Impact of Timing Synchronization in Wireless Sensor Networks for IoT Application

By

Ismail Zabih Ullah

Fall 2017-MS(EE-9)-00000206255

Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering (MS EE)

In

School of Electrical Engineering and Computer Science,

National University of Sciences and Technology (NUST),

Islamabad, Pakistan.

(April 2021)

Approval

It is certified that the contents and form of the thesis entitled "Impact of Timing Synchronization in Wireless Sensor Networks for IoT Application" submitted by ISMAIL ZABIH ULLAH have been found satisfactory for the requirement of the degree

Advisor : Dr. Syed Ali Hassan

Signature: ______________________

Date: 26-Apr-2021

Committee Member 1:Dr. Rizwan Ahmad

Signature: ______________________

Date: 28-Apr-2021

Committee Member 2:Dr. Hassaan Khaliq Qureshi

Signature: Hassaan Khaliq

Date: 27-Apr-2021

Committee Member 3:Dr. Umair Hashmi

Signature: Umair

Date: 26-Apr-2021

Dedication

To my parents, Khalil Ur Rehman and Shaheen Bibi, my phopho Naz-Gul Jamal, my brother SanaUllah Khan, my ever supporting sister Azeena bibi and Jibreel's mother Rahat Ul Ain.

Certificate of Originality

I hereby declare that this submission titled "Impact of Timing Synchronization in Wireless Sensor Networks for IoT Application" is my own work. To the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics, which has been acknowledged. I also verified the originality of contents through plagiarism software.

Student Name: ISMAIL ZABIH ULLAH

Student Signature: ________________

Acknowledgment

First and foremost I thank Allah Almighty for His blessings on me, He made things easy for me and without Him I am absolutely nothing and I think perhaps the best feeling in the world comes in those days when we know that He, our Lord is pleased with us for many good reasons. I would like to extend my gratitude to my advisor, Dr. Syed Ali Hassan for his enormous patience, he treats everyone like his friend, he is the best advisor everrrr. I would like to thank my buddy, Shah Zeb Khan, I am so lucky enough to have a friend like you, ever since childhood I am searching rare and precious 'Four-Leaves-Clover' in the lawn of our garden though I never found one but you, my friend, is that forth leaf, always there for me, I would like to thank my batch mate Murshid Karam-Shahzad as I am his proud first disciple, my crime partner Qamar Abbas who taught me a lot, my best senior sister in SEECS Dr. Huma Israr, our buddy, the master-chef Mazhar Shehzad, guy that possess cherubic face and a good heart Hashim Khan and left wing kamran Mangi and Jameel last but not the least our good compassionate friend in lab Amber Hina for serving late night tea and noodles and her entire group, fun-time powerhouse Gulmina and Ravina and others from my IPT Research Lab and HPC lab specially Moeen, our Table-Tennis rivalry with their lab shall be remembered. Finally I must say without them and their encouragement and guidance, I would not have been able to achieve what I have thus so far.

Table of Contents

1 Introduction and Background to Thesis

List of Abbreviations

IIoT	Industrial Intenet-of-Things
CPS	Cyber-physical system
PTP	Precision time protocol
RAN	Radio access network
RAT	Radio access technologies
URLLC	Ultra-reliable and low-latency communications
mMTC	Massive machine type communications
eMBB	Enhanced mobile broadband
mmWave	millimeter wave
ToA	Time-of-Arrival
AoA	Angle-of-Arrival
RSSI	Recieved signal strength intensity
TA	Timing Advance
MSE	Mean square error

List of Figures

Abstract

Rampant evolution of the fifth-generation mobile communication (5G) research and Internet of Things (IoT) opens up a new range of possibilities enabling ubiquitous wireless solutions in numerous fields that includes visceral surgeries, strident environmental monitoring, harsh industrial conditions, and military reconnaissance, however, these applications are restricted by various factors such as power consumption which is one of the significant concern. Techniques that use less energy in modulation such as FSK (Frequency Shift Keying) is more propitious for applications where reducing power consumption is the primary goal however FSK systems experience a blend of both time as well as frequency offsets (errors). In this thesis, we assess the deleterious effect of timing offsets in particular. A novel method is proposed for the estimation of timing offset error by sending a known pilot training sequences in pairs of two bits/symbols simultaneously, one after another, this process ameliorates the manipulation of known mathematical equations for obtaining. Method of moments (MoM) estimator that equates sample moments with theoretical moments is a long-established procedure for finding point estimators. we correctly estimated the Timing offset using a moment-based estimator in this thesis.

Chapter 1

Introduction and Background to Thesis

1.1 Evolution of 5G

1.1.1 Philosophy of 5G

The world's appetite for wireless speed has been unquenchable and fifth generation of cellular networks (5G) is another endeavour in this development leap that historically happens every decade. Technically every sentient being inhibits inside an ocean of electromagnetic signals and for the generation of millennials it is a digital sanctuary, we breath and respire inside connected digitized world. [1]

5G is considered a game changer, it is not just an improvement to its predecessor cellular network such as providing much higher data rates than 4G and LTE [3–7]. It is technological innovations and matchless engineering indignity. 5G is important for delivering connectivity for new vertical domain services and applications, such as factory automation and self - driving cars and asset tracking, smart grid, energy/ utility monitoring, smart homes, physical infrastructure, remote monitoring, beacons and connected shoppers. In reality, according to industry analysts IHS Markit, 5G would allow 12.33 trillion in global economic production by 2035. [8]. According to an IDC report, the amount of data generated, captured, and replicated around the world could increase from 33 Zettabytes (ZB) in 2018 to 175 Zettabytes (ZB) by 2025 [9]

The development in the many indispensable technologies of this decade, such as, ,massive connectivity, millimeter waves (mmWave), massive multi-input multi-output (MIMO), software defined networking (SDN), scalable Internet of Things (IoT),new radio access technologies (RAT), network function virtualization (NFV), Big data and mobile cloud computing etc., and their applications in many areas have revamped and revolutionize the wireless ecosystem of next generation 5G cellular network.

1.1.2 5G Network Services

The 5G network infrastructure will not only be able to offer mobile connectivity to end users, but it will also be able to provide coverage in the three sections below. [10, 11]:

- Enhanced mobile broadband (eMBB): 5G network is expected to deliver improved performance than its predecessor cellular networks in terms of wide-area coverage, increased data rate and high mobility to

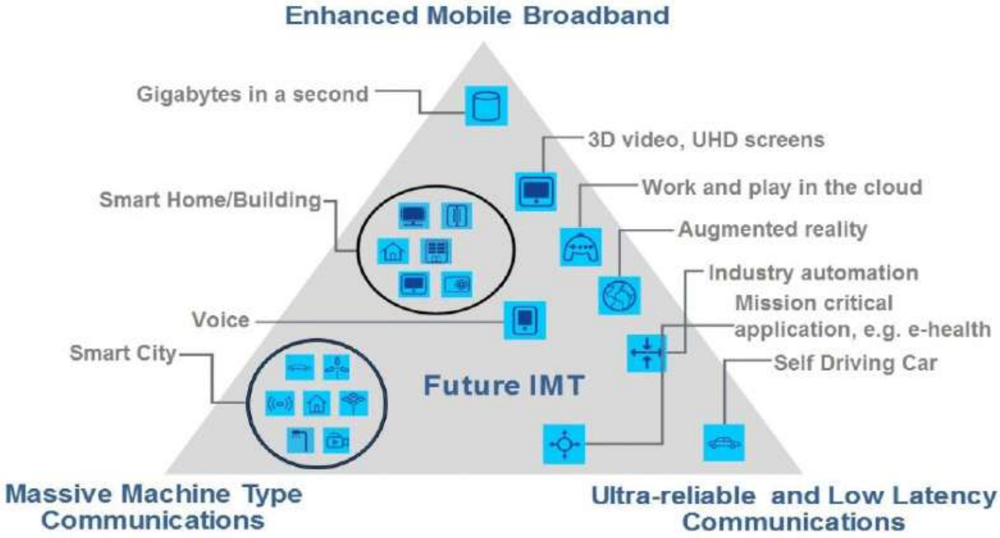


Figure 1.1: 5G services classification and its use cases in IMT 2020 [1, 2]

end users.

- Massive machine type communications (mMTC): Second category that attracted attention of academia as well as industry is mMTC, in this service, of deployment a very large number of sensors and other devices are accommodated in relatively small area i.e. over 1,000,000 devices/km square. Well practically these devices have low-cost and economical in nature, expected to have a battery life and capable of receiving insensitive data .

- Ultra-reliable and low latency communications (URLLC): This service is designed for applications that require a high level of latency as discussed in abstract of our thesis and strict reliability requirements. There is wide range of applications usage cases which have such stringent requirements such as factory automation, tactile internet, smart homes, modern system for transportation etc., as shown in Fig. 1.1.

