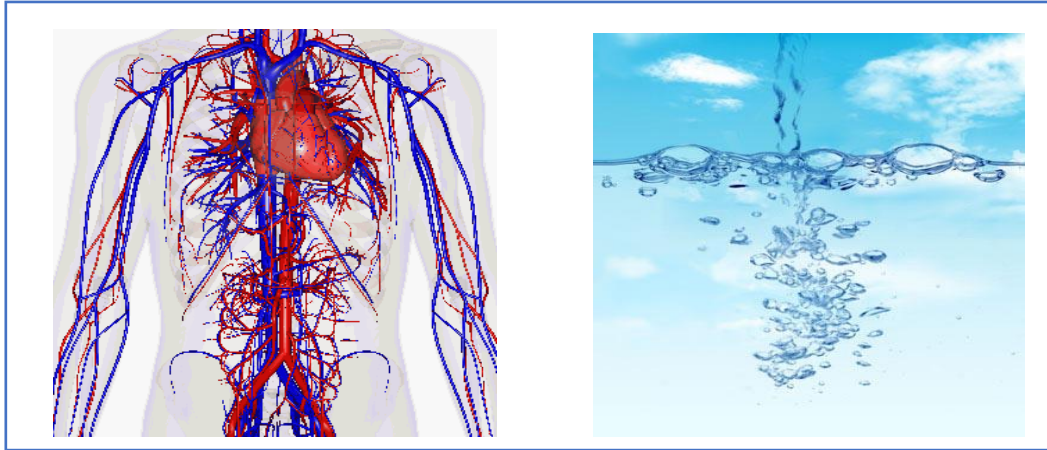


Figure 1.24 MC channel materials.

As shown in Fig. 1.24 MC channel can be comprised of materials that include water, air and blood vessels inside human body. These are some sources of channel materials used in MC these days.

Table 1-2 describes the major distinction concerning radio communication and MC according to different characteristics that mainly include medium, nature speed, distance covered and power consumption. It clearly described that, the major difference between RF communication and MC lies in their nature i.e. EM waves of RF nature while MC of molecular signal domain. Similarly, the propagation speed and power consumption is also very significant.

Table 1-2 Characteristically difference between radio and molecular communication

<u>Characteristics</u>	<u>Radio Communication</u>	<u>Molecular Communication</u>
Nature	Optical / Electronic signals	Biochemical signals
Speed	Speed of light (3×10^8 m/sec)	Sluggish speed (a few $\mu\text{m/sec}$)
Distance	Prolonged (m to km_s)	Brief (μm to m)
Environments	Aerial and wire medium	Air & Aquous medium
Encrypted Data	Speech, text, and video	Natural Phenomenon and biochemical reactions
Receiver's Procedure	Decoding of digital information	Bio-chemical reaction
Power Consumption	Very High	Low

1.6 Equalization

The transmitter communicates data across a channel in a transmission network. Before reaching the receiver, the channel distorts the transmitted signal. The "mission" of the receiver is to decide which signal was being sent by the transmitter. Equalization is the reciprocal of a signal distortion that is caused via channel. An equalization technique perhaps be principally embedded in the receiver block. There are diverse equalization methods that may cause to receivers of different structures which the every time best for detection, but rather are extensively employed as insignificant economical resolutions that ease the ISI issue in a communication system. The wireless channel equalization forms a foremost incitement in present and forthcoming communication systems

1.6.1 ISI-Free Transmission

Extending the symbol duration may declines the left-over signals in the channel. It may result in reduction in the data rate. At nano-scale, energy competency is reduced so a tradeoff between communication quality, data rate and efficiency of energy is needed. ISI free reception of signals has zero ISI at the sampling timings as shown in the Fig. 1.25. The reception of symbol 1 should not overlap with reception of other preceding symbols. As stated previously there are various schemes of communication in MC and amongst those MCvD is a predominantly operative and energy proficient technique intended for conveying information [27]. Owing to the nature of diffusion in MCvD, few information

particles might flop to accomplish to the destination in their expected time-period that may coincide with the subsequent messenger particles of diffusions, i.e. initiating ISI in the MC.

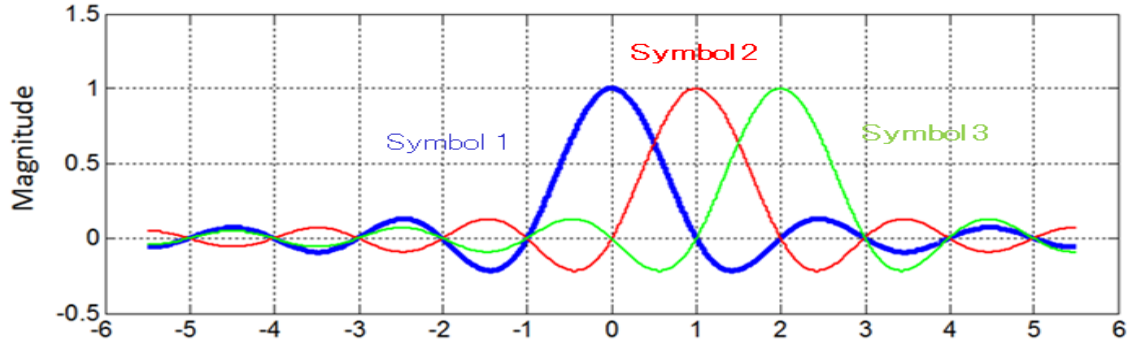


Figure 1.25 ISI free scenario for each symbol.

An incredibly prevalent way to decrease the amount of ISI at the recipient is to sustain the symbol life for a longer period of time and thereby encourage information molecules to meet their targets, thereby lessening the quantity of particles left behind in the communication channel. Conversely, expanding the symbol period drops the data rate as well, which is at present sluggish owing to the depiction of the diffusion of molecules. In fact, the energy consumption attributable to the incredibly low size of the nano-scaled instruments is another significant constraint in contact on nano-scales [11]. Consequently, data speed, communication quality and energy efficiency are perceived as a compromise. [45]

1.6.2 Time Domain Equalization

Time domain equalization (TDE) is traditionally utilized to confront the effect of multipaths. However, TDE can produce suitable and reasonable outcome, but with high complexity for channels with broad pulse response [46]. The process of channel inversion typically a TD equalizer is being applied at the receiver side before the demodulation procedure is being staged as shown in Fig. 1.26. It eliminates the possible effect of ISI and provides a pure signal to be detected. One of the drawbacks of this type of is the computational complication due to the execution of convolution operations with the received signal.

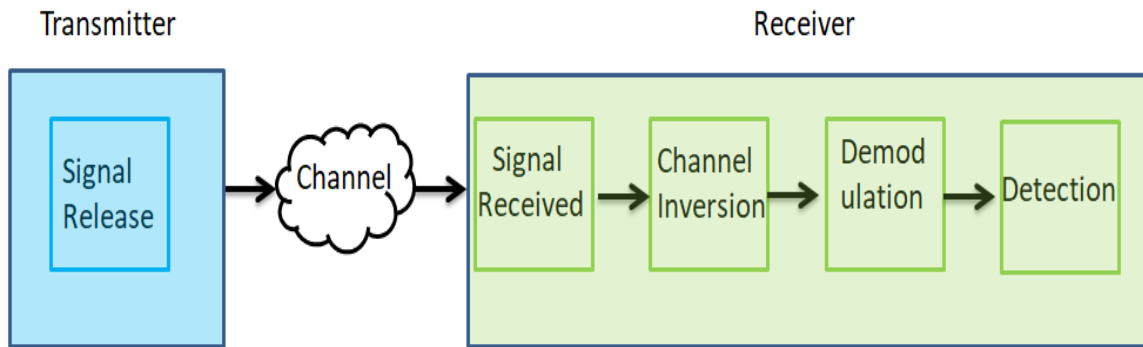


Figure 1.26 Block diagram of time domain equalization.

1.6.3 Frequency Domain Equalization

Frequency domain equalization (FDE) is considered as a proficient method to accomplish equalization of the signal. FDE is focused on the equal treatment of the convolution between two sequences and their transform in a frequency domain by a fast Fourier transform (FFT) [46]. Though, Fourier transform cannot be applied on the entire received signal, FDE must be executed on some sections of the receiver, using a discrete Fourier transform (DFT). As shown in Fig. 1.27 that FFT is applied to the received signal and then IFFT after the signal has been equalized and ready for rest of processing in time domain

A FDE problem with circular convolution tends to occur. In the case of EM waves signal, orthogonal frequency division multiplexing (OFDM), a conventional solution is to utilize a guard interval [47]. For the reason that fast Fourier transform (FFT) and uncomplicated channel reversal process, FDE is easier than the consequent TDE on channels including large delays on MC channels. The use of an overlap approach to reduce circular convolution problems is an alternative process. While this method raises the complication of the recipient not much, yet it benefits the improved signal efficiency [46].

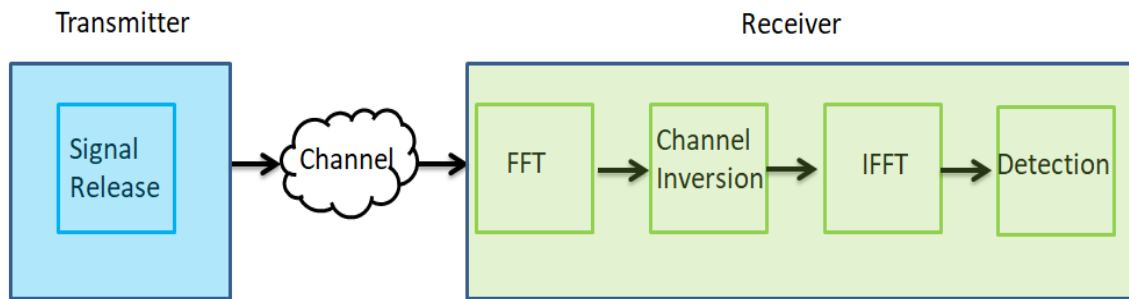


Figure 1.27 Block diagram of frequency domain equalization.

1.7 Types of Equalizers

There are two major categories of equalizers in general according to the type of operations. It includes linear as well as non-linear equalizers.

1.7.1 Linear Equalizers

These are typically feed-forward in structure, as the output is a linear combination of scaled and delayed versions of inputs. The linear equalization methods are commonly the simplest to implement and to comprehend theoretically. Conversely, on frequency-selective fading channels linear equalization methods usually suffer from enhancing the noise. The simple kind of a channel equalizer utilized to diminish the ISI is a linear equalizer [49]. The existing as well as the previous value of the obtained signal in this equalizer are linearly weighted and averaged by means of the adaptable filter coefficient for the required effects. A linear equalizer reduces errors without noise enhancement within the received symbol and transmitted symbol. While the linear equalizer results better, its efficiency for wireless channels with concentrated ISI is insufficient. A non-linear equalizer is an obvious choice for severe ISI channels [49].

1.7.1.1 Zero Forcing Equalizers

The ISI that is established by the transmission channel is eliminated by zero forcing (ZF) equalizer. It is intended for the noise restricted situation and does not take the noise into account. To diminish the effect of ISI in the signal it simply equalizes the signal by taking

the reciprocal of the CIR [50]. As shown in Fig. 1.28 the signal that received is equalized by channel inversion and then send to signal decision for further signal processing.

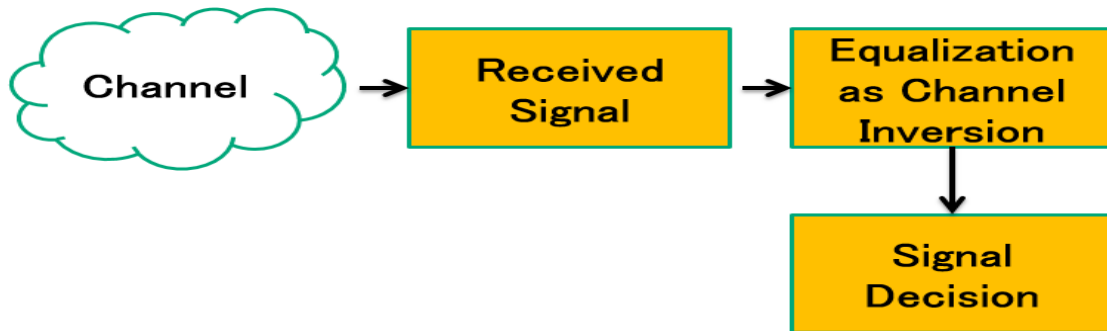


Figure 1.28 Block diagram of zero forcing equalizer.

1.7.1.2 Minimum Mean Square Error Equalizer

The key purpose of the minimum mean square error (MMSE) equalizer layout is to reduce a mean square error (MSE), that exists among the transmitted signal's symbol and the approximation at the output of equalizer. The equalizer's output is like a straight combination of an inputted received signal input to linear equalizers. There are three reasons for noticing this response: First, the better MMSE equalizer in infinite duration cancels the vanishing noise filter. Second, except for the noise, this unlimited infinite duration of equalizer is similar to the ZF filter and the two equalizers are also comparable in the non-appearance of noise. As shown in Fig. 1.29 the arriving signal is equalized that enhances the noise so to avoid this, signal after equalization is compared with the signal for which decision has been made to count the errors. Eventually, this ideal equalizer shows a clear sense of balance with the increase of noise and the reverse channel [51].

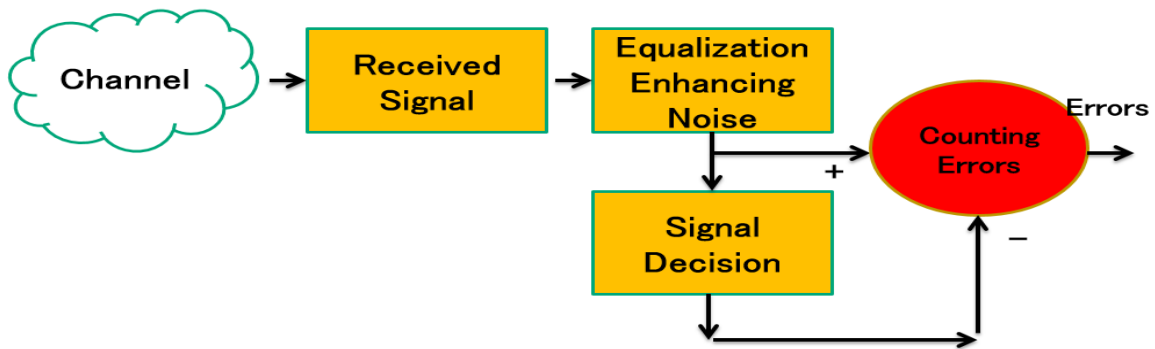


Figure 1.29 Block diagram of MMSE equalizer.

1.7.2 Non- Linear Equalizers

For situations where the signal interference is too high to reduce the effect of channel deficits, non-linear equalizers are implemented to mitigate linear equalizer. The intention for selecting non-linear equalizers is that the later execution in the medium that displays nullified channel response is not effective. So, enhancement of noise at these areas and stretched impulse response are still a challenge for the communication system. The fundamental cause for this problematic matter is due to processing of linear filtering and noise together, which causes problem of noise enhancement [52].

1.7.2.1 Maximum Likelihood Sequence Estimation

The submission of noise development after equalization is evaded by the maximum-likelihood sequence estimation (MLSE) as here an equalizing filter has not been applied. MLSE provides best performance as it examines all the potential data sequences and select that information data as output which has the supreme likelihood, i.e. probability. An MLSE equalizer was initially suggested in [52] where a simple estimator assembly executed with Viterbi algorithm was implemented. As shown in Fig. 1.30 the signal is received after passing through a channel and then delivered through a matched filter (MF) and then to the likelihood estimator. Before the signal is being sent to detector, the likelihood estimated signal is sent to the channel estimation then taken to the MF and MLSE simultaneously. Though, the computational complication of this estimation upsurges with huge delay spread and signal constellation pattern scope.

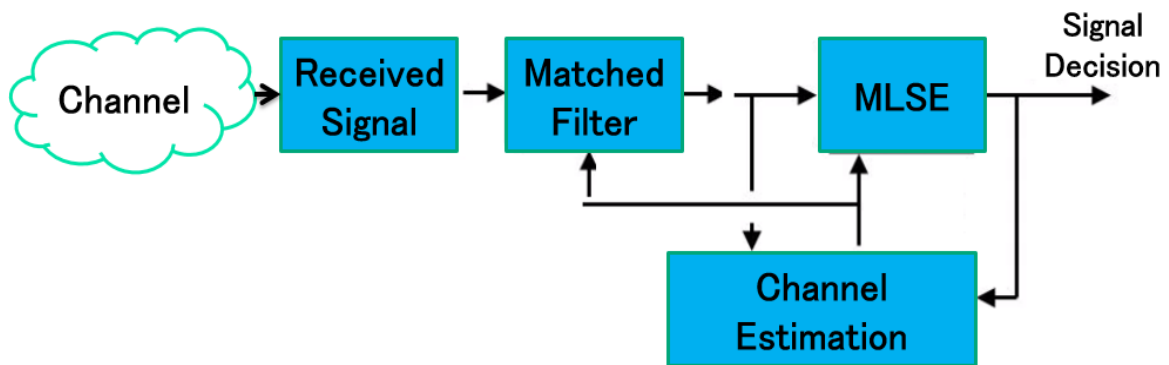


Figure 1.30 Block diagram of MLSE equalizer.

1.7.2.2 Decision-Feedback Equalization

A feed forward filter (FFF) with an input signal sequence (that is parallel to the linear equalizer) and a feedback-filter (FBF) together with the input signal identified earlier are utilized in the decision-feedback equalizer (DFE). An equalizer is a simple non-linear equalization system that is primarily advantageous for channels with severe distortion of amplitude. The FFF simply involves inputs of linear equalizer provided to decision device while the FBF depends on the outputs of a decision-making device [53].

Through the FBF the DFE evaluates the ISI contribution from the symbols that are already detected. The corresponding ISI would then be separated from the input symbols. The Fig. 1.31 illustrates a block diagram of a DFE equalizer. As signal is received it is passed all the way through a Linear FFF equalizer and then to detector after the decision has been made the signal is sent back to a comparator after passed through an FBF. The filter must be strictly causative, or the system is unpredictable, as it is in a feedback loop. The FBF does not suffer as it approximates the channel frequency response instead of opposing. DFEs are typically even better than the linear equalizers for channels that suffer from severe channel nulls that can be introduced.

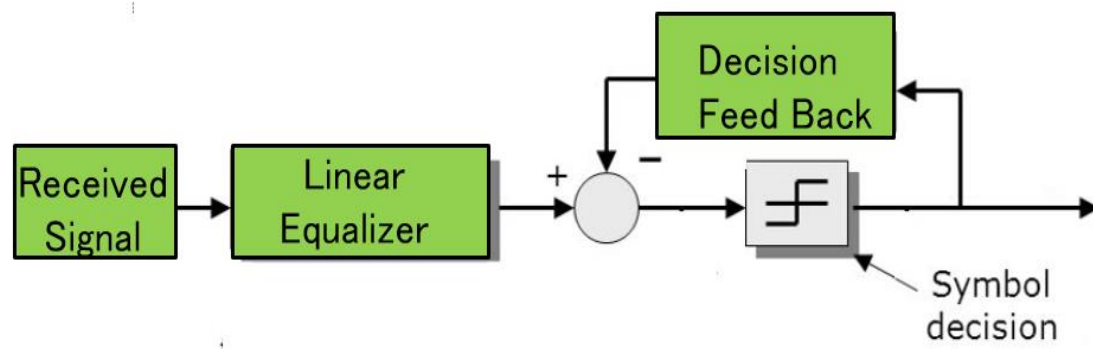


Figure 1.31 Block diagram of DFE equalizer.

1.8 Motivation and Relations of Research

1.8.1 Overall Motivation of Research

The research objective is to deliver a potential wireless propagation schemes in MC [6] and [7] and EM wave communication system [1], [2] and [4] with less channel impairments scheme by restricting from a presently unfeasible technology. As shown in Fig. 1.32, the progression of overall thesis has been discussed to lay out the foundation of research. The equalization schemes for distortion caused in propagation medium are discussed by analyzing channel characteristics of MC [42] and EM waves communications. Artificial biology methods, and traditional wireless communication using EM waves in specifically the engineering of natural circuits, permit currently to program logical errands inside living cells [61], therefore letting the system for the understanding of the above-mentioned biotic Nano equipment. The arrangement of MC system fabricated upon natural circuits is thus defined in this Ph.D. research work through classifying features to realize diffusion-based MC between biological cells [62]. A feasible MC scheme is then described in terms of system functions, from which methodical relations are derived for the diminution and the delay experienced by the data signal in the organic circuit [26] and [44]. The additional study objective is to examine the interfering signals produced and noise generated at the receiver of MC system [49]. Assumed an information signal directed by a source to a sink in a diffusion-based MC system, the interference might be also due to variations of the signal by itself or by extra simultaneous signals approaching beginning from other sources [61] and [62]. The investigation of these sorts of interfering signals in the form of interference is essential to plan interference alleviation methods and upsurge the performance of a communication systems [42] & [65].

In this Ph.D. thesis, ISI and the noise enhancement issues are mutually analyzed and investigated for a diffusion-based MC system while having assumptions of a Gaussian pulse-centered information coding and a limited number of transmitter and receivers in determined places [46] and [72]. Also, the wireless signal impairments due to different materials in an indoor environment are discussed and shortfalls in ITU indoor propagation models are identified [14] and [39].

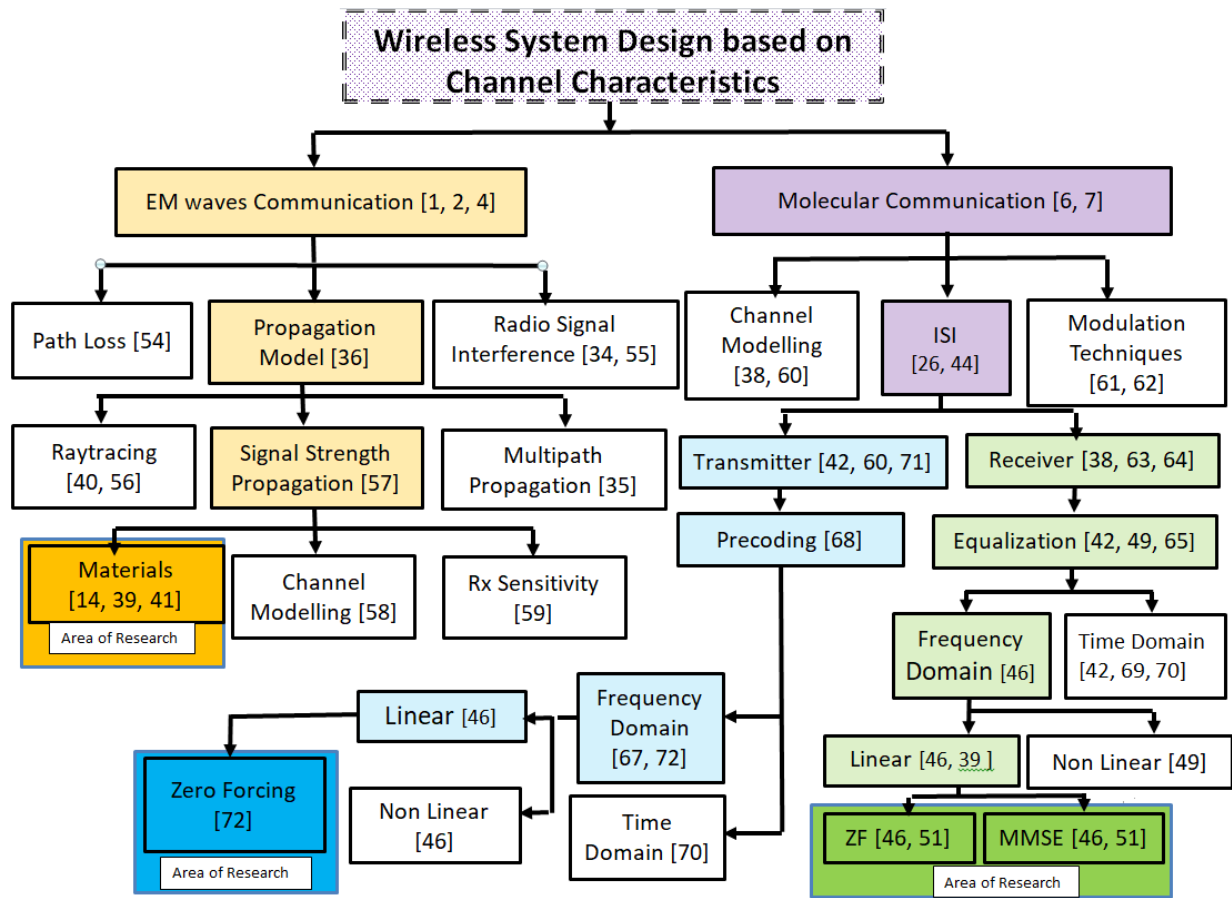


Figure 1.32 Overview of thesis.

1.8.2 Overview of research in EM waves communication

The indoor propagation deficiencies of EM signals are discussed in chapter 2, specifically Wireless LAN testing across various materials. In the first section the WLAN standards are introduced. To develop suitable design, implementation, and administration schemes for any wireless system, understanding of the radio propagation signals is necessary. Radio transmission is site-specific, and dependent on the type of location, operating frequency, mobile terminal velocity, network channels and other complex factors, differ considerably. The performance between functional dimensions and the theoretical model according Wi-Fi signal strength across different materials are analyzed in the following

sections. The outline of criterion of EM wave propagation research have been shown in Table 1.3

Table 1-3 Outline of proposal for EM wave channel characteristics.

Chapter 2	Purpose	Study effect of background materials on Wi-Fi signals in indoor environment
	Research Issue	Received EM wave signal power loss across various materials and path loss
	Proposed Scheme	Analysing the effect of materials and indoor propagation model
	Achievement	Updated indoor propagation model for Wi-Fi signals

For an efficient end to end EM wave communications the channel characteristics like radio signal interference, path loss due to distance that a signal covers [36] and propagation models [54] are need be considered as shown in Fig. 1.33. While selecting the propagation model there is a requirement of studying the ray tracing which is estimation of signal during transmission from transmitter to receiver [56], signal strength propagation where signal mapping is being done to estimate the coverage of EM signal [57] and multipath propagation where signal after releasing from the source reaches its destination as a sum of multiple signals [35]. As in this research, signal strength propagation is considered since it is easy to perceive the effect of materials at EM wave signal. In the literature, huge research has been done for discussing the receiver's sensitivity [59] and channel modelling [58]. There is a need of updating the international telecommunication union ITU indoor propagation model [14], for this instance received power loss is calculated across various materials and propagation model is updated accordingly. Path loss models are vital in wireless network planning as they facilitate site survey for RF simulations, evading tiresome measurements in an indoor environment. It supports network designer while assisting him to determine the best position of Wi-Fi router for better site coverage.

