PHASE NOISE ESTIMATION FOR WIRELESS COMMUNICATION SYSTEMS

BURÇ ARSLAN KALELİ

Department of Electronics Engineering

APPROVED BY:

____

Prof. Dr. Erdal Panayırcı

____

Asst. Prof. Dr. Habib Şenol

____

Asst. Prof. Dr. Hakan Doğan

APPROVAL DATE: 10/02/2011

PHASE NOISE ESTIMATION FOR WIRELESS COMMUNICATION SYSTEMS

by

BURÇ ARSLAN KALELİ

THESIS

Presented to the Faculty of the Graduate School of

Kadir Has University

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Electronics Engineering

KADIR HAS UNIVERSITY

February 2011

PHASE NOISE ESTIMATION FOR WIRELESS COMMUNICATION SYSTEMS

Abstract

In wireless communication systems information symbols are transmitted through a communication channel which are affected many degradation factors. Besides fading and multipath effect of channel, transmitted symbols are significantly suffered from various noise effects. Additive white Gaussian Noise (AWGN) is a well-known concept as noise which is mentioned above and usually considered as only degradation while the signal is transmitted. However, in certain circumstances, other degradation factors, for instance phase noise, could be equally or more important. In this thesis, it is focused on phase noise problem particularly.

Phase noise is rapidly time-varying and random disturbing effects on the phase of a signal waveform. Presence of phase noise is increased symbol errors for overall system. Therefore, this term must be eliminated in order to enhance the error performance. In this thesis, it is considered the problem of joint detection of continuous-valued information source output and estimation of a phase noise by using expectation maximization (EM) algorithm. In order to estimate phase noise, initial phase noise values are determined by cubic interpolation that utilizes pilot symbols.

In addition, computer simulations are performed for the proposed algorithm and the average mean square error (MSE) - signal to noise ratio (SNR) performance of source detector and phase noise estimator is presented for each iteration of the algorithm. Moreover, average MSE - pilot spacing performance curves of phase noise estimator are given for various SNR values.

KABLOSUZ HABERLEŞME SİSTEMLERİ İÇİN FAZ GÜRÜLTÜSÜ KESTİRİMİ

Özet

Kablosuz haberleşme sistemlerinde, bilgi sembolleri kanalda iletilirken çeşitli bozucu etkilere maruz kalmaktadırlar. Kanalın sönümleme ve çok yollu iletim etkilerinin yanı sıra, iletilen semboller çeşitli gürültü etkileri tarafından önemli ölçüde bozunmaya uğramaktadır. Bu bozucu gürültülerinden en çok bilineni toplamsal beyaz Gauss gürültüsü olmakla beraber, sinyal iletimi sırasında genelde tek bozucu etki olarak değerlendirilmektedir. Fakat, bazı durumlarda faz gürültüsü gibi diğer bozucu etkiler aynı ölçüde ya da daha önemli olabilmektedir. Bu tezde, özellikle faz gürültüsü problemi üzerine çalışılmıştır.

Faz gürültüsü, bir dalga şeklinin fazındaki ani, kısa süreli ve rastlantısal değişimini niteleyen bozucu etkidir. Faz gürültüsü etkisinin ortadan kaldırılması hata performansının iyileştirilmesi adına oldukça önemlidir. Bu çalışmada beklenti enbüyüklemesi (Expectation Maximization - EM) algoritması kullanılarak sürekli-değerli bir enformasyon kaynağı çıkışının sezimlenmesi ve çıkışı etkileyen bir faz gürültüsünün kestirimi problemi üzerinde durulmuştur. Faz gürültüsünün kestirimi için gerekli başlangıç faz gürültüsü değerleri pilot simgelerden yararlanılarak kübik enterpolasyon yöntemiyle oluşturulmaktadır.

Ayrıca, önerilen algoritma için bilgisayar benzetimleri yapılarak kaynak sezimleyicisi ve faz gürültüsü kestirimcisi için ortalama karesel hata (Mean Square Error - MSE) - sinyal gürültü oranı (Signal to Noise Ratio - SNR) başarımları algoritmanın her bir yineleme adımı için sunulmuştur. Ayrıca, faz gürültüsü kestirimcisinin ortalama karesel hata - pilot aralığı başarım eğrileri çeşitli sinyal gürültü oranları için verilmiştir.

