CHANNEL ESTIMATION FOR TERAHERTZ WIRELESS COMMUNICATION

PROJECT REPORT

Submitted by

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BONAFIDE CERTIFICATE

Certified that this project report titled **“CHANNEL ESTIMATION FOR TERAHERTZ WIRELESS COMMUNICATION”** is the bonafide work of **NANDHINI V [Reg. No. 15MCO007]** who carried out the research under my supervision. Certified further, that to the best of my knowledge the work reported herein does not form part of any other project or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

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INTERNAL EXAMINER

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ABSTRACT

Wireless communication has become one of the fastest growing industries during the few decades. The performance of the wireless communication depends on the knowledge of the channel state information at the receiver. This information describes how a signal propagate from the transmitter to receiver and represents the combined effect of scattering, fading and power decay. The radio channels in mobile radio systems are usually multipath fading channels, which cause inter-symbol interference (ISI) in the received signal. To remove ISI from the signal, there is a need of strong equalizer which requires knowledge on the channel impulse response (CIR). This is primarily provided by a separate channel estimator.

Usually the channel estimation is based on the known sequence of bits, which is unique for a certain transmitter and which is repeated in every transmission burst. Thus, the channel estimator is able to estimate CIR for each burst separately by exploiting the known transmitted bits and the corresponding received samples.

The channel estimation methods like Least square, Minimum mean square estimation and Orthogonal matching pursuit is done for OFDM system. The performance of the estimators is presented in terms of the mean square estimation error (MSE) and bit error rate (BER). The estimated error of OFDM system using LS is 0.005316 and OMP is 0.001651 for SNR of 15 in dB.

Terahertz communication is a key technology to satisfy the increasing demand for ultra-broadband wireless communication. THz band (0.1 to 10 THz) addresses the spectrum scarcity and improves the capacity of wireless communication. The characteristic of THz band is relatively different from present wireless channel and imposes technical challenges in the design and development of terahertz communication systems. This paper provides the analysis of channel modeling and channel estimation for THz band of LOS path. LOS propagation model is developed by adopting a molecular High Resolution Transmission (HITRAN) database

Terahertz channel estimation is done using Least Square estimation method. The MSE for the THz channel estimation using LS algorithm is from 0.0073 to $6.5198*10^{-06}$ for the range of SNR -30 to 20 in dB.

LIST OF FIGURE

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LIST OF ABBREVATIONS

ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
CoSaMP	Combining Compressive Sampling Matching Pursuit
CP	Cyclic Prefix
CS	Compressed Sensing
CSI	Channel State Information
CTF	Channel Transfer Function.
DFT	Discrete Fourier Transform
EM	Electro Magnetic.
FD-DPSK	Frequency Domain Differential Phase Shift Keying.
FDM	Frequency Division Multiplexing
HITRAN	High Resolution Transmission.
IDFT	Inverse Discrete Fourier Transform
ISI	Inter Symbol Interference
LOS	Line Of Sight
LS	Least Square
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MSE	Mean Square Error.
NLOS	Non Line Of Sight.
OFDM	Orthogonal Frequency Division Multiplexing
OMP	Orthogonal Matching Pursuit

PSD	Power Spectral Density.
RX	Receiver.
SNR	Signal to noise ratio.
SOMP	Subspace Orthogonal Matching Pursuit
TX	Transmitter.

CHAPTER 1

INTRODUCTION

In wireless communications, Multiple Input Multiple Output (MIMO) technology is one of the major attracting techniques because it offers increases in data throughput and coverage without additional bandwidth or transmitter power. It also provides high spectral efficiency. MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, 3GPPLTE, WiMAX and HSPA+ [4]. Orthogonal frequency division multiplexing (OFDM) is based on technology of multicarrier communication. The main idea of multicarrier communications is to divide the total signal bandwidth into number of subcarrier, thus helping to eliminate Inter Symbol Interference (ISI). It also allows the bandwidth of subcarriers to overlap without Inter Carrier Interference (ICI). In [6] OFDM therefore is considered as an efficient modulation technique. Its increased complexity over the conventional system caused by employing N modulators and filters at the transmitter and N demodulators and filters at the receiver are the disadvantages. This complexity can be removed by the use of the FFT and IFFT at the receiver and transmitter, respectively. The MIMO OFDM system consists of N_t transmit and N_r receiving antenna along with pilot carriers in frequency domain. MIMO OFDM is a new broadband wireless technology used in channel estimation due to high data rate and because of its strength against multipath fading effects. The major problem faced in channel estimation is how to obtain the channel state information correctly.

In training symbol based channel estimation the two types of arrangements are used. One is the block type and the another is comb type [6]. The block type arrangement channel estimation is done under the assumption of slow fading where the channel transfer function not changes rapidly while in comb type, the interpolation is used for the estimation. The technique LS estimation are widely used for channel estimation. In the Least square OFDM channel estimation, channel frequency response at pilot positions is acquired and then use these observations to interpolate the rest of the subcarriers. This method is simple to use. Generally, accurate channel estimation requires more pilots than channel coefficients. When the channel has large delay spread and contains many multipath signals, the pilot number raises rapidly. For

MIMO, the overhead of pilot symbols becomes considerable as number of transmitter antennas increases. A prior knowledge about the channel sparsity is a possible solution. Wireless channels are typically sparse in practice. Sparse channel refers to number of nonzero elements is less compared to channel coefficients. With some sparse recovery algorithms, the number of pilots can be considerably reduced. Matching pursuit (MP) and orthogonal matching pursuit (OMP) are commonly employed sparse recovery algorithm, which sequentially identifies a small subset of nonzero taps.

Nowadays, the wireless data communication is very traffic, which demands high speed communication. In particular, wireless data rates have doubled every eighteen months over the last thirty years [10]. Terahertz communication is considered as a key technology to satisfy this increasing demand for ultra-broadband wireless communication. THz communication will increases the spectrum capacity of the present wireless system [15]. Terahertz communication is 1000 times faster than the current wireless communication. Terahertz radiation is also known as sub millimeter radiation, it consists of electromagnetic waves within the ITU-designated band of frequencies from 0.3 to 3 terahertz. Wavelengths of radiation in the terahertz band correspondingly range from 3µm to 30µm. Because terahertz radiation begins at a wavelength of one millimeter and proceeds into shorter wavelengths, it is sometimes known as the sub millimeter band and its radiation as sub millimeter waves [11]. Terahertz radiation falls in-between infrared radiation and microwave radiation in the electromagnetic spectrum and it shares some properties with each of these. Like infrared, terahertz radiation travels in a line of sight and is nonionizing. Like microwave radiation, terahertz radiation can penetrate a wide variety of non-conducting materials.

Many applications of THz waves, like THz body scanners, medical imaging, security screening, manufacturing and quality control are based on these properties. The characteristics of THz radiation cause a high molecular absorption loss and spreading loss which result in a very high and frequency-selective path loss for line-of-sight (LoS) links.

LOS propagation path for the THz band was modeled by evaluating the effect of molecular absorption on the path loss [18]. Josep Miquel[16], developed the channel model based on the radiative transfer theory to compute the path loss and noise in the terahertz band.

The molecular absorption in THz frequency, which attenuates transmitted signal and also introduces color noises was also described. In [17], the atmospheric absorption of terahertz waves was divided into two absorption components as absorption lines of water vapor present in air and continuous absorption. The absorption parameters for major atmospheric molecules are found in databases such as JP and HITRAN and are measured based on the THZ-TDS.

1.1 DIGITAL COMMUNICATION SYSTEMS

A digital communication system is often divided into several functional units as shown in Figure 1.1. The task of the source encoder is to represent the digital or analog information by bits in an efficient way. The bits are then fed into the channel encoder, which adds bits in a structured way to enable detection and correction of transmission errors. The bits from the encoder are grouped and transformed to certain symbols, or waveforms by the modulator and waveforms are mixed with a carrier to get a signal suitable to be transmitted through the channel. At the receiver the reverse function takes place. The received signals are demodulated and soft or hard values of the corresponding bits are passed to the decoder. The decoder analyzes the structure of received bit pattern and tries to detect or correct errors. Finally, the corrected bits are fed to the source decoder that is used to reconstruct the analog speech signal or digital data input.

This description deals with the three blocks to the right in Figure 1.1 the modulator, the channel and the demodulator. The main question is designing certain parts of the modulator and demodulator to achieve efficient and robust transmission through a mobile wireless channel.

The wireless channel has some properties that make the design especially challenging it introduces time varying echoes and phase shifts as well as a time varying attenuation of the amplitude.

Orthogonal Frequency Division Multiplexing (OFDM) has proven to be a modulation technique well suited for high data rates on time dispersive channels [4]. There are some specific requirements when designing wireless OFDM systems, for example, choosing the bandwidth of the sub-channels used for transmission and to achieve reliable synchronization.