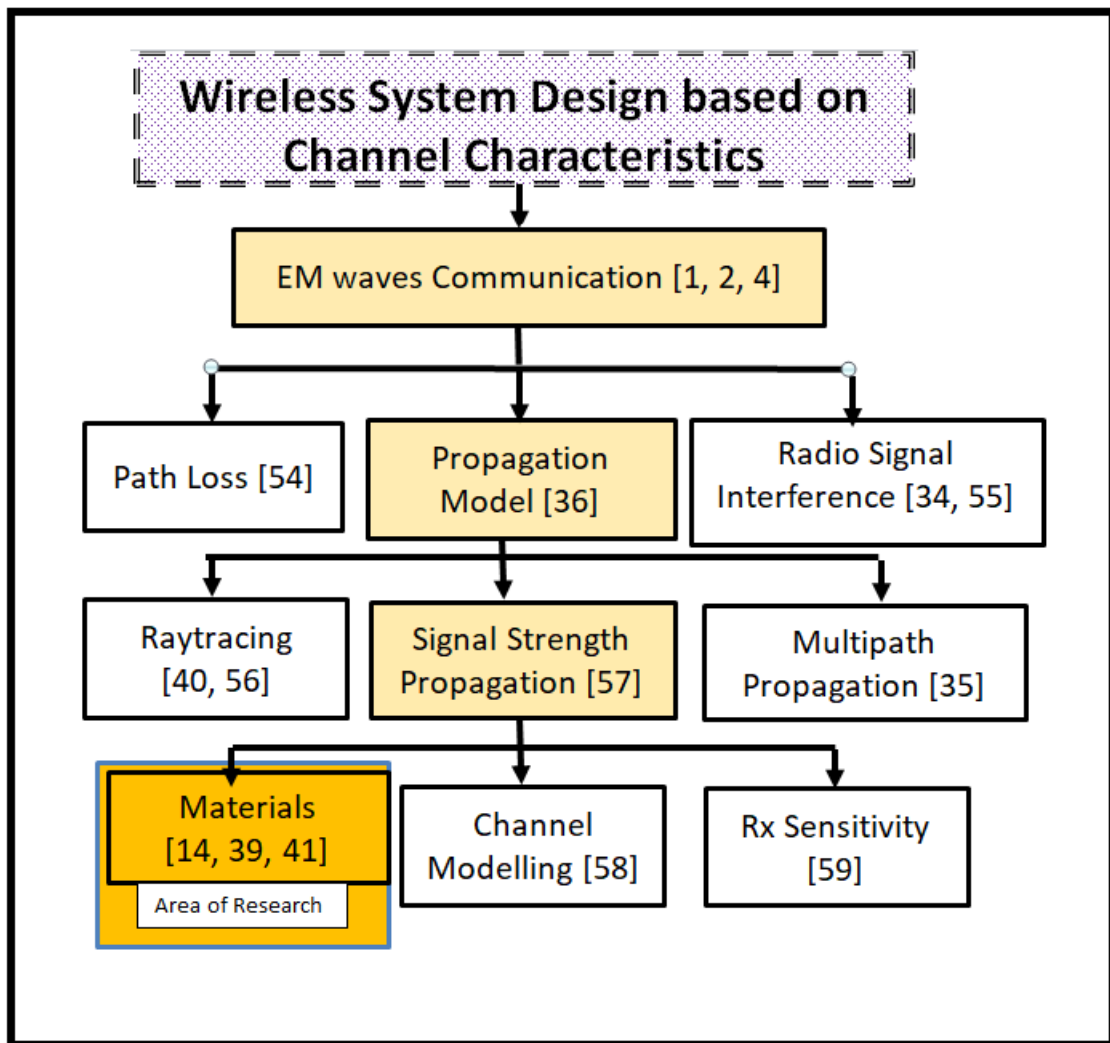


Figure 1.33 Overview of chapter 2.

1.8.3 Overview of research in Molecular Communication

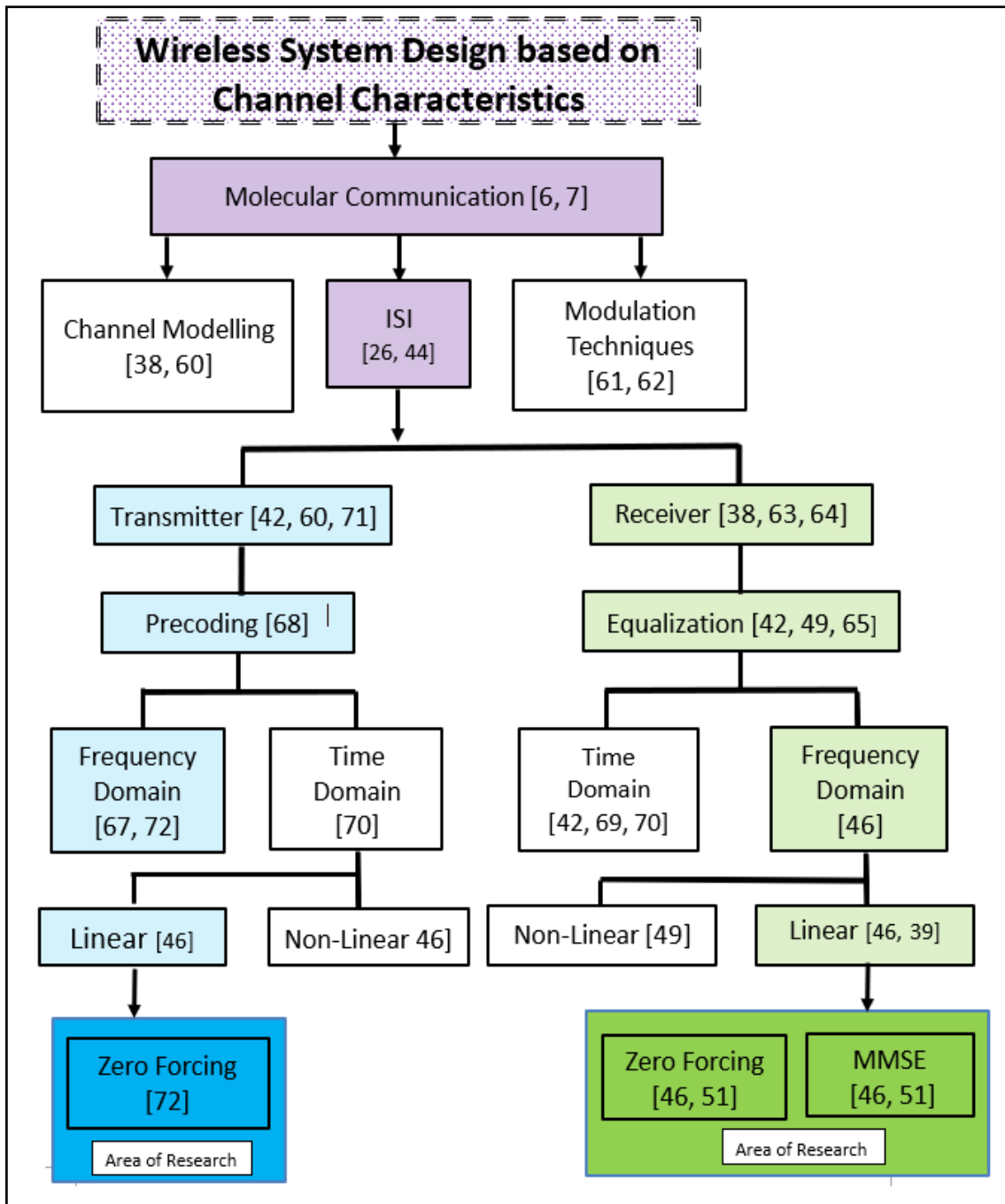


Figure 1.34 Overview of Chapter 3 & 4.

There are various issues in MC that are considered for the communication of data through tiny particles. As shown in Fig. 1.34 the research in MC is focus on modulation techniques [61] and [62] and channel coding [60]. Due to the nature of diffusion based MC the

particles travels all around in the atmosphere and reaches receiver lately and due to this, the problem of ISI arises at the receiver [26] and [44]. ISI is efficiently reduced by the implementation of equalization [42] and [49]. Research on TDE in MC is currently being focused on ISI cancellation [69] and [70]. As it is understood, easy and miniature size equipment is needed in Nano communication systems. Since multiplication operations are applied in the FDE rather than convolution [46], and are performed with simpler hardware implementation, it is proposed to equalize the received signal in frequency domain with reduced complexity. FDE consists of linear and nonlinear equalizers [49]. The easiest to execute are commonly the linear equalization methods [39]. Furthermore, ZF and MMSE are employed for FDE [51]. While ZF do not take account effect of noise, the MMSE perform as an ideal equalizer and shows a clear balance between the increase of noise and the reverse channel

The overview of research motivation of chapter 4 is shown in Fig. 1.34. As discussed earlier, MC is executed with the help of tiny particles which carries the data [6]. Therefore, the receiver hardware being miniature needs to be addressed [63]. While issues like Channel modelling [38] and [60] and Modulation techniques [61] and [62] have been studied thoroughly in recent past there is a need of investigating the ISI issue more profoundly [26]. One of the TDE requires implementation of convolution of signals which increases the complexity of hardware [70]. As FDE is mere multiplication of signals is easy to implement and execute. Primarily mitigating ISI at the receiver side over-burdens, the receiver hardware [67]. Consequently, one can relieve the MC receiver for doing extra work and thus MC transmitter may be utilised for additional processes to reduce the effect of ISI [40] and [61]. The linear FDE particularly ZF equalization is exploited to as at the transmitter does not know about the noise, so reciprocal of CIR is an efficient way of equalizing signal at the transmitter side [72].

1.8.3.1 Outline of Chapter 3

The implementation of FDE in MC systems is discussed in Chapter 3. In the first section the MC system and ISI cancelation requirements are presented. Table 1.4 shows the need of research to combat ISI and noise enhancement due to equalization at the receiver side.

Table 1-4 Outline of proposal for studying MC channel characteristics from receiver.

Chapter 3	Purpose	Study the effect of MC channel characteristics
	Research Issue	Inter-symbol interference and noise enhancement
	Proposed Scheme	FD Equalization with threshold at receiver side
	Achievement	ISI reduction at receiver side

1.8.3.2 Outline of Chapter 4

The purpose of chapter 4 is shown in Table 1-5. It introduces frequency domain precoding at the transmitter side of MC system. The second section describes the RC equivalent circuit of MC transmitter while third section illustrates the zero-forcing precoding. The implementation of threshold and approximation of equalized signal have been discussed in section four. In the preceding sections the performance of approximated signal with the conventional approach is analysed.

Table 1-5 Outline of proposal for studying MC channel characteristics from transmitter.

Chapter 4	Purpose	Study the effect of MC channel characteristics
	Research Issue	Inter-symbol interference reduction at receiver and limitation of a MC transmitter
	Proposed Scheme	Equalized waveform approximation at transmitter side.
	Achievement	ISI reduction with less hardware complexity of transmitter and receiver

Chapter # 2

2Analysis of Indoor Propagation Model for Wireless LAN

2.1 Introduction

A wireless LAN is combination of Wi-Fi AP and mobile clients usually a laptop or a PDA that comprise of a WLAN card. Whilst Ethernet cables are set up all over the physical structure for wired network communications, different buildings are then linked by fiber optic cables. Within WLAN, APs are positioned in a variety of locations around buildings to establish a network system, and if necessary, even outside the city. Mobile users interact initially establishes communication link with the base station also known as access points and then to the outside with rest of the world with the help of internet [13] as shown in the Fig. 2.1. The dotted line shows the wireless link between the AP and the device.

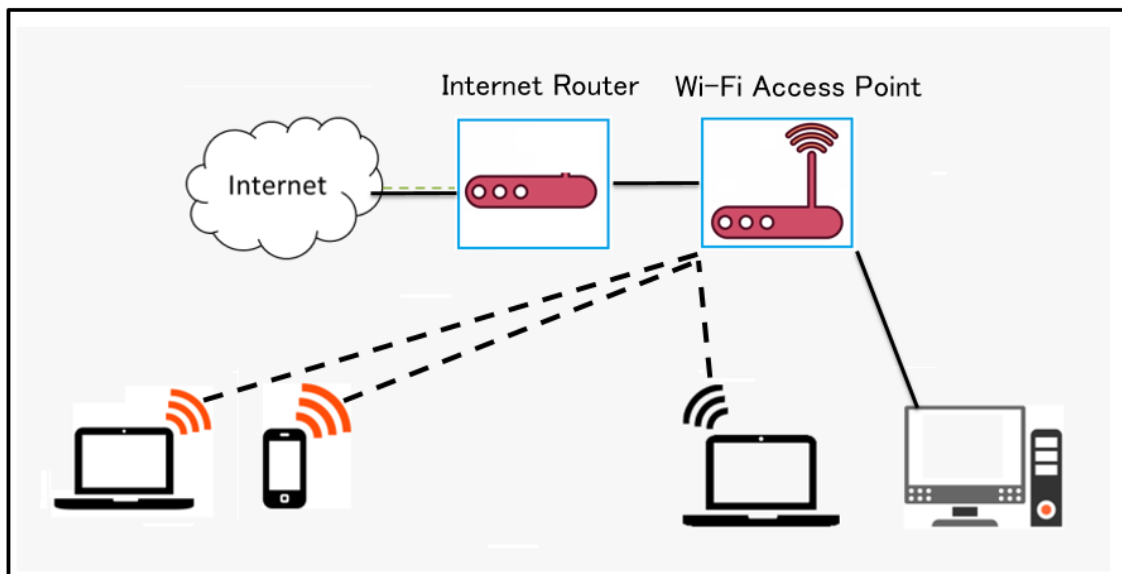


Figure 2.1 A typical Wi-Fi network.

WLAN connectivity is basically based on the fact that network information is transmitted through antenna as standardized electromagnetic waves. There are some issues to be emphasized as the radio waves broadcast or transmit through one device to the other. While it travels through indoor obstructions like wood, glass, concrete, brick, metal facades and even though a human body, the radio energy starts to slow and tends to reduce. The dynamics used as RF signal propagation includes NLOS, reflection, refraction,

dispersion and diffraction. Scattering of waves tend to occur when RF signal strikes an obstacles or surfaces that have rough and uneven surfaces and scatters the incident signal to multiple signals that causes the signal to decay [14].

In the future, it is believed that a combination of technologies will be exploited for linking devices together. Wi-Fi is one aspirant technology for radio network at micro level – attaching miniature scale devices to a broader network as Internet of Things – but some revisions will be required for example, in an indoor environment i.e. home/office, with a TV, printer, weather station, stereos, lights, sauna, etc. The devices that mainly remain inside our home can relate to some short-range technology such as Wi-Fi or Bluetooth [15].

One may want to connect to some of the devices in an indoor environment when he/she is away – outside or on vacation – and there is a need to connect the devices to the Internet. This in turn means there is a need of interoperability throughout the network. Wi-Fi is a popular short-range radio technology widely used today. Although mainly used for Internet access in the home and office, Wi-Fi is progressively getting implemented for other cases appropriately, covering from industrial automation to the sensors and actuators at home. However, due to specific technical challenges with the underlying IEEE 802.11 technology, such as high-power consumption, scalability, and range, major adaptation of Wi-Fi channel efficiency for IoT is still required [12].

This chapter aims at examining WLAN 802.11 propagation and to evaluate and analyze signal power in an interior atmosphere by considering WLAN at this location as a result of the impact of the surrounding environment. This research, in other words, aims to conduct an on-site general signal intensity research and then to observe the impact of impediments like wood, brick wall, glass, concrete in the form of floor penetration and additional aspects, like the existence of individuals in an indoor environment. A typical indoor propagation model is shown in the Fig. 2.2. It includes objects like tables, chairs, desks, cupboards, partition and metallic file cabinet, door, and windows. The signal from Wi-Fi AP propagates in all directions, so while reaching to a particular receive in the

vicinity of AP, the signal follows various paths and reflects from the surface of tables and other smooth surfaces, diffracts from the edges of chairs and refracts through the partition.

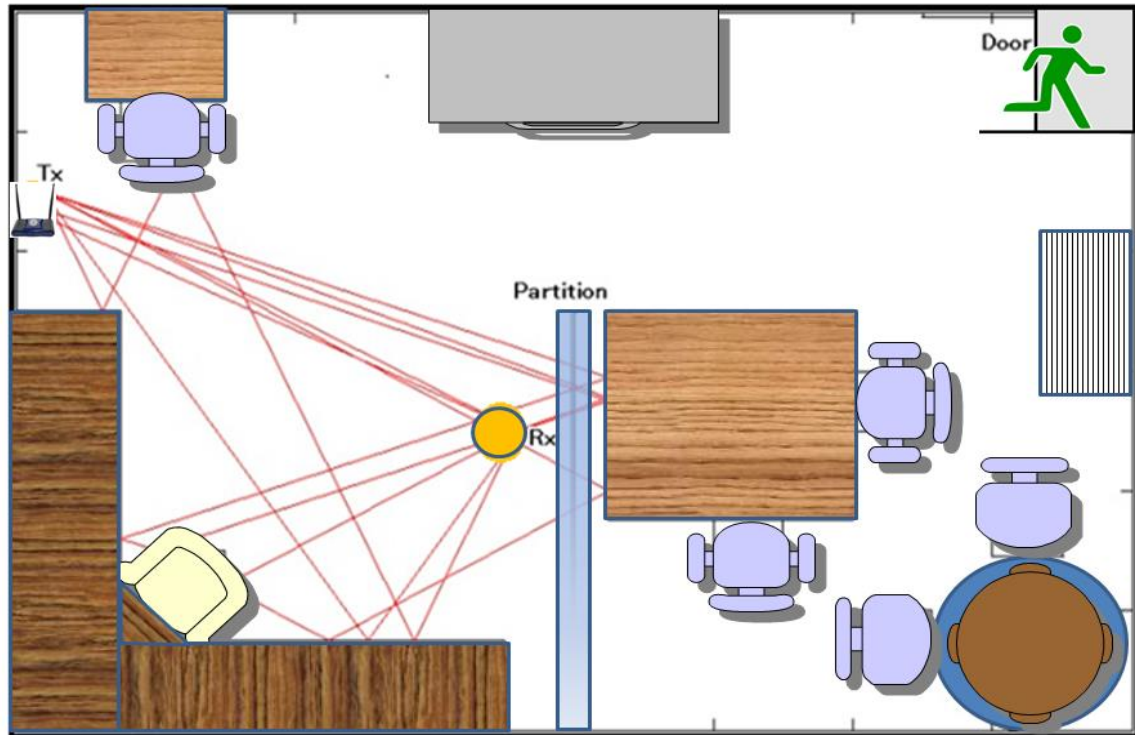


Figure 2.2 Indoor propagation of Wi-Fi waves.

There are few remarkable differences between Wi-Fi and other radios devices. The operating frequency of 2.4GHz is slightly greater than the mobile phones, walkies, and TV -used frequencies. The frequency band enables more information to be transmitted.

2.1.1 Benefits of WLANs

The use of a wireless Internet interface has many simple advantages, most of which apply to traditional wired LANs issues. The ease of wireless networking is an asset. Users have a connection to the network via broadband, as long as users are inside an AP servicing area. It is an exceptional benefit for mobile advertising agencies, logistics staff and information technology (IT) specialists who will have to gain access to data from anyplace in a city. Through the use of wireless technologies, user can roam anywhere virtually and can always access the data they need on the network [35].

Another advantage of WLAN is that the limitations on cable distance get less of a challenge. In many circumstances, the gap between the network and the end-consumer degrades the signal intensity as the walls, floors and permanent objects are routed on the cable.

The direct LOS connections to a network refute this through wireless communication. A radio AP or network card's signal intensity is usually in the middle of 5 and 50 meters (dependent on the size and construction of the building) and up to 300 meters in outside. The open-air range of 300 meters clearly overstretches the cable length of 110 m for the maximum unshielded twisted pair (UTP). Furthermore, by using several APs or using a wireless signal booster, a wireless signal can be enhanced even further [14].

2.2 Standards of WLAN

Standards are deployed across the globe for having compatibility with different hardware's and networks, products need to support several, if not all of the protocols at the same time. For example, smartphones these days cater up to date standards of WLAN i.e. IEEE 802.11 a / b / g / n / ac that covers all of the oldest and modern devices [54].

Most of the replace has simply helped to describe gradual developments in the standard, particularly in provisions of data speed. A summary when linked to the most frequently used versions are represented in Table 2-1. New Wi-Fi technology will hit the market in the next couple of years and more. These are quite diverse Wi-Fi techniques that can enable totally new hardware groups. Starting the Wi-Fi legacy which was started in 1997 and currently at Wi-Fi 6 which is still quite new. Currently in the market, there are routers available which follows the IEEE 802.11 ac protocol that is also known as Wi-Fi 5. These routers can cover a full range of a medium size household area [73]. For increasing the coverage of Wi-Fi signals, currently Wi-Fi mesh technology is used that acts as a repeater of Wi-Fi signals and covers up grey areas of an indoor environment. Wi-Fi mesh adapters can be utilized with a single Wi-Fi router to cover a wide-ranging area.

Table 2-1 Specifications of different Wi-Fi standards.

IEEE Standard	802.11	802.11 a	802.11 b	802.11 g	802.11 n	802.11 ac	802.11 ax
Year of Release	1997	1999	1999	2003	2009	2014	2019
Wi-Fi Alliance	Legacy	Wi-Fi 1	Wi-Fi 2	Wi-Fi 3	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6
Technology	FH & DS	OFDM	OFDM	OFDM DSSS	MIMO	MU-MIMO	MU-MIMO OFDMA
Frequency	2.4 GHz	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz & 5 GHz	2.4 GHz & 5 GHz	2.4 GHz & 5 GHz
Maximum Data Rate	2 Mbps	54 Mbps	11 Mbps	54 Mbps	600 Mbps	1.3 Gbps	10-12 Gbps

2.3 Radio Wave Propagation

To a significant degree radio signal propagation is a site-specific and depends on the characteristics of the environment, operational frequency, mobile terminal speed, interfaces and other dynamic factors that varies considerably. For the estimation of signal coverage, data size, barrier effects and best positioning for the deployment of specific stations, accurate classification of the broadcast channel by major factors and mathematical model is essential [15].

Transmission estimation implies that a transmitter with a specific receiver measures the radiation field intensity value at a specified range, as each mobile user has no wireless application. The signal's path loss is the rate of loss as the transmitter propagates electromagnetic power and sending radio signals all around i.e. omni directional and the target is at someplace around in the surrounding area so the received to transmitted power could be reduced to one-hundredth of its actual value.

2.3.1 Issues in Radio Waves Propagation.

As a wireless signal passes by obstacles such as glass, timber, foliage, and metallic facades, so the signal attenuates. Path loss is due to various mechanisms that occur during transmission

- ✓ NLOS
- ✓ Reflection
- ✓ Diffraction
- ✓ Scattering.

Radio propagation depends on:

- ✓ Terrain nature
- ✓ Operational frequency
- ✓ device's terminal speed
- ✓ Sources of different interfaces across which signal travels
- ✓ Additional complex aspects

A statistical model is essential for following aspects:

- ✓ Wireless signal coverage prediction
- ✓ Data rate
- ✓ Impact of hurdles
- ✓ Optimal location of mounting AP

Measurement of propagation means the ratio of signal power of a transmitter to a received signal power, that is calculated on a specific distance.

$$\frac{P_{tx}}{P_{rx}} = \frac{(4\pi d)^2}{G_t G_r \lambda^2} \quad (2.1)$$

where

G_t : Gain of the transmitter antenna

G_r : Gain of the receiver antenna

λ : Wavelength of the transmission (m)

d : Distance between the transmitter and the receiver (m)

P_{tx} : Power of transmitted signal

P_{rx} : Power of received signal

Wi-Fi signal is transmitted across the buildings, lobbies, halls and open areas. Received signal performance is slightly lesser than expectations and requirements of the users. APs which have no difficulty in reaching 300 meters outside face obstructions which are mainly present indoors such as devices and equipment in offices, homes or businesses [14].

Wi-Fi transceivers transmits Equivalent Isotropically Radiated Power (EIRP) which is the RF signals strength that is tarnished by wires and connectors, and can be improved by relays and high-gain antennas.

$$\text{Received Power} = \frac{\text{Radiated Power}}{\text{EIRP}} - \text{Path Loss} + \text{Receiver Gain} \quad (2.2)$$

2.3.2 Path loss models

The model for interior path-loss presumes that the AP and user device are interacting in an indoor environment. Either with site specific or site general models, the AP to user equipment (UE) path loss can be measured. Situational information is used for site-general models. Some indoor models are available that take into consideration signal attenuation through many walls and across several story's. The power loss is caused by transmission through walls and over and over barriers, as well as by ground absorption and the impact of the environment. The site-specific model takes account of losses due to each obstacle, but this is included in the distance models. [74]

2.3.3 ITU Path Loss Model

The site-general path-loss model proposed by international telecommunication union (ITU) in ITU-R P.1238-5 is provided by:

$$\mathbf{Loss}_{Total} = 20 \log_{10} f + G \log_{10} d + L_f(n) - 28 (dB). \quad (2.3)$$

where

G = Tx & Rx separation gap loss coefficient

f = frequency in MHz

d = separation distance between Tx & Rx in m (where $d > 1$ m)

L_f = floor penetration loss factor in dB

n = number of floors between Tx & Rx ($n \geq 1$).

In dB scale ITU path loss stands equivalent to

$$\text{Loss} = 20 \log 4\pi + 20 \log d - 10 \log G_t - 10 \log G_r - 20 \log. \quad (2.4)$$

The following Fig. 2.3 represents the ITU power loss vs. distance graph in an indoor environment. The path loss is presented with respect to the log distance for the Wi-Fi signal of 2.4 GHz. It is clearly noticed that the power loss surges as the gap amongst the transmitter and the receiver expands.