Acknowledgements

I would like to express my deep-felt gratitude to my advisor, Prof. Dr. Erdal Panayırcı, the head of Electronics Engineering Department at Kadir Has University, for his constant motivation, support, expert guidance, constant supervision and constructive suggestion for the submission of my thesis work. He was never ceasing in his belief in me, always providing clear explanations when I was lost, and always giving me his time. I wish all students would have an opportunity to experience his ability.

I also wish to thank Dr. Habib Şenol of the Computer Engineering Department at Kadir Has University. His suggestions and comments were invaluable to the completion of this work. He was extremely helpful in providing the additional guidance and expertise I needed, especially with regard to the chapter on phase noise estimation and simulation results.

This thesis would have been impossible if not for the perpetual moral support from my family and my friends. I would like to thank them all.

Table of Contents

List of Figures

Abbreviations

1G	:	First Generation
2G	:	Second Generation
3G	:	Third Generation
4G	:	Forth Generation
ADC	:	Analog to Digital Converter
AMPS	:	Advanced Mobile phone Service
AWGN	:	Additive White Gaussian Noise
CDMA	:	Code Division Multiple Access
DAC	:	Digital-to-Analog Converter
DCT	:	Discrete Cosine Transform
EDGE	:	Enhanced Data Rate for GSM Evolution
EM	:	Expectation Maximization
EVDO	:	Evolution Data Optimized
FDMA	:	Frequency Division Multiple Access
GMSK	:	Gaussian Minimum Shifting Key
GPRS	:	General Packet Radio Service
GSM	:	Global System for Mobile
HSDPA	:	High Speed Downlink Packet Access
ICI	:	Inter-carrier Interference
IEEE	:	The Institute of Electrical and Electronics Engineers
IP	:	Internet Protocol

ISI	:	Inter-symbol Interference
LMMSE	:	Linear Minimum Mean Square Error
LTE	:	Long Term Evolution
MAN	:	Metropolitan Area Network
ML	:	Maximum Likelihood
MSE	:	Mean Square Error
NTT	:	Nippon Telephone and Telegraph
NMT	:	Nordic Mobile Telephone
OFDM	:	Orthogonal Frequency Division Multiplexing
PLL	:	Phase Locked Loop
QoS	:	Quality of Service
RF	:	Radio Frequency
SNR	:	Signal to Noise Ratio
TDMA	:	Time Division Multiple Access
UMTS	:	Universal Mobile Telecommunication System
WiMAX	:	Worldwide Interoperability for Microwave Access
WLAN	:	Wireless Local Area Network

Chapter 1

Introduction

At the beginning of 90's, digital communication experienced a fast growth with the impact of the internet. From 1990 to 2009 the Internet grew from zero to two billion users and wireless mobile services grew from 10 million to 4.5 billion subscribers in 2009 around worldwide [1]. This rapid growth of the Internet is initiating the demand for higher speed Internet based services which is leading to growth of broadband wireless systems. In a short time, worldwide subscription for broadband wireless services reached over 480 million [1]. It's inevitable that these technologies, which were considered as luxury in previous years, are now essential and necessary. In other words, within the last two decades, communication advances have changed our life.

Our lives are still changing according to the developments and becoming increasingly dependent on mobile communication. Besides, user demands go beyond to simple speech transmission to "reach and share information everywhere and every time". This demand has directed the future of mobile and wireless communications towards to provide services without regard to location with high data rates. To achieve this goal, communication networks need to be support wide range of services which includes high quality voice, still images, streaming videos and high data rate applications. Therefore, this is obvious that, next generation communication systems will be defined as a combination of Internet and Multimedia communications and wireless mobile communications to achieve high data rates and high coverage concurrently.

However, this is a quite difficult problem. Local area networks supports high data rates for limited coverage. On the other hand, wireless mobile communication networks, namely cellular systems, supports low data rate services for high coverage area. The main problem is to design a system that services many users at high data rates with conceivable bandwidth and acceptable power consumption which also enables high coverage and quality of service (QoS).

To cope with this problem, many different transmission techniques are proposed over time. Currently, some of these techniques are actively under development. In this thesis, phase noise estimation problem is considered, particularly, for basic single carrier transmission systems.

1.1 A Brief History of Mobile Wireless networks

The first commercial mobile communication systems, which are based on analog cellular technology, were developed in the 80's, such as advanced mobile phone service (AMPS) in the USA, Nippon Telephone and Telegraph (NTT) in Japan and Nordic Mobile Telephone (NMT) in Norway etc. These systems ensured only speech transmission and almost each country offered its own system, naturally there were an incompatibility between them. Besides, call capacity of these analog systems were limited and quality of speech were not good enough. These systems were the first steps of mobile communication and called first generation (1G) communication systems.