Next generation 5G networks has the liberty to provide better services to end devices numerous domain usages specially to services like Internet of Things (IoT).Next technological advancement and next big thing to be revolutionised is IoT, this is going to be as big transformation as deployment of internet in 1960s. By this way billion of devices are going to connect to internet and this next technology has better intergration with internet world. With the massive growth in the usage of Internet of Things (IoT) devices, new techniques for providing improved connectivity, lower latency, and more efficient networks to meet the needs of IoT devices in smart applications have emerged. [12]. IoT application can utilize these new services provided by 5G network after deployment. The key enabler in this are URLLC and mMTC [13].

1.2 5G and IoT

IoT is gaining rampant attention as it is considered one of the most effective technology in transforming our lives. [14] Analysts at the business insider estimated that over more than 34 billion devices will be connected by 2025 [15]. However to meet such demands for deployment of IoT devices has to rely on an effective architecture for systematic communication. [16,17] With extended coverage, lower latency, higher throughput and better connectivity with massive bandwidth paved a way for the deployment of sensors connected to internet. The prospective 5G in tendon with IoT can make significant contribution by connecting billions of smart devices together through internet. Moreover smart sensors, artificial monitoring systems to create a massive IoT that is inundated by messages and signals jointly interacting in nature that has capabilty to share data even in absence of the human interactions. [15, 18]

The heterogeneous nature of applications make things to handle quite complicated, IoT system to diagnose if those particular end devices would satisfy need of those application for which architecture were designed [19,20]. Perfect architecture for IoT is quite an impossible task and every new applications have to face new challenges hence things ought to be improvised keeping in mind the particular needs. Excising IoT system for different applications use differnent domains forBLE, ZigBee, and other wireless technologies Wifi, LP-WA networks, and mobile networks (e.g., MTC using 3GPP, 4G (LTE)) are examples of other technologies, etc. In this way IoT is evolving quickly. Advance research includes using combinations of these domains for specific applications. IoT is gaining importance tremendously in manufacturing production as well as supply chains industry. Moreover in Industry 4.0 is based on the use of cyber physical system (CPS), in which data from all interconnected devices are collected data for the purpose of monitoring, centralizing control of the factory automation, perfect synchronization between cyber computational space and for real time data processing on floor can be efficiently be monitored [21].

1.2.1 Challenges of 5G IoT systems

There are still various challenges to contend with, in order to realize the full capacity of IoT despite enormous efforts of standardization authorities, alliances, and companies. These issues should be taken into account in different areas Application support infrastructure, business practices, social and environmental impacts Researchers are contemplating over it to overcome challenges of prospective requirements from the technological perspective. [16] In the last several years, extensive efforts have been carried out to investigate a number of complex topics for 5G IoT:

- High data rates requirement for future IoT applications of IoT needs 25 Mbps in many scattered nodes of an agglomerated systems such as HD streaming of the video in concerts , virtual reality (VR), and the augmented-reality (AR) and other applications. [22].

- Reliability resilience, 5G-IoT nodes accelerating with high speeds entailed in remote areas require enhanced coverage and handover efficiency. Such as vehicular IoT nodes moving at higher speeds [23].

- Connection density, huge number of nodes that are connected in 5G-IoT should have the capability to support the successful delivery of data in an area and time without losing synchronisation. [24]

- Security is one of the major concern for IoT devices, strategies to protect connectivity and privacy of the user, the 5G IoT requires an improved security implications and there is alot to do in terms of improving the security of the entire network holistically.

- Better battery life, devices deployed under harsh environmental conditions such as underwater, fire-burners, remote desert areas for military surveillance have to work over time and battery is major concern in such applications [25]. There are different modulation techniques specially redefined for IoT to cope with energy issues, however this is still one of the major challenge to cope. Wireless communication is all about Trade-offs and for such requirements researchers propose sacrificing bandwidth over energy by using such techniques, such as FSK modulation in our own case.

1.2.2 Energy efficiency in IoT

As the commercial deployment of the fifth generation 5G-IoT is advancing rapidly in many countries of the world, academia and researchers are still trying to overcome practical challenges. Two of the prominent areas in research with the ever growing need for consumers to find all the knowledge they need on the go as IoT is intended to connect all devices in near future. [26] Nodes topology, error detection, data management, energy consumption reduction are the primary issues for IoT. However, the construction of less power consumption rate is the main concern for the researchers, with the persistent need for processing of data. [26] and hence, persistent requirement for collecting data from different sources, proposition and implementation of theThe primary focus of researchers is on low-power rating sensors and many industries have underscored the importance of devising efficient strategies in terms of energy for data distribution that may resist re-calibrations of end devices such as sensors.

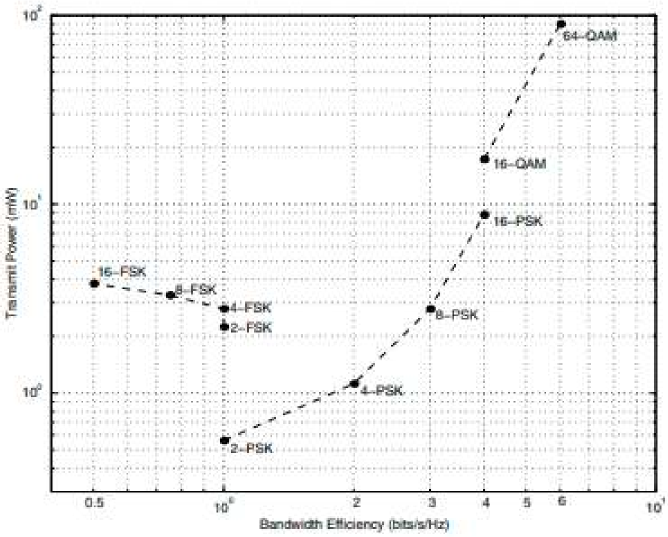


Figure 1.2: Transmit power versus bandwidth efficiency in fading channel [27]

1.3 Energy efficient modulation

In modulation such as M-ary, the symbols that are transmitted are deciphered from a set of M (M=2 in case of binary) different waveform. It is obvious from all this that log2 of M bits are transmitted in each symbol. We will revisit all modulation techniques to see which one suits better for IoT end devices. Basically modulation is changing either of the three characteristics of the wave, either phase, amplitude, frequency or any combination of them. M-ary Quadrature Amplitude Modulation (M-QAM), M-ary Frequency Shift Keying (M-FSK), and M-ary Phase Shift Keying are some examples (M-PSK).

Figure 1.2 tells us about transmitted power versus energy efficiency. Wireless communication is all about trade-off, we have to sacrifice one particular thing for achieving another thing, this is sort of a rule of thumb. So here in this case we can see clear distinction. M-PSK sacrifices power for the sake of bandwidth, hence MPSK is better modulation scheme in terms of spectral efficiency, however same is not true for energy efficiency. For an energy efficient communication we ought to move to M-FSK from QAM and PSK, ASK. [27]

Another significant point we discovered is that for M greater than 8, M-FSK is more effective than M-PSK/M-QAM.At small M, M-FSK is less energy-efficient, and non-coherent detection requires 6dB more power levels to achieve the same BER efficiency.The symbol SNR needed for M-PSK/M-QAM grows very quickly as the number of M increases.

1.3.1 Two primary sources of degradation in FSK

As we have seen that Noncoherent orthogonal M-ary frequency-shift-keying (M-FSK) is a perfect candidate for those IoT devices where the requirements of the bandwidths are not too stringent. While most research about modulation and demodulation techniques for the additive white Gaussian noise (AWGN) channel as well as Rayleigh fading channel aimed at the receiver when it is supposed to be timed precisely as well as for frequency .

It has been presumed that receiver already have ideal conditions and have all knowledge about the times for which FSK modulation changes the state and it also have a better knowledge about received carrier frequency. However while incorporating this in practice such precise information is seldom available and thus the receiver ought to to either estimate this knowledge from the signal that is received in an AWGN. While on the receiving end, time estimates and received carrier frequency estimations are made, between these calculations and their true values, there is the risk of a mistake. Degradation occurs as a result of the error risk rises due to a lack of perfect time and frequency synchronisation, the performance relative degrades, the ideal case is not possible when precise knowledge of time and frequency is unknown.

1.3.2 Frequency and Timing offset

In case when receiver carrier frequency is determined but the symbol epoch is unknown, the receiver measures an own symbol period, which is $Deltat$ seconds off from the real epoch. Due to the lack of time synchronisation, signal attenuation occurs in the detector that is matched to the entering frequency, as well as loss of orthogonality because of which signal spillover into the remaining detectors. It is denoted by λ in our work.

The symbol epoch is set properly even if the receiver carrier frequency is uncertain The receiver creates its own frequency estimate, which is by ρt seconds off from the exact carrier frequency. . Owing to the unavailability of frequency synchronisation, signal attenuation occurs in the detector that is matched to the incoming frequency, as well as loss of orthogonality, which causes signal spillover onto the other detectors. It is denoted by ρ in our work.

1.4 Estimation Theory

For current era of wireless communications as well as signal processing estimation theory provides a large number of techniques that has a wide range of application such channel estimation is one of the most popular among all of them. Moreover channel estimation, equalization, synchronization are also estimated with the help of these techniques and theories.