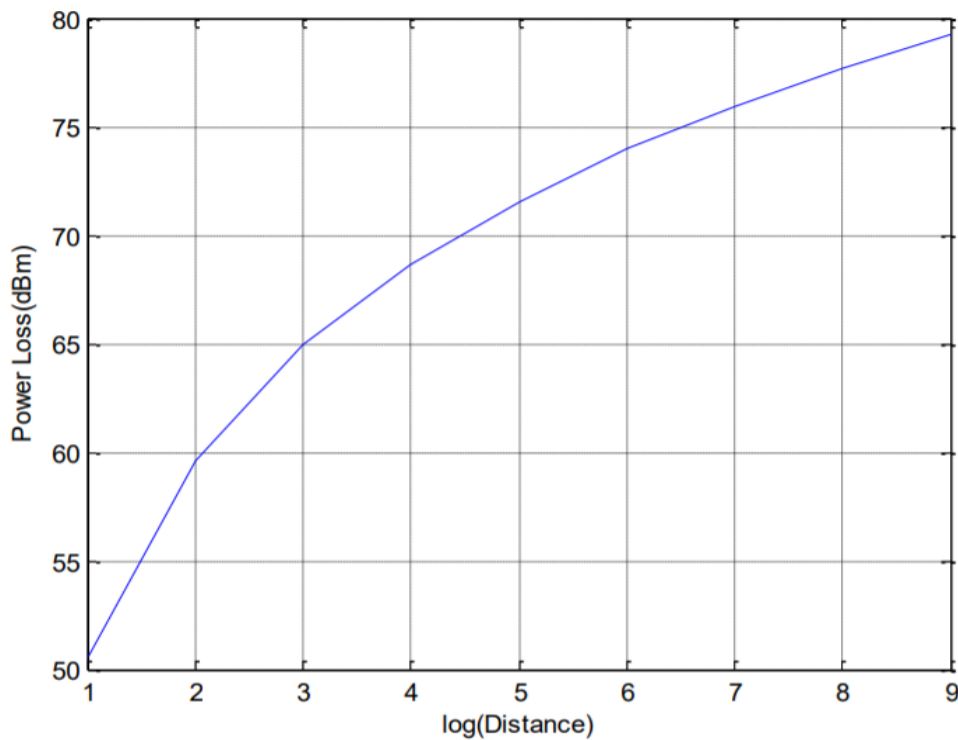


Figure 2.3 ITU Power Loss vs. distance graph.

Table 2-2 Wi-Fi signal loss in dB's across various materials.

Material	2.4 GHz	5GHz
<u>Interior drywall</u>	<u>3-4</u>	<u>3-5</u>
<u>Cubicle wall</u>	<u>2-5</u>	<u>4-9</u>
<u>Wood door</u> <u>(Hollow- Solid)</u>	<u>3-4</u>	<u>6-7</u>
<u>Brick/Concrete wall</u>	<u>6-18</u>	<u>10-30</u>
<u>Glass/Window</u> <u>(not tinted)</u>	<u>2-3</u>	<u>6-8</u>
<u>Double-pane coated</u> <u>glass</u>	<u>13</u>	<u>20</u>
<u>Bullet-proof glass</u>	<u>10</u>	<u>19</u>
<u>Steel/Fire exit door</u>	<u>13-19</u>	<u>25-32</u>

The Wi-Fi signal loss across various materials is described in Table 2-2. This table has been provided by ITU for a general reference. The losses in dBs have been provided for both Wi-Fi operating frequency. As seen in the Table 2-2, losses tend to be more for 5 GHz as compared with 2.4 GHz for the same material. The lowest loss is due to the interior dry wall while. For Wi-Fi 2.4 GHz band, the wooden door has a loss of 3-4 dB, while glass window has a loss of 2-3 dB. In ITU loss model, there seems to be the combined loss for concrete and brick with loss broadly ranging from 6 to 18 dB.

Energy is emitted by the transmitter antenna in every direction in the form of a wave front and interference occurs. The power lost while energy is spreading into the air is known as free space path-loss that varies by the distance obscured and operating frequency of WLAN. Additionally, as seen by the Fig. 2.4, the further the receiver, the higher the path loss and resulting in lower signal power. Here the path loss is calculated in terms of signal strength versus log distance. The resulting product of long term fading and short-term fading is the path-loss.



Figure 2.4 Signal strength vs log distance in terms of fading signals.

Multipath fading is a mechanism that should be considered in the design or development of the network of RF communication. The signal after traveling some distance reaches the receiver not only through definite straight trajectories but likewise by means of reflection from surrounding entities like construction structures, roads, foliage and water surface, etc. that lies in the proximity to pivotal track.

The short-term fading (also known as fast fading) implies to signal strength changes among the transmitter and the receiver when the distance of the two shifts by about half a wavelength at a small distance. Long-term fading (also known as slow fading) indicates changes in signal intensity between the Tx and Rx when a gap between the two is much greater than "variation" due to changes in terrain, and is more significant variation in signal strength between Tx & Rx. Indoor fading is typically short-term while fading in outdoor environment is long-term [36].

The sum of the different signals transmitted is the composite cumulative signal at the radio receiver. Since the path lengths are distinct, the signals add and subtract, based on their respective phases. In any environment, multi-path dissipation occurs, and paths

change for some reason. This shifts not just the relative strengths but also its phases as the lengths of the change in direction [14].

The fading of multipaths can also induce radio signal distortion. Because the various ways that the signals will take vary in duration, the signal sent over a single instance can reach the receiver over period. This may contribute to confusion of phase and intersection of symbols as data is transmitted. As a result, functions that mitigate the impact of these concerns may be integrated into the radio communications system [35].

Variations in the comparative route distances will occur at times. This could be attributed to either the moving radio Tx or Rx or either of the objects having a reflective moving surface. It allows the signal periods to shift as the antenna is received, resulting in a disparity in signal intensity due to the different manner that the signals are interpreted. That is why there are also signs of the fading. Often there will be adjustments to the relative lengths of the signal path. This may either be due to the moving radio transmitter or user or either of the entities having a moving contemplative coating. It causes the signal times period to change as the antenna is transmitted and the signal amplitude varies due to the different perception of the signals. This is the reason that, there are also indications of the decline in signal strength.

2.4 Problem Formation

As shwon in the Fig. 2.5 as the flow diagram, the signal that being transmitted from the Wi-Fi AP is propaogated in all directions. The receiver in the form of a laptop receives the signal and measures the received signal strength and path loss. There are various factors that affect the transmitted signal are studied. While analysing the signal strength accorss different materials an updated indoor propagation model has been developed which caters those materials that are found more frequently in an indoor environment.

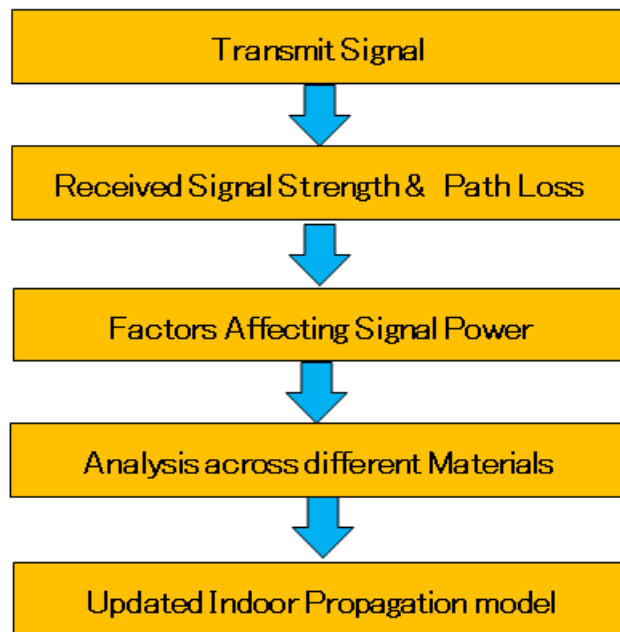


Figure 2.5 Flow diagram of problem formation.

2.5 Performance Results & Analysis

The purpose is to examine and analyze the losses countering substances like wood, glass, brick, and concrete. Therefore, primary assignment is to pinpoint particular places that are appropriate for captivating wireless signal strength measurements. These sites can be located solely across in an indoor environment because they are generally used in our households, workplaces and educational institutions. So, the finest location to take on measurements remained to choose a spot that has negligible other ecological influences such as, wind, sunlight etc. being as the intention is to calculate only the signal strength due to a particular substance, and no additional issues in the natural environment.

2.5.1 Performance metrics

The data is obtained in an open indoor environment as well as across materials such as glass, bricks, concrete and wood for the observation of the Wi-Fi signal. This is because these are common materials used in an indoor environment such as the home, office, cafés and schools.

The wireless adapter ‘Intelligent’ has been chosen because it supports all the IEEE WLAN standards. In addition to receiving signals, the distance covered by signals in the

environment without obstruction is 300 m. It provides for both 2.4 GHz and 5.0 GHz wireless-LAN with IEEE 802.11 a/b/g/n/ac standards. In this research 2.4 GHz has been chosen because 2.4 GHz waves travels long distance and can pass through the hollow and solid materials. The 2.4 GHz is slow in speed but covers majority of indoor environment. In WLAN environments, it can provide 300 Mbps of data rate. It has a respectable software utility i.e. graphical user interface to calculate signal strength od received. The sensitivity of Wi-Fi signal receiver is -83dBm while it transmits at +15 dBm. The core graphical user interface (GUI) is demonstrated in the Fig. 2.6. Where one can easily take thee readings of transmit and receive signal strength while one can select the signals from a specific Wi-Fi AP's and cancelling other AP's to not superimpose the signal effect of other AP's.

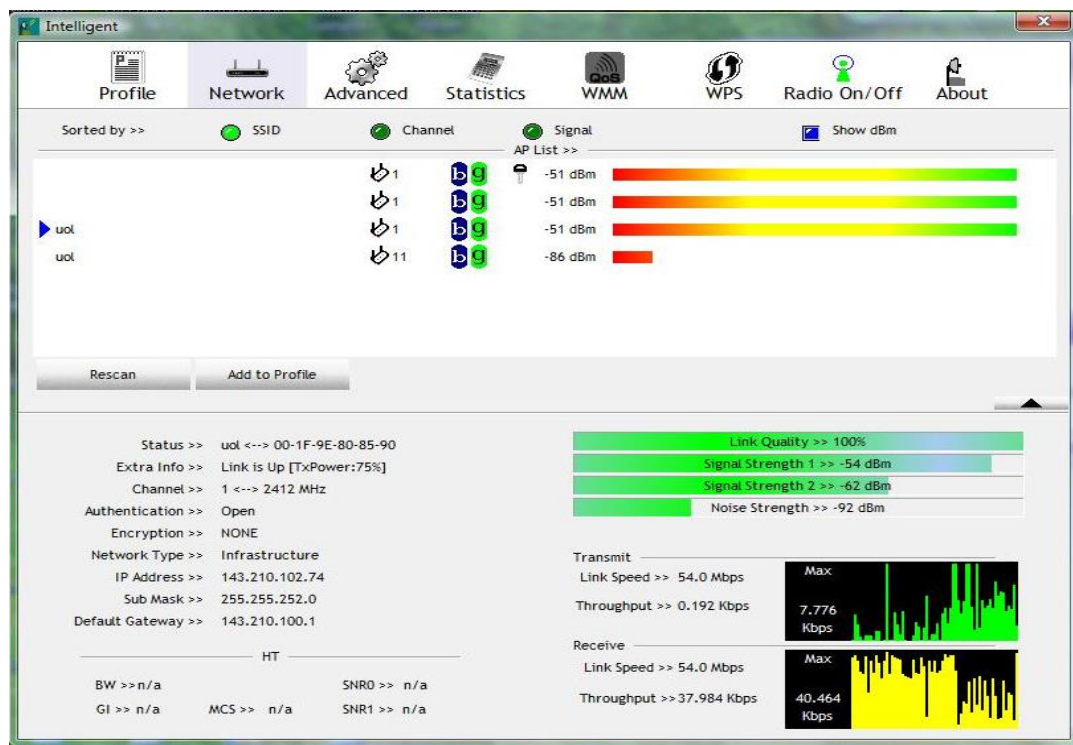


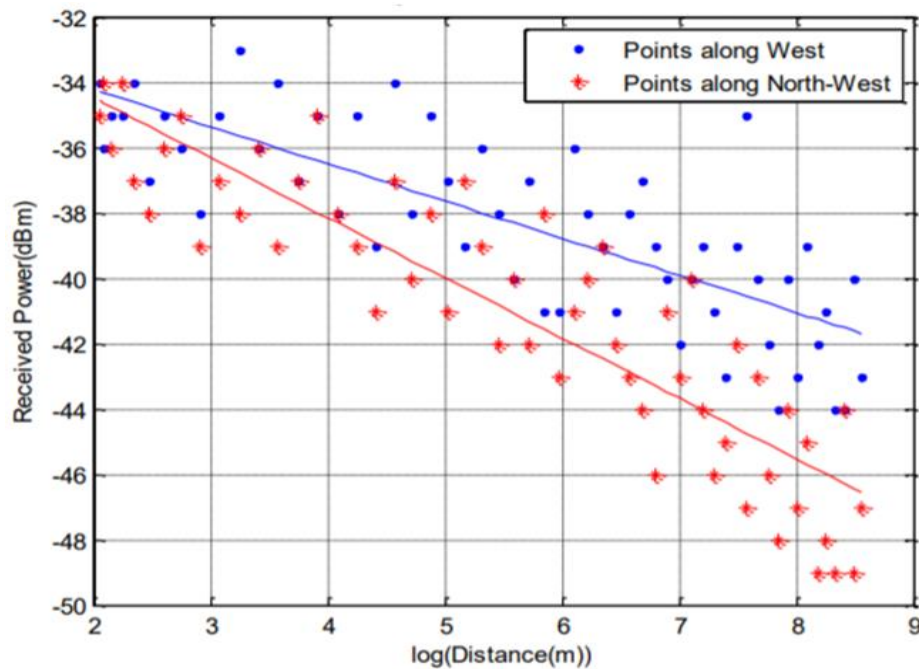
Figure 2. 6 User interface of Wi-Fi adapter.

The reading of MS Excel sheet is then obtained by means of a MATLAB simulation and the empirical model for small zone indoor propagation is compared with ITU model.

2.5.2 Effect of People presence in the Room

The plot in the Fig. 2.7 and Fig. 2.8 show the comparison of WLAN signals concerning presence of people and absence of people in the middle of the transmitter and the receiver.

These calculations are prepared at each location of separation from transmitter to receiver. The taken measurement spots and the path loss line-up in navy blue are the scatter-plot and best-fit line while there are not any human beings amid sender and UE, while the points and the line the line of best fit in red are represented when there is are human beings in the vicinity. The area is taken to be an empty 4m*6m room. While with the presence of people, there are 14 people inside the room that does not have any other item. The plot shows the relation between Tx to Rx distance for the received power. The distance value is plotted on the x-axis stated in log (meters) while on the y-axis the obtained power at the receiver is characterized that is indicated in dBm.



The graph in Fig. 2.7 shows the difference when there is an empty room and when there are people in the room and WLAN signal must bear the humans for its complete end to end communication. While analyzing the graph, as the gap between Tx & Rx increases,

the power received at Rx have a tendency to decrease. The blue data points are for the empty room, the received power ranges from -34 dBm at 2m to -44 dBm at 8m from the transmitter. The least-square-line at 2m indicates the power to be -34.25dBm while the received power at 8m is -41.25dBm. In Fig. 2.7 data points and the best possible line-up indicated by red is the correlation of the received power and the log-distance when people are present in between Tx and Rx. At 2m distance the received power is -35dBm. The received power drops to -48dBm when distance between Tx & Rx is 8m. The best fit line illustrates around -34.50 dBm power at 2m while at 8m the received power plunges to -45.50 dBm.

Fig. 2.8 shows the measurements for path loss also known as power loss in the scenario of LOS between Tx and Rx. The red data points are for the room with presence of people, the power loss ranges from 54 dBm at 2m to 67 dBm at 8m from the transmitter. The best fit line at 2m reveals the value 54.50 dBm and at 8m the power loss is 65.50 dBm.

The blue data points and the straight line in Fig. 2.8 show the correlation between the path loss and the distance (log) when there exist people in the vicinity of the Tx and Rx. The power loss happens to be 54 dBm at 2m distance from Tx to Rx. The power loss surges to 63 dBm at 8m. The least square line demonstrates the power loss of 54.25 dBm at 2m and which then increases to 61.50 dBm at 8m .

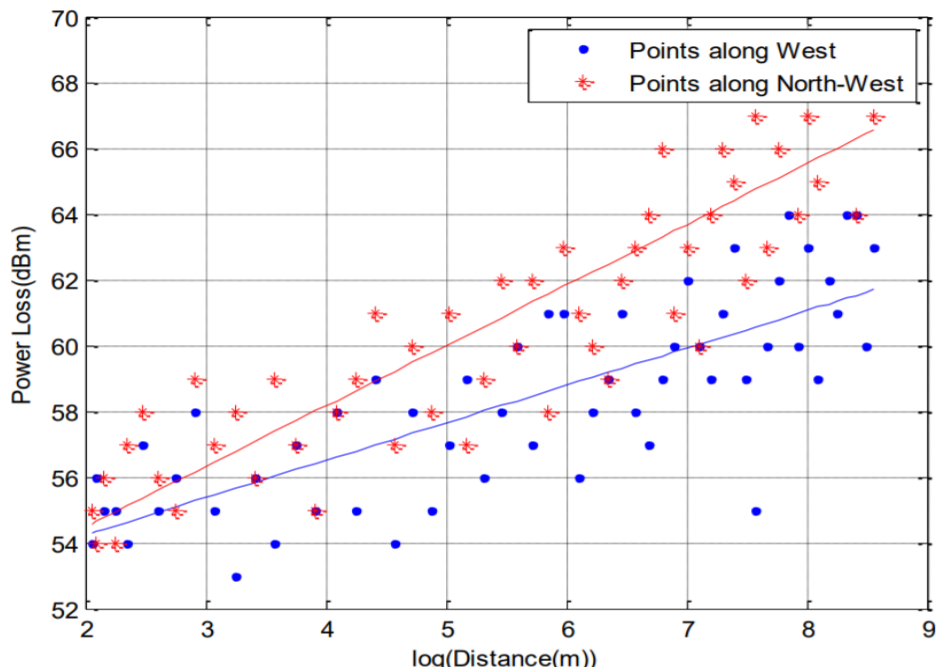


Figure 2.8 Power loss vs distance regarding presence of people.

Since we live in the real world, as predicted from the ITU model, the practical power loss at 6m remains 62 dB, whereas the ITU model happens to be 74 dB. This is because ITU has a floor penetration factor of 15 dB, but the ground loss was not taken into consideration in that case because every floor has its own access points. The Wi-Fi signal has an effect known as diffraction, that signal loss due to the surface of the obstacles should also be considered here.

When analyzing the scatter plot that with models of ITU's that is shown in Fig. 2.3, it was found that the ITU path loss model holds extra power losses than the realistic assessments as the ITU model is a typical model and it does not cater the effect of people in an indoor environment specifically .

2.5.3 Impact of Glass on Wi-Fi Signals

Initially, the readings are taken when Tx and Rx are positioned side by side of a glass divider. The measurements are carried starting at the 3m away from the transmitter because the transmitter is placed at the ceiling parallel to the glass wall. Investigations are carried out at 30 cm interval along the path parallel to the glass.

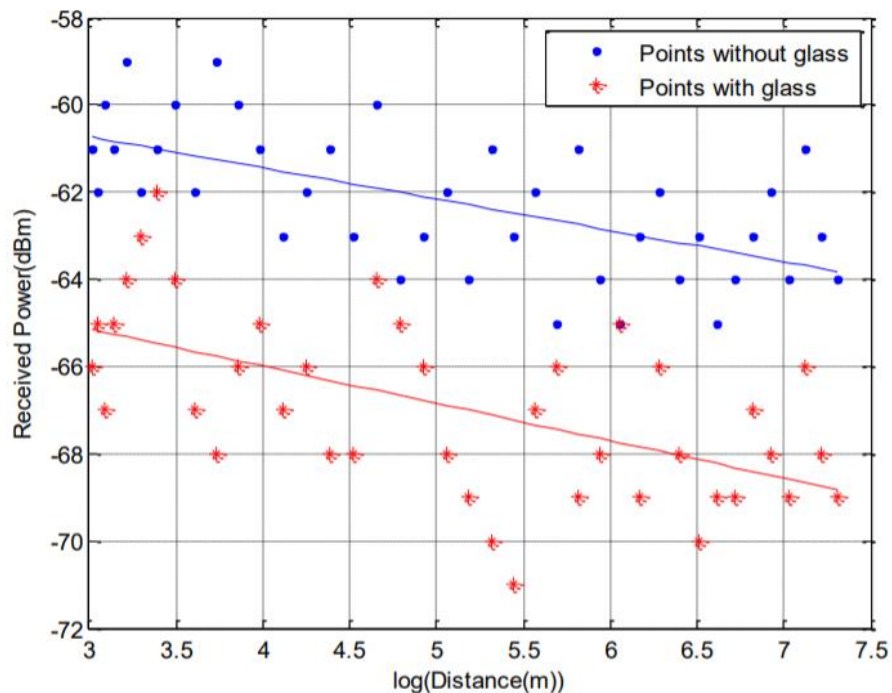


Fig. 2.9 Received power vs distance with and without glass

As the measurements are undertaken in a real-life situation; therefore, obtained power is fluctuating even if the receiver is static for some time. After concluding measurements for the LOS path, as the transmitter remains stationary, so the receiver is positioned now towards the other side of the glass wall-up of thickness 1cm. The received power readings are taken along the same path as shown in Fig. 2.9.

The Fig. 2.9 indicates the correlation between the power received at the UE and the log distance while there exist a glass walls in between the Tx and Rx. Here, the distance between the AP to UE is 3m from the earliest observational point and 7.2m for the final observational point. The signal power levels for data without the effect of glass be blue data points in the figure. At 3m, the received signal power approaches -61 dBm that reduces to -64 dBm at 7.2m. The least square line shows around -60.25 dBm power loss at 3m and it is reduced to -63.80 dBm at 7.2m. The red data points are for the measurements taken with the effect of glass, the received power ranges from -66 dBm at 3m to -69 dBm at 7.2m from the transmitter. The best fit line-up at 3m indicates the received to be of -65.15dBm and at 7.2m the arriving signal strength at the receiver is -68.75dBm.

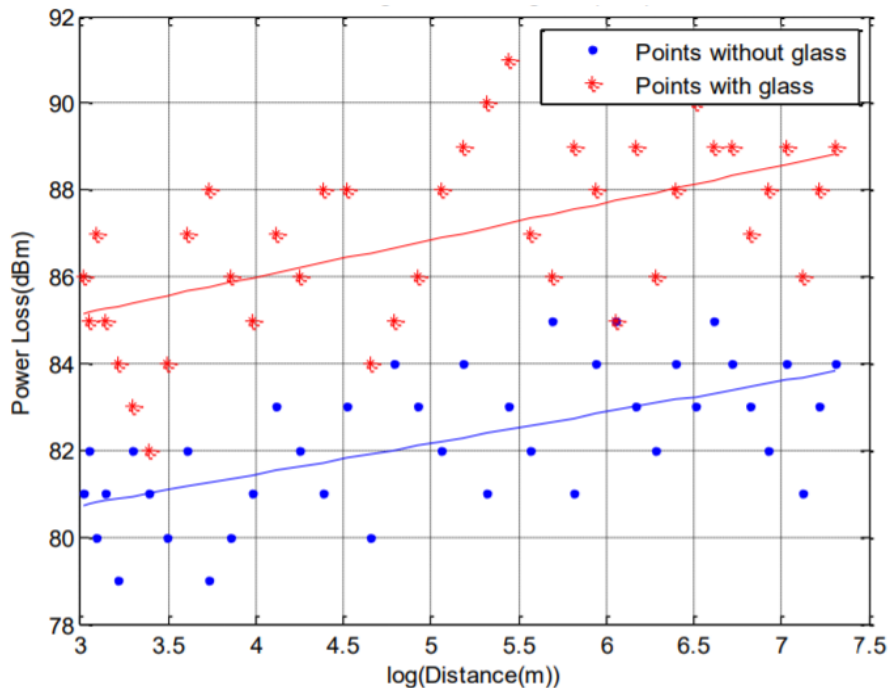


Figure 2.10 Power loss vs distance with and without glass

Fig. 2.10 shows the measurements for path loss in LOS between transmitter and receiver with the presence of glass wall in the vicinity that are represented by the blue data points. The power loss ranges from 81 dBm at 3m to 84 dBm at 7.2m from the transmitter. The best fit line at 3m demonstrates 80.7 dBm while power loss at 83.90 dBm at 7.2m the power loss is 83.90 dBm. The red scatterplot and the straight line-up in Fig. 2.10 show the correlation between the power loss and the log distance for NLOS glass scenario. The power loss is 85 dBm as the transmitter to receiver distance is 3m. The collected power at the receiver increases to 89 dBm when they are 7.2m apart. The least square line shows around 84.9 dBm path loss at 3m and is increased to 88.90 dBm at 7.2m.

Due to the fact that glass wall is having a glossy exterior so RF signals when hit a material e.g. glass so some of the signals reflect from the surface whereas some signals refract and penetrate within the glass. The slope i.e. (m) of curve line for losses with respect to glass is 0.8546 with constant of 78.5729 and for losses without glass the slope (m) lessens to 0.7174 with a constant 82.5744.

So

$$\text{Power} \propto (\text{Distance})^{-\nu} \quad (2.5)$$

$$\text{Power} = \text{constt} * (\text{Distance})^{-\nu} \quad (2.6)$$

Applying log at both sides

$$\log(\text{Power}) = \text{constt} - \nu \log(\text{Distance}) \quad (2.7)$$

Equation for losses with glass

$$\log(\text{Power}) = 82.5744 - 0.7174 \log(\text{Distance}) \quad (2.8)$$

Equation for losses without glass

$$\log(\text{Power}) = 78.5729 - 0.8546 \log(\text{Distance}) \quad (2.9)$$

By solving the equations (2.8) & (2.9), an indoor propagation model for losses due to glass can be designed.