The second generation (2G) technology is based on digital cellular technology. The most well-known 2G service is Global System for Mobile (GSM) which is started its operations in Finland in 1992. Unlike 1G, 2G systems commonly used more efficient modulation techniques to provide better quality of speech. For instance, GSM used 2-Level Gaussian Minimum Shifting Key (GMSK). 2G also used multiplexing technologies such as, time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA) to ensure the coordinated access between multiple users. Thus, the call capacity of the system is increased. At last stages, two services which are general packet radio service (GPRS) and enhanced data rate for GSM evolution (EDGE) are developed in order to provide more data rates. These technologies are overlaid on current 2G technologies and called 2.5G. [2]

Appearance of higher demand for data services are initialized the development of third generation (3G) networks, namely multimedia support. Two main technologies are developed within 3G concept which are Universal mobile telecommunication system (UMTS) and CDMA2000. Though some enhancements such as evolution data optimized (1xEVDO) for CDMA2000 and high speed downlink packet access (HSDPA) for UMTS high data rates are provided for users.

Currently, fourth generation (4G) wireless networks are under development. 4G is defined as internet protocol (IP) Packet switching network which provides higher data rates and higher capacity. Main goal of 4G is to replace the current cellular networks with a single worldwide cellular core network standard based on IP for voice, video and data services [3]. Some services such as mobile Worldwide Interoperability for Microwave Access (WiMAX) and first release long term evolution (LTE)

1.2 Evolution of Wireless Local Area Networks to Metropolitan Area Networks

As it is seen from previous section, the first mobile wireless systems aren't designed for data services because internet concept was still immature. The design objectives of wireless local area networks (WLAN) are completely different than mobile wireless networks, namely high data throughput is more important than mobility. The IEEE 802.11 is standardized in 1997 and provided users 2 Mbps data rate [2]. After that, several amendments are made this standard and capabilities are increased.

However, despite high data rates, coverage was an important drawback for WLAN's because these systems are designed for connectivity in office or home environments. A new technology is clearly needed to provide high throughput broadband connection over large areas for fixed or mobile users. For this reason WiMAX standard is developed by IEEE 802.16 metropolitan area network (MAN) research group.

When evolution of mobile wireless networks and wireless local area networks is considered, there still exists a big gap between the mobility offered by mobile wireless networks and high data rates offered by WLAN technology. As mentioned in previous section, this intersection point is directed to 4G researches as shown in figure 1.1.

1.3 The Challenges of Wireless Channels

All wireless digital communication systems possess several functional blocks similar to digital communication systems as shown in the figure 1.2. Even if a wireless network is complicated, the entire system can be expressed as a collection of links which are transmitter, channel and receiver.

The main function of the transmitter is, to receive data from higher protocol layer and send them to receiver as electromagnetic waves. The important parts of the digital domain are encoding (source and channel respectively) and modulation. The function of the source encoder is to represent the data by bits in efficient way. On the other hand, channel encoder adds redundant bits to data which enable detection and correction of transmission errors in the receiver. The modulator prepares the data for wireless channel by grouping and transforming to certain symbols or waveforms. The modulated signal is converted into a