1.4.1 Method Of Momenet estimation

The Method of Moment (MoM) estimation includes equating theoretical moments to the sample moments of given population. MoM for the point estimation is one of the most efficient method for solving tedious and rigorous problems that are quite non-linear in nature

1.5 Thesis Motivation

In an IoT realm,energy-efficiency and battery constraints are among major challenges specially for applications that are working under severe conditions and harsh environments, such as military reconnaissance, underwater surveillance and remote deserts. Since FSK modulation consumes less energy compared to other modulation schemes and is best contender for such applications, however A combination of time and frequency offsets occur in practical M-FSK systems (errors). The motivation of this thesis is study estimate and assesses the deleterious effect timing-offset in particular by method-of-moment approach.

1.6 Thesis Contribution

The thesis work presents the following main contributions:

- Estimated and assesses the deleterious effect of timing-offset
- Estimated variance of noise N which is subsequently used to derive timing-offset λ in Rayleigh faded environment
- Method of moments (MoM) estimator that equates sample moments with theoretical moments is a long-established procedure for finding point estimators. Using a moment-based estimator, we correctly measure the Timing offset.
- A novel method is proposed for the estimation of timing offset error λ by sending a known pilot training sequences in pairs of two bits/symbols simultaneously, one after another, this process ameliorates the manipulation of known mathematical equations for obtaining λ.
- We verified these results in Wolfram Mathematica 11.8 and simulated results in MATLAB

1.7 Thesis Organization

The organization of the thesis is presented in following manner. First literature review of the major concepts provided in this thesis is highlighted in Chapter 2 to provide a flow for the readers. In chapter 3, a system model for deriving the timing-offset λ in Rayleigh faded environment. Method of Moments (MoM) based estimator is proposed for first and cross statistics of received data to estimate variance of noise N which will subsequently be used to derive timing-offset λ in Rayleigh faded environment In Chapter 4, we investigate and examine the proposed system's performance. In Chapter 5 discusses the results found during performance analysis of proposed system model. Finally in the end, chapter 6 presents the conclusions and further proposes the future work.

Chapter 2

Literature Review

In this section, we highlighted challenges related to energy-efficient models for sensors networks in an IoT realm and estimation techniques used for evaluating the nuance parameters such as frequency and timing-offsets for the purpose of omitting faults, offsets and errors which are main hurdles in achieving our objectives, we also put light on related work. Although IoT devices are now used widespread in variety of applications such as drought and harsh environmental conditions and such Micro-sensors must operate for years on a minimal amount of energy. As a result, a level of optimization is required to reduce the energy dissipation of such devices. There are a number of factors such as using application specific routing algorithms that consumes less power, RF front-end circuitry designed to over come the energy dissipation, overhauling of the entire system to lower the demand of battery energy [28]. Perfect synchronisation, on the other hand, is difficult, and any new energy-efficient [29] design must address this issue by addressing one or more aspects while keeping in mind the requirements for those specific applications.

Among all such practices for achieving designs [30] that dissipates less power one is using energy-efficient modulation schemes. Since for it is clear from previous studies that frequency based modulation performs far better in terms of energies than other techniques, however the trade-off for such techniques comes at a cost of bandwidth. Since the next generation of mobile communication that is 5G networks is going to rule the world for at-least next decade and bandwidth in this case is a trivial issue as 5G provides humongous range of speed, connectivity as well as bandwidth, hence both academia and industry is focusing on energy more than bandwidth at the moment.

The *prima facie* solution is use frequency based modulation that is more energy efficient [27] and it gives better results, consuming less power however practical system that involves such modulation faces a number of challenges [31]. Among these challenges are frequency and timing-offsets. Due to these offsets in system receiver is unable to estimate accurate symbol time-epoch hence it executes it's own times which off-course intermingles one symbols into another and hence symbols have to be re-transmitted at the cost of energy and bandwidth. Moreover this also causes signals spillover into remaining branches of the detector matched circuits that causes loss of orthogonality. [32] calculated estimation of the SNR for a non-coherent binary frequency shift keying, while [33] did same for Rice-fading.

We took our inspiration from [34] problem of frequency offset is outright ingeniously and artistically evaluated. We implemented that paper and solved stochastic mathematics with help of Wolfram Mathematica 11.3. We accurately evaluated frequency offset and got better results. We accurately evaluated frequency offset p and got better cognizance for our own work. However quadratic equation at the end of [34] for estimation of frequency offset were comparatively trivial due indistinguishable and homogeneous nature of those equations. In our case due to inaccurate timing epoch the second integral part yields quite long and different set of equation in every particular case, such as case-2 and case-3. Hence it almost impossible to solve it that way.

Similarly in [35] and [36] used Non-coherent Frequency shift keying (FSK) modulation, these thesis works have used Maximum likelihood (ML) estimate approaches with and without data. For analysing the performance of the generated estimators, Cramer-Rao lower bound expressions are generated. Similarly [31] have explained the deleterious effects of offsets and modelled it mathematically in detail. First the frequency offset ρ are incorporated into non-coherent orthogonal M-FSK system and showed results that how an increase in the nuisance parameter causes an increase in probability of bit-error rate, in same paper they also explained the effects of timing-offset which they denoted by λ.

It is shown that both these offsets causes a considerable amount of loss in energy as date has to be re-transmitted. Combined effects of both timing as well as frequency offsets have been evaluated, it is clearly shown that degradation in far more when both these effects collectively attacks the system. However non of this above work explains any estimation of timing-offsets, while frequency offset by the method of moment approach is estimated by [37]. More related work to this can be seen in [32, 33, 38–40] similarly timing synchronisation is discussed in [41, 42] and in MISO system performance of FSK is discussed in [42, 43] hence the main focus of our thesis is to estimate the timing-offsets. Similarly a lot of work has been done on 5G networks related to energy efficiency, battery proficiency and better transmission techniques. [38, 44–62] ,

Chapter 3

Methodology and System Model

3.1 Brief Overview

Method of Moments (MoM) based estimator is proposed for first and cross statistics of received data to estimate variance of noise N which will subsequently be used to derive timing-offset λ in Rayleigh faded environment.

A novel method is proposed for the estimation of timing offset error λ by sending a known pilot training sequences in pairs of two bits/symbols simultaneously, one after another, this process ameliorates the manipulation of known mathematical equations for obtaining λ. We identified and derived suitable equations acquired from different branches of correlators for obtaining λ by sending aforementioned pairs of symbols, We verified these results in Wolfram Mathematica 11.8 and simulated results in MATLAB.

3.2 System Model

Taking a Rayleigh fading system into consideration that takes on binary FSK modulation, where a block of ν symbols encounter fading. When the symbol carrier frequency at the receiver is known but the symbol period is unknown, the receiver determines its own symbol epoch that is $Deltat$ second off from the true time. Due to the lack of time synchronisation, attenuation and loss of orthogonality occur in the detector that is matched to the incoming frequency, causing signal overflow into the other detectors. The received signal can be described as follows

$$r(t) = \begin{cases} \sqrt{P_s}\alpha(t)\exp(-j2\pi(f_c + f_i)t + \theta) + n(t) & 0 \leq t \leq T \\ \sqrt{P_s}\alpha(t)\exp(-j2\pi(f_c + f_j)t + \theta) + n(t) & T \leq t \leq 2T \end{cases} \tag{3.1}$$

where P_s is the signal power, $\alpha(t)$ is the Rayleigh fading envelope , f_c is the carrier frequency, and f_i and f_j are the frequency that corresponds to the message signal coming one after another due to error in timing error. Here we assumed that signal $S_i(t)$ is followed by signal S_j. Since the local time estimate is not accurately known hence receiver operates in the period of (Δt, $\Delta t + T$) , thus output of the integrator is matched to the transmitted signal S_m is given by

$$v_m = \int_{\Delta t}^{\Delta t+T} r(t).\sqrt{P}\exp(j * 2 * \pi(f_c + f_m)t)dt \tag{3.2}$$

$$v_m = \int_{\Delta t}^{T} \sqrt{P} \exp(-j * 2 * \pi(f_c + f_i)t) \sqrt{P} \exp(j * 2 * \pi(f_c + f_m)t)dt + \int_{T}^{\Delta t + T} \sqrt{P} \exp(-j * 2 * \pi(f_c + f_j)t) . \sqrt{P} \exp(j * 2 * \pi(f_c + f_m)t)dt \quad (3.3)$$

$$v_m = 2P \int_{\Delta t}^{T} \exp(-j * 2 * \pi(f_c + f_i)t) \exp(j * 2 * \pi(f_c + f_m)t)dt + \int_{T}^{\Delta t + T} \exp(-j * 2 * \pi(f_c + f_j)t) . \exp(j * 2 * \pi(f_c + f_m)t)dt + n \quad (3.4)$$