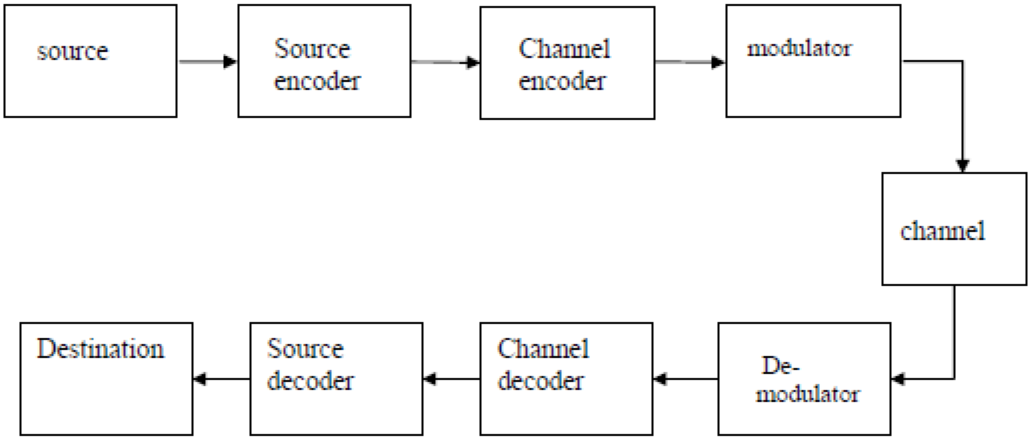

Fig1.1 Functional Block of a Communication System

For mobile or wireless applications, the channel is often described as a set of independent multipath components. The time varying impulse response can be described by [3]

$$h(t) = \sum_{i=1}^{M} a_i(t)\delta(\tau - \tau_i(t)) \tag{1.1}$$

Where $a_i(t)$ denotes the complex valued tap gain for path number i , τ_i (t) is the delay of tap i, and δ is the delta function. Among the most important parameters when choosing the modulation scheme are the delay and the expected received power for different delays. Large delays for stronger paths mean that the interference between the different received signal parts can severe, especially when the symbol rate is high so that the delay exceeds several symbols. In that case one have to introduce an equalizer to mitigate the effects of inter symbol interference (ISI). Another alternative is to use many parallel channels so that the symbol time on each of the channels is long. This means that only a small part of the symbol is affected by ISI and this is the idea behind orthogonal frequency division multiplexing.

1.1.1 WIRELESS SYSTEMS

Wireless Systems are operating in an environment which has some specific properties compared to fixed wireline systems and for special design considerations. In a wired network, there are no fast movements of terminals or reflection points and the channel parameters are changing very slowly. In addition, time dispersion is less severe in a wired system, though it might still be a hard problem due to high data rates. In a mobile system the terminals are moving around, the received signal strength as well as the phase of the received signal, are changing rapidly. Further, the signal transmitted over the radio channel is reflected by buildings and other means of transportation on the ground, leading to different paths to the receiver, as shown in Figure 1.2.

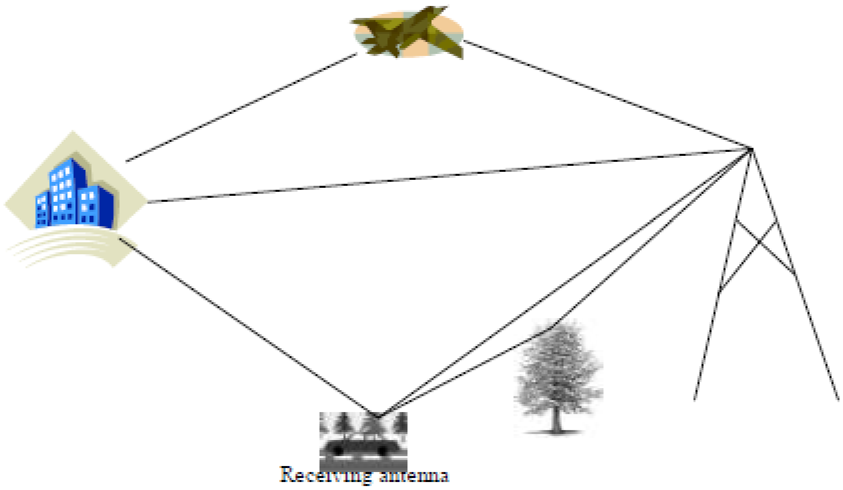

Fig. 1.2 Multipath Reception

If the length of the paths differs, the received signal will contain several delayed versions of the transmitted signal according to the channel impulse response defined in Equation (1.1). The delays make it necessary to use complex receiver structures. In a mobile wireless system, the terminals are of course intended to be portable. This means that power consumption is important since batteries sometimes will power the equipment. Therefore, low complexity and low power consumption are properties that are even more desirable in wireless systems than in a wired system.

1.2 OBJECTIVE OF THE WORK

In this work, various methods of channel estimation is investigated. The main objective of this project is to investigate the performance of channel estimation in OFDM systems and the terahertz channel. Main factors affecting the performance of an OFDM system are multipath delay spread and channel noise. The performance of OFDM and terahertz channel is assessed using Matlab.

i. For channel estimation the algorithms like LS, MMSE and OMP are used for wireless OFDM system. The performance is assessed using MSE.

ii. The channel estimation of terahertz channel for LOS path is also done using LS algorithm its MSE is also calculated.

This report is organized as follows: In Chapter 3, mobile radio channels and OFDM are presented. In Chapter 4, the description of OFDM system. In Chapter 5, an overview of different approaches of channel estimation in OFDM systems is presented. We also discuss different channel estimation. Chapter 6, is the terahertz channel estimation. Chapter 7, demonstrates Simulation Results and Discussion of channel estimation of OFDM System and terahertz channel estimation. Chapter 8, concludes the project and areas for future work are also suggested.

CHAPTER 2

LITERATURE SURVEY

In this chapter, literatures related to channel estimation of MIMO OFDM systems and terahertz channel modelling are discussed. Terahertz frequency for communication is explained by researcher in the recent past. THz channel is quite different from the current wireless channel. A brief review of the existing channel modeling in the THz range is presented in this chapter.

2.1 REVIEW OF OFDM CHANNEL ESTIMATION

The highlights of channel estimation technique based on pilot aided block type training symbols using LS and MMSE algorithm is discussed in [1]**.** The MMSE is compared with LS and the MMSE performs better than the LS where the performance metric is Bit error rate, symbol error rate, mean square. The MMSE estimator assumes a priori knowledge of noise variance and channel covariance. So, the performance of MMSE estimator is better than that of the LS estimator. Moreover, its complexity is large compared to the LS estimator. Whereas for high SNRs the LS estimator is both simple and adequate.

A fast algorithm for sparse channel estimation based on a greedy algorithm called orthogonal matching pursuit (OMP) is proposed in [2]. Channels with a sparse impulse response arise in a variety of wireless communication applications, such as high definition television (HDTV) terrestrial transmission and underwater acoustic communications. The fast OMP is faster and easier to implement. Therefore, it is an attractive alternative to the L1-minimization approaches.

The work of improving various channel performance measures based on the comparison of various channel estimation algorithms is done in [3] and this suggest a new technique which provides better performance. The channel is estimated using least square (LS), minimum mean-square error (MMSE), DFT based channel estimation, linear minimum mean square error (LMMSE), dual diagonal linear minimum mean square error (DD-LMMSE) is done.

In [4], the author provided the detailed study of MIMO-OFDM system description with MATLAB results. the authors have analyzed the channel estimation techniques also provided with comb and block type pilot channel estimation.

The authors have analyzed the channel estimation technique based on pilot aided block type training symbols using LS and MMSE algorithm in [5] The comparison of BER performance for the two algorithms LS and MMSE is done. The MMSE is compared with LS and the MMSE perform s better than the LS where the performance metric is Bit error rate, mean square error.

The author discussed the channel estimation of OFDM system in [6] using LS, MMSE, DFT based Channel estimation can improve the performance through DFT and IDFT based LS algorithm and LMMSE algorithm. The comparison of bit error rate performance for all the above algorithms are done. The proposed method is to estimate the impulse response of the channel and hence to reduce mean square error (MSE) and bit error rate (BER)

In paper [7], author briefly study an occasional quality structure of receiver was proposed in order that the LS technique and linear interpolation were used for initial channel estimation. The comparison of BER performance for the algorithms LS and MMSE is done.

Analysis of sparsity of sparse MIMO channel and the leakage effect with fixed Fourier basis in the spatial angular domain is studied in [8], to enhance the sparsity of the MIMO angular channels proposing an optimized over complete Fourier basis dictionary, which is obtained by a sparsity criterion, to represent the signals with the best basis. By converting the compressed sensing from multiple measurement vectors to a single measurement vector, the reconstruction of the MIMO channel is simplified and makes better use of the sparsity of the MIMO channels.