At Distance = 3m,

$$\log(\text{Power}) = 82.5744 - 0.7174 \log(3)$$

$$\text{Power loss} = 82.11 \text{ dBm}$$

While comparing the theoretical and analyzed values the, NLOS i.e. the effect of glass assessment at 3m distance for theoretical assessment is 82.11 dBm as compared to 85 dBm. It is because shiny and plain surface of glass reflects the signal as well so that is why in actual the losses are a bit more.

There are two dimensions of glass that were considered. For the glass of thickness of 1 cm, 4 dB power loss is being observed. It is observed that losses tend to increase with the increase in thickness of glass sheet. For the glass thickness of 2 cm the loss is found to be of 6 dB. Whereas relating to ITU indoor propagation model, the loss owing to glass is 2-3 dB. It's because in real-world the RF signal bear other aspect of channel degradation just as scattering, reflection, diffraction that do perform key role in the loss of signal as the receiver towards the other side glass wall is considered for NLOS. It is also observed that the ITU model does not cater the thickness of glass as well.

2.5.4 Impact of Bricks on Wi-Fi Signals

The graph shown in the Fig. 2.11 demonstrates the correlation between the received power and the distance when there exists a brick wall among the transmitter and the receiver. Readings with steps of 2 wavelength (12.5 cm) are made for 7 metres. The profile of the wall is 30 cm in width. Measurements are drawn around the wall gap between the receiver and the AP diagonally, so that loss rises with the length of the structure of wall.

From the Fig 2.11, for the LOS path, the received power is represented by blue data points. The received power is -43 dBm when the receiver is just beside the transmitter and as farther the receiver is moved, the received power is reduced simultaneously to -50 dBm at 7m. The least-square line reveals the received power is -43.10 dBm at 0m and -66.20 dBm at 7m.

The red points and line in Fig. 2.11 represent the data when there exist a brick wall amid transmitter and receiver. For the brick wall case, the transmitter is stage set on any side of the wall at 30cm way due to the width of the wall. The reading was recorded at 50cm from the transmitter. Due to the presence of brick wall, the distance between the wall and receiver is 20cm. This is set to be the base point for the measurements of NLOS due to brick wall. The signal power levels diminished by the brick wall starts from -54 dBm to -64dBm when the gap between transmitter and receiver is around log (7) m. The best line curve shows the received signal power to be at -54 dBm to -66 dBm at log (7) m.

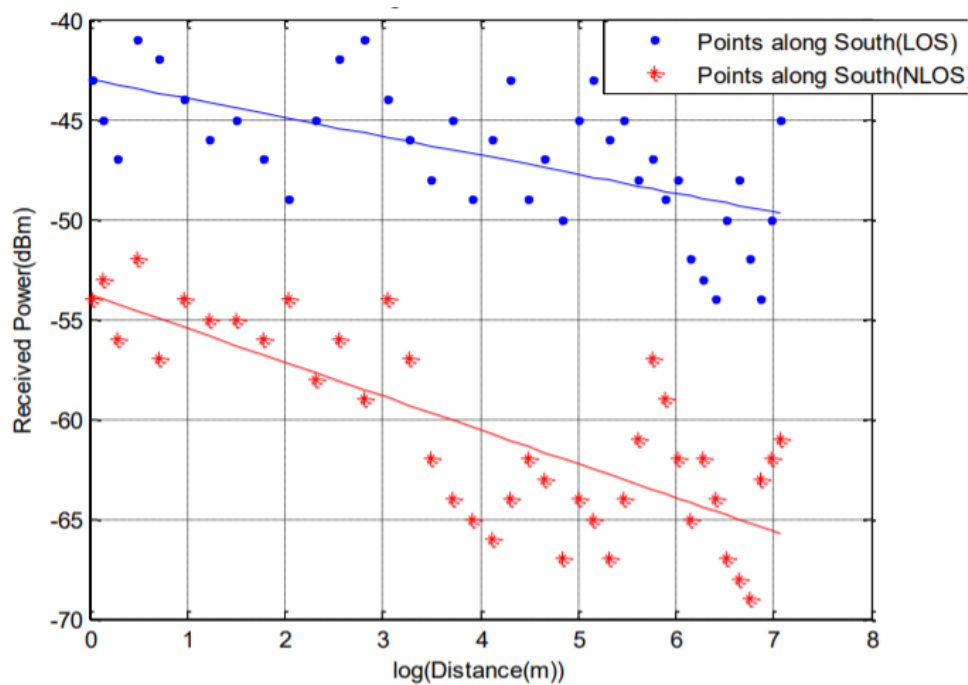


Figure 2.11 Received power vs distance across brick wall LOS and NLOS.

Fig. 2.11 shows the measurements for path loss also known as power loss in NLOS amid Tx and Rx. The red data points are for the hall with the walls made of red brick fit in the middle of the Tx and Rx. The path loss ranges from 74 dBm at 0 m to 83 dBm at 7m from the transmitter. The best fit line at 0m indicates the power loss to be 74.50 dBm while 7m the path loss increases to 86.0 dBm.

The blue data points and the straight line in Fig. 2.12 show the correlation between the path loss and the log distance when there is LOS situation amongst the Tx and the Rx in a hall with brick walls. The power loss is 63.5 dBm at 0m i.e. transmitter and receiver is next to each other. The path loss increases to 70 dBm at 7m. The least square line establishes the power loss of 63.5 dBm at 2m that increases to 69.50 dBm at 7m.

Since we live in the real world, as predicted from the ITU model, the practical power loss due to bricks at 7m is 84 dBm, whereas the ITU model is 74 dB. It is because ITU model is typical model that does not cater effect of bricks merely in an indoor environment. In ITU propagation model, the concrete and brick effect are taken together. In ITU loss model the ground loss was not taken into consideration in that case because in actual Wi-Fi signal also encounters diffraction, scattering and absorption as well, that signal loss due to the surface of the obstacles should also be considered here.

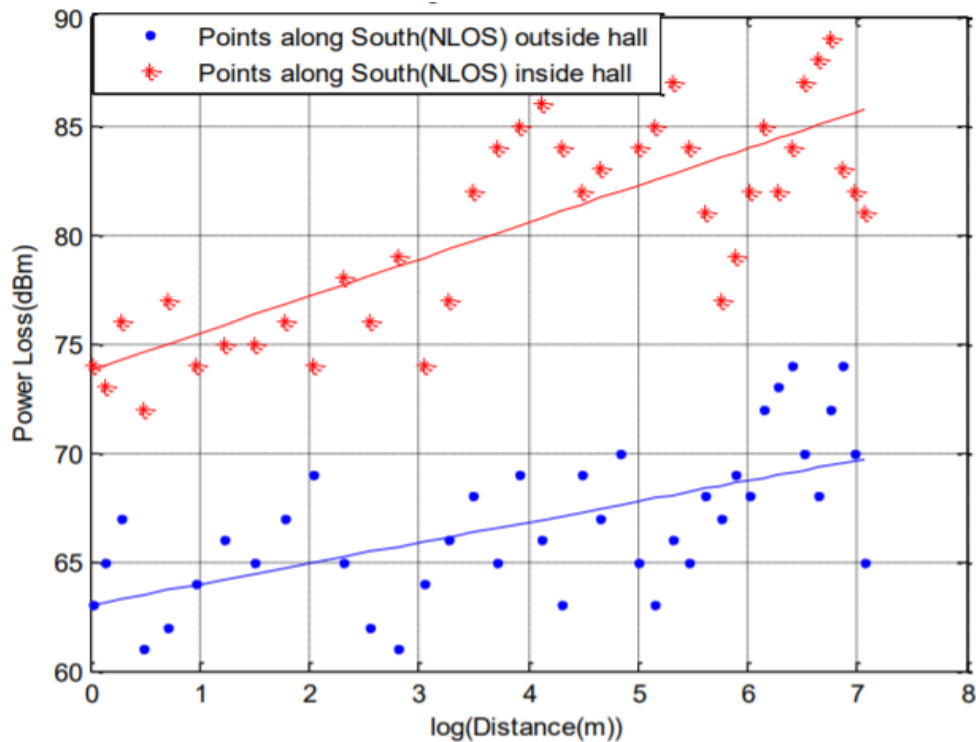


Figure 2.9 Power loss vs distance across brick wall against LOS and NLOS.

While glancing at the ITU model, the loss curve have a tendency to form a straight line for smaller distances. Since, it fluctuates so quickly in the vicinity because AP is installed in conjunction with other nearby AP's so due to that the signal strength changes all of sudden. It is also noted that, signal power fluctuates more quickly in a LOS setup as compared to NLOS situation. The Tx is positioned at the ceiling of the room , it creates LOS situation for Wi-Fi consumers at one side while NLOS situation for users at other side of the wall so this is the reason, it establishes a difference of 15 dB in calculations. While relating to the Table 2-2: the path loss owing to bricks is 6-18 dB that ranges in between ITU range.

Now establishing the line equation for path loss according to E.q. (2.7).

For LOS slope, $m = 0.9504$ and $Constt = 63.0107$

$$\log(\text{Power}) = 63.0107 - 0.9504 \log(\text{Distance}) \quad (2.10)$$

At Distance = 2m ,

$$\log(\text{Power}) = 63.0107 - 0.9504 \log(2) \quad (2.10)$$

$$\text{Power loss} = 62.30 \text{ dBm}$$

For NLOS slope, $m = 1.6926$ & $constt = 73.7819$

$$\log(\text{Power}) = 73.7819 - 1.6926 \log(\text{Distance}) \quad (2.11)$$

At Distance = 2m,

$$\log(\text{Power}) = 73.7819 - 1.6926 * \log(2)$$

$$\text{Power loss} = 73.2820 \text{ dBm}$$

While comparing the theoretical and analyzed values the, NLOS i.e. the effect of glass assessment at 2m distance for theoretical assessment is 73.2820 dBm as compared to 74 dBm which validates our results.

2.5.5 Impact of Wood on Wi-Fi Signals

For analysing the effect of wood between Tx and Rx, a wooden wall is placed. The transmitter is positioned next to the wooden wall. Wooden walls have a thickness of 10 cm. Investigations are carried out at 25 cm interval along the path parallel to the wooden wall for LOS. The measurements are carried in the real-time situation; so the received power is fluctuating even if the recipient is motionless for some time it is due the fact that there are other wooden materials like, desk, chairs etc. in the vicinity. After finalizing readings for LOS scenario, the receiver is positioned towards other side of the wooden wall. The width of the wooden wall is 10 cm.

The Fig. 2.13 shows the correlation amongst power received and log distance when there is a wooden partition in the middle of Tx & Rx. The signal power levels for data without the effect of wood be blue data points in Fig.2.13. At 1m away from the Tx, received signal power is about -34 dBm that is reduced to -48.5 dBm at 10m. The least square line shows -33.5 dBm power loss at 1m and it is reduced to -47.14 dBm at 10m. The red data points are for the measurements taken with the effect of wood i.e. NLOS. The received power ranges from -37 dBm at 1m to -54 dBm at 10m from the transmitter. The best fit line at 1m demonstrates the value -35.15dBm and at 10m the received signal power is -52.75dBm.

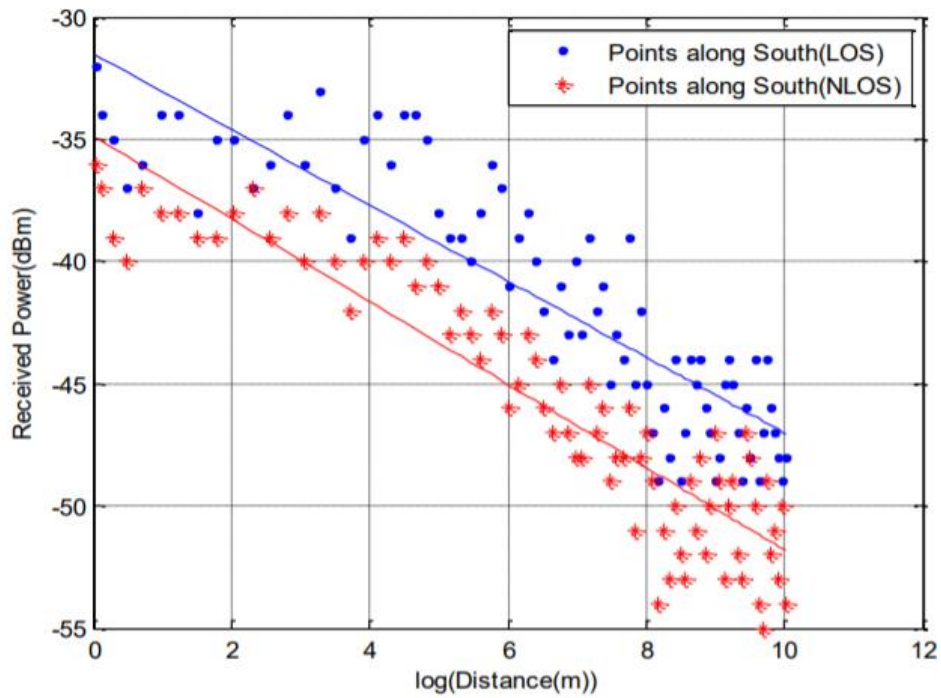


Figure 2.10 Received power vs distance across wooden wall for LOS and NLOS.

Fig. 2.14 shows the measurements for path loss in LOS between transmitter and receiver with the presence of wooden wall in the vicinity that are represented by the blue data points. The power loss ranges from 54 dBm at log (1) m to 69 dBm at log (10) m from the transmitter. The best fit line at 1m reveals the value 53.7 dBm and at 10 m the path loss is 67.90 dBm. The red data points and the straight line in Fig. 2.14 demonstrates the correlation between the power loss and the log distance when there is the presence of wooden wall in between the transmitter and the receiver. The power loss is 57 dBm as the transmitter to receiver separation is 1m. The power loss increases to 74 dBm while they are 10 m away from each other. The least square line reveals 55.5 dBm path loss at 1m and increased to 73.90 dBm at 10m.

Once realizing the relation of LOS and NLOS readings. Since passing through the hollow wooden wall, there has been a rise of 5 dB of signal power loss. The transmitted signal refracts from the woody wall and subsequently entering and penetrating the adjacent room where it deflects from the table surface, scatters by way of rough face of some indoor furniture.

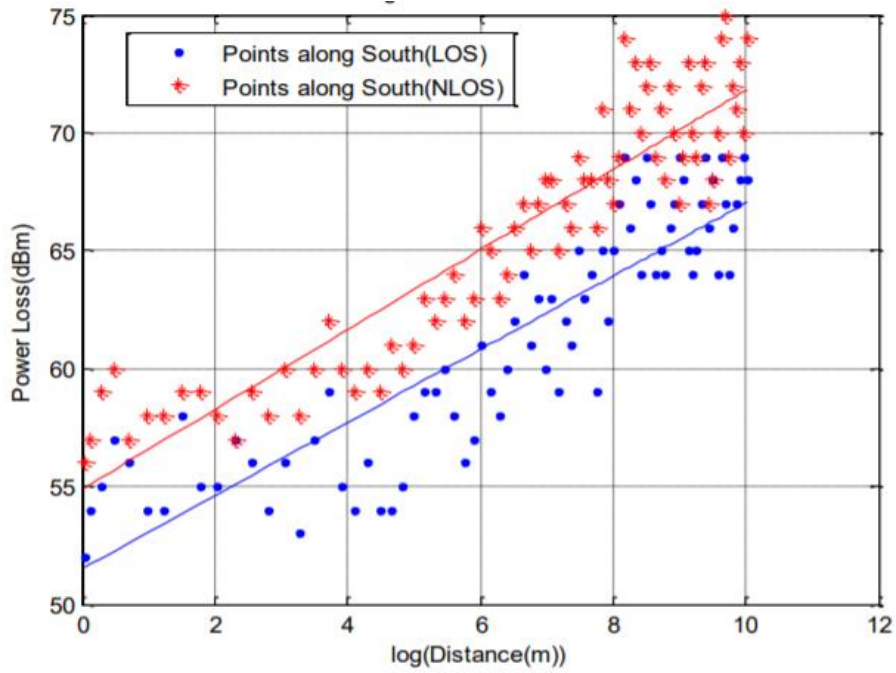


Figure 2.11 Power loss vs distance across wood for LOS and NLOS.

The power loss anticipated by futile wood is 3-4 dB when compared with the Table 2-2. In reality, the signal faces other variables such as distortion, diffraction and dispersion, because the signal through the glass wall is NLOS, they contribute to decaying the signal. According to ITU propagation model, table 2-2 also does not indicate the width of the wooden material. This is portrayed and displayed by Fig. 2.13 and Fig. 2.14, that represent the dispersion of signal in this scenario,

The power loss line equation has now been established.

For LoS $m = 1.5499$ & $Constt = 51.5115$

$$\log(Power) = 51.5115 - 1.5499 \log(Distance) \quad (2.11)$$

For NLoS $m = -1.5499$ & $constt = 57.8741$

$$\log(Power) = 57.874 - 1.5499 \log(Distance) \quad (2.12)$$

At Distance = 2m,

$$\log(Power) = 57.874 - 1.5499 * \log(2)$$

$$\text{Power loss} = 57.37 \text{ dBm}$$

While comparing the theoretical and analyzed values the, NLOS i.e. the effect of glass assessment at 2m distance for theoretical assessment is 57.37 dBm as compared to 57.75 dBm which validates our results.

2.5.6 Impact of Concrete on Wi-Fi Signals

While analysing the effect of concrete the Tx and Rx are positioned initially at the similar floor for LOS investigating. After that NLOS analysis the receiver are placed at the base of 2nd floor. The measurements are taken starting at the 3m away from the transmitter because the transmitter is placed at the ceiling. The thickness of concrete floor is 27cm. The environment was taken to be an indoor sports hall having concrete at its floor, walls, and roof.

The Fig 2.15 shows the received signal power with respect to log(distance) to analyze the effect of concrete. For the LOS path, the received power is represented by blue data points. The received power is -43.5 dBm when the receiver is at log (1)m from the transmitter and as more the receiver is shifted, the received power is reduced altogether to -55 dBm at 8m. The best fit line depicts the received power to be -43.20 dBm at 1m and -56.40 dBm at 8m of log distance.

The red points and line in Fig. 2.15 represent the data NLOS when readings are taken from at the 2nd floor. From the graph the impact of concrete in in the middle of Tx & Rx can be easily observed. With regard to the concrete, the signal is attenuated by the presence of concrete. The received signal power level shows its maximum strength of -62 dBm and it is across -74dBm as the gap between the Tx & the Rx is around log (8) m. The best line curve shows the received signal power to be at -61 dBm to -72 dBm at log (8) m.

Fig. 2.16 shows the measurements for path loss also known as power loss in NLOS between AP and UE. The red data points are for the hall with the walls and roof made of concrete. The path loss ranges from 82 dBm at 1 m to 91 dBm at 8m from the Tx. The best fit line at 1m indicates the value of 81.50 dBm and at 8m the power loss is 91.50 dBm.

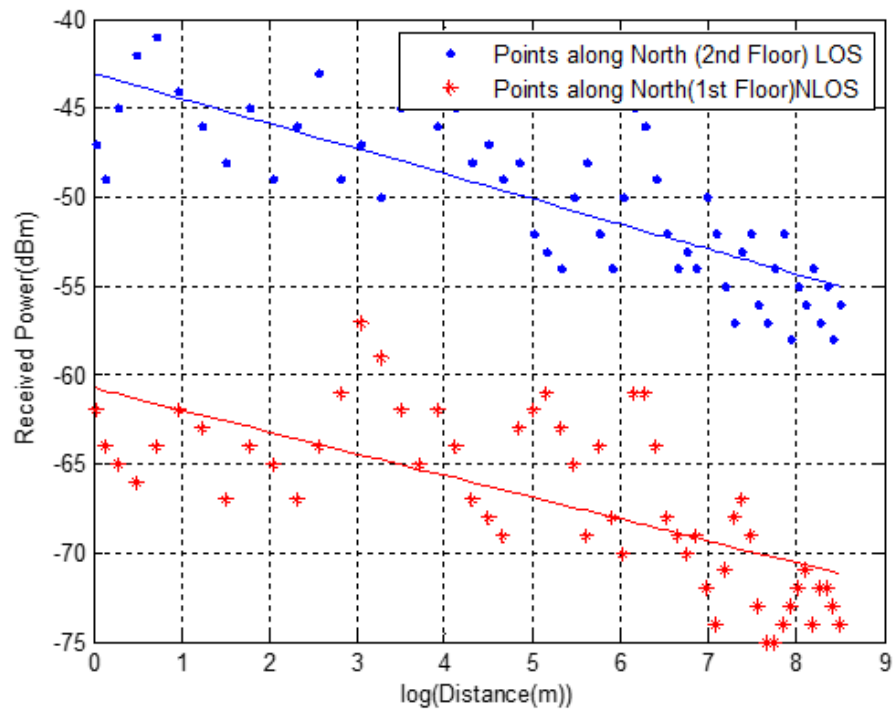


Figure 2.12 Received power v/s log(distance) for viewing effect of floor loss.

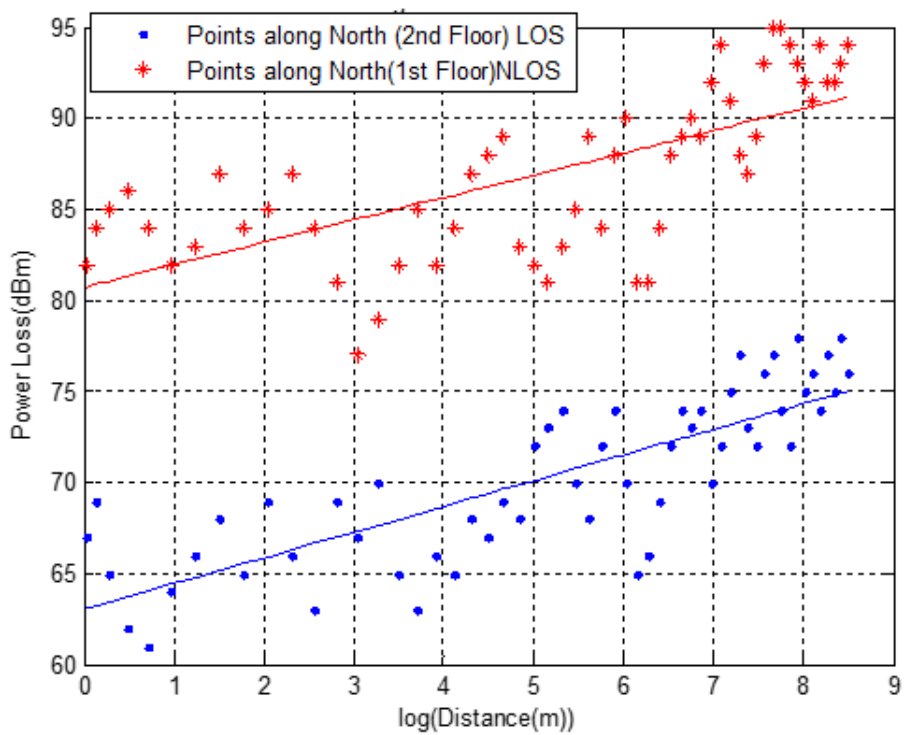


Figure 2.13 Power loss v/s log(distance) for presenting effect of floor loss.

The blue data points and the straight line in Fig. 2.16 show the correlation among the power loss and the log distance when there is LOS between Tx and Rx in a concrete hall. The power loss is 64 dBm at log distance is 1m. The power loss surges to 78 dBm at 8m log distance. The least square line demonstrates 63.75 dBm power loss at 1m and 74.50 dBm at 8m.

The loss at the same position on the first floor is shown to be almost 16 dB as compared to the loss in the second floor, that is close to AP. The loss due to concrete is 6-18 dB in accordance with Table 2-2. So here the expected losses are in between the provided range in ITU model.

The ITU indoor loss model has been compared since it accepts floor effect. Therefore, it is observed that at 4m the loss is 73dB, although it is basically 86 dB according to ITU model. The estimated path loss due to ITU loss is 80 dB at 7m while 89 dB in practice. Thus, the loss is more in practical scenario than that presented by ITU, since ITU model does not apply to all the materials utilized in concrete i.e. steel, and carpet over the concreated surface. Apart from these active materials reflection, dispersion and diffraction effect has also not been taken into account.

At this point establishing the line equation for path loss.

For NLOS i.e. at 2nd floor, $m= 1.2296$ & $Constt = 80.7291$

$$\log(\text{Power}) = 80.7291 - 1.2296 * \log(\text{Distance}) \quad (2.13)$$

For LOS i.e. at 1st floor, $m= 1.4114$ & $constt = 63.0493$

$$\text{Log}(\text{Power}) = 63.0493 - 1.4114 * \log(\text{Distance}) \quad (2.14)$$

At Distance = 2m,

$$\log(\text{Power}) = 80.7291 - 1.2296 * \log(2)$$

$$\text{Power loss} = 80.23 \text{ dBm}$$

While comparing the theoretical and analyzed values the, NLOS i.e. the effect of glass assessment at 2m distance for theoretical assessment is 80.23 dBm as compared to 85.0 dBm which is a bit higher than the real power loss. It is because as the 2nd floor has a carpet layer above the floor and inside concrete there is also some steel rod presence as well that also increases power loss.

2.6 Conclusion

Scientists and engineers have taken an interest in this area to develop widespread developments, applications, and discoveries in the wireless communications field. In this wireless world's WLAN is the essential way of communication. In our homes and offices, it is the most popular technology used nowadays. With the increased reliance to communicate together with the outside world via the cyberspace, it is getting increasingly important. Compared with the local area network, wireless internet connection offers a vibrant, free environment and mobile connectivity to a network. Owing to its simple design, this technology is becoming widely used by masses.

ITU's Indoor framework does not have sufficient material parameters, that is why new indoor wireless model for communication is required to meet the wireless signal behaviour when facing obstacles. Wi-Fi has been used for years, but in older systems there have not been properly solved use cases that need lower capacity, scalability, and a longer range. The next IEEE 802.11 standards can offer the support of Wi-Fi to meet these requirements, making them a strong contender among other communication technologies.