3.2.1 Special Cases

Now we are considering special cases, these cases are categorised on basis of data bits/symbols that are send in a regular intervals. By sending a known pilot training sequences in pairs of two bits/symbols simultaneously, one after another for ameliorating the manipulation of known mathematical equations for obtaining λ. Since we are considering a BFSK system hence we have four known cases explained below

3.2.2 Cases-1 (i, i)

In this case we send a known sequence of bits first by sending i bit which is received by both corelators in a time instant of (Δt to T). This unspecified symbol epoch is executed by receive itself. For the sake of simplicity we assumed this time instant same for all four cases. Later same i bit is send off which is received in a time instant of (T to $\Delta T + t$). It is assumed that corelator-1 has i bit that can be perfectly matched to it. Corelator-1 yields an output can be modeled as

$$\begin{aligned} v_m 1 = 2P \int_{\Delta t}^{T} & \exp(-j * 2 * \pi(f_c + f_i)t) \exp(j * 2 * \pi(f_c + f_i)t)dt \\ + \int_{T}^{\Delta t + T} & \exp(-j * 2 * \pi(f_c + f_i)t). \exp(j * 2 * \pi(f_c + f_i)t)dt + n \end{aligned} \tag{3.5}$$

Simplifying equation 3.5 gives the output as

$$v_{m1} = P\alpha(T - \Delta t) + P\alpha\Delta t = PT\alpha = E_s\alpha \tag{3.6}$$

similarly correlator-2 is modelled as

$$\begin{aligned} v_m 1 = 2P \int_{\Delta t}^{T} & \exp(-j * 2 * \pi(f_c + f_i)t) \exp(j * 2 * \pi(f_c + f_j)t)dt \\ + \int_{T}^{\Delta t + T} & \exp(-j * 2 * \pi(f_c + f_i)t). \exp(j * 2 * \pi(f_c + f_j)t)dt + n \end{aligned} \tag{3.7}$$

3.2.3 Cases-2 (i, j)

In this case we send a known sequence of bits first by sending i bit which is received by both corelators in a time instant of (Δt to T). Later another bit j bit is send off which is received in a time instant of (T to $\Delta T + t$). It is assumed that corelator-1 has i bit that can be perfectly matched to it. Correlator-1 yields an output can be modeled as

$$
\begin{aligned}
v_{m1} = 2P \int_{\Delta t}^{T} & \exp(-j * 2 * \pi(f_c + f_i)t) \exp(j * 2 * \pi(f_c + f_i)t)dt \\
& + \int_{T}^{\Delta t + T} \exp(-j * 2 * \pi(f_c + f_j)t). \exp(j * 2 * \pi(f_c + f_i)t)dt + n \\
= -\frac{i(\exp(-i.2(f_i - f_j)\pi T) \exp -(-i.2(f_i - f_j)\pi(T + \Delta t))P\alpha}{2(f_i - f_j)\pi} & + P\alpha(T - \Delta t)
\end{aligned}
\tag{3.8}
$$

Similarly correlator-2 can be modelled as

$$
\begin{aligned}
v_{m1} = 2P \int_{\Delta t}^{T} & \exp(-j * 2 * \pi(f_c + f_i)t) \exp(j * 2 * \pi(f_c + f_j)t)dt \\
& + \int_{T}^{\Delta t + T} \exp(-j * 2 * \pi(f_c + f_j)t). \exp(j * 2 * \pi(f_c + f_j)t)dt + n \\
& = -\frac{i(\exp(-i.2(f_i - f_j)\pi T) \exp(f_i - f_j)\pi.\Delta t)}{2(f_i - f_j)\pi} + P\alpha.\Delta t
\end{aligned}
\tag{3.9}
$$

3.2.4 Cases-3 (j, i)

In this case we send a known sequence of bits first by sending j bit which is received by both corelators in a time instant of (Δt to T). Later another bit i bit is send off which is received in a time instant of (T to $\Delta T + t$). It is assumed that corelator-1 has i bit that can be perfectly matched to it.

Correlator-1 yields an output can be modeled as

$$\begin{aligned} v_{m1} = 2P &\int_{\Delta t}^{T} \exp(-j \ast 2 \ast \pi(f_c + f_j)t) \exp(j \ast 2 \ast \pi(f_c + f_j)t)dt \\ + &\int_{T}^{\Delta t+T} \exp(-j \ast 2 \ast \pi(f_c + f_i)t). \exp(j \ast 2 \ast \pi(f_c + f_j)t)dt + n \\ &= -\frac{i(\exp(-i.2(f_i - f_j)\pi T) \exp(f_i - f_j)\pi.\Delta t)}{2(fi - f_j)\pi} + P\alpha.\Delta t \end{aligned} \tag{3.10}$$

Similarly correlator-2 can be modelled as

$$\begin{aligned} v_{m1} = 2P &\int_{\Delta t}^{T} \exp(-j \ast 2 \ast \pi(f_c + f_j)t) \exp(j \ast 2 \ast \pi(f_c + f_j)t)dt \\ + &\int_{T}^{\Delta t+T} \exp(-j \ast 2 \ast \pi(f_c + f_j)t). \exp(j \ast 2 \ast \pi(f_c + f_j)t)dt + n \\ = &-\frac{i(\exp(-i.2(f_i - f_j)\pi T) \exp -(-i.2(f_i - f_j)\pi(T + \Delta t))P\alpha}{2(f_i - f_j)\pi} + P\alpha(T - \Delta t) \end{aligned} \tag{3.11}$$

3.2.5 Cases-4(j, j)

$$\begin{aligned} v_m 1 = 2P &\int_{\Delta t}^{T} \exp(-j \ast 2 \ast \pi(f_c + f_j)t) \exp(j \ast 2 \ast \pi(f_c + f_i)t)dt \\ + &\int_{T}^{\Delta t+T} \exp(-j \ast 2 \ast \pi(f_c + f_j)t). \exp(j \ast 2 \ast \pi(f_c + f_j)t)dt + n \end{aligned} \tag{3.12}$$

$$\begin{aligned} v_m 1 = 2P &\int_{\Delta t}^{T} \exp(-j * 2 * \pi(f_c + f_j)t) \exp(j * 2 * \pi(f_c + f_j)t) dt \\ &+ \int_{T}^{\Delta t + T} \exp(-j * 2 * \pi(f_c + f_j)t). \exp(j * 2 * \pi(f_c + f_j)t) dt + n \end{aligned} \quad (3.13)$$

Simplifying equation 3.5 gives the output as

$$v_{m1} = P\alpha(T - \Delta t) + P\alpha\Delta t = PT\alpha = E_s\alpha \quad (3.14)$$

3.3 Method of Moment

The Method of Moment (MoM) estimation includes equating theoretical moments to the sample moments of given population. MoM for the point estimation is one of the most efficient method for solving tedious and rigorous problems that are quite non-linear in nature.

3.4 Estimation of λ

Method of Moments (MoM) based estimator is proposed in this section, first and cross statistics of received data to estimate variance of noise N which will subsequently be used to derive timing-offset λ in Rayleigh faded environment.

3.4.1 Statistical properties of signals

There are four possible cases explained above, to better analyse the statistical properties of the signals we briefly explained case-2 below.

$$X_{i=}\left|S_i\alpha_{i}+n_i\right|^2 \tag{3.15}$$

The channel gains, α_{i} and the noise elements n_i are zero mean complex Gaussian random variables with variance of $S/2$ and $N/2$ per real dimension respectively. For non-coherent BFSK condition for orthogonality is $1/T$ From equation 3.8 and 3.9 we get

$$A_{3\_1}=\left|P.\alpha\left(\frac{e^{-j\cdot 2\cdot\pi}-e^{-j\cdot 2\cdot\pi(1+\lambda)}}{j2\pi/T}\right)+P.\alpha(T-\Delta t)\right|^2 \tag{3.16}$$

and for corelator-2 we get

$$A_{3\_2}=\left|-P.\alpha\left(\frac{e^{-j\cdot 2\cdot\pi}-e^{-j\cdot 2\cdot\pi\lambda}}{j2\pi/T}\right)+P.\alpha\Delta t\right|^2 \tag{3.17}$$

3.4.2 Estimation of Noise

To estimate the Noise, we use first order self and cross statistics from the obtained data. which will subsequently be used in the estimation of Timing-offset λ. We borrowed our concept from reference to be given here Dr. Ali's paper. Expending equation 3.15 we get

$$y=\left|(S_i\alpha)^2+(n)^2+2\ (S_i\alpha)(n)\ \right| \tag{3.18}$$

$$E(y) = \left| E(S_i\alpha)^2 + E(n)^2 + 2\ E.(S_i\alpha).(n)\ \right| \tag{3.19}$$

As we have explained the statistical properties of these signals hence

$$E(y) = A_{31}S + N \tag{3.20}$$

Similarly and the first cross-moment is given as

$$E(A_{31}A_{32}) = 2A_{31}A_{32}S^2 + SN(A_{31} + A_{32}) + N^2 \tag{3.21}$$

In practice, we replace the theoretical averages in previous equations with those of sample averages, i.e $E(y) = \frac{1}{k}\sum_{i=1}^{k} y_i$ Hence, we denote the sample averages as $X = \frac{1}{k}\sum_{i=1}^{k} y_i$ and $Y = \frac{1}{k}\sum_{i=1}^{k} y_2$ and $E(XY) = Z$ equation 3.20 and 3.21 can be solved simultaneously to get the estimate of the noise N

$$\hat{N} = \frac{1}{2}(X + Y - \sqrt{X^2 - 6XY + Y + 4Z}) \tag{3.22}$$

3.4.3 Estimation of Timing Offset

We tried a plethora of mathematical procedures and for estimation of offset λ However, due to the problem's extremely non-linear existence, it turned out to be very difficult to solve and does not produce accurate results for estimation of λ. We took our inspiration from [4]. In [4] problem of frequency offset is outright ingeniously and artistically evaluated. We implemented that paper and solved stochastic mathematics with help of Wolfram Mathematica 11.3. We accurately evaluated frequency offset p and got better cognizance for our own work. However quadratic equation at the end of [4] for estimation of frequency offset were comparatively trivial due indistinguishable and homogeneous nature of those equations. In our case due to inaccurate timing epoch the second integral part yields quite long and different set of equation in every particular case, such as case-2 and case-3. Hence it almost impossible to solve it that way.