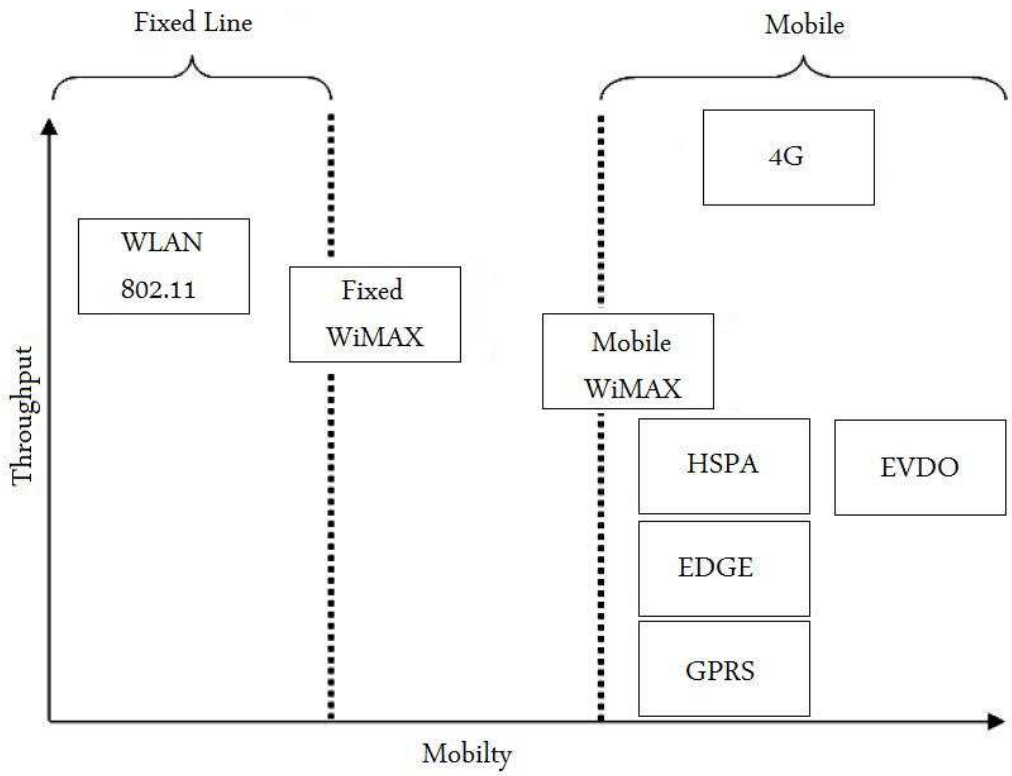

Figure 1.1: Wireless Technologies

representative analog waveform by digital-to-analog converter (DAC) and upconverted to desired radio frequency (RF) bands by an RF module. Then this signal transmitted as an electromagnetic wave by an antenna.

The receiver performs the reverse of these operations respectively. Received RF signal is downconverting and then signals at other frequencies are filtering out. Digital signal is converted from baseband signal by analog-to-digital converter (ADC). The received signal demodulated by demodulator and decoder analysis the received data for errors or corrects errors. Finally original bits are reproduced by source decoder.

Mobile wireless channel is one of the most explicit factors which inhibit the performance of wireless communications systems. The radio wave propagation is dramatically influenced

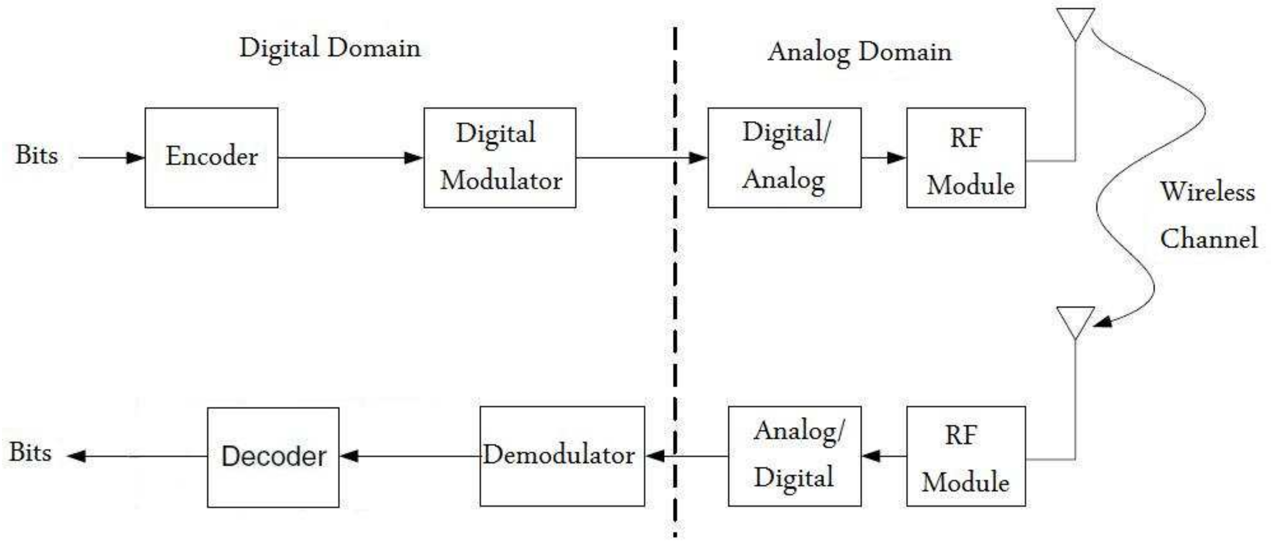

Figure 1.2: Digital Wireless Communication System

by environmental conditions. The signal arrives at the receiver by different propagation paths at different delays. These signal components are called multipath components and this phenomenon is called multipath propagation. The different paths can be classified as direct path, reflected path, diffracted path and scattered path as show in the figure 1.3. Besides, the channel parameters are changing quite rapidly in wireless systems due to the movements of terminals or reflection points between them. Further, time dispersion is very severe that raises a lot of problems. In a mobile system, the strength of the receive signal and also its phase changes very rapidly due to movement of terminals. As it is seen, operating environment of wireless systems have some specific properties unlike fixed wire-line systems, hence, required some special design considerations.