Table 2-3 Calculated power loss across different materials.

Obstacle	Loss
Glass (1 cm Thick)	5 dB
Wood Wall (10 cm Thick)	6 dB
Pure Brick Wall (30 cm Thick)	17 dB
Roof (27 cm Thick)	15 dB

Chapter # 3

Implementation of Frequency Domain Equalization at the Receiver side of Molecular Communication Systems

3.1 Introduction

MC is a nanoparticle-pulsated, diffusion-based communication system in which data are recognized in the way particles, such as bacteria, pheromones etc. are distributed, disseminated, and obtained. In biological science, this standard model was studied initially as cells for intracellular and intercellular connection that are effectively incorporated into the nature [6]. Diffusion-driven communication is one of the highly reassuring communication system methods for the compatibility of nano-balancing systems with live organisms and biochemical instruments, e.g. air spreading pheromones within insects and calcium response inside biological cells [44]. There are number of application fields of MC including biological engineering, health care, manufacture and monitoring environment, have an interest in MC[6]. Standard transmission in biochemical and biophysical systems, allowing it to be suitable for natural activities. For example:

- Directing Chemical Substances
- Intensive Medicine Delivery
- Planning Lab-on-a-chip Frameworks
- Modern Manufacturing i.e. observing Chemical Reactors
- Molecular Communication for internet of nano things IoNT.

MC has a few promising features over conventional wireless correspondence, with the most eminent ones being versatility and vitality competency. For instance, in nature, MC is utilized for inside cell and among different cell interchanges at the smaller scale like micro and nanoscales, and utilized as pheromones correspondence among similar living species at the macroscale. Additionally, these frameworks disburse significantly less vitality contrasted with radio-based correspondence frameworks [63].

There are diverse categories of MC that have been studied so far, and they can be considered on the base of particles propagation in the medium [64]. There are three main types of MC that are acknowledged from the previous literature, as shown in Figure 3.1, as the walkway based, the advection based, and the diffusion based. These categories are also described on the basis of how impulsive is the dissemination of the particles. The little impulsive is the category of MC, the more predictable is the trail monitored by the particles throughout their promulgation, and vice versa.

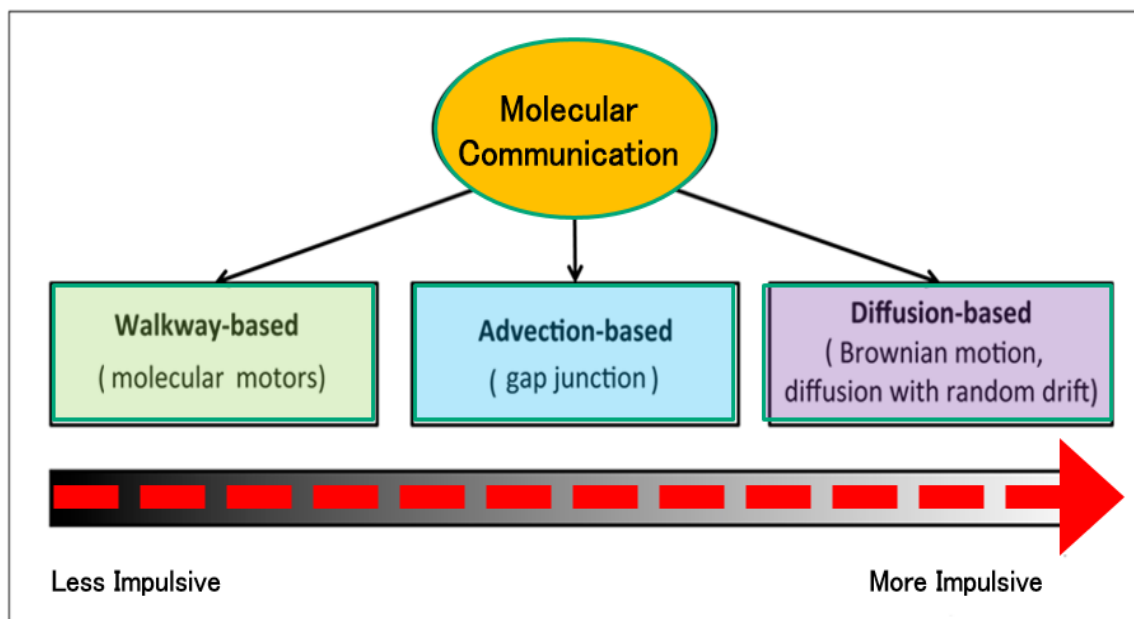


Figure 3.1 Types of MC system.

The molecules spread over the walkway MC, via pre - determined paths, through active transport and connect the transmitter to the receiver. The literature on this form of MC provides the most known example with the use of molecular engines [60].

With MC based on diffusion, the molecules spread through diffusion into the fluid medium, the flow of which is determined and consistent, as well as the molecular or advective transport. The use of gap junctions [65], which are nano-fluidic pipes connecting the transmitter and the receiver, is one example of this type of MC. MC based on advection can additionally be achieved by carrier units whose movement is restricted by certain paths on average, despite the use of a random component.

The molecules in the diffusion-based MC spread to the fluidic medium spontaneously. MCs based on diffusion were analyzed in [43], where the information molecules are located in an uneven randomness path, the Brownian motion, to cover the gap concerning transmitter and receiver. Random advection in the fluidic medium may also affect the molecules in diffusion-based MC. The focus of the proposed research is on diffusion-based MC. The choice of selecting diffusion based MC is inspired by subsequent opinions. Firstly, molecule diffusion is at the foundation of all the above-mentioned MC choices. Diffusion is replicated to be an inevitable propagation outcome laid over on the molecular motor transport. Secondly, diffusion-based MC is pondered the supreme common and general MC possibility in the nature, illustrations are established in the calcium signaling amongst cells [44], the pheromones communication between animals and the communication amongst neurons [11]. Significantly, the diffusion based MC obligates the prospective advantage from the observation of natural surroundings for the intentional design of bio compatible and bio inspired results.

3.2 MC Receiver

The inflow of the transmitted molecules is identified by MC receiver (MC-Rx) into their location and senses programmed information, such as concentration and type of molecules, in a physical property of these molecules. As seen in Fig. 3.2, Molecular receptor antennas that consist of a bio - recognition unit are tucked into a transducer, that are utilized to transform the received molecules. The transduction unit is the molecular channel-recipient interface / boundary which produces an electrical pulse for further processing. It involves a selective molecular detection event for the information carrier molecules, for example, it responds selectively to the molecules that are targeted towards MC-Rx. The transducer component then produces a processing signal based on the received molecular reaction, e.g. electrical pulses. Lastly, to detect the information originally transmitted by the transmitter, the output of transducer is sent to a processing unit [65].

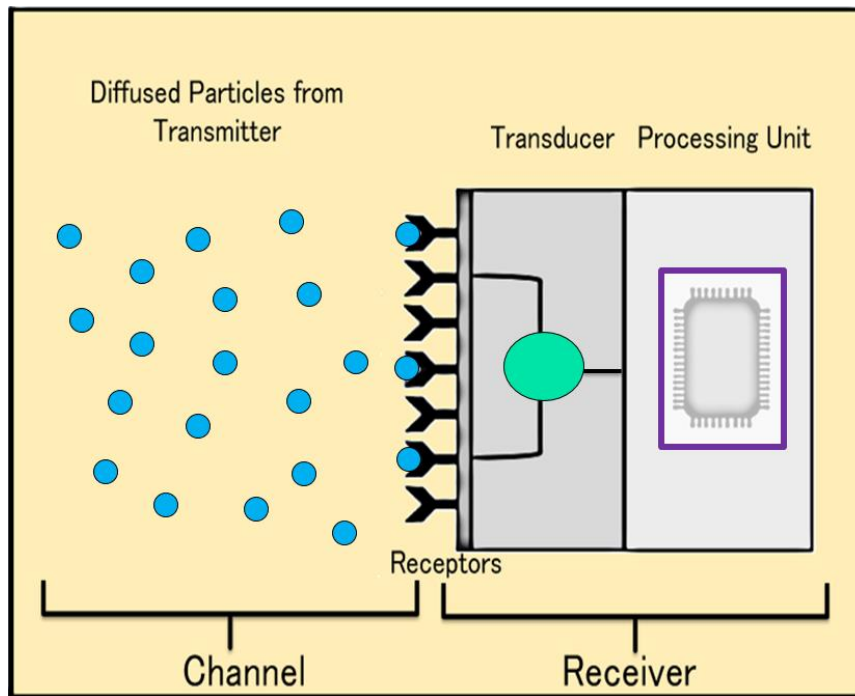


Figure 3.2 A typical MC receiver.

While the MC-Rx is designed, its competence for a mobile nano-machine with limited computer, cognitive flexibility and energy supplies that requires independent functioning should be considered in MC configuration.

3.2.1 Biological MC-Rx Architectures

Biological networking within living cells has seen remarkable advances over the past decade, by altering the biological genetic material trails or by establishing brand-new artificial ones. As a result, the engineered cells, i.e. bacteria, can be operated as biological machines for different applications e.g., sensors and actuators. Bio-nano-technology, by performing transportation and reception functions reception functions natural biological calls, is also an auspicious tool for developing molecular nano-devices for internet of bio-nano-things (IoBNT) applications [66].

The organic MC-receivers are promising because of their existence in lively applications such as supervision and observation of the living organism, e.g. human or animal diseases,

the restoration of organic tissues and parts of the body, targeted treatment of cancer, immune response assistance and nervous systems integrated synthetic products.

3.2.2 Nanomaterial-based Artificial MC-Rx Architectures

In-vivo as well as in-vitro applications can be utilized in the MC-Rx with artificial structures where bio-compatibility of the device and its bio-stability response must be investigated. Artificial MC-Rx can be utilized in areas such as environmental protection for identification of fiber, waste, poisonous or harmful chemicals, monitoring of food and water contamination and healthy processing of hazardous products, in addition to biomedical applications like as safety surveillance or drug distribution, which can also be carried out using biological MC-Rx [8].

3.3 System Design

The supposed model of MC system can be seen in Fig. 3.3. The transmitter produces and transmits particles into the media of transmission. The transmitter transmits the information-bits and modulate them by means of a device to transmit chemical molecules in the channel. At the receiver side, the particles are counted by the sensor and the amount of molecules absorbed during every time slot [3] is accumulated.

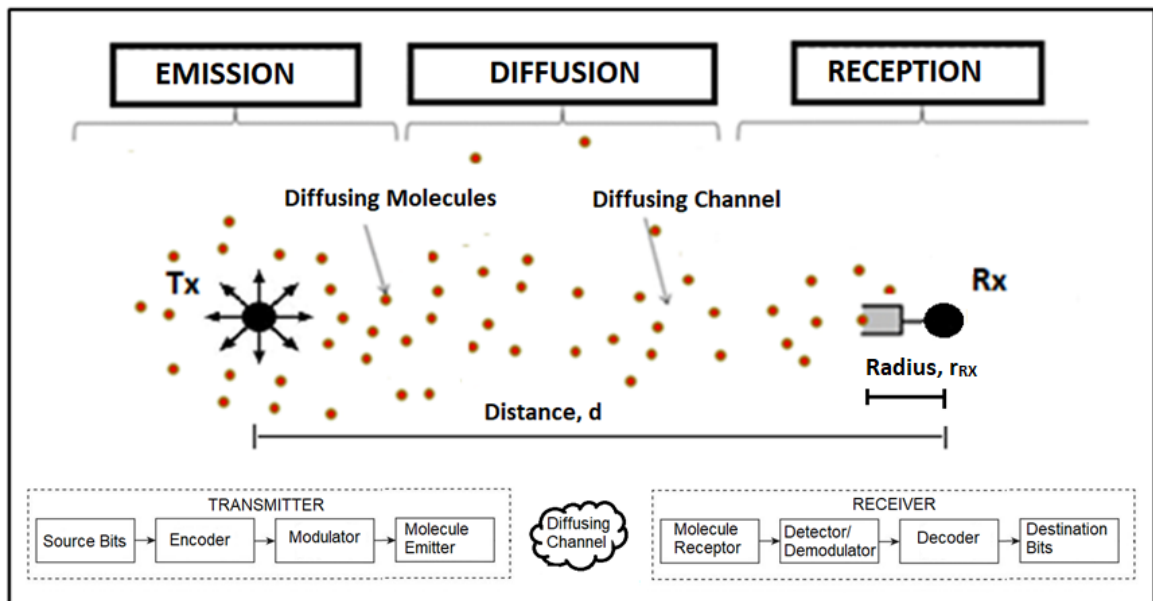


Figure 3.3 Molecular communication system.

A pre-determined demodulation threshold measures the amount of molecules consumed during each slot time. A microcontroller programs the demodulator and decoder block [9].

Complications that arise in a MCvD scheme can be congregated into two classes. The first type includes the glitches produced by the arbitrary mobility of the carrier molecules, i.e., dissemination of molecules. The haphazard motion of the carrier molecules restricts the volume of influential data related to the expected received signal, therefore it intensifies the rendering process of the data. It should be noticed that binary concentration shift keying (BCSK) commonly employs a already settled threshold at the receivers which will help in deciding the data to be received by the receiver. These threshold standards are typically premeditated empirically as follows: as soon as the data is received and the diffusion of data particles are ended, the receiver estimates the bit error rate for several detection threshold values and selects the best threshold that diminishes the rate of expected error, [17]. This process entails the receiver to recognize the communicated signal, which may form the process to be superfluous.

Conversely, a detailed sequence of model symbols can be calculated before the data is sent and the optimal threshold empirically delivered, as mentioned above. Owing to high sensitivity of the right threshold values to the order and the quantity of the distributed data symbols, this method may lead to complexities. If the system is to be illustrated adequately, the pilot symbols must be repeatedly sent, so that the system behavior can be understood in detail. Specific MC system parameters include optimal threshold values. This should be replicated from the beginning, if any of the system parameters, e.g. diffusion coefficient, transmitter or receiver radius and distance from transmitter to receiver etc. varies slightly.[28].

3.4 Problem Formation

As shown in the Fig. 3.4 as the flow diagram, the signal that being transmitted from the MC transmitter is received by the MC receiver. As the signal is being propagated in all direction there are multiple signals that creates a problem of receiving multiple signals at the receiver. This lead the receiver to face the ISI problem. Inorder to sort out the ISI, equalization of received signal should be applied at the receiver. As the signal is equalized

simultaneously noise enhancement also occurs. To diminish noise enhancement, channel threshold selection is implemented to neutralize the undesirable enhancement of noise.

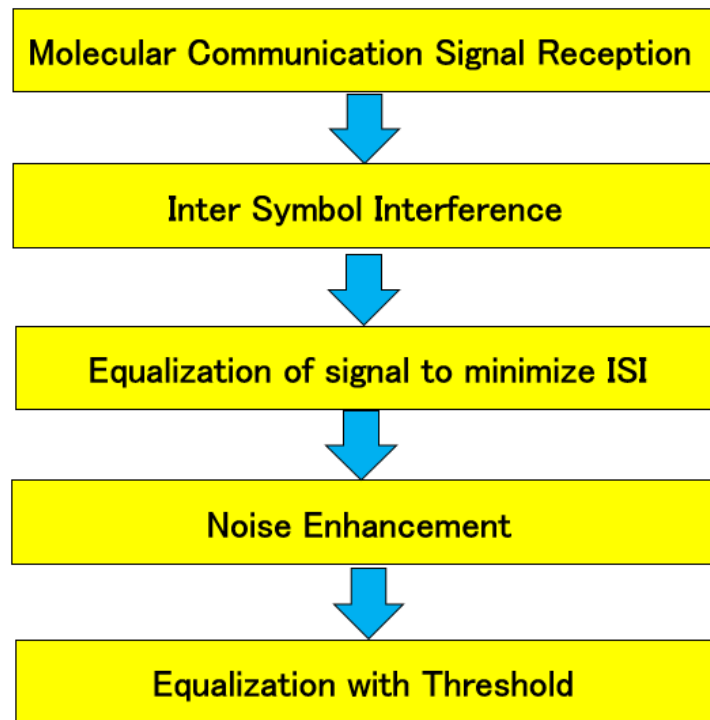


Figure 3.4 Problem formation.

3.5 ISI Introduction in MC systems

MC networks with biological cells are typically designed to relay message that is a time-varying control signal for the biological process .

The MC method that has fascinated the consideration of the communications research community is free diffusion [10, 43]. Previous investigational work has already established a operational macroscale model of diffusive communication system with drift in [42, 44]. Dissemination of molecules can be exhibited as a arbitrary random walk where particles strike by other particles in the propagation atmosphere. The principal benefit of MC is its effortlessness i.e. it's energy efficient, as particles that are disseminated by a source can freely travel lacking any exterior power or set-up requirements. The absence

of proper structure among nodes means that diffusion is suitable for the establishment of ad-hoc systems between portable devices. Diffusion can be very quick over little distances, and is a basic way of communication in the natural environment; various natural inside cell procedures depend on diffusion for restricted amounts of molecules to proficiently spread equally inside and among cells, as described in [7].

Nevertheless, the distance that a chemical signal in the form of particle travels is directly proportionate to the square-root of time it does to diffuse. Therefore; if the receiver is located farther out, MC systems must accommodate progressively longer propagation times. The randomness of the transmitter in diffusive MC is thus influenced in two ways by the reliability of a contact connection (i.e. between the broadcaster and the corresponding receiver First, molecules that not reach the receiver in due time (i.e. within the period of the symbol) when they're intended to arrive. Secondly, in a later period of time, molecules can reach the level of ISI. Some molecules may not reach the recipient depending on the model of the MC system .

The diffusion channel 's characteristics perform vital part in the distribution of the particles. Various molecules enter receiver whilst very little are remain around a channel that arrive later or vanished in the medium [20]. The ISI is a significant diffusion challenge. Any of the carrier molecules could fail in their anticipated duration to arrive at the receiver and in a subsequent symbol period can interfere with data molecules[21]. Higher data rates and improved performance are needed for MC systems, although noise and ISI are limited. Research on ISI mitigation in TDE is currently concentrated in MC[70]. As it is known, a simple and miniature equipment is required in nano communications systems. During FDE, multiplication operations are performed rather than applying tedious operation convolution and executed via simpler hardware. The use of FDE based on an MMSE criteria will benefit from channel frequency selectivity and thus increase its bit error rate (BER) performance [46].

[43] and [75] both have to deal with the same noise raise problem with the traditional MMSE equalization scheme by using decision feedback channel estimate. A decision input as well pilot integration at the receiver may be used to execute the channel

estimation. Only sub-carriers with high estimated channel response follow the decision feedback channel estimation in the conventional system[75]. If the estimated channel response is small, then only the pilot symbols are used to estimate the response. This last case is the same as the scheme suggested for this research with a threshold of zero.

MC channels appear to have low pass filter features where maximum amplitude channel responses focus on a zero-frequency portion. To avoid noise enhancement high frequency (HF) components should be removed rather than being equalized. Thus, in order to not emphasize noise power if equalizing coefficient is less than a threshold, this study proposed an FDE framework that removes frequency components of signal accordingly.

3.6 Channel Model

Significantly, MC analysis needs a thorough consideration of the data molecules propagation in the surrounding environment. The performance metrics e.g. throughput and consistency of the system can't be pronounced lest the passage between the transmitter and its receiver is described. Aimed at diffusive MC, the system should be capable of modeling the conduct of particles from the time they are disseminated by the source till sensed by the receiver and detached from the atmosphere.

Diffusion of molecules is a noisy process; it is an inadequate method which is best pronounced by a predictable CIR, i.e., the volume of data particles anticipated at a receiver once particles are transmitted by the source. The factors of the diffusive natural environment, that includes its dimensional geometry i.e. whether its 1-D or 3-D, the distance between MC-Tx to MC-Rx, the time elapsed since the molecules were released, and the diffusion coefficient of the molecules constitutes the anticipated CIR. Additional occurrences can likewise influence the performance of the diffusing molecules and henceforth the CIR.

According the description given above, MC CIR, $h_X(\tau)$ is characterized as the amount of molecules that will be reckoned on the receiver after a delay of τ , assuming that

the N molecules are instantly discharged by the transmitter at time $t = 0$. Below is the response of a channel impulse to a point transmitter [64]

$$h_x(\tau) = N * \operatorname{erfc} \left(\frac{d - r_{Rx}}{\sqrt{4D\tau}} \right) . \quad (3.1)$$

In Eq. (3.1), the channel is assumed to remain constant in the communication, i.e. a static channel is expected to be. Here $\operatorname{erfc}(\cdot)$ is known as the complementary error function. The coefficient of diffusion, D and recipient radius r_{Rx} have the pre-determined constant values. According to the restrictions on particle's power and magnitude, a basic modulation process for nano-molecules is assumed to be introduced.

According to the impulse response of a low pass filter the amplitudes are high at low frequencies but as the frequency increases the amplitude reduces accordingly. The problem arises that at high frequencies there is a risk of evident noise which may possibly occupy these frequencies as the signal is received. So, noise enhancement occurs which degrades the system performance.

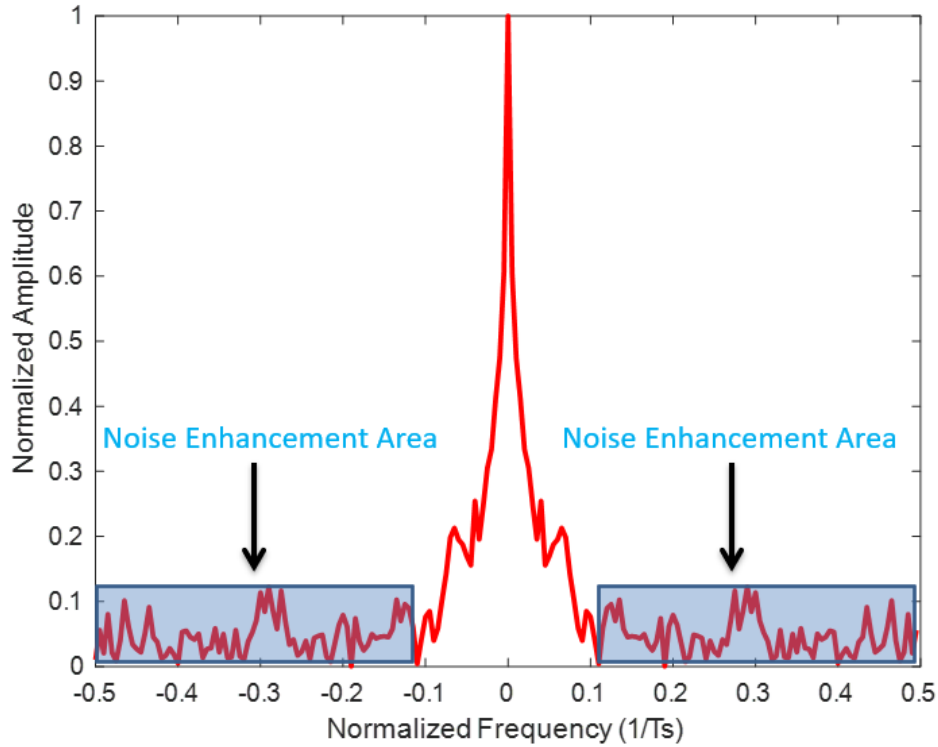


Figure 3.5 MC channel impulse response.

A typical CIR of a MC is shown in Fig. 3.5. It shows the similar behavior as of low pass filter response [44]. The CIR depicts that the amplitude tends to reduce as there is an increase in frequency, that makes it evident for noise to superimpose at the higher frequencies. Fig. 3.5 represents CIR of MC in frequency domain. The CIR is presented with respect to the normalized frequency. The digital transmission system frequently utilizes digital frequency, that is the ratio of the analog frequency and the sampling frequency. Generally, it ranges from 0 to 1, so in Fig. 3.5 the channel components are taken for frequency 0 to 0.5 and then shifted to see the response in negative frequencies as well. It is clearly seen that at zero frequency the CIR has maximum amplitude.

3.7 Method of Processing

The transmitter releases a preordained amount of molecules into the aqueous medium for the duration of every single symbol. The n th on-off modulation symbol is represented with $s(t)$ and

$$s(nT_s) = \begin{cases} 1 & \text{for information bit} = 1 \\ 0 & \text{for information bit} = 0 \end{cases} \quad (3.2)$$

where T_s is the symbol period.

The anticipated signal that ranges to the receiver side can be stated as

$$r(t) = s(\tau) \circledast h_x(\tau) + \sigma(t) \quad (3.3)$$

where $\sigma(t)$ is known as the additive white Gaussian distributed noise (AWGN) and \circledast denotes convolution [60]. In MC the structure of received signal $r(t)$ is analogous to that of AWGN channel with interfering signals in traditional wireless communication systems and variance of the normal distribution appeared at the receiver side is the power of the noise

3.8 Proposed Threshold Implementation Scheme

Equalization removes ISI in the FDE MMSE. The analog-digital converter, on the receiver side, samples the signal received and converts it to the frequency domain signal with the aid of M -point FFT. The k th frequency component of the received signal is given

as:

$$R_k = H_{xk} S_k + \sigma_k \quad (3.4)$$

where S_k is the k th element of the transmit signal, H_{xk} is the k th element of the channel response, and σ_k is the noise element in the k th frequency component. The coefficient of FDE MMSE for the k th frequency component of the received signal is given as [4]

$$W_k = \frac{H_{xk}}{H_{xk}^2 + \frac{\sigma_0}{E_s}} \quad (3.5)$$

where σ_0 is the noise spectrum density and E_s is the symbol energy. Equation (3.5) is also known as Wiener filter that is most favorable in provisions of the mean square error. In other words, with reversed filtering and noise compressing it reduces the overall mean square error. Wiener filtration is a linear estimate of the original signal that is emitted from transmitter.