We proposed another method for this purpose. First we send a pilot symbols of i and subsequently j that yielded mathematical equations as below

$$H_{1=}\frac{(\exp(i2\pi T)-\exp(i2\pi(1+\lambda))P\alpha}{i2\pi T}+P\alpha(T-\Delta t) \tag{3.23}$$

similarly for second branch we get

$$H_{2=}\frac{(\exp(i2\pi T)-\exp(i2\pi(1+\lambda))P\alpha}{i2\pi T}+P\alpha\Delta t \tag{3.24}$$

After this part we send a pilot symbols of j and subsequently i that yielded mathematical equations as below

$$H_{3=}-\frac{(\exp(i2\pi T)-\exp(i2\pi(1+\lambda))P\alpha}{i2\pi T}+P\alpha\Delta t \tag{3.25}$$

while the second branch yielded as below

$$H_{4=}-\frac{(\exp(i2\pi T)-\exp(i2\pi(1+\lambda))P\alpha}{i2\pi T}+P\alpha(T-\Delta t) \tag{3.26}$$

As explained in the paper [5] it is explicitly explained that $\lambda=\frac{\Delta T}{t}$ first we implicitly derive Δt

$$\Delta t = \frac{H_1 + H_4}{2P\alpha} \tag{3.27}$$

From H_2 and H_3 we get

$$H_3 + H_4 = 2P\alpha(T - \Delta t) \tag{3.28}$$

$$T = \frac{H_1 + H_2 + H_3 + H_4}{2P\alpha} \tag{3.29}$$

and finally we have from 3.29 and 3.27

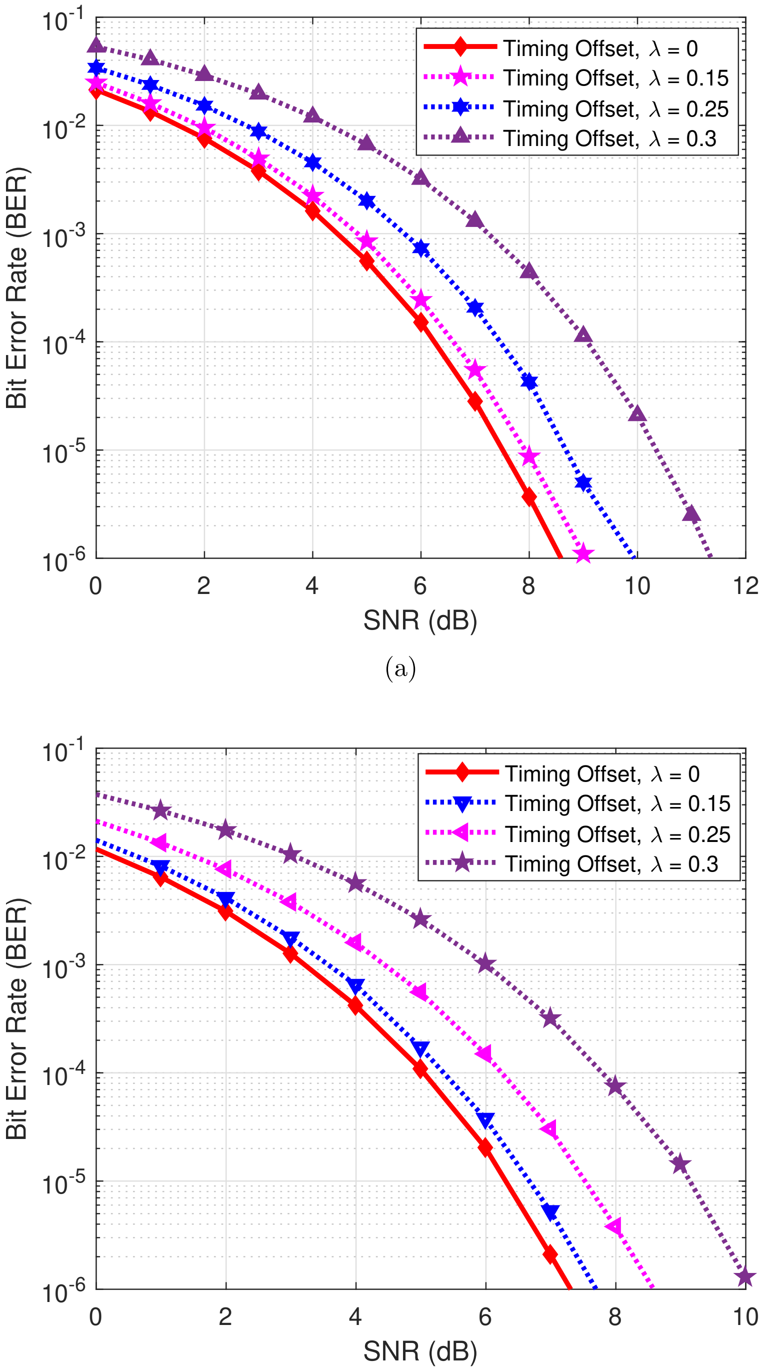
$$\lambda = \frac{H_1 + H_4}{H_1 + H_2 + H_3 + H_4} \tag{3.30}$$

Chapter 4

Results and Discussions

In this chapter, we will first discuss the deleterious effects caused due to inaccurate timing epoch. First we simulated and accessed different values of timing offset in the presence of AWGN channel and later we simulated these effects for various values of timing offset in presence of both Rayleigh fading channels and AWGN. These effects are far more worse in presence of Rayleigh fading channel. It is worth mentioning that these graphs for timing offset in the presence of Rayleigh fading is not available anywhere in literature, hence this is one of the contribution to wireless communication community.

In second section we discussed the estimation of variance of the noise in different scenarios and later we calculated mean square error for noise estimation. For, third section we discussed the estimation of timing offset for different values of SNR. In final part we will show how estimation of these factors saves energy Eb/N0 for different values of λ. For M-FSK the situation is astonishing, higher modulation is more robust to errors than lower level of M. This comparison make FSK a better candidate



(a)

(b)

Figure 4.1: Bit error probability (BER) for continuous phase M-FSK system in AWGN scenario with timing offset errors (a) Using M=2 (b) Using Using M=4

4.1 Effects of Timing-offset in different modulation schemes

The effect of timing-offset is far more deleterious than frequency offset. Lack of orthogonality occurs due to non precise timing epoch. Hence to attain the same bit error rate more energy is consumed that compromises our main object for energy efficiency. As values of λ increases the BER decreases.