The discussion of the channel estimation of hybrid compressed sensing algorithm as subspace orthogonal matching pursuit (SOMP) is done in [9]. SOMP first identifies the channel sparsity and then iteratively refines the sparse recovery result, which essentially combines the advantages of orthogonal matching pursuit (OMP) and subspace pursuit (SP). Since SOMP still belongs to greedy algorithms, its computational complexity is in the same order as OMP with frequency orthogonal random pilot placement, the technique is also extended to MIMO OFDM systems.

2.2 REVIEW OF TERAHERTZ CHANNEL MODEL

Akyildiz and Jornet [10], discussed the Terahertz Band (0.1–10 THz) communication and the in-depth view of device design and development challenges for THz Band [10]. The limitations and possible solutions for high-speed transceiver architectures are highlighted. The challenges for the development of new ultra-broadband antennas and very large antenna arrays are explained. There exist many novel communication challenges such as propagation modeling, capacity analysis, modulation schemes, and other physical and link layer solutions. Some applications of the terahertz band at the macro scale and the micro scale are explained.

Farnoosh Moshir and Suresh Singh, explained the problem of building a communication channel based on modulation of terahertz pulses [11]. The channel model based on measurements carried out on a terahertz time-domain system is developed. Frequency domain differential quadrature phase shift keying (FD-DQPSK) and Adaptive FD-DQPSK pulse modulation schemes are implemented. These modulation schemes results the data rates of about 1 Tbps for distances of up to three meters.

In [12], the authors have discussed about the wireless communication over indoor Terahertz (THz) channels. For the non-line-of-sight (NLOS) propagation, a very high reflection loss depending on the shape, material, and roughness of the reflecting surface affects the THz wave propagation. By considering these peculiarities the LOS path, NLOS path and equivalent channel model is implemented based on Kirchhoff scattering theory and ray tracing algorithm. It proposed the capacity of channel model, which observe that the LOS component dominates the performance and for NLOS component it achieves 100 Gbps.

Piesiewicz, and Kleine-Ostmann [13],described the reflective properties of building materials found in a typical office environment. The angular dependent reflection coefficients of different building materials were determined using terahertz time domain spectroscopy in transmission geometry and Fresnel’s equations, which is more efficient than a set of measurements in reflection geometry for different angles. Determines the refractive index and absorption coefficient for glass, plaster and wood materials.

S. Priebe, M. Jacob and C. Jansen, presented the non-specular scattering at rough surfaces in the THz frequency range by means of the Kirchhoff scattering theory [14]. It illustrates the angular dependent scattering behavior of a rough surface for the three dimensional radiation and calculated the scattered power for single scattering point. It also calculated the total scattered power for multipath reflection by the implementation of Kirchhoff scattering in the ray tracing algorithm.

Song and Nagatsuma [15], highlighted the present and future terahertz communication. In present technologies for THz communications it focus on channel modeling, device technologies for the front-end, and demonstrations for testing the feasibility of THz communications. Although high-gain antennas should probably be employed because of the large free-space loss at THz frequencies, the huge bandwidth of THz waves will enable to achieve data rates of 10 Gbps or higher easily even with simple data modulation.

Anamaria Moldovan and Steven Kisseleff [16], they considered the design of uncoded point-to-point THz transmission systems using realistic transmit, receive, and equalization filter. The problem of equalizing a very long dispersive channel impulse response by utilizing a frequency-division based scheme with multiple sub-bands is highlighted. The iterative power allocation algorithm is developed to maximize the data rate.

Cheng Wang and Changxing Lin, describes a 140-GHz wireless link whose maximum transmission data rate is 10 Gbit/s[17]. A high-performance transmitting and receiving front end is developed by sub-harmonic mixer and multiplier based on Schottky barrier diodes, a waveguide H ladder bandpass filter, a Cassegrain antenna. 16 quadrature amplitude modulation is adopted to improve the spectrum efficiency. 32-way parallel demodulation architecture based on frequency-domain implementation of the matched filter and timing phase correction is modeled. An adaptive blind equalization algorithm is also realized to enhance the tolerance for channel distortion.

However, no literature is available for terahertz channel estimation. But channel state information is a vital parameter for the detection of transmitted signal.

CHAPTER 3

MOBILE RADIO CHANNELS AND OFDM

In this chapter the propagation characteristics of mobile radio channels and basics of OFDM are presented. Radio channel is the link between the transmitter and the receiver that carries information bearing signal in the form of electromagnetic waves. The radio channel is commonly characterized by receiver and transmitter. Fading is used to describe the rapid fluctuations of the amplitude of a radio signal over a short period of time or travel distance, so that large scale path loss effects may be ignored. Characteristics of radio channel and a basic of OFDM such orthogonality principle, use of IFFT and DFT in OFDM.

3.1 PROPAGATION CHARACTERISTICS OF MOBILE RADIO CHANNELS

In an ideal radio channel, the received signal would consist of only a single direct path signal, which would be a perfect reconstruction of the transmitted signal. However, in a real channel the signal is modified during transmission. The received signal consists of a combination of attenuated, reflected, refracted, and diffracted replicas of the transmitted signal. Generally, the channel adds noise to the signal and can cause a shift in the carrier frequency if either of the transmitter or receiver is moving (Doppler Effect). Understanding of these effects on the signal is important because the performance of a radio system is dependent on the radio channel characteristics.

3.1.1 Multipath Effects

3.1.1.1 Attenuation

Attenuation is the drop in the signal power when transmitting from one point to another. It can be caused by the transmission path length, obstructions in the signal path, and multipath effects. Any objects which obstruct the line of sight of the signal from the transmitter to the receiver, can cause attenuation. Shadowing of the signal can occur whenever there is an obstruction between the transmitter and receiver. It is generally caused by buildings and hills, and is the most important environmental attenuation factor. Shadowing is the most severe in heavily built up areas, due to the shadowing from buildings. However, hills can cause a large problem due to the large shadow they produce. Radio signals diffract off the boundaries of obstructions, thus preventing total shadowing of the signals behind hills and buildings. However, the amount of diffraction is dependent on the radio frequency used, with high frequencies scatter more than low frequency signals. Thus,high frequency signals, especially, Ultra High Frequencies (UHF) and microwave signals require line of sight for adequate signal strength, because these scatter too much. To overcome the problem of shadowing, transmitters are usually elevated as high as possible to minimize the number of obstructions.

3.1.1.2 Frequency Selective Fading

In any radio transmission, the channel spectral response is not flat. It has dips or fades in the response due to reflections causing cancellation of certain frequencies at the receiver. Reflections off near-by objects (e.g. ground, buildings, trees, etc) can lead to multipath signals of similar signal power as the direct signal. This can result in deep nulls in the received signal power due to destructive interference. For narrow bandwidth transmissions if the null in the frequency response occurs at the transmission frequency then the entire signal can be lost. This can be partly overcome in two ways. By transmitting a wide bandwidth signal or spread spectrum as in the case of CDMA, any dips in the spectrum only result in a small loss of signal power, rather than a complete loss. Another method is to split the transmission up into many carriers carrying low rate data, as is done in OFDM

3.1.1.3 Delay Spread

The received radio signal from a transmitter consists of typically a direct signal plus signals reflected off object such as buildings, mountains, and other structures. The reflected signals arrive at a later time than the direct signal because of the extra path length, giving rise to a slightly different arrival time of the transmitted pulse. The signal energy confined to a narrow pulse is spreading over a longer time. Delay spread is a measure of how the signal power is spread over the time between the arrival of the first and last multipath signal seen by the receiver.

3.2 INTRODUCTION TO OFDM

OFDM is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero. That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period.