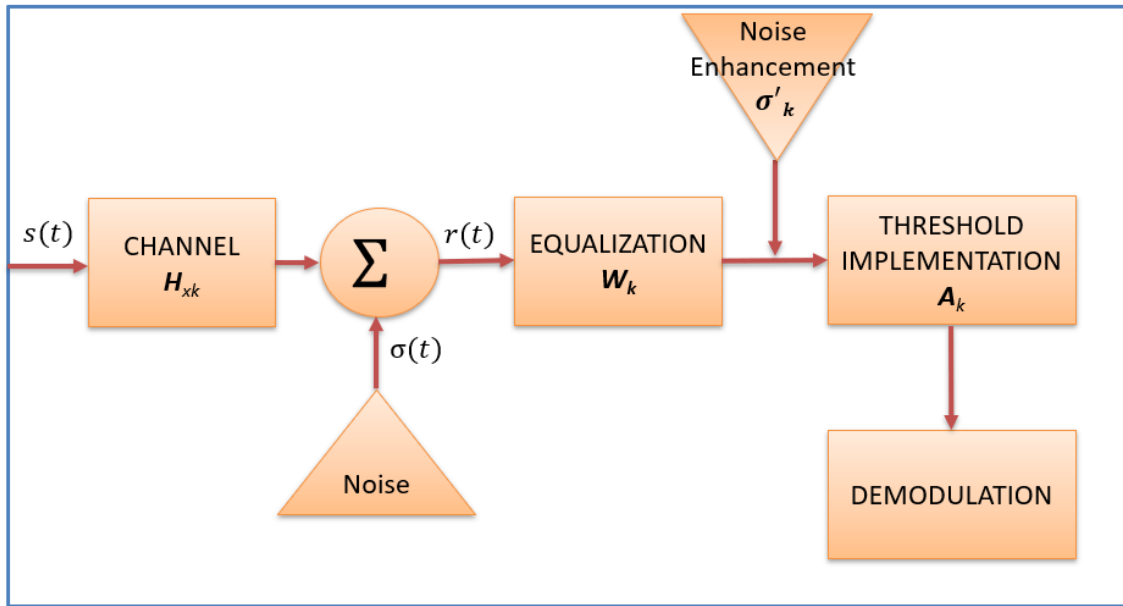


Fig. 3.6 Block diagram of proposed system

The block diagram whole system process is shown in Fig. 3.6. The transmitted signal $s(t)$ is transmitted by transmitter, propagated through channel response H_{xk} and received by the receiver as $r(t)$ which includes noise $\sigma(t)$ as well. From now onwards, FD signal

processing is implemented, to remove ISI. The received signal is equalized with respect to MMSE weights W_k . After the signal is equalized, due to the nature of signal as low pass filter, the noise enhancement $\sigma' (t)$ strikes the signal components at higher frequency. To remove the noise enhancement, the threshold is implemented a_k for the channel response H_{xk} to nullify all the signal components less than threshold. After wards the recovered signal is nearly equal to the transmitted signal $s(t)$ which is then taken for demodulation.

The issue with equalizing the obtained signal seems to be that equalization often stresses noise. The channel response must be matched with the pre-selected threshold in the proposed scheme, and the signal components set to null after equalization, if the resulting CIR is less than the threshold. To diminish the impact of noise development all the way through equalization. This process is symbolized as

$$A_k = \begin{cases} 0 & \text{for } H_{xk} < T_h \\ W_k R_k = W_k H_{xk} S_k + W_k \sigma_k & \text{for } H_{xk} \geq T_h \end{cases} \quad (3.6)$$

where A_k is the proposed equalized signal that incorporates threshold, R_k is the received signal and W_k is the MMSE equalizer coefficient for the k th frequency component. T_h is the preselected threshold value that is set for the normalized channel impulse response and it is less than and equal to 1.0. where T_h is the pre-selected estimate of threshold. If the channel response is too little, the term towards the right side of equality, $W_k N_k$, increases as the denominator of the right term in Eq. (3.5) approaches to $\frac{N_0}{E_S}$ that might be a minor value. Consequently, to avoid noise enhancement, W_k is set to zero for $H_{xk} < T_h$.

The frequency response of the MC channel for the FDE MMSE with the threshold ($\{R_k\}$ in Eq. 3.4). In Fig. 3.7 different cases of received signal have been shown, i.e. No signal, Delayed Signal, On Signal, and ISI signal. The symbol period is described as 0.5 sec. i.e. 1 sec for two symbols. It can be clearly seen that for On Signal represented by red has one maximum amplitude at the start of 1 second duration while ISI signal represented by black has one 2 maximum peaks for the duration. Similarly, the Delayed signal

represented by blue has one maximum amplitude at the middle of the time sequence at around 0.5 seconds while No Signal resented by green remains at zero amplitude throughout the 2-symbol duration transmission time. At this moment while mitigating the effect of ISI, the receiver experience noise enhancement when the signal is equalized.

As it can be seen in Fig. 3.7 that ISI does affect the MC channel that curtail the data rate. Now to improve this data rate an efficient frequency domain equalization technique can be applied. In this system, noise impacts produced by ISI has been focused. It can be characterized as the quantity of obstructing particles having a random probability distribution or pattern that may be analyzed statistically and confuses the recognition procedure. This interference at the receiver side reveals that the rate of received particles relies not only on the present diffusion of particles, but then again likewise on the earlier diffused bits. This effect leads to rise in error rate in demodulation since noise in the form of particles are added into the entire number of received bits.

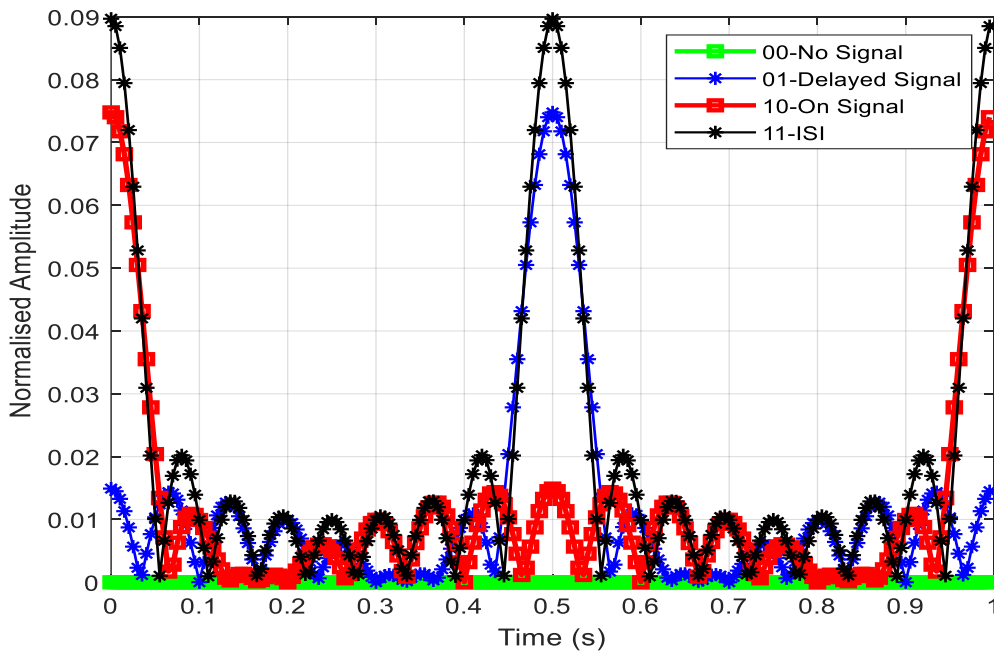


Figure 3.7 Different cases of received signal

Previously, as it has been described that the MC CIR remains constant and due to the random nature of particle propagation, ISI is being observed at the receiver. Also the MC CIR shows the behavior of low pass filter, i.e. majority of the power is concentrated

around zero frequency component, so in order to suppress the noise enhancement along the frequency spectrum at values that are away from the zero frequency component.

The threshold has been introduced in the channel response which straight away makes the amplitudes to zero at those values which are more than the threshold as portrayed in the Fig. 3.8. It represents the normalized channel response with and without threshold with respect to normalized frequency. The threshold has been selected according to the MC channel response. Threshold 0.10 is represented by green-star line, 0.12 is represented by red-circle line while 0.14 is represented by blue-x line. It is clearly visible that the number of data points selection increases as the threshold decreases and vice versa. Threshold is selected to limit the transmission bandwidth per symbol, so as the threshold is increased, less number of frequency will be utilized and receiver will not consider the data that lies at higher frequencies.

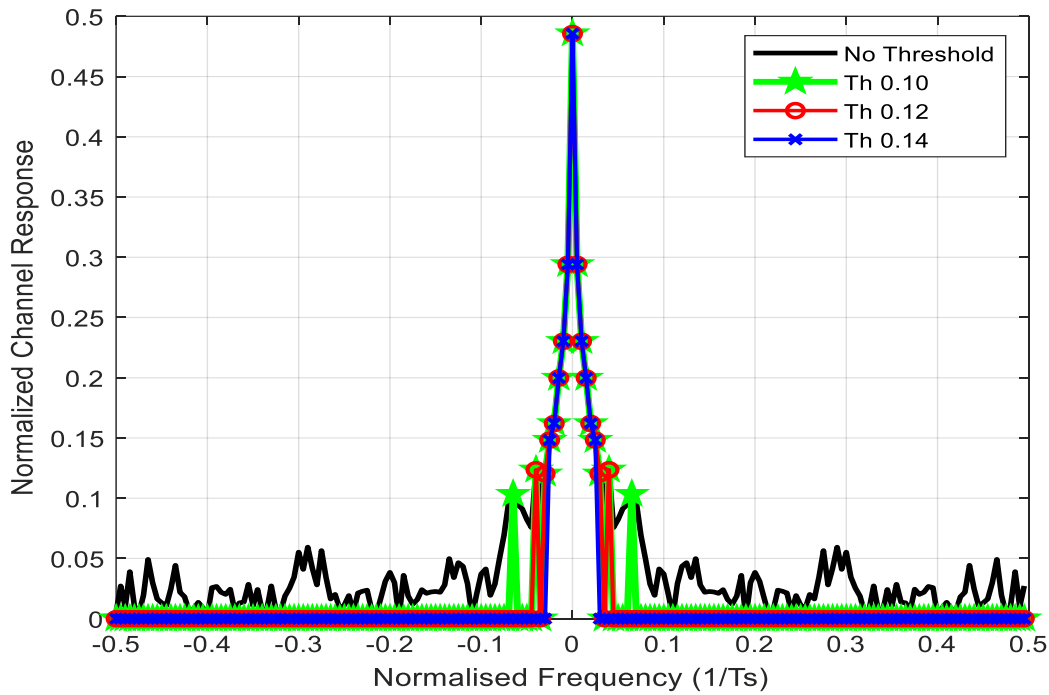


Figure 3.8 Normalized channel response.

3.9 Simulation Conditions

Table 3-1 Simulation parameters.

<u>Simulation Parameters</u>	<u>Values</u>
Number of Symbols	10^5
Symbol Duration (T_s)	1 sec
Threshold Range	[0 - 0.2]
Transmitter Radius (T_{RX})	1 μm
Receiver Radius (R_{RX})	1 μm
Molecules Released (N)	10^3 mol
Distance to Receiver (d)	5 & 8 μm
Diffusion Coefficient (Alcohol)	$9.59 * 10^{-5} \text{ m}^2/\text{s}$

In this research simulation on-off keying has been employed for the transmission of molecules. The transmitter and receiver are considered to of same size. The simulation considerations are described in Table 3-1. For each BER plot, number of symbols transmitted are 10^5 that are diffused and the diffusion coefficient of alcohol is $D = 9.59 * 10^{-6} \text{ m}^2/\text{s}$. The radius of the receiver is $r_{RX} = 1 \mu\text{m}$ and the distance between the transmitter and the receiver is $d = 5 \text{ \& } 8 \mu\text{m}$ respectively. As presented in Table 3-1. The total number of molecules transmitted are $N = 10^3$. The FFT size is taken to be, $M = 200$.

3.10 Performance Result & Analysis

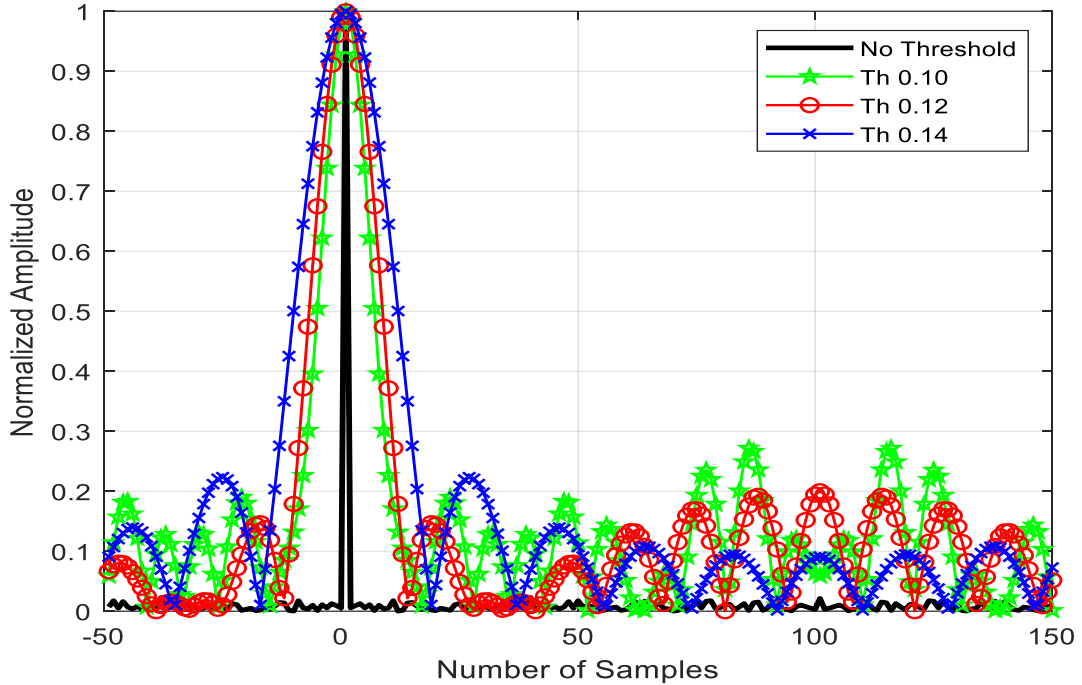


Figure 3.9 Equalized signal before detection.

In Fig. 3.9 threshold 0.10 is represented by green-star line, 0.12 is represented by red-circle line, 0.14 is represented by blue-x line while No Threshold is shown by black line. The On signal has been considered for transmission while the signal is received and equalized, the equalized signal experiences noise enhancement due to the presence of ISI that can be minimized due to the induction of threshold into the MC system.

From Fig 3.9 it is evident that at the point of 100 samples, the pulse amplitude induces ISI, as 100 samples are the symbol interval. At 100 samples, the ratio between the average amplitude and the amplitude depends on the thresholds as shown in Fig. 3.8 . The interference with the following pulse is fairly small when the limit value is 0.10, or 0.14, whereas the interference with the following pulse is high if it is 0.12. The performance of the system is therefore closely related to the ISI level.

3.10.1 MC system analysis for 5 μ m distance

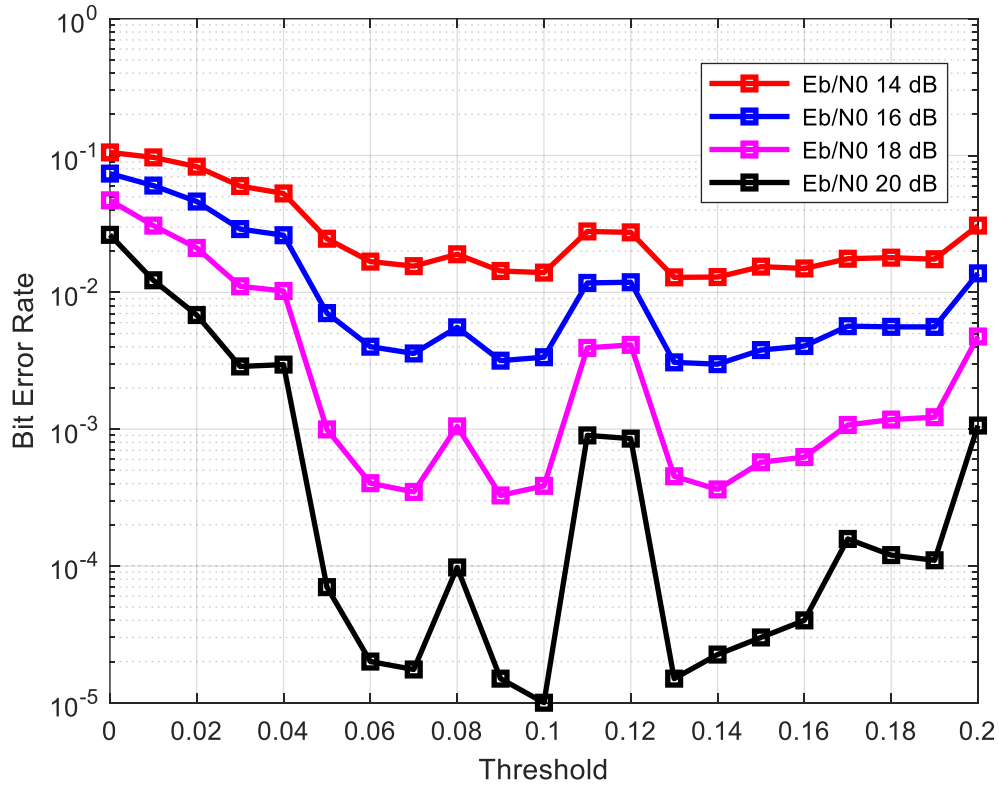


Figure 3.10 Relation between BER and threshold at 5 μ m.

As illustrated in Fig. 3.10, BER declines significantly until the threshold is varied and approaches 0.10. The BER rises at 0.11 and 0.12 stages, however. This is because the system performance is affected by the ISI. Fig. 3.9 & Fig. 3.10 mutually correlate to each-other. The increase in the BER at the different threshold values means that the selection of a given threshold value is not only based on the noise change, but also on the pulse waveform. The pulse wave type and the noise level following the equalization therefore determine if threshold values are selected.

In Fig. 3.10 threshold verses BER for On Off keying OOK is shown for different E_b/N_0 values . On the x-axis BER while on the y-axis Threshold ranging from 0 to 0.2 is taken. The graph values are taken when the distance among transmitter and receiver is 5 μ m. as the threshold is increased, it is seen that for both of the systems, the BER is decreases until it reaches the 0.10 , while increases in the for 0.11 and 0.12 respectively and then the BER for rest of the threshold values.

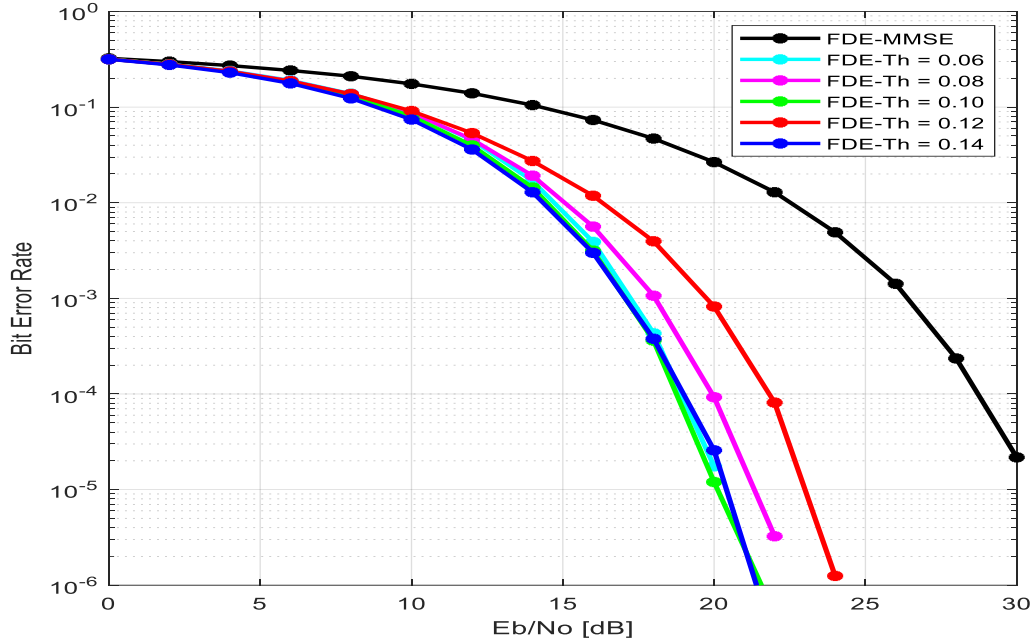


Figure 3.11 Relation between BER and E_b/N_0 at $5\mu\text{m}$.

The BER performance compared with the bits-energy-to-noise-spectrum-density (E_b / N_0) are shown in Fig. 3.11. The traditional FDE-MMSE feedback channel estimates indicate the worst quality of performance due to noise enhancement at a threshold value of zero. On the other hand, it is obvious that for a threshold value of 0.10 the proposed system achieves the best results possible. Since the threshold is from 0.06 to 0.14, BERs display weaker BERs as a consequence of the ISI with the other threshold values. Among all the threshold values, 0.12 depicts the worst performance. This can also be verified by Fig. 3.10. In both figures, threshold 0.12 depicts the worst performance while threshold 0.10 shows the best performance with minimum BER

3.10.2 MC system analysis for $8\mu\text{m}$ distance

In Fig. 3.12 where distance, d between MC transmitter and receiver is shifted to $8\mu\text{m}$ while rest of the simulation parameters remains same is shown. It is clearly depicted that the minimum BER is achieved at the threshold value of 0.05 while after that the BER increase to a maximum value at threshold 0.08 & 0.1 respectively. After that, the BER reduces and remains constant. The BER vs. threshold graph is being implemented for

different E_b/N_0 values ranging from 14 dB to 20 dB with a step size of 2 dB. The best performance is achieved at 20 dB E_b/N_0 with a threshold of 0.05.

The rise in the BER at particular values of threshold shows that a simple threshold value cannot be used in the Molecular Communication so we have to normalize and optimize the threshold. The increase and plunge in BER at particular threshold values shows the novelty in the FDE system design.

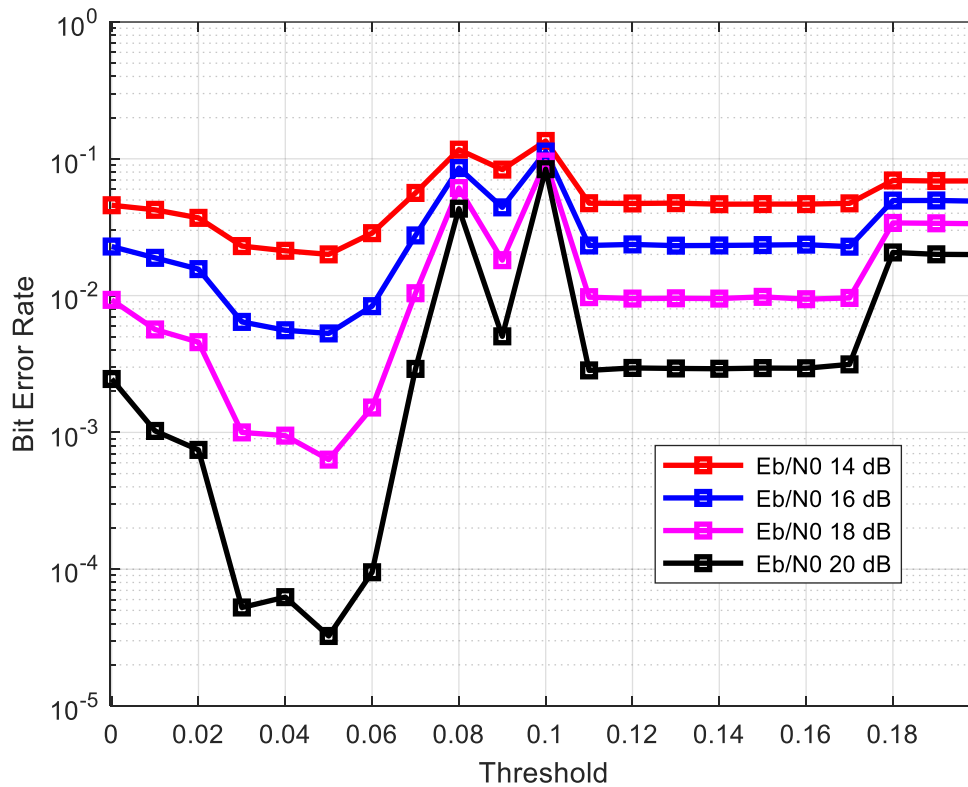


Figure 3.5 Relation between BER and Threshold at $8\mu\text{m}$.

The BER efficiencies compared with the bits from energy to noise from spectrum density (E_b / N_0) are shown in Fig. 3.13. A conventional FDE-MMSE with an estimate of the feedback channel at a value of zero due to noise improvement reveals the worst performance. On the other hand, for a 0.06 threshold value, the proposed method provides optimum performance. Since the threshold is from 0.06 to 0.14, it displays poor system performance in terms of BER as a consequence of the ISI with the other threshold values. Among all the threshold values, 0.10 depicts the worst performance. This can also be

verified by Fig. 3.12. In both figures, threshold 0.10 depicts the worst performance while threshold 0.06 shows the best performance with minimum BER.

While discussing the relation between threshold and system performance with respect to the distance between MC transmitter and receiver, it is observed that as the distance changes the threshold value for optimum system performance also changes as well.