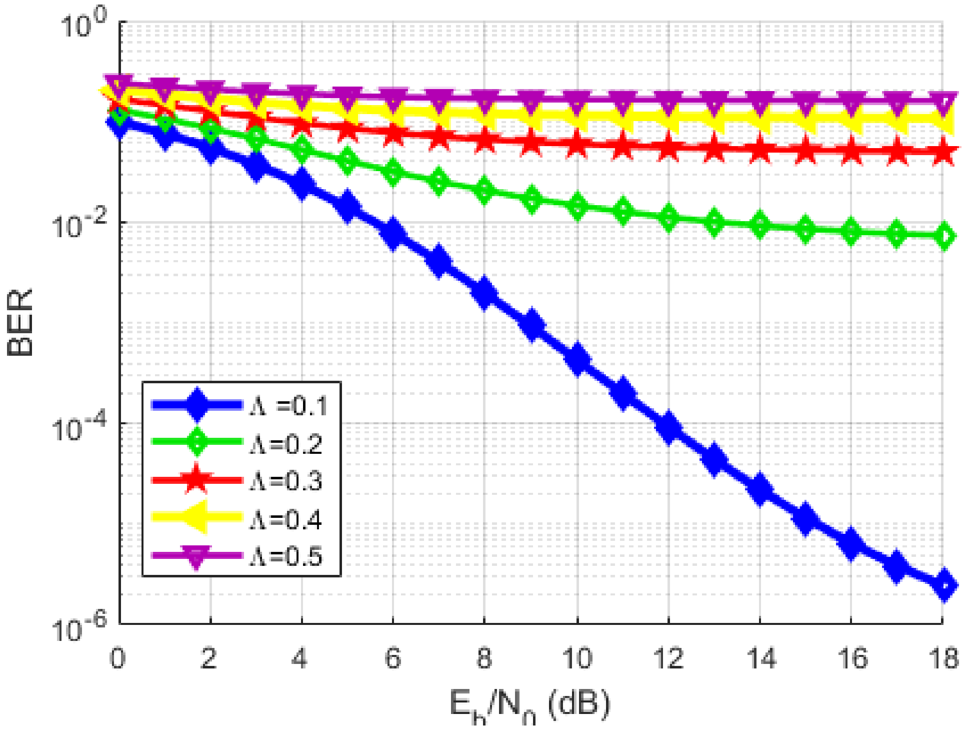


Figure 4.2: Bit error probability (BER) for continuous phase B-PSK system in AWGN scenario with timing offset errors

4.2 Effects of Timing-offset in Rayleigh Fading environment

As we have discussed earlier, non-coherent detection gives us an attractive alternative as require no carrier phase tracking but still the effect of timing offset errors on the bit error rate of on-coherent FSK in Rayleigh is quite undesirable. λ is the normalized timing error and is defined as $\lambda = \delta t/T$, where λ is the actual frequency error, and T is the symbol period. The performance degradation is not severe even for moderately small timing errors. It requires about 2dB of Eb/No to compensate for a frequency error of $\lambda =$ 0:1, which corresponds to a 20 modulation index error

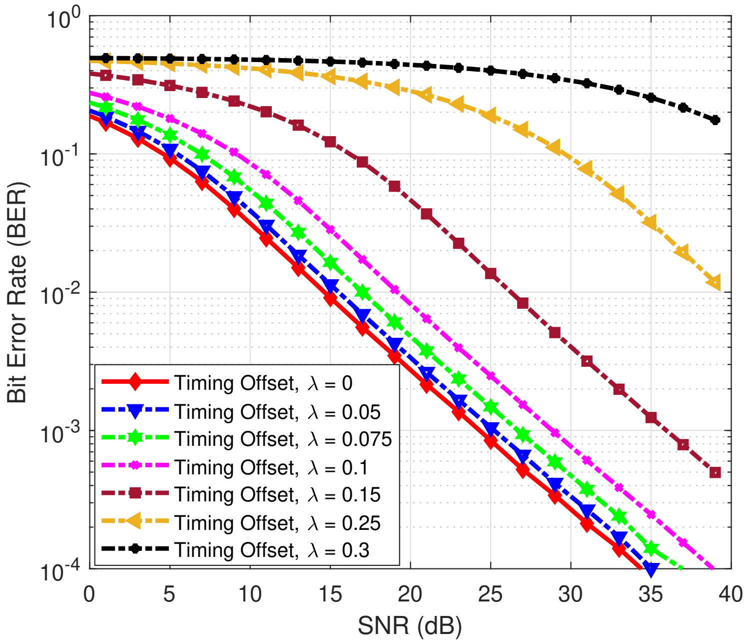


Figure 4.3: Bit error probability (BER) for continuous phase 2-FSK (Binary) system in AWGN scenario with varying timing offset errors

4.3 Noise estimation

We have shown in section 3.4.2 how noise estimator is derived when perfect timing epoch is not unknown. To evaluate the performance of noise estimator we have simulated mean square error and variance of the estimator. The mean squared error (MSE) of an estimator $\widehat{\theta}$ is given by $E_0\left[\left(\widehat{\theta}-\theta\right)^2\right]$. For an unbiased estimator, the values of MSE approaches variance. From Fig. 4.4 and 4.5, MSE and Variance of Noise estimator for different SNR values are plotted. It can be proved mathematically that for unbiased estimator value of MSE approaches variance of the estimator.

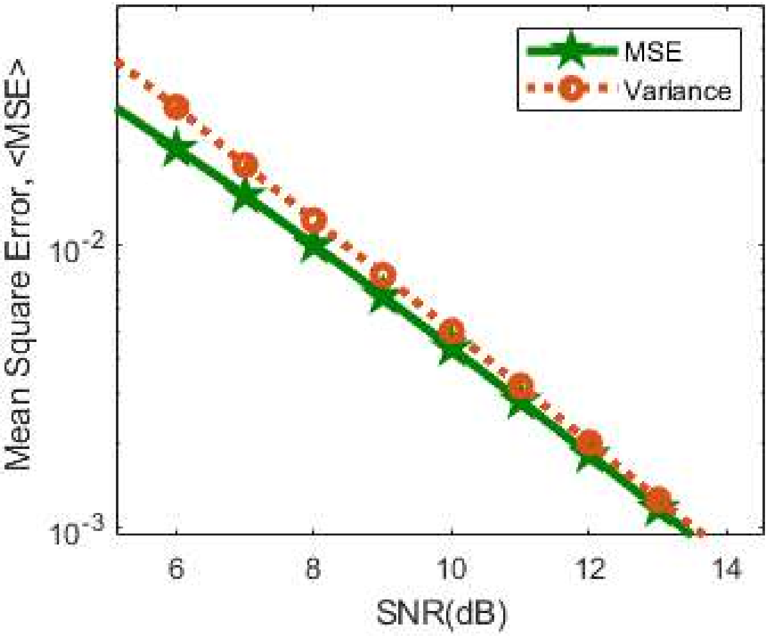


Figure 4.4: Mean square error and Variance of Noise estimator for different SNR values

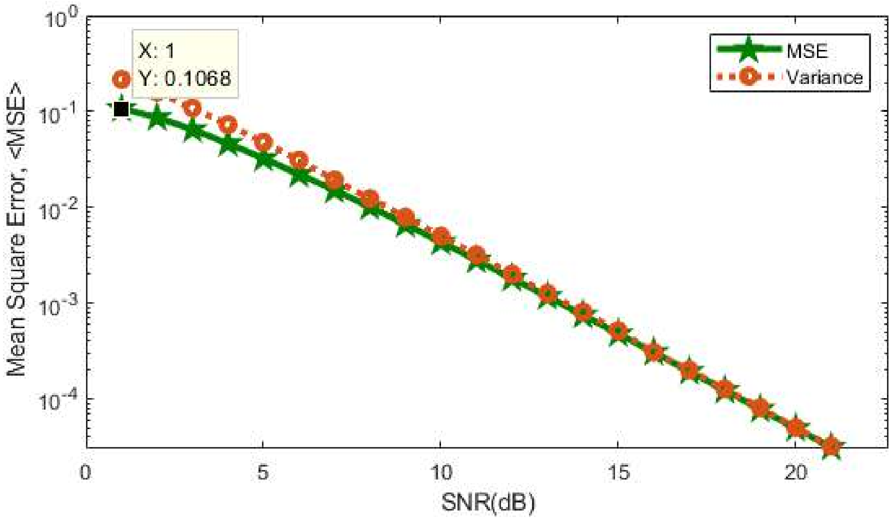


Figure 4.5: Averaged mean square error for SNR values

4.4 Timing-offset estimation

Mathematical deviation for the timing offset λ is shown in the section 3.4.3. In this section we shown will show the estimation of timing-offset for different values of SNR. In following few lines we will discuss how values of SNR(dB) are taken precisely in MATLAB 2019 and what values for sake of simplicity are assumed 1.

For FSK modulation noise variance in terms of power spectral density N_0 is given by

$$\sigma^2 = \frac{N_0}{2} \tag{4.1}$$

For FSK modulation the symbol energy is given by

$$E_s = R_m R_c E_b \tag{4.2}$$

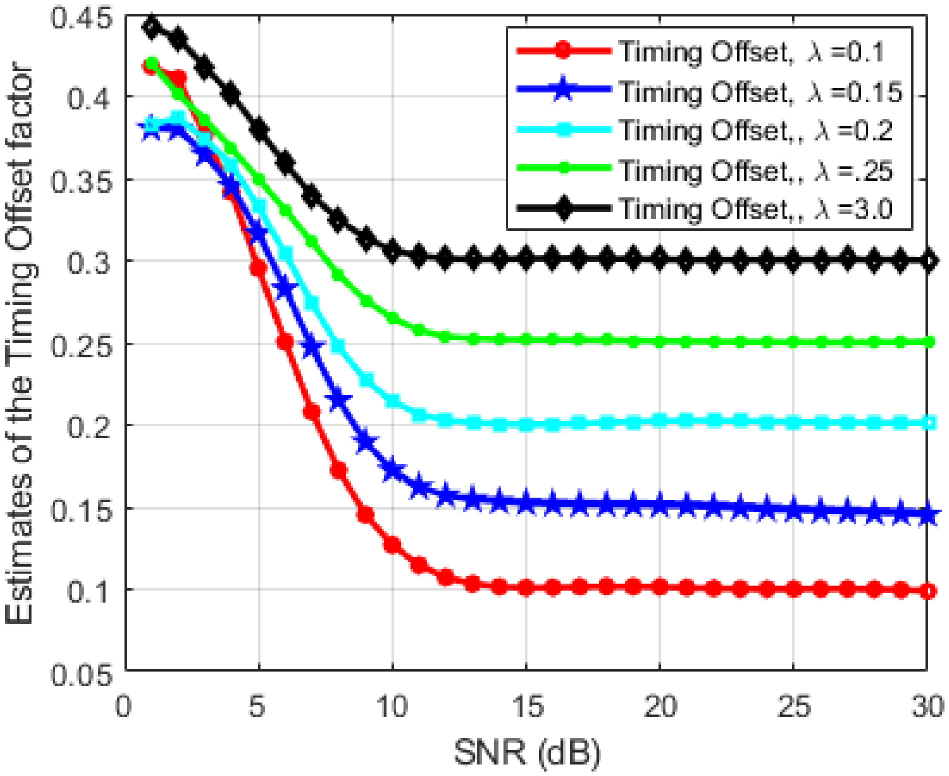


Figure 4.6: Estimation of λ Method of moment estimator for the data-aided estimator scenario.