The frequency spectrum of an OFDM transmission is illustrated in Figure 3.1

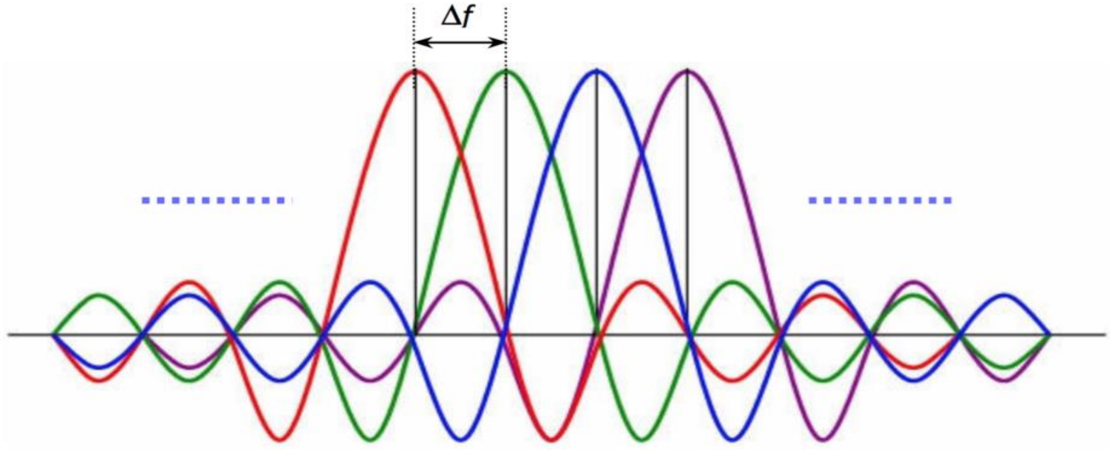

Fig.3.1 Carriers based OFDM spectrum

From the above figure the frequency spectrum of one carrier exhibits zero-crossing at central frequencies corresponding to all other carriers. At these frequencies, the intercarrier interference is eliminated, although the individual spectra of subcarriers overlap. It is well known, orthogonal signals can be separated at the receiver by correlation techniques. The receiver acts as a bank of demodulators, translating each carrier down to baseband, the resulting signal then being integrated over a symbol period to recover the data.

3.3 GENERATION OF OFDM SYMBOLS

A baseband OFDM symbol can be generated in the digital domain before, modulating on a carrier for transmission. To generate a baseband OFDM symbol, a serial digitized data stream is first modulated using common modulation schemes such as the phase shift keying (PSK) or quadrature amplitude modulation (QAM). These data symbols are then converted to parallel streams before modulating subcarriers. Subcarriers are sampled with sampling rate N /T, where N is the number of subcarriers and T is the OFDM symbol duration. The frequency separation between two adjacent subcarriers is 2π / N. Finally, samples on each subcarrier are summed together to form an OFDM sample. An OFDM symbol generated by an N-subcarrier OFDM system consists of N samples and the mth sample of an OFDM symbol is given by

$$x_m = \sum_{n=1}^{N} X_n e^{j\frac{2\pi mn}{N}} \qquad 0 \leq \mathrm{m} \leq \mathrm{N\text{-}1} \qquad (3.1)$$

Where X_n is the transmitted data symbol on the nth carrier. Equation (3.1) is equivalent to the N-point inverse discrete Fourier transform (IDFT) operation on the data sequence. It is well known that IDFT can be implemented efficiently using inverse fast Fourier transform (IFFT). Therefore, in practice, the IFFT is performed on the data sequence at an OFDM transmitter for baseband modulation and the FFT is performed at an OFDM receiver for baseband demodulation. Size of FFT and IFFT is N, which is equal to the number of sub channels available for transmission, but all of the channels needs to be active. The sub-channel bandwidth is given by

$$f_{sub-carr} = \frac{1}{T} = \frac{f_{samp}}{N} \qquad (3.2)$$

Where f_{samp} is the sample rate and Ts is is the symbol time. Finally, a baseband OFDM symbol is modulated by a carrier to become a bandpass signal and transmitted to the receiver. In the frequency domain, this corresponds to translating all the subcarriers from baseband to the carrier frequency simultaneously.

CHAPTER 4

SYSTEM DESCRIPTION

In this chapter, a brief description of OFDM system is given. The whole description of the system is based on discrete domain.

4.1 DESCRIPTION OF BASE BAND OFDM SYSTEM

The OFDM system based on pilot channel estimation is given in Figure 4.1.

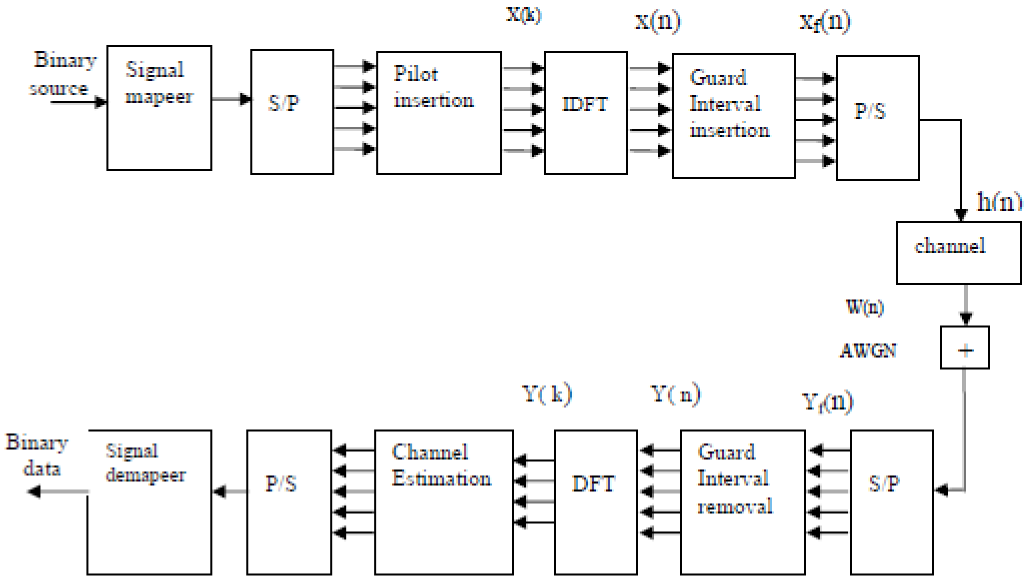

Fig. 4.1 Baseband OFDM system

The binary information is first grouped and mapped ac-cording to the modulation in “signal mapper”. After inserting pilots either to all sub-carriers with a specific period or uniformly between the information data sequence, IDFT block is used to transform the data sequence of length into time domain signal with the following equation.

$$x(n) = IDFT\{X(k)\} = \sum_{k=0}^{N-1} X(k) e^{i(2\pi kn/N)} \quad n=0,1,\ldots N-1 \qquad (4.1)$$

Where N is the DFT length. Following IDFT block, guard time, which is chosen to be larger than the expected delay spread, is inserted to prevent inter-symbol interference. This guard time includes the cyclically extended part of OFDM symbol in order to eliminate inter-carrier interference. The resultant OFDM symbol is given as follows

$$x_f(n) = x(N + N) \tag{4.2}$$

where n=-N_g ,-N_g+1,……,-1.Thus x_f(n)=x(n) where n=0,1,2,…N-1. N_g is the length of the guard interval.

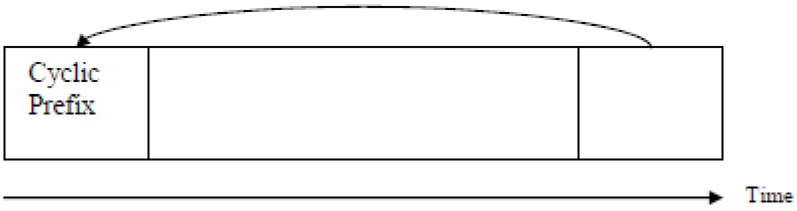

Fig 4.2 Cyclic Prefix of an OFDM block

The transmitted signal x_f(n) will pass through the frequency selective time varying fading channel with additive noise. The received signal is given by

$$y_f(n) = x_f(n) * h(n) + w(n) \tag{4.3}$$

where w(n) is Additive White Gaussian Noise (AWGN) and h(n) is the channel impulse response. The channel response can be represented by the equation 4.4

$$h(n) = \sum_{i=0}^{r-1} hie^{j(2\pi/N)\,fdiTn}\delta(\lambda - \tau_i) \qquad 0 \le N \le N-1 \tag{4.4}$$

where r is the total number of propagation paths, hi is the complex impulse response of the i th path,fdi is the i th path Doppler frequency shift, λ is delay spread index, T is the sample period and τ_i is the i th path delay normalized by the sampling time. At the receiver, after passing to discrete domain through A/D and low pass filter, guard time is removed.

$y_f(n)$ for $-N_g \le n \le N-1$

$y(n)=y_f(n+N_g)$ for $n=0,1,\ldots N-1$

Then y(n) is sent to DFT block for the following operation.

$$Y(k) = DFT\{y(n)\} = \frac{1}{N}\sum_{n=0}^{N-1} y(n)e^{-j(2\pi kn/N)} \qquad k=0,1,\ldots N-1 \qquad (4.5)$$

Assuming there is no ISI, shows the relation of the resulting Y(k) to H(k) = DFT{h(n)}, and W(k) = DFT{w(n)},with the following equation,

$$Y(k) = X(k)H(k) + W(k) \qquad (4.6)$$

Following DFT block, the pilot signals are extracted and the estimated channel $\hat{H}(k)$ for the data sub-channels is obtained in channel estimation block. Then the transmitted data is estimated by

$$\hat{X} = \frac{Y(k)}{\hat{H}(k)} \qquad k=0,1,\ldots N-1 \qquad (4.7)$$

Then the binary information data is obtained back in "signal demapper" block. Based on principle of OFDM transmission scheme, it is easy to assign the pilot both in time domain and in frequency domain.