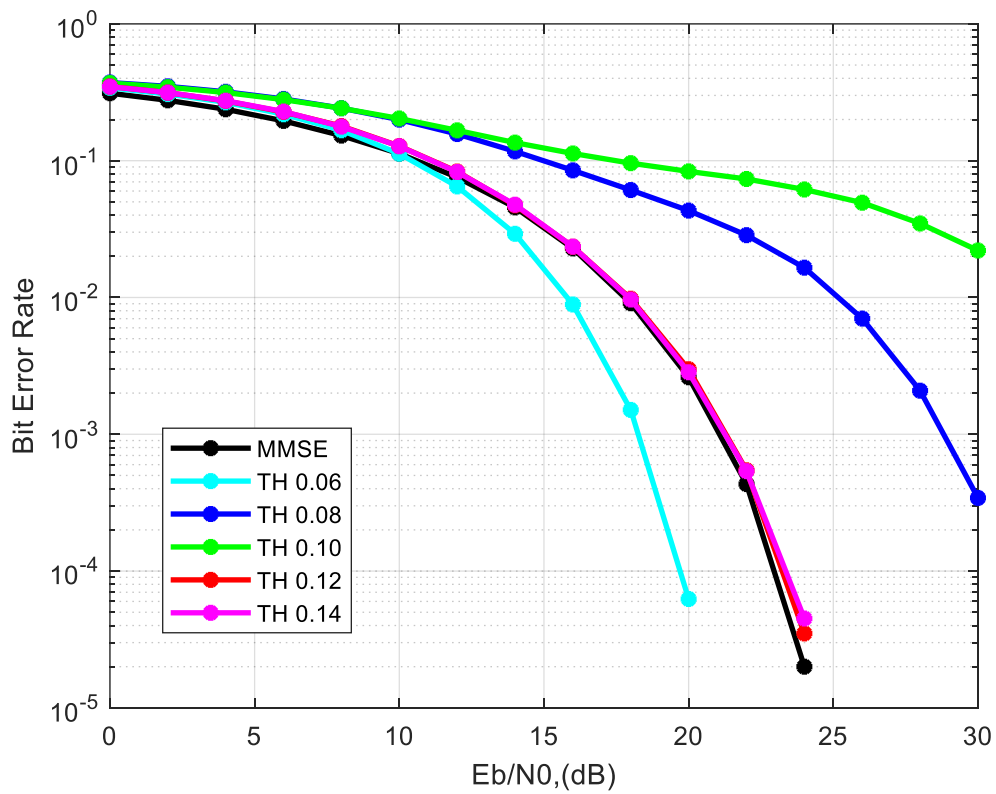


Figure 3.6 Relation between BER and E_b/N_0 at $8\mu\text{m}$.

3.11 Conclusion

This chapter has addressed equalization of the frequency domain on the MC receiver side. To boost device efficiency for diffusion-based molecular communication FDE MMSE with threshold has been suggested. The technique proposed is used to eliminate the noise increase induced by the limited threshold of FDE MMSE equalization. As shown in the previous sections, large channel responses are focused on a zero-frequency component. The sum of ISI after FDE varies depending on the threshold value. Therefore, after FDE effects on the BER output, a compromise between noise improvement and the pulse waveform.

Chapter # 4

Implementation of Frequency Domain Precoding at the Transmitter side of Molecular Communication Systems

4.1 Introduction

Diffusion-based MC is a unique and utmost desirable approaches intended for the interactions between nanoscale devices because of its distinctive affinity to biochemically active entities and instruments, for example the distribution of aerial pheromones between insects or the reproduction of calcium between active and living cells, and from these tremendous submissions can be taken into account in nano-sensing and nano-medicine [70].

According to the expulsion of molecules from transmitter MC can be divided into two main types.

■ Instantaneous Release

Instantaneous release of the molecules is ideal for communication which requires rapid fade out. For example, release of a volatile substance which evaporates quickly in the air.

■ Continuous Release

This type of communication requires constant discharge of data molecules e.g. healthcare applications, drug delivery for effective absorption of medication and 24/7 Monitoring of human body. In healthcare applications of molecular communication, continuous release of molecules is of importance in the existence of an appropriate concentration of drugs during the treatment period at the target site.

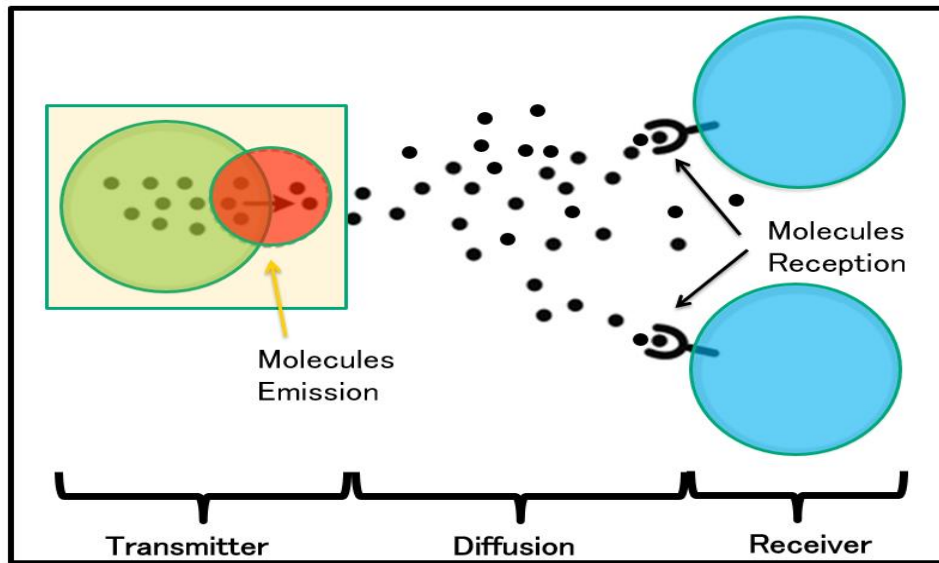


Figure 4.1 An end to end MC System.

As shown in Fig. 4.1, the MC system comprises of a transmitter, a surrounding environment known as channel and the receiver. The message is being encoded in tiny particles known as data molecules which after getting emitted from the transmitter diffuse in to the channel and after traveling a certain distance it reaches the receiver where it is accepted and encoded message is decoded for the real message. There are various issues that are being discussed for efficient data transfer between source and destination.

ISI is one of the concerns of MC. There are various methods in the literature to transmit and receive the ISI. In [51] the reduction of noise by equalizing a signal with FDE was solved by reaching a threshold on the side of a receiver. In a certain situations, a transmitter has to cover the more complexity of a network. Therefore, FD precoding of signal at the transmitter side is examined and CIR with thresholds are also implemented in the proposed framework. The estimate of equalized waveform is also employed because of the restriction of the transmitter on MC. Under the scheme suggested, an approximated rectangular waveform is transmitted that relates to the majority of precoding waveform and system performance has been investigated.

4.1.1 Zero Forcing Precoding

Precoding is the process of removing of ISI by equalizing the signal before transmission so that the receiver should be relaxed for extra processing to tackle the problem of ISI. It could be done in TD as well as in FD. The famous precoding technique is incorporating zero forcing equalization at the transmitter side. The strategy for linear equalizer design for ZF is to select the equalizing coefficient to be the inverse of the channel that will remove the ISI:

$$W_k = \left| \frac{H_{xk}^*}{H_{xk}^2} \right| \quad (4.1)$$

In Eq. (4.1) ISI is forced to be zero due to ZF equalizer where H_{xk} is the CIR at the k th frequency bin and $(.)^*$ denotes the conjugate.

Presenting in some sense ZF linear equalizer is the opposite of the matched filters (MF). It offers attenuation at the frequencies that are boosted by the channel, but it offers amplification when channel attenuate the frequency. Generally, a ZF linear equalizer has an inexhaustible range of noise when the response in the channel is zero at one or possibly multiple frequencies, and it performs badly when the channel has an almost spectral zero at one or more frequencies [68].

4.2 Molecular Communication Transmitters

Molecular communication transmitter (MC-Tx) encodes and releases the information molecules (IM's) appropriately in the physical properties of molecules, such as intensity, size, and release time. For this purpose, info to be transmitted must be assigned to bits by source and then by channel, so that the information is represented by fewer bits, and extra data bits to the original data are added in order to correct the transmission error. The processing unit encodes molecular information and controls the release of IMs by a preset modulation system. Finally, the MC-Tx energy and IM molecules must be supplied by a source of power for releasing and information molecules generator / container [46]. These components are interconnected with an MC-Tx as shown in the Figure. 4.2. The release of molecules is decided by the concentration of inside and outside of transmitter.

The transmitter tends to release molecules into the channel when the inside concentration is more than outside.

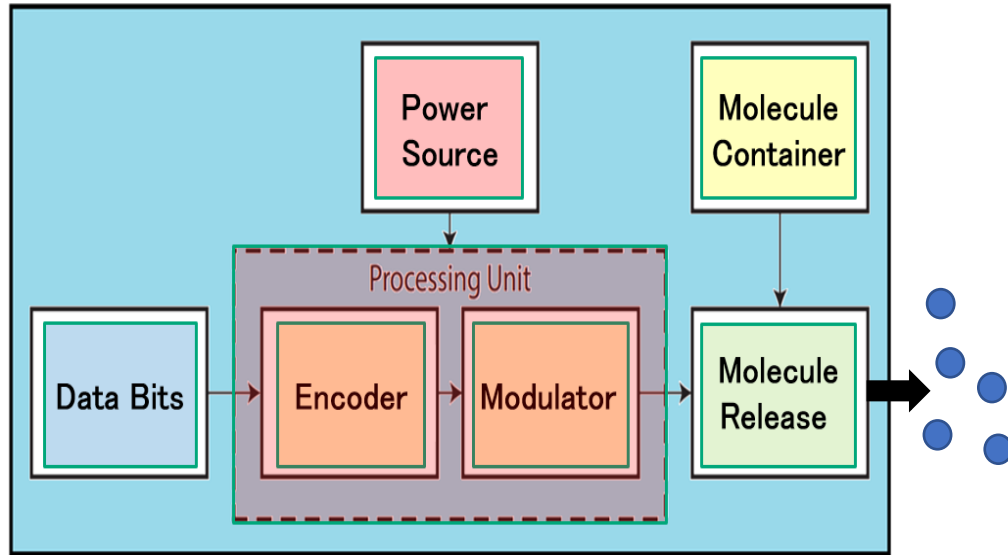


Figure 4.2 Molecular communication transmitter module.

4.2.1 RC circuit-based MC Tx

A parallel resistance capacitance (RC) circuit as shown in Fig. 4.3 can be modelled as MC Tx [71]. It can be related to the charging of a capacitor that leads to accumulation of molecules inside the transmitter. Similarly, when transmitter tends releases molecules then it relates to the capacitor being discharged.

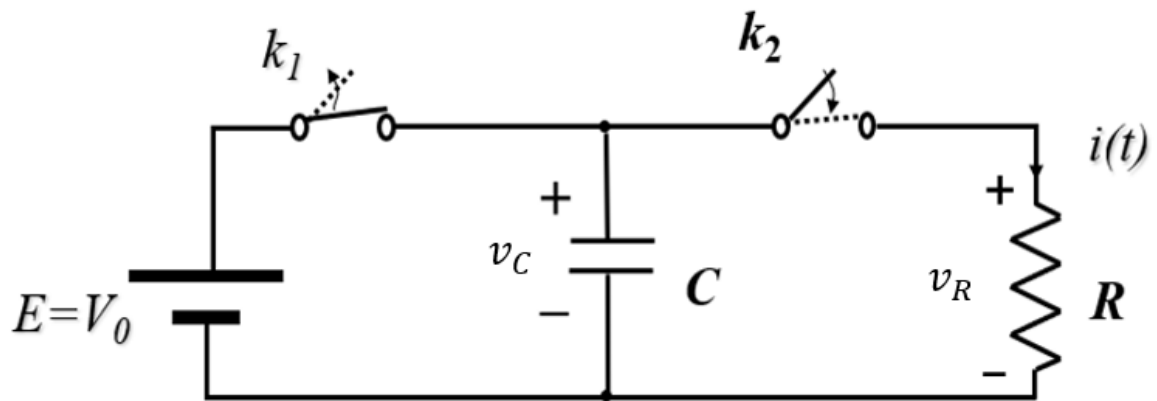


Figure 4.3 RC equivalent MC transmitter.

In Fig.4.3., the linear time-invariant capacitor with capacitance C is charged to a potential V_0 by a constant voltage source at this moment the switch k_1 is closed while k_2 is at opened state. At $t=0$ the switch k_1 is opened, and switch k_2 is closed simultaneously. A charged capacitor is attached to a resistor, now the capacitor charge flows out to the resistance R in the form of current $i(t)$.

A linear time-invariant capacitor with capacitance C is charged to a potential V_0 by a constant voltage source.

Kirchhoff's laws and Fig. 4.3 dictate the following equations:

According to Kirchhoff's voltage law (KVL),

$$v_c(t) = v_R(t) \quad t \geq 0 \quad (4.2)$$

where v_c is the voltage across capacitor while v_R is the voltage across resistor.

According to Kirchhoff's current law (KCL),

$$i_c(t) + i_R(t) = 0 \quad t \geq 0 \quad (4.3)$$

where i_c is the current in capacitor branch while current across the resistor is i_R .

The two branch equations for the two circuits elements are:

$$\text{Resistor} \quad v_R(t) = Ri_R \quad (4.4)$$

$$\text{Capacitor} \quad i_c = C \frac{dv_c}{dt} \quad \text{and } v_c = V_0 \quad (4.5)$$

Equivalently,

$$v_c(t) = V_0 + \frac{1}{C} \int_0^t i_c(t') dt' \quad (4.6)$$

Eq. (4.4) emphasizes the initial condition.

Therefore, the two branch voltages v_c and v_R and two branch currents i_c and. The circuit has been given with a full mathematical explanation and all unknown parameters can be resolved

$$\frac{dv_C}{dt} = i_C = -i_R = \frac{v_R}{R} = \frac{v_C}{R} \quad \& \quad v_C = V_0 \quad (4.7)$$

$$C \frac{dv_C}{dt} + \frac{v_C}{R} = 0 \quad \text{for } t \geq 0 \quad \& \quad v_C = V_0 \quad (4.8)$$

This is a first-order linear homogeneous differential equation. The solution is in the exponential form, i.e.

$$V_C(t) = K e^{S_0 t} \quad (4.9)$$

Where

$$S_0 = -\frac{1}{RC} \quad (4.10)$$

This easily verified by direct substitution of Eqs. (4.9) and (4.10) in the differential Eq. (4.8). In Eq. (4.9) from the initial conditions, K is a constant that needs to be determined.

Setting $t=0$ in Eq. (4.9), implies $v_C(0) = K = V_0$. Therefore, the solution to the problem is given by

$$V_C(t) = V_0 e^{-(\frac{1}{RC})t} \quad t \geq 0 \quad (4.11)$$

The rate of concentration of particles by the source is provided by:

$$c_{out}(t) = \frac{d}{dt} q_T(t) \quad (4.12)$$

As already explained in Fig. 4.1, the transmitter is modelled as a cubical container with an inside molecule concentration, c_{in} , an opening that links the interior to the exterior of the transmitter. The concentration at the outside of transmitter is denoted by c_{out} . When data bits increase i.e. $p_t(t)$, the transmitter increments c_{in} .

Increasing $q_T(t) \rightarrow$ incrementing the outgoing particle flux

\rightarrow the production of output molecules.

The particle concentration rate $q_T(t)$ obtained at the transmitter is the current $i_R(t)$ that flows through the resistor R . Particle concentration rate $q_T(t)$ at the MC source is the input current $I_{in}(t)$. The particle concentration gradient $\nabla C_T(t)$ at the MC source the voltage $V_0(t)$. The particle concentration rate $q_T(t)$ at the transmitter is analogous to the current $I_R(t)$ passing all through the resistor R .

The particle concentration rate $q_T(t)$ is the given by the particle concentration per unit time exiting the transmitter that's the particle concentration flux $J_T(t)$. The relationship among $J(d, t)$ the particle concentration flux and $\nabla_c (d, t)$ at time t and distance d is offered by the Fick's first law of diffusion.

$$J(d, t) = -D\nabla_c (d, t) \quad . \quad (4.13)$$

where D is the diffusion coefficient.

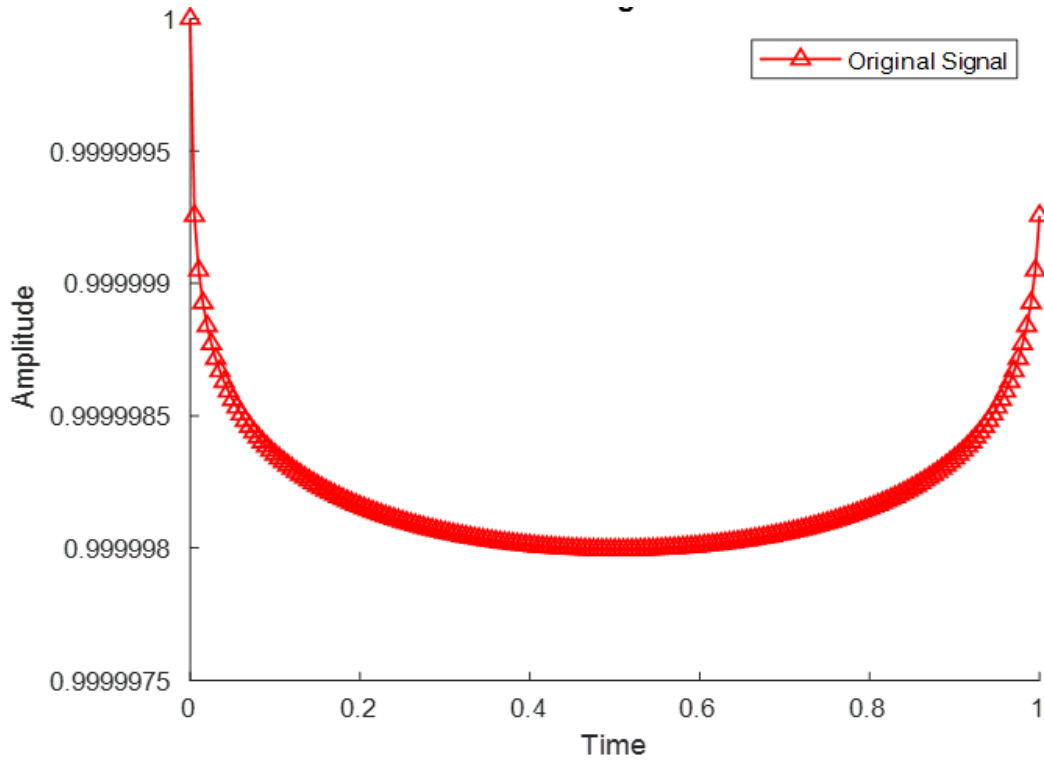


Figure 4.4 RC circuit equivalent waveform in time domain.

As shown in Fig. 4.4 the output of the RC circuit is nearly a constant with a certain amplitude for a certain period. Here it can be seen that the amplitude ranges between 0.999985 to 0.999995 for a time period of 1 sec. This develops the RC circuit to be equal to maximum amplitude of almost equal to 1. It can be concluded that MC-Tx with constant release of molecules can be modeled as RC circuit. According to the equivalent RC circuit of the MC transmitter the output waveform is almost a rectangular waveform.

So, it can be determined according to the calculations done above that,

$$I_R(t) = J_T(t) \quad (4.14)$$

&

$$V_C(t) = \nabla_C(t) \quad (4.15)$$

$$\Rightarrow I_R(t) = Dv_c(t) \quad (4.16)$$

So according to the ohms law,

$$V = IR \quad (4.17)$$

\Rightarrow

The constant resistance value becomes

$$R_e = 1/D \quad (4.18)$$

Therefore, The value of capacitance

$$C_e = 1 \quad (4.19)$$

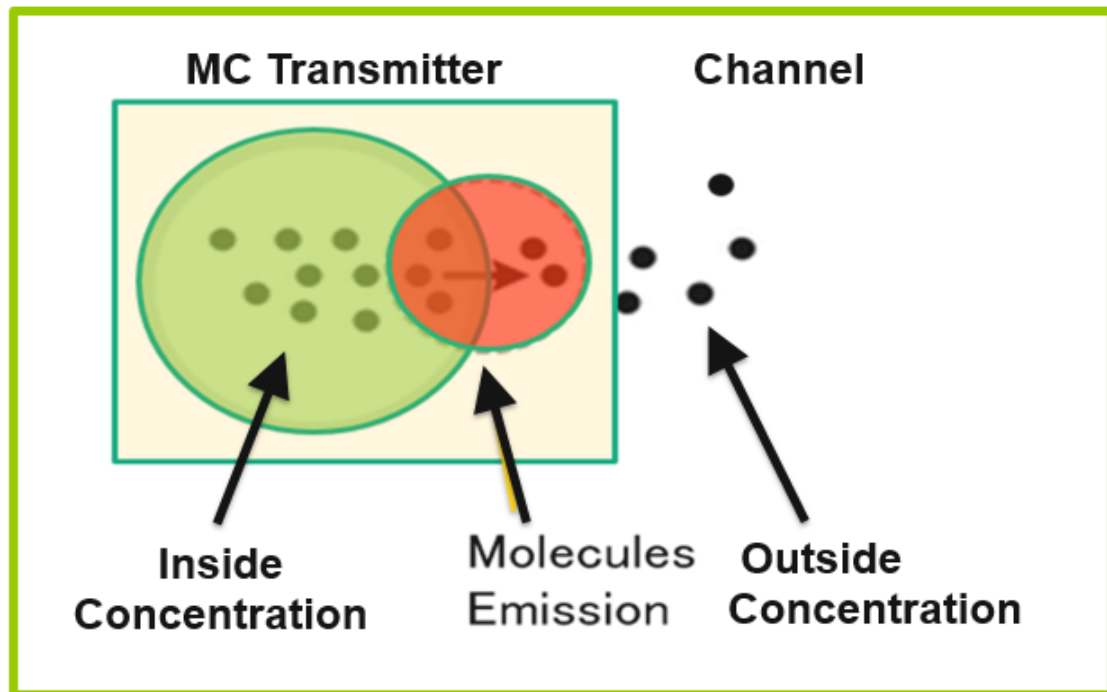


Figure 4.5An MC transmitter.

As shown in the Fig. 4.5 rate of molecules emission rely on the change between the inside concentration of particles inside transmitter and outside concentration of molecules in the channel. Relating it to the RC parallel circuit, the charging of the capacitor is the inside concentration while discharging of the transmitter is termed as outised concentrartion of molecules. It is also assumed that there is a constant relaese of molecules in the surrounding vacinity which is applicable in majority of fields in our daily life.

4.3 Problem Formation

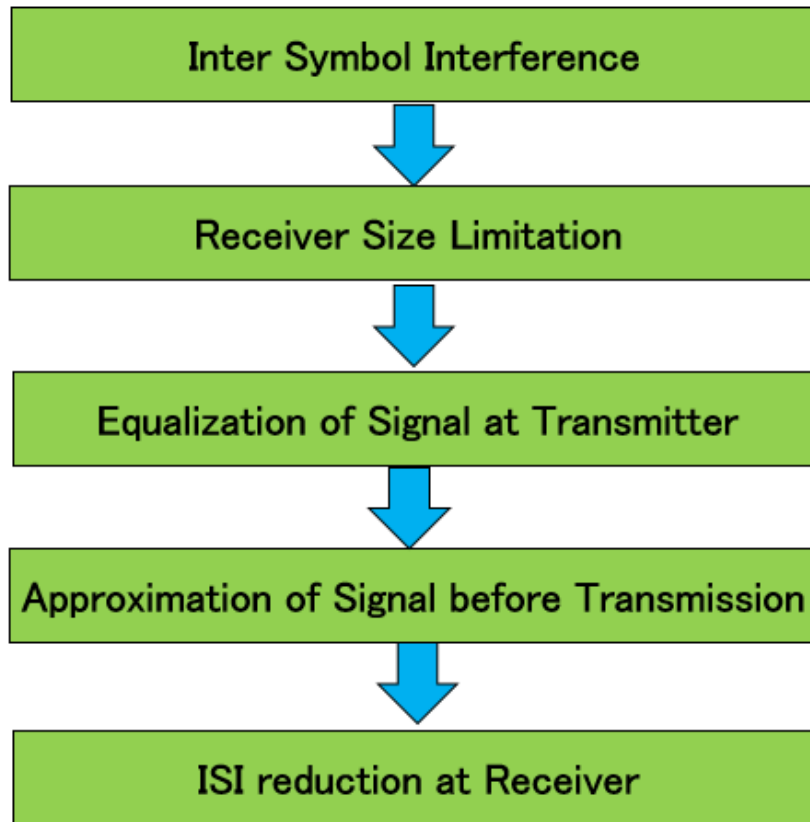


Figure 4.6 Problem formation.

The basic problem for an efficient communication system via MC is the presence of ISI at the receiving side as shown in Fig. 4.6. As with our previous understanding, MC receiver hardware size must be kept small so that it be kept as portable so for that reason, MC-Rx must be relieved of extra processing. In order to give relief to the receiver, transmitter can be equipped with additional signal processing. With this intention, in order to mitigate ISI, equalization should be performed at the MC-Tx. Precoding at the transmitter can be accomplished by approximating the communicated signal. Hence received signal will be free of experiencing ISI and ultimately efficient end to end communication link is accomplished.

4.4 System Design

In [51] is the proposed MC structure pattern. A slit opening in the diffusion medium creates and releases N numbers of molecules. The transmitter loads the information bits and equalizes the signal in a frequency zone and modulates them by a system which can generate biochemical particles in a channel into a biochemical signal. The molecules distributed are initially uniformly spread all over the surrounding area. In shape of molecules, the particle is measured to be low absorption in order to disperse the molecules into an environment with a diffusing coefficient, D . They dispersed in the environment conferring to Brownian motion and arrive at a receiver [2]. Presently, particles in the shape of small droplets of alcohol are presumed. The n th on-off modulation symbol with a duration, T_s , is denoted with s as

$$s = \begin{cases} 1 & \text{for information bit} = 1 \\ 0 & \text{for information bit} = 0. \end{cases} \quad (4.20)$$

The transmitting pulse has been estimated by an RC parallel equivalent circuit that is given by [71, pp. 20-22]

$$v_X(t) = s e^{-\left(\frac{1}{RC}\right)t} \quad t \geq 0 \quad (4.21)$$

where v_X is the output voltage level of transmitter in the form of alcohol molecules. The value of constant resistance value is given as $R = \frac{1}{D}$ where D is the diffusion coefficient and the value of capacitor $C = 1$. The resulting waveform is almost rectangular [71, p 21] because the RC value is as high as Fig 4.7 displays the resulting rectangular waveform. Only amplitude and pulse duration are assumed to be adjustable due to the restriction in the transmitter. The rectangular pulse is a standard form of pulse waveform modeled in [3].