Where E_s is Symbol energy per modulated bit (x), $R_m = log_2(M)$ $R_C$is the code rate of the system if a coding scheme is used. In this example, since no coding scheme is used Rc = 1. Eb is the Energy per information bit.Assuming ES=1 for our case. Eb/N0 can be represented as (using above equations),

$$E_b/N_0 = E_s/R_mR_cN_0 = E_s/R_mR_c2\sigma_0 = E_s/2R_mR_c\sigma_0 \tag{4.3}$$

From the above equation the noise variance for the given Eb/N0 can be calculated as

$$\sigma^2 = \left[2R_m R_c \frac{E_b}{N_0} \right]^{-1} \tag{4.4}$$

For sake of simplicity we have assumed that signal power P=1 and H is simulated as $1/\sqrt{2} * Randn(1,0) + jRandn(1,0)$. hence signal power in our case is assumed as 0.707 while noise power changes for each value of Eb/N0 value hence this way we get perfect SNR values in natural numbers with perfect precision. In figure 4.6 shows the estimates of λ the timing-offset factor using method of moment approach.

Chapter 5

Conclusion and Future Work

5.1 Concluding Notes

In this thesis, we have studied deleterious effects of timing offset in a case when symbol time epoch is unknown to the receiver, first we simulated and accessed different values of timing offset in the presence of AWGN channel and later we simulated these effects for various values of timing offset in presence of both Rayleigh fading channels and AWGN. We also simulated the scenarios of imperfect symbol epoch for other modulation schemes and showed that FSK is the best candidate as increase in timing-offset factor does not worsen detection comparatively to an extend as in other modulation schemes. We also estimated variance of noise N which is subsequently used to derive timing-offset λ in Rayleigh faded environment. Graphs for the Mean square errors as well variance of the estimator is shown. As MSE approaches variance in higher SNR values we concluded that our estimator is unbiased.

We proposed a novel method for the estimation of timing offset error λ.

Our model is different from other models for estimation as we send simultaneous known bits in pairs in four intervals. We are sending a known pilot training sequences in pairs of two bits/symbols simultaneously, one after another, we ameliorates the manipulation of known mathematical equations for obtaining λ. We use method of moment approach for this purpose.

5.2 Future Work

Since we took our initial inspiration for estimation of timing-offset factor from estimation of Carrier frequency offset and we know all basic poetic undertones and underlying mathematical concepts for all these errors hence the future work for our work is to estimate these effects under both timing as well as frequency offsets. A comparative analysis of these errors can show how much energy can be saved by estimating these errors. Saving good amount of energies can be a quintessence of energy efficacy for energy constrain IoT devices that works under harsh environment.

Bibliography

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5g be?" *IEEE Journal on selected areas in communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[2] S. Zeb, A. Mahmood, S. A. Hassan, S. H. Ahmed, and M. Gidlund, "Impact of Indoor Multipath Channels on Timing Advance for URLLC in Industrial IoT," in *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2020, pp. 1–6.

[3] I. WP5D, "Minimum requirements related to technical performance for IMT-2020 radio interface (s)," 2017.

[4] S. Mumtaz, A. Alsohaily, Z. Pang, A. Rayes, K. F. Tsang, and J. Rodriguez, "Massive Internet of Things for industrial applications: Addressing wireless IIoT connectivity challenges and ecosystem fragmentation," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 28–33, 2017.

[5] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *System Sciences (HICSS), 2016 49th Hawaii International Conference on.* IEEE, 2016, pp. 3928–3937.

[6] A. Mahmood, M. I. Ashraf, M. Gidlund, and J. Torsner, "Over-the-Air Time Synchronization for URLLC: Requirements, Challenges and Possible Enablers," in *2018 15th International Symposium on Wireless Communication Systems (ISWCS).* IEEE, 2018, pp. 1–6.

[7] G. P. Yost and S. Panchapakesan, "Improvement in estimation of time of arrival (TOA) from timing advance (TA)," in *Universal Personal Communications, 1998. ICUPC'98. IEEE 1998 International Conference on*, vol. 2. IEEE, 1998, pp. 1367–1372.

[8] J. Gomes, I. Marika, A. Petri, L. Isotalo, B. Sahlin, and J. Melén, "Cyber security business models in 5g," *A Comprehensive Guide to 5G Security, M. Liyanage, I. Ahmad, AB Abro, A. Gurtov, and M. Ylianttila, Eds. Wiley*, pp. 99–116, 2018.

[9] D. R.-J. G.-J. Rydning, "The digitization of the world from edge to core," *Framingham: International Data Corporation*, 2018.

[10] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1201–1221, 2017.

[11] I. F. Akyildiz, S. Nie, S.-C. Lin, and M. Chandrasekaran, "5G roadmap: 10 key enabling technologies," *Computer Networks*, vol. 106, pp. 17–48, 2016.

[12] M. R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, “Internet of things in the 5G era: Enablers, architecture, and business models,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, 2016.

[13] L. Wan, Z. Guo, Y. Wu, W. Bi, J. Yuan, M. Elkashlan, and L. Hanzo, “4G\/5G Spectrum Sharing: Efficient 5G Deployment to Serve Enhanced Mobile Broadband and Internet of Things Applications,” *ieee vehicular technology magazine*, vol. 13, no. 4, pp. 28–39, 2018.

[14] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, “A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications,” *IEEE Internet of Things Journal*, vol. 4, no. 5, pp. 1125–1142, 2017.

[15] N. Angelova, G. Kiryakova, and L. Yordanova, “The great impact of internet of things on business,” *Trakia Journal of Sciences*, vol. 15, no. 1, pp. 406–412, 2017.

[16] K. Shafique, B. A. Khawaja, F. Sabir, S. Qazi, and M. Mustaqim, “Internet of things (iot) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5g-iot scenarios,” *Ieee Access*, vol. 8, pp. 23 022–23 040, 2020.

[17] S. Zeb, Q. Abbas, S. A. Hassan, A. Mahmood, R. Mumtaz, S. H. Zaidi, S. A. R. Zaidi, and M. Gidlund, “NOMA enhanced backscatter communication for green IoT networks,” in *2019 16th International Symposium*

on Wireless Communication Systems (ISWCS). IEEE, 2019, pp. 640–644.

[18] F. Jameel, S. Zeb, W. U. Khan, S. A. Hassan, Z. Chang, and J. Liu, “NOMA-Enabled Backscatter Communications: Toward Battery-Free IoT Networks,” *IEEE Internet of Things Magazine*, vol. 3, no. 4, pp. 95–101, 2020.

[19] Q. Abbas, S. Zeb, and S. A. Hassan, “Age of Information in Backscatter Communication,” in *Wireless-Powered Backscatter Communications for Internet of Things.* Springer, 2021, pp. 67–80.

[20] Q. Abbas, S. Zeb, S. A. Hassan, R. Mumtaz, and S. A. R. Zaidi, “Joint optimization of Age of Information and Energy Efficiency in IoT Networks,” in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, pp. 1–5.

[21] J. Lee, B. Bagheri, and H.-A. Kao, “A cyber-physical systems architecture for industry 4.0-based manufacturing systems,” *Manufacturing letters*, vol. 3, pp. 18–23, 2015.

[22] I. F. Akyildiz, S. Nie, S.-C. Lin, and M. Chandrasekaran, “5g roadmap: 10 key enabling technologies,” *Computer Networks*, vol. 106, pp. 17–48, 2016.

[23] S. Zeb, A. Mahmood, H. Pervaiz, S. A. Hassan, M. I. Ashraf, Z. Li, and M. Gidlund, “On TOA-based Ranging over mmWave 5G for Indoor Industrial IoT Networks,” in *2020 IEEE Globecom Workshops (GC Wkshps*, 2020, pp. 1–6.