CHAPTER 5

CHANNEL ESTIMATION OF OFDM SYSTEM

A wideband radio channel is normally frequency selective and time variant. For an OFDM mobile communication system, the channel transfer function at different subcarriers appears unequal in both frequency and time domains. Therefore, a dynamic estimation of the channel is necessary. Pilot-based approaches are widely used to estimate the channel properties and correct the received signal. In this chapter Block type pilot arrangement is investigated for channel estimation.

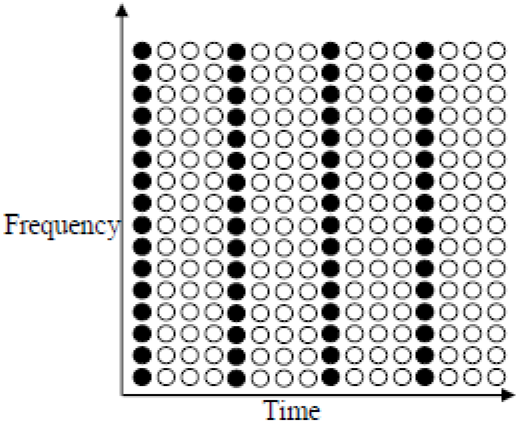

Fig. 5.1 Block type pilot arrangement

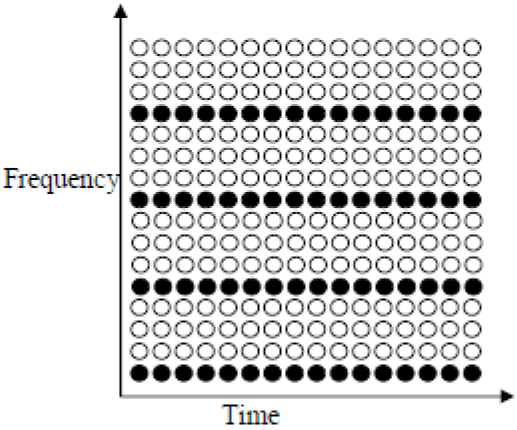

Fig. 5.2 Comb type pilot arrangement

The first kind of pilot arrangement shown in Figure 5.1 is denoted as block-type pilot arrangement. The pilot signal assigned to a particular OFDM block, which is sent periodically in time-domain. This type of pilot arrangement is especially suitable for slow-fading radio channels. Because the training block contains all pilots, channel interpolation in frequency domain is not required. Therefore, this type of pilot arrangement is relatively insensitive to frequency selectivity. The second kind of pilot arrangement shown in Figure 5.2 is denoted as comb-type pilot arrangement. The pilot arrangements are uniformly distributed within each OFDM block. Assuming, that the payloads of pilot arrangements are the same, the comb-type pilot arrangement has a higher re-transmission rate. Thus, the comb-type pilot arrangement system provides better resistance to fast-fading channels. Since only some sub-carriers contain the pilot signal, the channel response of non-pilot sub-carriers will be estimated by interpolating neighboring pilot sub-channels. Thus, the comb-type pilot arrangement is sensitive to frequency selectivity when comparing to the block-type pilot arrangement system.

5.1 CHANNEL ESTIMATION BASED ON BLOCK-TYPE PILOT ARRANGEMENT

In block-type pilot based channel estimation, OFDM channel estimation symbols are transmitted periodically, in which all sub-carriers are used as pilots. If the channel is constant during the block, there will be no channel estimation error since the pilots are sent at all carriers. The estimation can be performed by using either LSE or MMSE [6]. If inter symbol interference is eliminated by the guard interval, the matrix notation is:

$$Y = XFh + N$$

$$= XH + N$$

$$Y = \begin{bmatrix} Y[0] \\ Y[1] \\ : \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & ... & 0 \\ 0 & X[1] & ... & : \\ : & ... & ... & 0 \\ 0 & ... & 0 & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ : \\ H[N-1] \end{bmatrix} + \begin{bmatrix} N[0] \\ N[1] \\ : \\ N[N-1] \end{bmatrix}$$

Where,

$$F = \begin{bmatrix} {W_N}^{00} & ... & ... & {W_N}^{0(N-1)} \\ : & ... & ... & : \\ : & ... & ... & : \\ {W_N}^{(N-1)0} & ... & ... & {W_N}^{(N-1)(N-1)} \end{bmatrix}$$

$${W_N}^{nk} = \frac{1}{\sqrt{N}} e^{-j2\pi(n/N)k}$$

where Y is the received signal matrix and X is the transmitted signal matrix. F is the DFT matrix. ${W_N}^{nk}$ is the coefficients in F matrix.

5.1.1 LEAST SQUARE CHANNEL ESTIMATION

The Least square estimate of the channel can be expressed as $\hat{H}_{LS}$ where $X^H X\hat{H} = X^H Y$, [4] which gives the solution to the LS channel estimation as in [4]

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1} Y \tag{5.1}$$

Thus, denote each component of the LS channel estimate $\hat{H}_{LS}$ by $\hat{H}_{LS}$ [k] where k = [0,1,2,…,N-1].Since X is assumed to be diagonal due to the ICI-free condition, the LS channel estimate $\hat{H}_{LS}$ can be written for each subcarrier as

$$\hat{H}_{LS}\,[\mathrm{k}]=\frac{Y[k]}{X[k]} \tag{5.2}$$

where k=[0,1,2,…,N-1]. The mean-square error (MSE) of this LS channel estimate is given as

$$MSE_{LS}=E\{(H-\hat{H}_{LS})^{H}(H-H_{LS})\}$$

5.1.2 MINIMUM MEAN SQUARE ERROR CHANNEL ESTIMATION

The Minimum Mean Square estimate of the channel can be expressed as $\hat{H}_{MMSE}$ where it employs the second-order statistics of the channel conditions to reduce the mean-square error.

$$\hat{H}_{MMSE}=FR_{hy}R^{-1}{}_{yy}\,y \tag{5.3}$$

Where F is Matrix of DFT and R_{hy} is cross correlation of H and Y

$$R_{hy}=E\{hy^{H}\}=R_{hy}F^{H}X^{H} \tag{5.4}$$

5.2 ORTHOGINAL MATCHING PURSUIT

The received signal x(t) of a channel in response to the known transmitted signal x(t) is [8]

$$y(t)=h(t)*x(t)+v(t)=\int h(\tau)x(t-\tau)d\tau+n(t) \tag{5.5}$$

Here $*$ denotes linear convolution, *h*(*t*) is the channel impulse response, and *n*(*t*) is additive noise. The channel impulse response h(t). The received signal *y*(*t*) then can be expressed as the sum of *M* scaled and delayed replicas of *x*(*t*).

$$y(t)=\sum_{m=1}^{M}\alpha_{m}x(t-\tau_{m})+n(t) \tag{5.6}$$

As pointed out above, a type of channels often displays large delays, but have a small nonzero support. In this paper, considering the problem of identifying the sparse channel response *h*(*t*) from the known transmitted signal *x*(*t*) and the received signal *y*(*t*). After sampling with sampling period T_s, the discrete-time version is obtained[8]

$$Y = \Phi H + N \tag{5.7}$$

where the vectors $Y = [y(0), y(1),.., y(N-1)]^T$, $H = [h(0), h(1),..., h(N-1)]^T$ and $N = [n(0), n(1),..., n(N-1)]^T$ are formed from the samples of $x(t)$, $h(t)$ and $n(t)$, respectively. Since all of the signals are sufficiently zero-padded to length N, the linear convolution equals the circular convolution and the N × N DFT matrix [2] with the first column being denoted $X = [x(0), x(1), x(2),..., x(N-1)]^T$ .For a K-path channel, H has only K nonzero elements whose locations and values are the K time-delays and amplitudes respectively if the time-delays are integer multiples of the sampling period. In [2][8] Since H is sparse, thus $K<<N$. In this work, focusing on to estimate the discrete version of the channel response.

5.2.1 OMP ALGORITHM FOR CHANNEL ESTIMATION

In this, elaboration of the OMP (Orthogonal Matching Pursuit) algorithm for sparse channel estimation is discussed. The main aim is to find the sparsest solution of the linear equation $Y = \Phi H + N$,which leads to the most compact representation of Y. Therefore, it is natural to consider channel estimation as a problem of sparse approximation. Since h has only K nonzero components, the received signal $Y = \Phi H + N$ is a linear combination of K columns from Φ. The columns of $\Phi = [\phi_1,..., \phi_N]$ are called the dictionaries in the context of sparse approximation. To identify the ideal channel response h, it needs to determine which columns of Φ participate in the received signal vector Y. The OMP is an iterative algorithm which sequentially identifies the K dominant channel coefficients. The idea of the OMP algorithm is to select dictionaries in a greedy manner. At each iteration, like the basic MP algorithm [2], OMP chooses one column of Φ that is best correlated with the residual from the previous iteration. Then its contribution to Y is subtracted off. Thus, summarize the detailed steps of the OMP-based channel estimation method in Algorithm.