Fundamentally, there are two phenomenon of wireless communication which makes the problem interesting and challenging. Unlike wire-line communication these phenomenon are more significant for wireless communication systems. First one is "fading" which can be described as a deviation of attenuation, delay and phase shift of a signal while transmitting

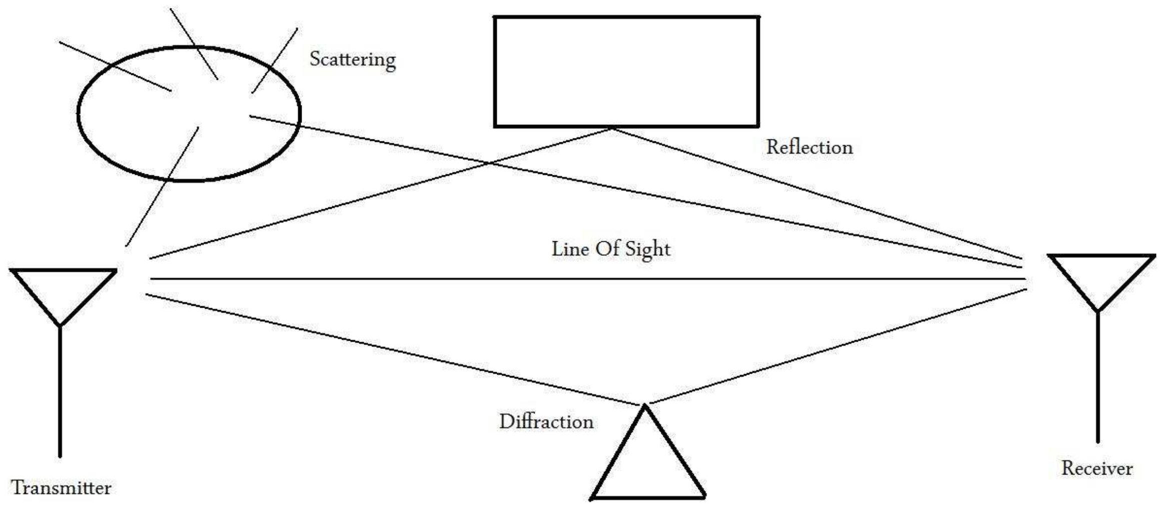

Figure 1.3: Multipath Effect of Wireless Channel

from the source to receiver due to small-scale effect of multipath, as well as large-scale effects such as shadowing by obstacles and pathloss owing to distance. The second one is "interference" which alters or disturbs a signal by another signal while it is travelling along a channel between transmitter and receiver. The interference can be between signals from a common transmitter to multiple receivers (for instance downlink of a cellular system), between transmitters communicating with a receiver (for instance uplink of a cellular system), or between various transmitter-receiver pairs (for instance interference between users different cells) [4].

In such channels, these problems are caused high probability of errors and effected the overall system performance negatively. A lot of techniques are offered in literature such as channel coding and adaptive equalization as a solution of these problems, however it is quite difficult to use these techniques in high data rate systems because of inherent delay or cost of hardware. An alternative solution is offered as multi carrier modulation, and orthogonal frequency division multiplexing (OFDM) is appeared one of the appropriate technique which is proposed in 1966 [5].

However, one of the biggest problem is phase noise sensitivity for all proposed techniques either single carrier and multi carrier systems. Therefore, phase noise estimation problem is considered in this thesis.

1.4 Phase Noise

Rapidly time-varying and random disturbing effects on the phase of a signal waveform are known as phase noise [6]. This problem occurs in early stages of receiver part, especially in demodulation stage. The time-varying multiplicative effects such as, Doppler Shifts and oscillator jitter, and synchronization problems between the transmitter and receiver, can be considered as basic reasons of phase noise. These disturbances can effects the overall performance of the communication system by degrading the error performance, therefore phase noise estimation has critical importance.