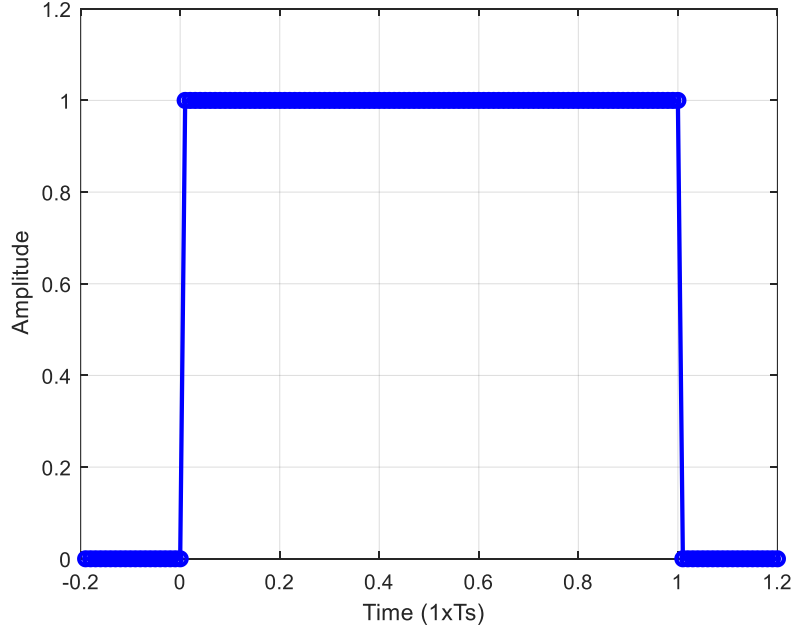


Figure 4.7 RC circuit generated rectangular pulse.

The impulse response of an MC channel is defined as the probable number of molecules measured in one specific position due to the continuous and constant release of a transmitter at a time $t=0$. The broadcasting phase is described as Brownian movement, and the channel's pulse response is denoted by $h_X(\tau)$ which is due to the conversion by means of a conversion circuit in the receiver from the number of molecules obtained with a sensor to a delay τ and expressed by [3]:

$$h_X(\tau) = N \operatorname{erfc} \left(\frac{d - r_{RX}}{\sqrt{4D\tau}} \right) . \quad (4.22)$$

Here d is the distance between the transmitter and the receiver and r_{RX} is the radius of the receiver. It is supposed that the channel stays persistent during the communication in Eq. (3), while diffusion coefficient is given by

$$D = \frac{k_B T}{6\pi\delta r_H} \quad (4.23)$$

where k_B is the Boltzmann constant, T the temperature of the surrounding environment, δ is the dynamic viscosity of the liquid, and r_H is the radius of received molecules.

After the diffusion process, a single chemical receptor is used to receive information content. The recipient lists the incoming molecules on the receiving side by means of a

sensor and records the amount of data particles involved across each time span [69]. The greatest problem for symbol identification is to interact with that in the present time frame, i.e. symbol interference, and to the symbol interval, with the molecules arriving in the receptor in the next time slot [70]. In each time-span, the number of inserted molecules is matched with an adaptive threshold to detect errors. The source has a r_{RX} radius and is located at d from the transmitter core. The probable signal received by the receiver is

$$r(t) = v_X(\tau) \circledast h_X(\tau) + \sigma(t) \quad (4.24)$$

where $\sigma(t)$ is known as the additive white Gaussian distributed noise (AWGN) and \circledast implies convolution [60].

4.4.1 Step by step Procedure

An end to end procedure for implementation of the FDE precoding at the transmitter side is given as follows.

1. On & Off pulse formation
2. Converting the CIR & data pulses in FD
3. Equalize the signal with ZF weights in FD
4. Converting to TD for normalization
5. Approximating the normalized and equalized signal
6. Signal ready to be released from the Transmitter
7. Converting to FD for multiplication with channel
8. Converting back to TD for signal to be detected at the receiver
9. Creating multipath scenarios at the receiver.
10. Adding noise
11. Detecting errors for system performance

4.5 Proposed Precoding Scheme

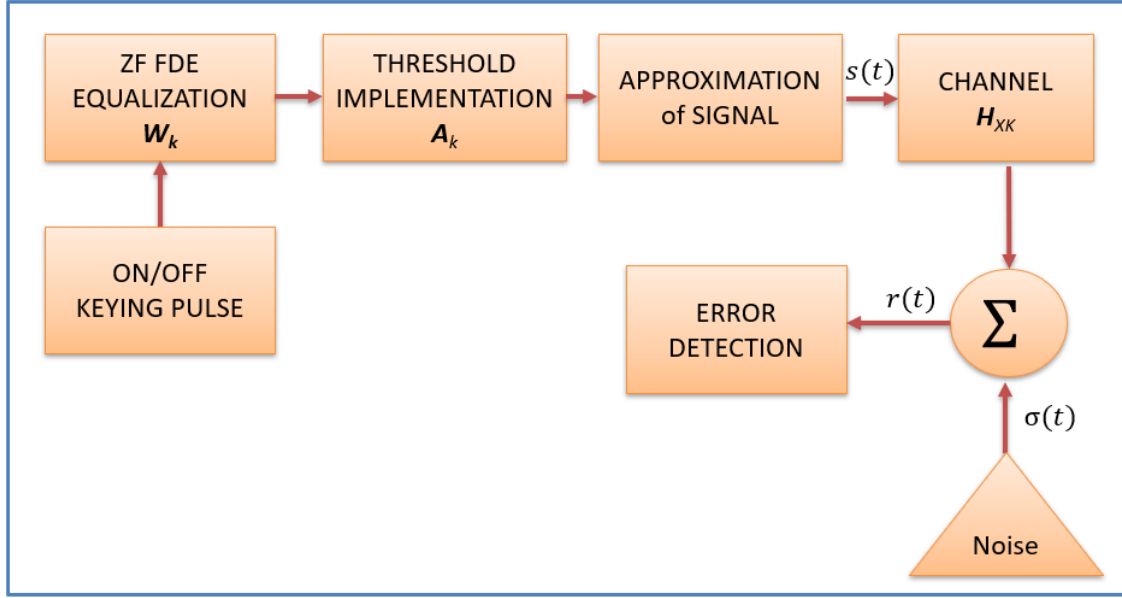


Figure 4.8 Block diagram of proposed scheme.

Block diagram of overall procedure including the proposed scheme has been illustrated in Fig. 4.8. It is clear from the figure that initially a information pulse has been generated through on/off keying (OOK). The signal is converted to FD. Then the signal is equalized with ZF through FDE. Then again, the threshold has been implemented for the signal to be equalized and is approximated to rectangular wave, afterwards the signal is ready to be released from transmitter. The signal passes through the channel and makes to the receiver. Here the noise has been added and then errors are counted for the system performance.

Precoding eliminates ISI by a transmitter side equalization. Depending on the channel response, the transmission waveform may be equalized in the frequency domain. The ZF coefficient for the k th frequency of the signal is defined as

$$W_k = \frac{H_{xk}^*}{|H_{xk}|^2} \quad (4.25)$$

where H_{xk} is the channel response on the k th frequency bin and $(.)^*$ denotes the conjugate.

The pre-coded signal is correlated with a predetermined threshold in this suggested scheme and the frequency elements are set to zero after equalization when the channel output is below the given threshold level. This is because the MC channel [51] is transmitted only with low frequency components. The key portion of the signal can then be approximated to a rectangular wave, since the transmitter will produce only the rectangular wave shape. The coefficients selection process is shown as

$$A_k = \begin{cases} 0 & \text{for } H_{xk} < T_h \\ W_k s_k & \text{for } H_{xk} \geq T_h \end{cases} \quad (4.26)$$

where A_k is the proposed pre-coded signal and T_h is the preselected threshold value that is set for the normalized channel impulse response. s_k is on-off modulation symbol on the k th frequency bin that has already been defined in Eq. (4.20).

Fig. 4.9 displays the waveform with one symbol length. The "Original" represents the equalized signal without the threshold being implemented. According to the size limit for the MC broadcaster listed in [71 pp. 20-21] for the RC circuits, an acceptable technique is needed in order to approximate the equalized signal to a rectangular waveform. By the rectangular pulses with a duration equal to the time frames of the positive wave part, the signal waveform exceeding zero level is approximated. In the Figure. 4.9 "Rect Wave" is described in this waveform. For the central main part of the waveform comprising the highest amplitude, the approximate rectangular waveform is chosen to transmit as it inhabits the main part of the signal waveform energy.

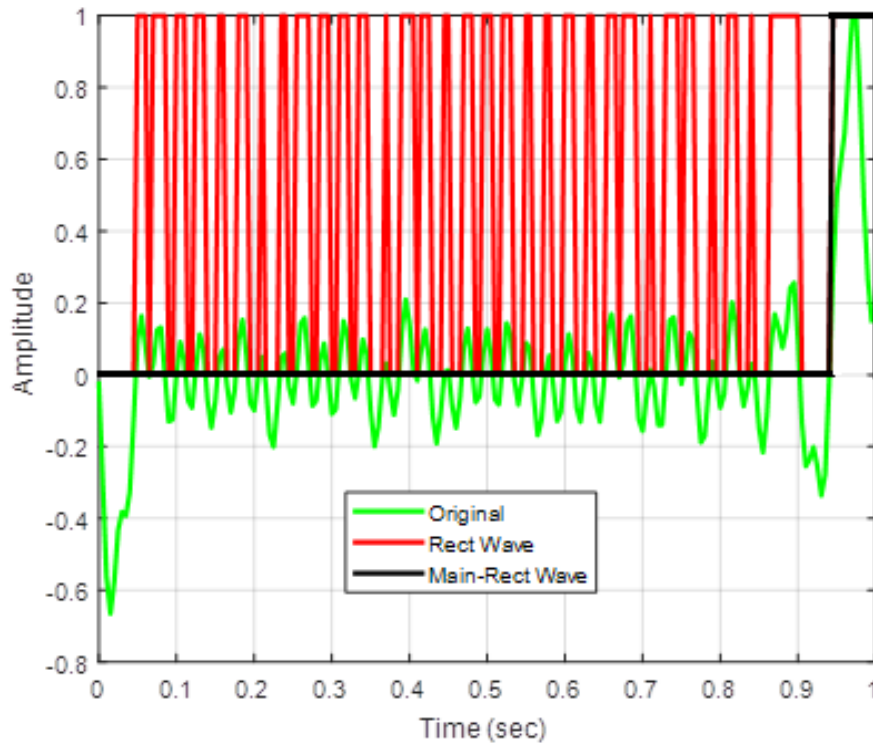


Figure 4.9 Equalized wave vs. rectangular wave.

Fig. 4.10 characterizes the CIR in frequency domain of MC. The CIR is presented with respect to the normalized frequency. Digital frequency is the ratio of analog frequency to sampling frequency in the digital communication system. As normally it ranges from 0 to 1, so in Fig. 4.8 the channel components are taken for frequency 0 to 0.5 and then shifted to see the response in negative frequencies as well. It is clearly seen that at zero frequency the CIR has maximum amplitude.

The equalized wave also known as Main-Rect wave at the transmitter that needs to be transmitted is the signal waveform of our interest. The Main-Rect Wave is then multiplied by the CIR in FD to create the received signal.

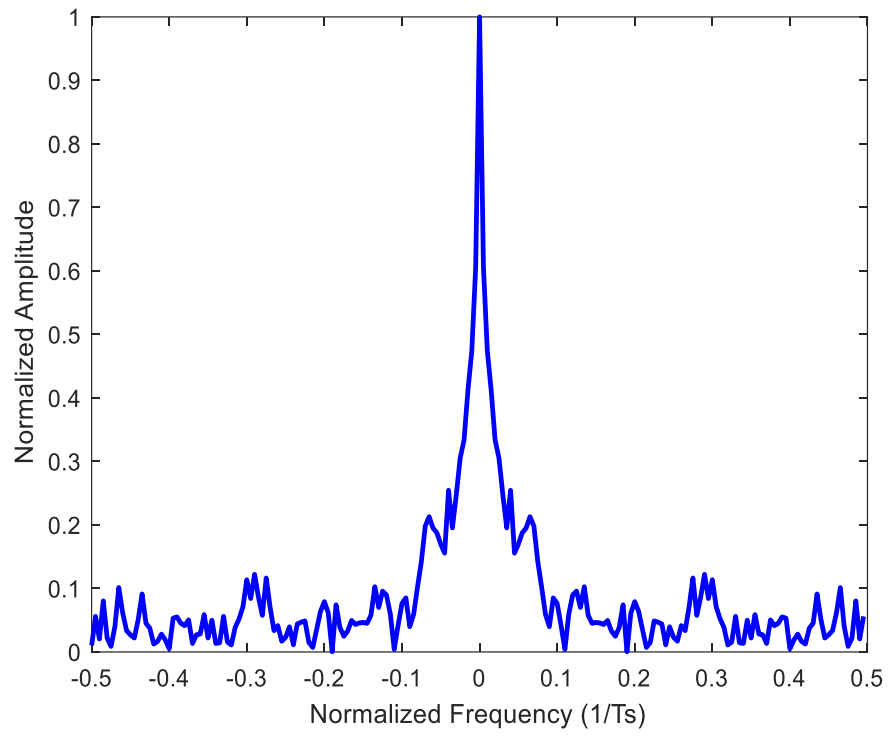


Figure 4.10 MC channel impulse response.

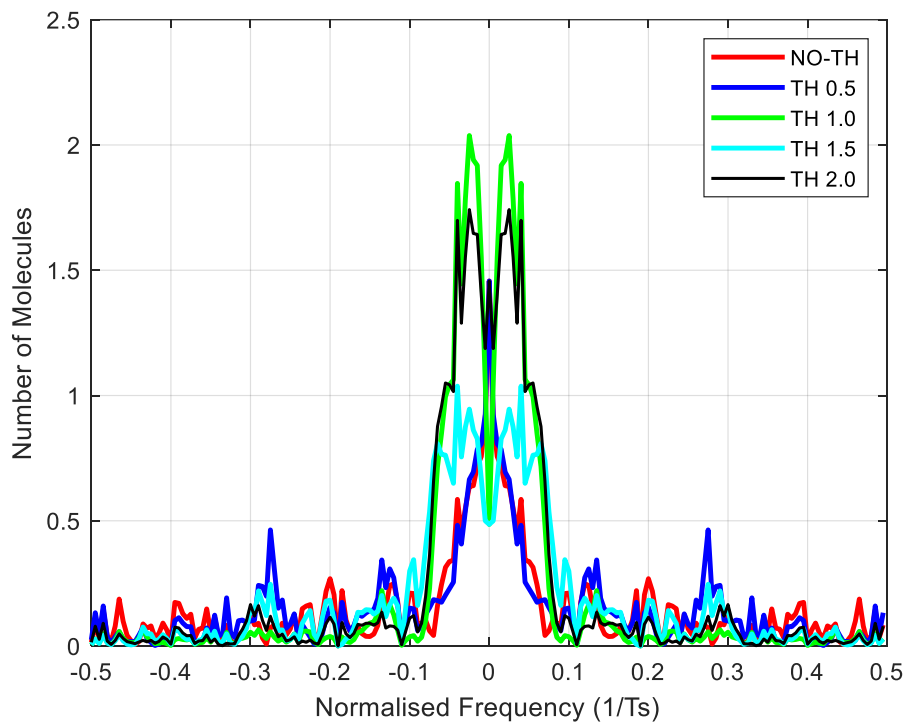


Figure 4.11 Received pulse of main rectangular waveform in frequency domain.

In the frequency domain the signal received at the source is shown in Fig. 4. 11. The same MC channel impulses are meant to be referred to in [2] which suggest that only low frequency components are transmitted through the MC tube. The main method in this respect is to select the major part for approximation due to the restraint of the MC transmitter design and for one-bit transmission with rectangular pulse waveform. The performance with "NO-TH" is $Th=0$, while the other threshold range is varying between zero and 2.0. From Fig it's simple. 4.9 the maximum energy is transferred through the MC channel for a value of 1.0 threshold.

4.6 Simulation Conditions

For numerical assessment all through computer simulation modeling subsequent simulation conditions are presumed; 10^5 symbols are transmitted for each BER plot and the diffusion coefficient of alcohol is $D = 9.59 * 10^{-6} \text{ m}^2/\text{s}$. The radius of the receiver is $r_{RX} = 1 \text{ }\mu\text{m}$ and the distance between the transmitter and the receiver is $d = 5 \text{ }\mu\text{m}$. As presented in Table 4-1. The total number of molecules transmitted are $N = 10^3$. The size of the FFT is $M = 200$. The normalized threshold for ZF precoding is set to 1.0. E_b is the bit energy while N_0 is the noise spectrum density derived through the variation of outputs of the conversion circuit that converts the number of received molecules to the electrical signal. The interval of 1 symbol duration is taken as 1 sec, while for the end to end system performance symbol interval, T_s is taken as 0.5 sec in the simulation indicating that ISI occurs when half of the symbols overlap [2].

Table: 4-1 Simulation parameters for precoding implementation

<u>Simulation Parameters</u>	<u>Values</u>
Number of Symbols	10^5
Symbol Duration (T_s)	1 sec
Threshold Range	[0 – 0.2]
Transmitter Radius (T_{RX})	1 μm
Receiver Radius (R_{RX})	1 μm
Molecules Released (N)	10^3 <u>mol</u>
Distance to Receiver (d)	5 μm
Diffusion Coefficient (Alcohol)	$9.59 * 10^{-5} \text{ m}^2/\text{s}$

4.7 Performance Result & Analysis

The bit-error-rate (BER) performance for different thresholds is produced in Fig. 4.12. At this point threshold has been varied from zero to 2.0 with a step size of 0.5. The zero threshold is labeled as No-Th that shows the worst performance. This the performance of simply the ZF precoding implementation the MC transmitter side. Similarly, as the threshold is increased the system performance is improved. It has been unambiguously obvious that the finest performance is represented by taking threshold value of 1.0 i.e. TH 1.0. This can be validated by the results shown in Fig. 4.11 where maximum amplitude has been observed for received signal at the TH 1.0. For rest of the other threshold values the BER performance is degraded. Among the numerical values of thresholds, for TH 2.0, the system shows the degraded performance. Hence it can be easily shown that the selecting an optimum threshold according the received signal amplitude is the optimal practice for best system performance.

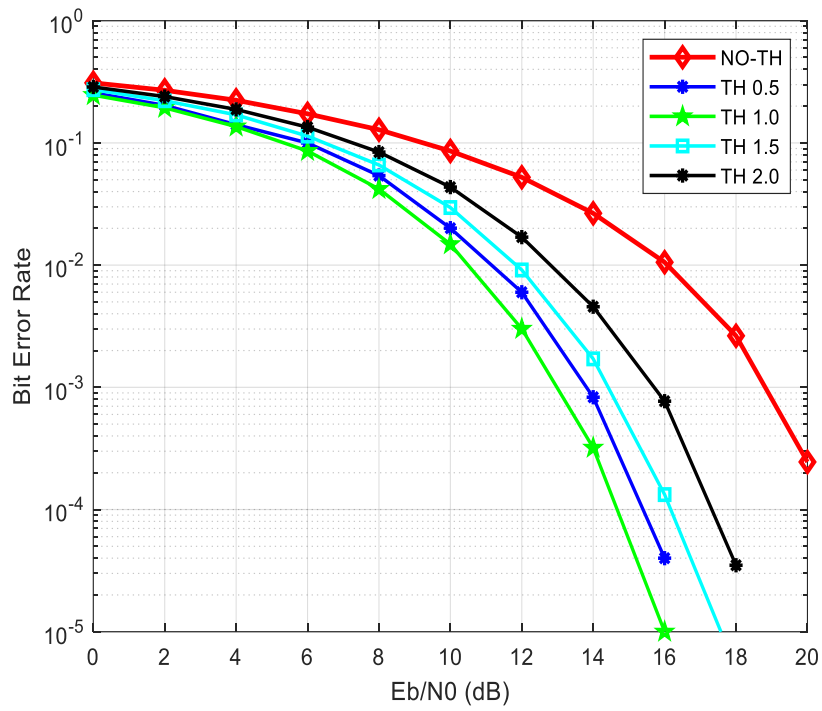


Figure 4.12 BER vs. E_b/N_0 for different thresholds.

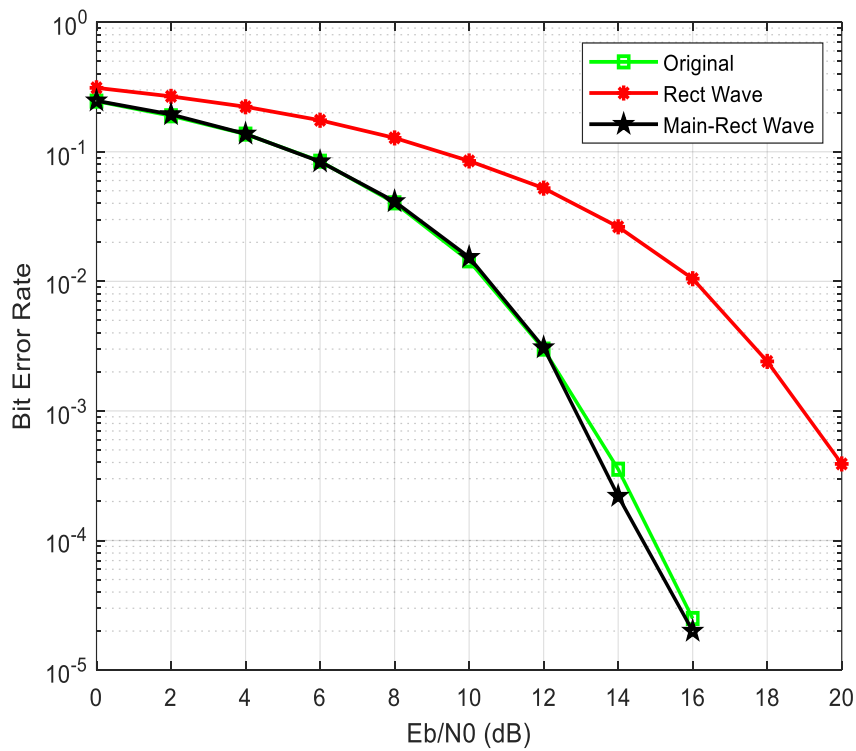


Figure 4.13 BER vs. E_b/N_0 for different for different schemes.

The BER performance versus bit-energy-to-noise-spectrum-density (E_b/N_0) for different systems is presented in Fig. 4.13. It seems that "Original" threshold precoding performs better. At an E_b / N_0 of 14 dB when a transmitter integrates precoding and the approximation of rectangular wave signal, i.e. "Rect Wave," reveals worse results. In addition, it is evident that the proposed method to introduce ZF precoding with the Rectangular threshold approximation for the most of the output waveform, i.e. "Main-Rect Wave," is nearly equal to the "Original Wave" output. That in return validates system performance that implementing precoding at the transmitter side or equalization at the receiver side both are comparable for MC systems. One reason for the rect wave to have the worst performance is also due to the system burden, as 'Rect wave' creates extra burden on the transmitter and utilizing all of the operational frequency bandwidth while 'Main-Rect Wave' incorporates only the major part of the signal which utilizes the main part of the signal.

4.8 Conclusion

This chapter presents precoding with zero forcing having a selected threshold, that mostly aims to improve the system performance for MC based diffusion. The MC recipient has to be simple for many reasons as the price and size of the recipient unit according to the nature of nanotechnology. The source, the base station, must then apply the channel precoding to boost the end of MC signal contact with the threshold and prediction. In the above sections, the frequency components clustered around zero frequency components going through the MC channel have been set out. The threshold implementation increases device performance. The traditional, standard precoding for a zero-threshold value incorporating the rectangular wave approximation displays the worst results due to the presence of ISI. On the other hand, with a threshold value of 1.0, the suggested scheme achieves improved efficiency. Also in the main segment of the original waveform with a fixed amplitude and the estimated precoding is the approximated rectangular waveform output that shows equivalent performance with the original waveform.

Chapter # 5

Overall Conclusion

In this research potential wireless propagation schemes in MC and EM wave communication system with less channel impairments scheme by restricting from a presently unfeasible technology were investigated. The channel impairments specially ISI and the noise enhancement issues are jointly analyzed for a diffusion-based MC system under while assuming a Gaussian pulse-centered information coding and a limited number of transmitter and receivers in determined places. Also, the wireless signal impairments in an indoor environment have also been discussed.

The Wi-Fi signal loss due to various materials that includes common indoor environment materials e.g. wood, glass, bricks and concrete have been discussed and related with ITU propagation model. Among these signal strengths across concrete has been measured to be high as 15dB while across glass it was as low as 5dB. It is noted that the ITU model has certain drawbacks as it does not cater all the objects in an indoor environment e.g. carpet, tiles, metallic and plastic shelves.

Apart from that the end to end MC system configuration has also been studied. Out of various types of MC, MC via diffusion has been considered since it is most commonly utilized in the BANs to monitor inside human systems. There are various issues in MC, but ISI tops the table. To encounter that, techniques are being developed and executed at the destination as well as at the source. The novelty of FDE have also been discussed and has been instigated at the receiver side as well as at the transmitter side. As seen in the above chapters that huge volume of MC signal is concentrated at around zero frequency component. i.e. MC channel impulse response shows the low pass filter behavior. Thus, leading us to think about bandwidth and time wastages for sending data for long symbol duration that also lead to the noise enhancement at high frequencies, thus in return permitting to apply the threshold at the channel response so that equalizing only high concentrated amplitude at low frequencies improves the system performance.

According to the nature of nanotechnology, In the first phase of research the signal is equalized at the receiver's end while MC receiver has to be simple for many grounds like price and dimensions of receiver unit. As in molecular communication it is believed that receiver is portable and there is a constraint in the dimensions of receiver. Therefore, at the last phase of this research equalization at the transmitter side has been implemented. Hence, the transmitter, base station, will do the tedious job of precoding and forecasts the channel for the better end to end signal communication. It was noted that equalization at receiver and precoding at the transmitter side brings almost similar system performance.

The application of MC systems in BAN suggests that the MC-Rx should be portable, and while any equipment that desires to be portable, must be compact in size. So, in order to specify the optimum design of MC hardware for both transmitter and receiver, the MC-Rx should be relieved from additional hardware size and signal computation. For this motivation, it is preferred that for best end to end MC, precoding at transmitter should be employed due to its simple computation and taking the extra estimation burden from receiver hardware.

In this Ph.D. thesis, the inter symbol interference (ISI) and the noise enhancement issues are jointly analyzed for a diffusion-based MC system under the assumptions of having a Gaussian pulse-based information coding and a limited number of transmitter and receivers in determined places. Also, the wireless signal impairments in an indoor environment have been discussed.

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