5.2.2 ALGORITHM

Input: The N-dimensional transmitted signal x and received signal y, and the sparsity level K of the channel response.

Output: Channel response estimate H_e and an index set I_K denoting the K indices of the non-zero elements of H.

Steps:

1.Construct the dictionary matrix Φ which is a DFT matrix .

2.Initialize the residual value $r_0 = y$

Index set $I_0 = \{ \quad \}$

Iteration count k = 1 :1: sparsity level K

3.Finding the index and the value

Find index $p_k = \arg \max_{j \notin I_{K-1}} \left| < r_{k-1,} \phi_j > \right|$

4. Augment the index set and the matrix of selected dictionaries as $I_k = \{I_{k-1} , p_k\}$ and $\Phi_k = \{\Phi_{k-1}, \phi_{pk}\}$.

5. Recompute the coefficients by solving a least-squares problem using $H_e = (\Phi^T * \Phi)^{-1} * \Phi^T * y$

6.Update the residual value $r = r - (\Phi^T * r) * \Phi$.

7.End the iteration.

In the chapter, methods for channel estimation of OFDM systems is discussed. Estimation algorithms like LS, MMSE, OMP is briefly explained.

CHAPTER 6

TERAHERTZ CHANNEL ESTIMATION

Wireless data traffic has exponentially grown in the past years, and this has been accompanied by an increasing demand for higher speed wireless communication. In particular, wireless data rates have doubled every eighteen months over the last three decades. Terahertz (0.1–10 THz) band communication is envisioned as a key technology to satisfy this increasing demand for ultra-broadband wireless communication. THz Band communication will alleviate the spectrum scarcity and capacity limitations of current wireless system. Terahertz communication is 1000 times faster than the current wireless communication, it can achieve data rate of 1 Tbps. In this chapter, a brief overview of THz radiation is discussed, along with the channel characteristics at THz band.

6.1 TERAHERTZ RADIATION

Terahertz radiation also known as sub millimeter radiation, it consists of electromagnetic waves within the ITU-designated band of frequencies from 0.1 to 10 terahertz[10]. Wavelengths of radiation in the terahertz band correspondingly range from 1µm to 100µm. Because terahertz radiation begins at a wavelength of one millimeter and proceeds into shorter wavelengths, it is sometimes known as the sub millimeter band and its radiation as sub millimeter waves. Terahertz radiation falls in-between infrared radiation and microwave radiation in the electromagnetic spectrum as shown in the Figure 6.1, and it shares some properties with each of these. Like infrared and microwave radiation, terahertz radiation travels in a line of sight and is non-ionizing. Like microwave radiation, terahertz radiation can penetrate a wide variety of non-conducting materials. Terahertz radiation can pass through clothing, paper, cardboard, wood, masonry, plastic and ceramics. The penetration depth is typically less than that of microwave radiation. Terahertz radiation has limited penetration through fog and clouds and cannot penetrate liquid water or metal. The earth's atmosphere is a strong absorber of terahertz radiation in specific water vapor absorption bands, so the range of terahertz radiation is limited enough to affect its usefulness in long-distance communications. However, at distances of 10 meters the band may still allow many useful applications in imaging and construction of high bandwidth wireless networking systems, especially indoor systems. In addition, producing and detecting coherent terahertz radiation remains technically challenging, though inexpensive commercial sources now exist in the 0.1–10 THz range (the lower part of the spectrum), including gyrotrons, backward wave oscillators, and resonant-tunneling diodes.

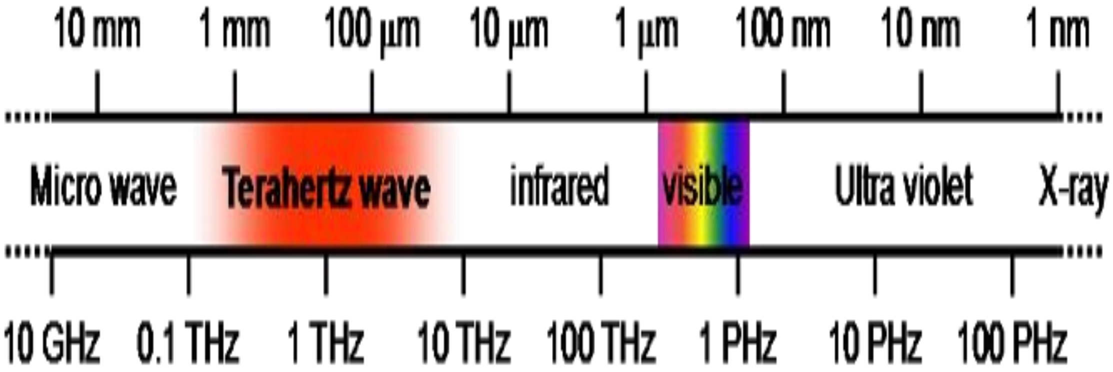

Fig 6.1 Terahertz radiations in the electromagnetic spectrum

6.1.1 SOURCES OF TERAHERTZ RADIATION

6.1.1.1 Natural sources

Terahertz radiation is emitted as part of the black-body radiation from anything with temperatures greater than about 10 Kelvin. While this thermal emission is very weak, observations at these frequencies are important for characterizing the cold 10–20K dust in the interstellar medium in the Milky Way galaxy, and in distant starburst galaxies.

6.1.1.2 Artificial sources

Single-cycle or pulsed sources used in terahertz time domain spectroscopy such as photoconductive, surface field and optical rectification emitters. Electronic oscillators based on resonant tunneling diodes have been shown to operate up to 700 GHz.

Argonne National Laboratory created a compact device that could lead to portable, battery-operated terahertz radiation sources. The device uses high-temperature superconducting crystals, which comprise stacks of Josephson junctions, which exhibit a property known as the Josephson effect. When external voltage is applied, alternating current flows across the junctions at a frequency proportional to the voltage. This alternating current induces an electromagnetic field. Even a small voltage can induce frequencies in the terahertz range.

The engineers at Harvard University achieved room temperature emission of several hundred nanowatts of coherent terahertz radiation using a semiconductor source. THz radiation was generated by nonlinear mixing of two modes in a mid-infrared quantum cascade laser.

The researchers at Georgia Institute of Technology's Broadband Wireless Networking Laboratory and the Polytechnic University of Catalonia developed a method to create a graphene antenna: an antenna that would be shaped into graphene strips from 10 to 100 nanometers wide and one micrometer long. Such an antenna would broadcast in the terahertz frequency range.

6.1.2 TERAHERTZ APPLICATION

Terahertz radiations are used in many research fields they are medical imaging, safety, scientific use and imaging, communication, manufacturing, and power generation.

6.1.2.1 Medical Imaging

Terahertz radiation is not ionizing radiation and its low photon energies in general do not damage tissues and DNA. Some frequencies of terahertz radiation can penetrate several millimeters of tissue with low water content (e.g., fatty tissue) and reflect back. Terahertz radiation can also detect differences in water content and density of a tissue. Such methods could allow effective detection of epithelial cancer with an imaging system that is safe, non-invasive, and painless. Some frequencies of terahertz radiation can be used for 3D imaging of teeth and may be more accurate than conventional X-ray imaging in dentistry.

6.1.2.2 Security

Terahertz radiation can penetrate fabrics and plastics, so it can be used in surveillance, such as security screening, to uncover concealed weapons on a person, remotely. This is of particular interest because many materials of interest have unique spectral "fingerprints" in the terahertz range. This offers the possibility to combine spectral identification with imaging.

The compact sized THz camera for security screening applications, imaged guns and explosives concealed under clothing. Passive detection of terahertz signatures avoid the bodily privacy concerns of other detection by being targeted to a very specific range of materials and objects.

6.1.2.3 Scientific use and Imaging

THz time-domain spectroscopy (THz TDS) and THz tomography are able to perform measurements on, and obtain images of, samples that are opaque in the visible and near-infrared regions of the spectrum. THz-TDS produces radiation that is both coherent and spectrally broad, so such images can contain far more information than a conventional image formed with a single-frequency source.

6.1.2.4 Manufacturing

Many possible uses of terahertz sensing and imaging are proposed in manufacturing, quality control, and process monitoring. These in general exploit the traits of plastics and cardboard being transparent to terahertz radiation, making it possible to inspect packaged goods.