In literature, there are several methods exist for phase noise estimation. This problem was solved by a feedback algorithm that operated according to Phase Locked Loop (PLL) mechanism a long time ago [7], [8]. However, these algorithms are not appropriate for burst transmission in order to needed long acquisition periods. In addition, most of such PLL's are designed in analog form and would be needed may operations for digital conversation.

In the other approach, phase noise is approximated as piecewise constant over an observation interval. Therefore, a feedforward algorithm can be used to estimate the local time average of phase in order to assumed constant in each subintervals [8], [9]. However, subintervals have to be small for strong phase noise in which case the phase noise estimate is sensitive to the channel noise.

Other significant results are obtained by a linear minimum mean square error (LMMSE) estimation algorithm for a single carrier broadband system which is using Wiener filters proposed in [10] for stationary model of phase noise. This is one of the easiest but suboptimum solution because neglects all spatial correlations for each noise process. In addition, for the estimation of a temporally non-stationary random phase noise sequences which have a low magnitude with compared to symbol rate, such as Wiener phase noise, various approaches can be found in literature [11, 17].

Recently, one of the popular method which is used for the iterative estimation of Markov-type phase noise is a sum product algorithm and factor graph framework proposed in [18]. However, in this research it is assumed that receiver has detailed knowledge about phase noise statistics. Therefore, this algorithm seems quite inadequate for real applications.

In [19], [20], discrete cosine transform (DCT) based basis expansion model is applied for phase noise estimation from pilot symbols. Additionally, in [21] same pilot base algorithm is used for initial estimation of phase noise, and then an iterative algorithm is used by making of soft decisions of the unknown data symbols to improve this estimation. Maximum likelihood (ML) algorithm is also used in [22] for the estimation of the average of the phase noise over a block of data. However, random variations of the phase are neglected in the algorithm.

It is mentioned in section 1.3 that OFDM is chosen as basis technique for next generation wireless systems, because of high spectral efficiency and ability to divide a dispersive multipath channel into parallel frequency flat subchannels. Moreover, by applying a cyclic prefix is also protected the OFDM symbol from delayed version of previous symbol and cancelled inter-symbol interference (ISI). However, the performance of an OFDM system can also be significantly degraded by the presence of random phase noise because it effects the orthogonality between subcarriers and occured inter-carrier interference (ICI). This sensitivity is one of the major drawbacks of OFDM. The effect of phase noise on the performance of an OFDM system is also strongly concerned in the literature [23, 27].

1.5 Objectives and Outline of Thesis

In this thesis, phase noise estimation problem for wireless communication systems is deeply investigated. The main objective of this research is to construct an effective and low complexity phase noise estimation algorithm unlike proposed in literature for a wireless communication system which is affected by a strong phase noise. In addition, suggested algorithm and the existing algorithms are compared with respect to computational complexity, and the usefulness of proposed scheme is discussed.

The algorithm, mentioned above, is performed by MATLAB simulations and MSE vs SNR performance is obtained. Besides these, detection of information source output has an importance in algorithm. In the context of this research, a detector is designed and performed by MATLAB simulations. At last, average MSE - pilot spacing performance curves of phase noise estimator are studied for various SNR values.

The thesis organized as follows: in Chapter 2, the basics of phase noise are presented. It is explained that reasons and characteristics of phase noise, and its mathematical model. In chapter 3, system model and proposed algorithm is presented. Chapter 4 demonstrates the simulation results of proposed algorithm and chapter 5 concludes the thesis and summarizes the results of the work. Future works are also suggested.

Chapter 2

Phase Noise

2.1 Introduction

AWGN channel is a well-known concept for everyone who has taken digital communication courses. Conventionally, this is usually considered as only degradation while the signal is transmitted. In general, white Gaussian noise comes from many natural sources such as thermal noise which is vibrations of atoms or black body radiation from the earth and other warm objects. Human made noises are also considered as white noise. White means that frequency spectrum is continuous and uniform for all frequency bands. In addition, it is additive because signal is statistically independent from noise, and obviously noise samples have Gaussian distribution. In the time domain Additive White Gaussian noise, which is denoted $n(t)$,can be shown as,

$$r(t) = Asin(2\pi f_c + \phi) + n(t), \tag{2.1}$$

where A is the amplitude and ϕ is a constant that represents arbitrary phase offset. f_c is center frequency of the oscillator.