[24] S. Li, L. Da Xu, and S. Zhao, “5g internet of things: A survey,” *Journal of Industrial Information Integration*, vol. 10, pp. 1–9, 2018.

[25] S. Zeb, Q. Abbas, S. A. Hassan, A. Mahmood, and M. Gidlund, “Enhancing Backscatter Communication in IoT Networks with Power-Domain NOMA,” in *Wireless-Powered Backscatter Communications for Internet of Things.* Springer, 2021, pp. 81–101.

[26] S. Higginbotham, “Ericsson ceo predicts 50 billion internet connected devices by 2020,” *Ericsson. DOI at: http://gigaom.com/2010/04/14/ericsson-sees-the-internet-of-things-by-2020*, 2011.

[27] A. Wang, S. Cho, C. Sodini, and A. Chandrakasan, “Energy efficient modulation and mac for asymmetric rf microsensor systems,” in *Proceedings of the 2001 international symposium on Low power electronics and design*, 2001, pp. 106–111.

[28] R. I. Ansari, S. A. Hassan, and C. Chrysostomou, “A swipt-based device-to-device cooperative network,” in *2017 24th International Conference on Telecommunications (ICT).* IEEE, 2017, pp. 1–5.

[29] ——, “Energy efficient relay selection in multi-hop d2d networks,” in *2016 International Wireless Communications and Mobile Computing Conference (IWCMC).* IEEE, 2016, pp. 620–625.

[30] H. K. Narsani, S. A. Hassan, and S. Saleem, “An energy-efficient approach for large scale opportunistic networks,” in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall).* IEEE, 2018, pp. 1–5.

[31] S. Hinedi, M. Simon, and D. Raphaeli, “The performance of noncoherent orthogonal m-fsk in the presence of timing and frequency errors,” *IEEE transactions on communications*, vol. 43, no. 2/3/4, pp. 922–933, 1995.

[32] S. A. Hassan and M. A. Ingram, “Snr estimation for a non-coherent binary frequency shift keying receiver,” in *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference.* IEEE, 2009, pp. 1–5.

[33] U. Javed and S. A. Hassan, “Snr estimation for non-coherent m-fsk receivers in rice fading environment,” *IEEE communications letters*, vol. 17, no. 9, pp. 1786–1789, 2013.

[34] S. A. Hassan and M. A. Ingram, “Snr estimation in a non-coherent bfsk receiver with a carrier frequency offset,” *IEEE transactions on signal processing*, vol. 59, no. 7, pp. 3481–3486, 2011.

[35] U. Javed and S. A. Hassan, “Snr estimation for non-coherent m-fsk receivers in rice fading environment,” *IEEE communications letters*, vol. 17, no. 9, pp. 1786–1789, 2013.

[36] A. Arshad and S. A. Hassan, “Maximum likelihood snr estimation for non-coherent fsk-based cooperative networks over correlated rayleigh fading channels,” in *2015 IEEE Wireless Communications and Networking Conference (WCNC).* IEEE, 2015, pp. 636–641.

[37] S. A. Hassan and M. A. Ingram, “Pilot assisted snr estimation in a non-coherent m-fsk receiver with a carrier frequency offset,” in *2012 IEEE International Conference on Communications (ICC).* IEEE, 2012, pp. 3698–3702.

[38] ——, “Modeling of a cooperative one-dimensional multi-hop network using quasi-stationary markov chains,” in *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*. IEEE, 2010, pp. 1–5.

[39] A. Arshad and S. A. Hassan, “Snr estimation in a non-coherent mfsk receiver with diversity combining,” in *2014 International Wireless Communications and Mobile Computing Conference (IWCMC)*. IEEE, 2014, pp. 588–593.

[40] U. Javed and S. A. Hassan, “Snr estimation for non-coherent m-fsk receivers in rice fading environment,” *IEEE communications letters*, vol. 17, no. 9, pp. 1786–1789, 2013.

[41] M. Hussain and S. A. Hassan, “Imperfect timing synchronization in multi-hop cooperative networks: Statistical modeling and performance analysis,” in *2014 IFIP Wireless Days (WD)*. IEEE, 2014, pp. 1–3.

[42] ——, “Performance of non-coherent fsk virtual miso systems in correlated rayleigh fading,” in *2015 IEEE Radio and Wireless Symposium (RWS)*. IEEE, 2015, pp. 108–110.

[43] S. Afridi and S. A. Hassan, “Spectrally efficient adaptive generalized spatial modulation mimo systems,” in *2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC)*. IEEE, 2017, pp. 260–263.

[44] S. A. Hassan, “Performance analysis of cooperative multi-hop strip networks,” *Wireless personal communications*, vol. 74, no. 2, pp. 391–400, 2014.

[45] A. Afzal and S. A. Hassan, "Stochastic modeling of cooperative multi-hop strip networks with fixed hop boundaries," *IEEE Transactions on Wireless Communications*, vol. 13, no. 8, pp. 4146–4155, 2014.

[46] M. Hussain and S. A. Hassan, "Performance of multi-hop cooperative networks subject to timing synchronization errors," *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 655–666, 2015.

[47] ——, "The effects of multiple carrier frequency offsets on the performance of virtual miso fsk systems," *IEEE Signal Processing Letters*, vol. 22, no. 7, pp. 905–909, 2014.

[48] M. S. Zia and S. A. Hassan, "On the impacts of composite fading on large-scale multi-user mimo systems," *IEEE Communications Letters*, vol. 19, no. 12, pp. 2286–2289, 2015.

[49] M. Ahsen, S. A. Hassan, and D. N. K. Jayakody, "Propagation modeling in large-scale cooperative multi-hop ad hoc networks," *IEEE Access*, vol. 4, pp. 8925–8937, 2016.

[50] M. A. Aslam and S. A. Hassan, "Analysis of linear network coding in cooperative multi-hop networks," *Wireless Personal Communications*, vol. 95, no. 4, pp. 4967–4981, 2017.

[51] H. Munir, S. A. Hassan, H. Pervaiz, Q. Ni, and L. Musavian, "Resource optimization in multi-tier hetnets exploiting multi-slope path loss model," *IEEE Access*, vol. 5, pp. 8714–8726, 2017.

[52] S. A. R. Naqvi, S. A. Hassan, H. Pervaiz, and Q. Ni, “Drone-aided communication as a key enabler for 5g and resilient public safety networks,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 36–42, 2018.

[53] R. I. Ansari, C. Chrysostomou, S. A. Hassan, M. Guizani, S. Mumtaz, J. Rodriguez, and J. J. Rodrigues, “5g d2d networks: Techniques, challenges, and future prospects,” *IEEE Systems Journal*, vol. 12, no. 4, pp. 3970–3984, 2017.

[54] T. Munawar, S. Saleem, S. A. Hassan, and S. M. H. Zaidi, “Estimation of modulation index for partial response cpm signal,” *IEEE Access*, vol. 6, pp. 7664–7674, 2018.

[55] R. I. Ansari, H. Pervaiz, S. A. Hassan, C. Chrysostomou, M. A. Imran, S. Mumtaz, and R. Tafazolli, “A new dimension to spectrum management in iot empowered 5g networks,” *IEEE Network*, vol. 33, no. 4, pp. 186–193, 2019.

[56] M. S. Aslam, A. Khan, A. Atif, S. A. Hassan, A. Mahmood, H. K. Qureshi, and M. Gidlund, “Exploring multi-hop lora for green smart cities,” *IEEE Network*, vol. 34, no. 2, pp. 225–231, 2019.

[57] B. B. Chaoudhry, S. A. Hassan, J. Speidel, and H. Jung, “Energy efficiency of a decode-and-forward multiple-relay network with rate adaptive ldpc codes,” *Sensors*, vol. 19, no. 21, p. 4793, 2019.

[58] M. Anjum, M. A. Khan, S. A. Hassan, A. Mahmood, H. K. Qureshi, and M. Gidlund, “Rssi fingerprinting-based localization using machine

learning in lora networks," *IEEE Internet of Things Magazine*, vol. 3, no. 4, pp. 53–59, 2020.

[59] S. S. Sheikh, M. Anjum, M. A. Khan, S. A. Hassan, H. A. Khalid, A. Gastli, and L. Ben-Brahim, "A battery health monitoring method using machine learning: A data-driven approach," *Energies*, vol. 13, no. 14, p. 3658, 2020.

[60] H. Khan, S. A. Hassan, and H. Jung, "On underwater wireless sensor networks routing protocols: A review," *IEEE Sensors Journal*, vol. 20, no. 18, pp. 10 371–10 386, 2020.

[61] Q. Abbas, S. A. Hassan, H. Pervaiz, and Q. Ni, "A markovian model for the analysis of age of information in iot networks," *IEEE Wireless Communications Letters*, 2021.

[62] S. A. Hassan and M. A. Ingram, "Snr estimation for m-ary non-coherent frequency shift keying systems," *IEEE transactions on communications*, vol. 59, no. 10, pp. 2786–2795, 2011.