6.1.2.5 Power Generation

NASA has done recent work with using terahertz radiation in the "5-30THz range" to vibrate a nickel lattice loaded with hydrogen in order to induce low energy nuclear reactions but has found that generating the radiation using existing technologies to be very inefficient.

6.2 CHANNEL CHARACTERISTICS

The characteristic of free space at THz band includes various losses and are discussed.

6.2.1 CHANNEL LOSSES

The channel losses in the terahertz band are spreading loss, absorption loss and reflection loss. Spreading loss is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction. It does not include factors such as the gain of the antennas used at the transmitter and receiver, nor any loss associated with hardware imperfections. Spreading loss is proportional to the square of the distance between the transmitter and receiver, and also proportional to the square of the frequency of the radio signal. A transmitted signal attenuates over distance because the signal is being spread over a larger and larger area. This form of attenuation is known as free space loss.

The absorption loss is depends on the signal frequency and the atmospheric gases. In the THz band, the absorption level of atmospheric gases is very strong which is caused by molecular resonances primarily due to water vapor and oxygen [12]. The molecular absorption is caused by the transmitted EM wave is shifting the molecules in the medium to higher energy states. The energy, equivalent to the difference between the higher and the lower energy state of a molecule, determines the absorption energy that is drawn from the EM wave. This has a direct impact on the absorption frequency as the absorbed energy is $E = hf$, where h is the Planck’s constant and f is frequency. The absorption coefficient depends on frequency and gives the THz band a very peculiar frequency selective spectral absorption profile.

In an indoor scenario, the propagation path might be reflected by the presence of obstacles like moving people, furniture, or many diverse objects [14]. The signal power is scattered at the time of reflection. This attenuation is called reflection loss. The characteristics of the reflection are governed by the scattering coefficient ρ . Scattering loss is depends on the roughness factor of the reflected material.

The transmission distance of ultrahigh-speed THz communication is very limited due to the very high path loss in the terahertz channel. But it offers high bandwidth with several gigahertz wide transmission windows, so it achieves high data rate. The objective of this project is to model the THz channel and to analyze the symbol error rate performance using adaptive frequency domain differential phase shift keying modulation (FD-DQPSK).

6.3 CHANNEL MODELING

The physical mechanisms governing a wireless transmission in the THz band are different from those which affect schemes operating in the lower frequency bands. Therefore, already existing channel models cannot be used for THz communications. So, new method of channel modeling and capacity analysis for the terahertz communication is discussed in this chapter Wireless channel model over the indoor terahertz channel is developed considering the molecular absorption and based on Kirchhoff scattering theory and ray tracing algorithm for LOS and NLOS propagation paths respectively.

6.3.1 LINE OF SIGHT PROPAGATION

The propagation model for communications in the THz band for LOS conditions has been developed. This model accounts for the total path loss that an EM wave in the THz band suffers from due to absorption and spreading loss when propagating over very short distances.

Spreading loss is the loss in signal strength of an electromagnetic wave, which attenuates the transmitted signal over distance because the signal is being spread over a larger and larger area. This attenuation is called spreading loss. Spreading loss is directly proportional to the frequency of the signal and the distance between the transmitter and receiver.

The (free space) spreading $A_{spread}(f,r)$ loss accounts for the loss due to the expansion of the wave as it propagates through the medium at a distance r is given by,

$$A_{spread}(f,r) = \frac{(4\pi fr)^2}{c^2} \tag{6.1}$$

Absorption loss depends on the signal frequency and the atmospheric gases. In the THz band, the absorption level of atmospheric gases is very strong which is caused by molecular resonances primarily due to water vapor and oxygen. The molecules in the air absorb the signal energy as it propagates through the air [11]. This attenuation is called atmospheric attenuation. Absorption coefficient $\alpha_{molec}(f, T_K, p)$ is the necessary parameter for calculating absorption loss. Calculated the absorption coefficient using the HITRAN (High resolutions and transmission) simulation which influences the parameter temperature, frequency and pressure of the air.

The total attenuation that an EM wave of a frequency f suffers from due to molecular absorption when traveling over a distance r is given by,

$$A_{abs}(f, r) = e^{\alpha_{molec}(f, T_K, p)r} \tag{6.2}$$

The total path loss $A^{dB}(f, r)$ can be expressed as the sum of the molecular absorption loss and spreading loss in

$$\begin{aligned} A^{dB}(f, r) &= A^{dB}{}_{abs}(f, r) + A^{dB}{}_{spread}(f, r) \\ &= \alpha_{molec}(f, T_K, p) r 10 \log_{10} e + 20 \log_{10}\left(\frac{4\pi f r}{c}\right) \end{aligned} \tag{6.3}$$

6.3.1.1 HITRAN

HITRAN is an acronym for High Resolution Transmission is a compilation of spectroscopic parameters that a variety of computer codes use to predict and simulate the transmission and emission of light in gaseous media including the atmosphere, laboratory cells, etc. The original version was compiled by the Air Force Cambridge Research Laboratories (1960s). HITRAN is maintained and developed at the Harvard-Smithsonian Center for Astrophysics, Cambridge MA, USA.

HITRAN is the worldwide standard for calculating or simulating atmospheric molecular transmission and radiance from the microwave through ultraviolet region of the spectrum. The current version contains 47 molecular species along with their most significant isotopologues. These data are archived as a multitude of high-resolution line transitions, each containing many spectral parameters required for high-resolution simulations [13]. In addition there are about 50 molecular species collected as cross-section data. These latter include anthropogenic constituents in the atmosphere such as the chlorofluorocarbons.

The spectrum of molecular gases is computed by the line-by-line models of spectral calculation in HITRAN compilation.

Molecules absorb and emit radiation only at certain discrete frequencies or wave numbers, corresponding to allowable changes in their quantum energy levels. This produces a unique spectrum for each gas species. It consists of several quantities they are wave number $\left(cm^{-1}\right)$ ν, transmittance τ_v, emissivity ε_v, absorptivity α_v.

Kirchhoff's law equates the absorptivity to emissivity at each wave number. Further, in the absence of scattering or reflections, the absorptivity is the compliment of the transmittance. Each line in the absorption spectrum has a certain width and depth, and is centered at a particular wave number. The line positions and shapes are determined by the quantum mechanical properties of the molecule, and are affected by macroscopic conditions like pressure and temperature. The line parameters are derived by fitting a variety of laboratory spectra, measured over a range of conditions. Each absorption line is thereby characterized by a small set of parameters. With these parameters, an absorption line can be modeled at any given pressure, temperature and gas concentration. The collection of line parameters for a group of absorption lines is called a line list. For the simulation of the transmittance spectrum of a gas mixture in a given spectral range, the absorption lines of each gas must be calculated. Lines whose centers fall outside the spectral range, but whose wings extend into the range, must be included. The complete spectrum is effectively the product of the individual absorption line spectra. Algorithms that simulate molecular spectra in this way by accumulating the spectra of each individual absorption line are known as line-by-line models.

6.3.1.2 LOS CHANNEL MODEL

Wireless channel transfer function in the THz frequency consists of two components they are LOS and NLOS path. In this work LOS path is modeled using HITRAN simulation tool which primarily accounts for molecular absorption and spreading loss. The channel estimation of LOS path of THz channel is done using Least Square Estimation. Its MSE is calculated for the corresponding values of SNR.The magnitude of the LOS path,

$$H^{LOS}(f,r) = H_{spread}(f,r).H_{abs}(f,r) \tag{6.4}$$

With

$$H_{spread}(f,r) = \frac{c}{4\pi fr},$$

$$H_{abs}(f,r) = e^{-\frac{1}{2}\alpha_{molec}(f,T_K,p)r}$$

Where $\alpha_{molec}(f,T_K,p)$ is the absorption co-efficient.

6.4 TERAHERTZ CHANNEL ESTIMATION USING LS ALGORITHM

The THz channel estimation is done using the Least Square algorithm for the LOS path. The transmitted data X is generated and modulated using QAM modulation. The terahertz channel is modelled using $H_{spread}(f,r)$ and $H_{abs}(f,r)$.The tera hertz channel coefficients for LOS path is H.

$$H = H_{spread}(f,r) * H_{abs}(f,r)$$

The data modulated is passed to the terahertz channel where the AWGN noise is added to it. It is denoted as Y. The estimated channel coefficients of terahertz channel using LS algorithm is $\hat{H}_{LS}$

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1} Y \tag{6.5}$$

The Mean square error for the LS estimation in tera hertz channel is calculated using

$$MSE_{LS} = E\{(H - \hat{H}_{LS})^H (H - H_{LS})\} \tag{6.6}$$

In this chapter, a brief overview of THz radiation is discussed, along with the channel characteristics at THz band. In chapter 6 also the channel estimation method of terahertz channel is discussed. However, there is no literature is available for terahertz channel estimation. In this work, the simplest method of channel estimation of LS algorithm is discussed also the MSE determination is done.