The AWGN channel is a good and sufficient model for many conditions however, in certain circumstances, other degradation factors could be equally or more important. For instance, fading, co-channel interference, antenna efficiency and phase noise. Particularly, a communication systems which is effected by a phase noise (θ) is considered therefore, in general, the output of oscillator with phase noise is can be written as,

$$r(t) = Asin(2\pi f_c + \theta(t) + \phi) + n(t). \tag{2.2}$$

Phase noise is one of the biggest difficulties in communication systems and phase noise estimation problem has a great importance. The carrier phase must be known at the receiver stage for the recovery of transmitted symbols. Therefore, the phase term which is disturbed due to the synchronization problem between the transmitter and receiver, and Doppler shifts problems, must be eliminated. Unlike white Gaussian noise, phase noise is residual and time varying.

2.2 Mathematical Model of Phase Noise

In the literature, early studies on phase noise are focused on fiber optical communication and later on radio oscillators. Since these early studies, the most accepted model for phase noise $\theta(t)$ is a Wiener process. This model initially derived empirically and then analytically showed that it is accurate. For more information about phase noise modeling process referred to [28] and [29]. In addition to Wiener process model, there are a lot of complex models are proposed in literature to describe the phase noise process both in fiber and radio communications [30]. However, because of the simplicity of Wiener Process and sufficiency of describing phase noise process, this model is used in literature.

The phase noise $\theta(t)$ is modeled as wiener process,

$$\theta(t) = 2\pi \int_0^t u(t)dt \qquad for \quad (t > 0), \tag{2.3}$$

where $u(t)$ is a zero mean white Gaussian noise process. In case of N_0 is defined as double sided power spectral density of $u(t)$, the variance of $\theta(n)$ which is zero-mean Gaussian process,

$$var[\theta(t)] = (2\pi)^2 N_0 t. \tag{2.4}$$

As seen from (2.4), as t increases in time, the variance of $\theta(t)$ also increases concurrently. Therefore, the phase of $s(t)$ is clearly a random variable uniformly distributed over $[0, 2\pi)$. It is obvious that, estimation of these random variables are quite difficult. There already exist a lot of estimation algorithms for this challenging problem and most of them achieve a good performance under their design conditions. In next chapter, a novel approach for this estimation problem is presented.

2.3 Power Spectral Density of Phase Noise

Power spectral density describes the distribution of power of a signal for each frequency in spectrum. It is well-known that white noise has a flat power spectral density, namely, contains equal power within a fixed bandwidth at any center frequency. However, this situation is different for phase noise. The Fourier transform pair gives the spectrum of pure cosine wave as,

$$\cos(2\pi f_o t) \Leftrightarrow \frac{1}{2}[\delta(f - f_o) + \delta(f + f_o)]. \tag{2.5}$$

When (2.2) is checked, it is clearly seen that $r(t)$ is a noise process itself because of noise process $\theta(t)$ is added directly to this term. Therefore, the power spectrum can be calculate as a Fourier transform of the autocorrelation function,

$$R_{ss}(t, t + \tau) = E[y(t)y(t + \tau)]. \tag{2.6}$$

Here, $r(t)$ is nonstationary if ϕ has fixed value which is a known constant. However, in real systems ϕ is totally random therefore, during mathematical modeling ϕ is assumed as a random variable. If ϕ is chosen as uniformly distributed over $[0, 2\pi)$, then autocorrelation function can be calculated since $r(t)$ is stationary. We find that $R_{ss}(t, t + \tau) = R_{ss}(\tau)$,

$$R_{ss}(\tau) = \frac{A^2}{2} \cos(2\pi f_o \tau) e^{-2\pi^2 N_0 |\tau|}. \tag{2.7}$$

The Fourier transform of $R_{ss}(f)$ gives the power spectral density of $r(t)$ which is $S_{ss}(f)$,

$$S_{ss}(f) = FT\{R_{ss}(\tau)\} = \frac{A^2 N_0}{(2\pi)^2}\left[\frac{1}{1+\left(\frac{f-f_o}{\pi N_0}\right)} + \frac{1}{1+\left(\frac{f+f_o}{\pi N_0}\right)}\right]. \tag{2.8}$$