CHAPTER 7

SIMULATION RESULTS

In this chapter, the simulation of the Channel estimation of OFDM system and THz channel estimation is evaluated using the MSE curves for the various SNR values is discussed.

7.1 SYSTEM PARAMETERS FOR OFDM SYSTEM

OFDM system parameters used in the simulation are indicated in the Table 7.1. The aim is to achieve better channel estimation performance. Simulations are carried out for different signal to noise ratio(SNR). The simulation parameters to achieve the results are listed in table 7.1.

Table 7.1. Simulation Parameters

Parameters	**Specification**
FFT Size	256
No of Subcarriers	256
Number of Transmitter antenna	1
Number of Receiver antenna	1
Signal Constellation	QAM
No of Blocks	1
Channel Model	Rayleigh Fading
Channel Taps	1

The MSE curve obtained by using LS, MMSE and OMP algorithm shown in Fig 7.1 respectively. From the obtained result the MMSE estimated result is better compared to the LS estimator. The MMSE estimator assumes a priori knowledge of noise variance and channel covariance. So the performance of MMSE estimator is better than that of the LS estimator. Moreover, its complexity is large compared to the LS estimator. Whereas for high SNRs the LS estimator is both simple and adequate. Comparing the MSE of OMP Algorithm it is much closer to LS but it’s a complex algorithm.

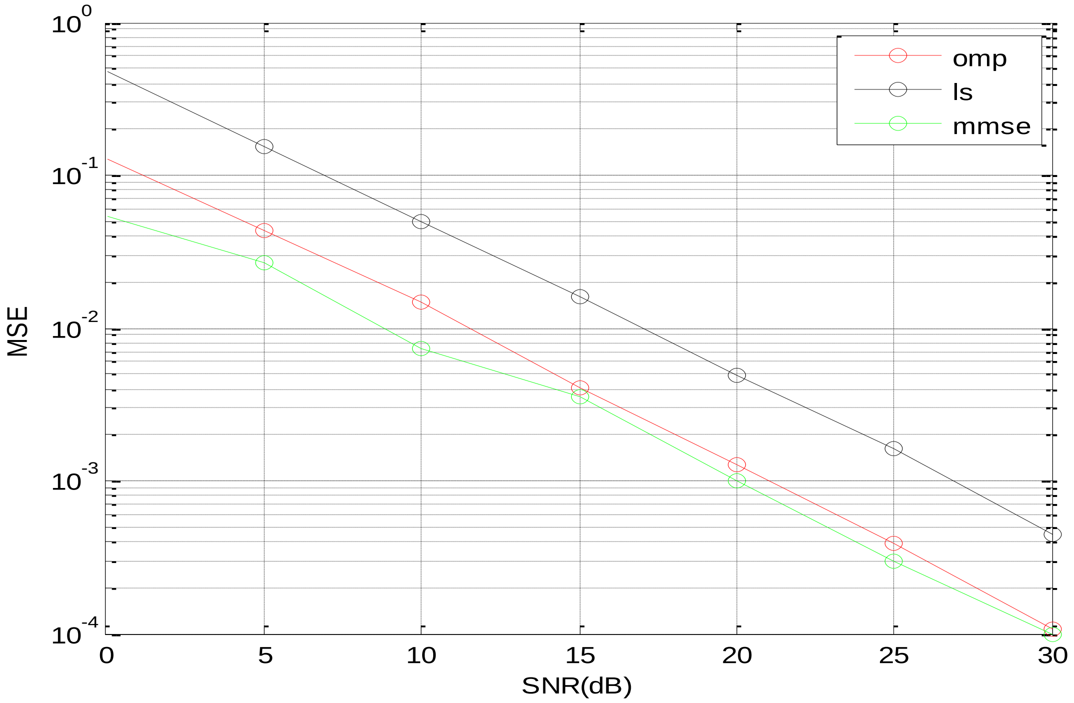

Fig 7.1 MSE OF LS, MMSE AND OMP ESTIMATORS

Fig 7.1 compares the performance of LS and MMSE algorithm in terms of estimation error. Estimation error with MMSE algorithm is less than that of LS algorithm the second order channel statistics are pre-requisite for the implementation of MMSE algorithm. The obtained result is considering all the subcarriers as pilot carrier.

The OMP is a sparse recovery algorithm provides the MSE of OFDM system with the sparse level k=6.The performance of OMP algorithm depends upon the sparsity level.

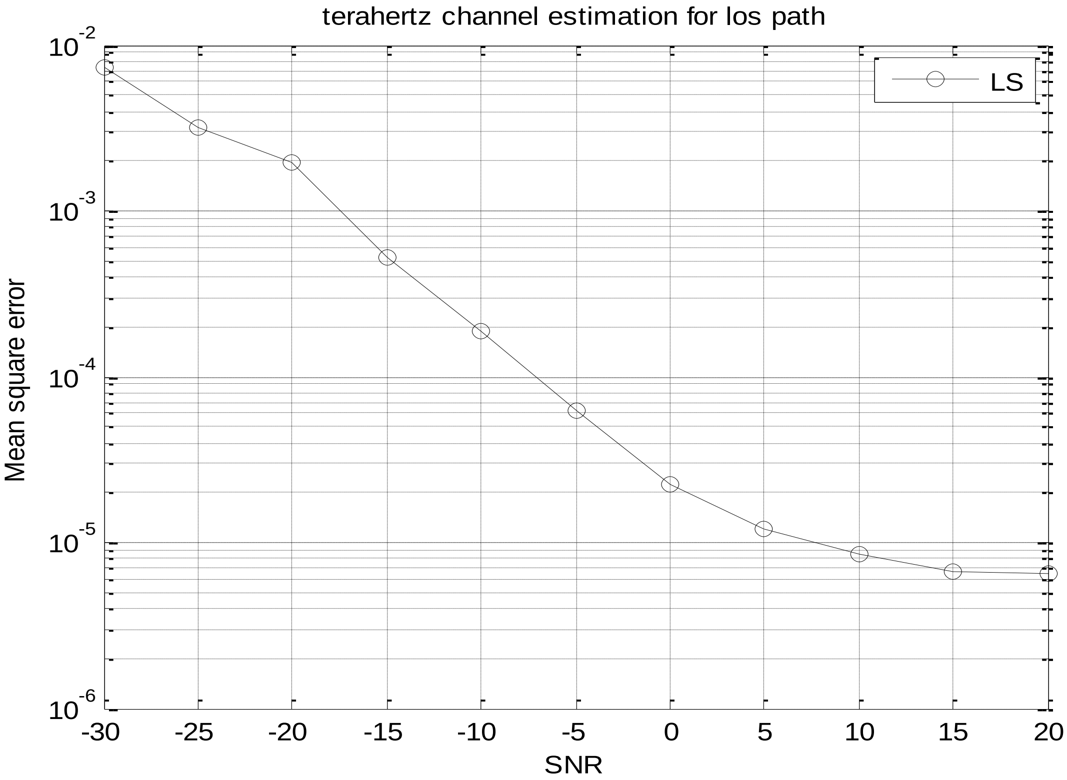

Fig 7.2 MSE OF TERAHERTZ CHANNEL USING LS ESTIMATOR

Figure 7.2 shows the output of THz channel estimation using LS Algorithm. The terahertz channel is modelled for LOS path. Using HITRAN simulation tool the absorbtion coefficients are calculated and for r=2.5 (roughness factor) the H_{LOS} is calculated and modelled as THz channel.

The chapter 7 portrays the results of mean square error for LS, MMSE and OMP algorithms and estimation of terahertz channel is done. The MSE of terahertz channel is calculated using LS algorithm for the range of SNR -30dB to 20dB. However, there is no literature is available for terahertz channel estimation. But channel state information is a vital parameter for the detection of transmitted signal.

CHAPTER 8

CONCLUSION

Channel state information is one of the vital parameters in MIMO-OFDM System. Pilot based channel estimation algorithms are discussed in this paper. MMSE algorithm is compared with LS algorithm. MMSE algorithm needs the channel statistics for the estimation of the channel. The complexity of MMSE algorithm as per the simulation results, the performance of MMSE algorithm is better than LS algorithm in terms of MSE. Practically wireless channel is a sparse channel. The OMP algorithm is a sparse recovery algorithm where OFDM System channel estimation of a sparse channel is done. The terahertz channel estimation for LOS path is done using the Least Square algorithm. The MSE is calculated for the varying SNR -30 to 20 in dB. For future work the usage of pilot carriers in OFDM system can be minimized thus resulting in improving the spectral efficiency also sparse channel estimation using CS techniques can be done. In terahertz communication the MMSE, OMP Estimations of Terahertz channel can be done for NLOS and LOS path of the channel, its corresponding MSE can be calculated.

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