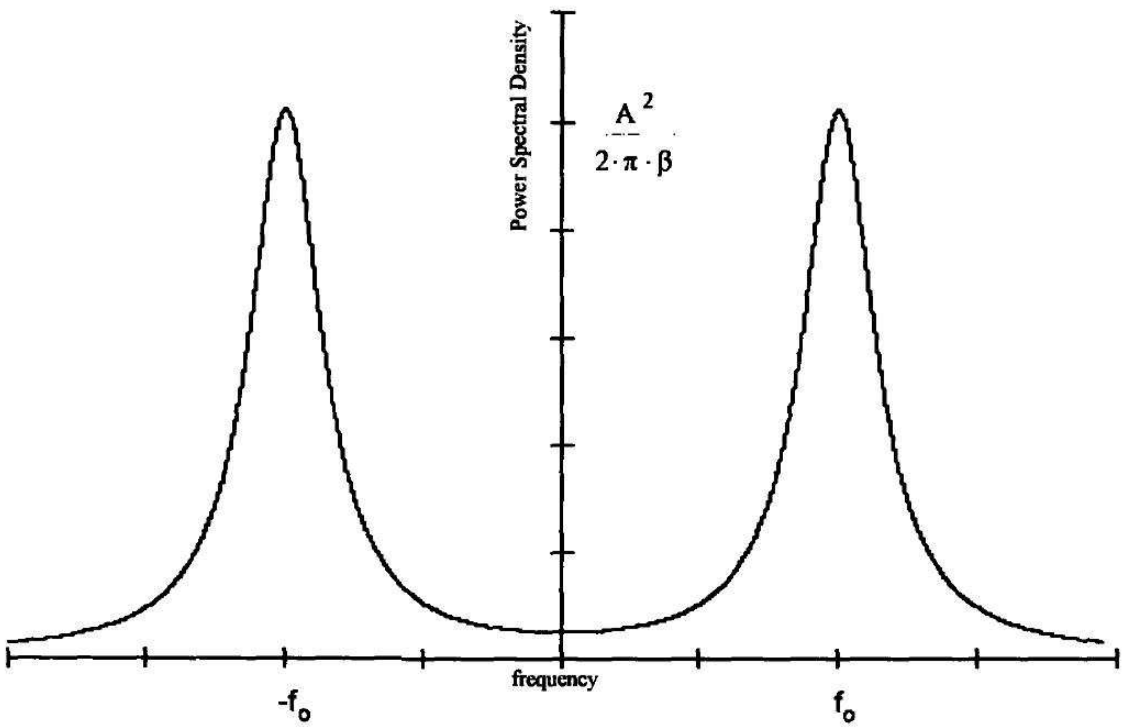

Figure 2.1: Lorentzian Power Spectral Density.

The half power bandwidth of sinusoid which is corrupted by phase noise is $2\pi N_0$. This is referred to linewidth and denoted by β. This word is usually used in the literature to describe 3 -db bandwidth of phase noise power spectrum. For each optical and radio frequency sources linewidth values are different. In practice, once the receiver design is done, the phase noise linewidth is known. In cases where a variation causes the change of the linewidth β, some adaptive methods can be implemented to track this change.

Chapter 3

Phase Noise Estimation

As indicated previous chapters, wireless communication systems need an accurate time reference because of their structure. Various users share same channel, necessitating modulation and demodulation of the messages in these systems. In addition, reliable modulation and demodulation is highly dependent on accuracy of oscillators. Furthermore, in order to reach desired high data rates in next generation high speed communication systems, this accuracy has an important role because the frequency instabilities of the carrier degrades the overall performance of the system. Therefore, an effective phase noise estimation is considerably important to cope with this problem and enhance the performance of systems. In this thesis, an optimal phase noise estimation algorithm is generated for continuous-valued data transmission which is affected by a phase noise.

In this chapter, after the estimation problem is briefly examined ,the system model and also system parameters are given which are used in the model are presented. In addition, developed phase noise estimation algorithm is introduced step by step and details about EM based estimation is given in the rest of the chapter.

3.1 Overview of Estimation Problem

As it is known that estimation is a large concept which is at the heart of many signal processing systems such as, communications, biomedicine and seismology etc. Carrier frequency estimation or phase noise estimation in communication; estimation of the heart rate of a fetus in biomedicine; or estimation of the underground distance of an oil can be good example. Obviously seen that the common problem here is needing to estimate the values of a group of parameters. In the simplest form, we have the N point data set $\{x[0], x[1], x[2], ..., x[N-1]\}$ which depends on an unknown parameter θ. Therefore, we would like to determine θ based on the data or to define an estimator[31],

$$\widehat{\theta} = g(x[0], x[1], x[2], ..., x[N-1])$$

where, g is some function. This is the basic mathematical model of parameter estimation problem. For this problem, let's consider the receiver side observation relation of a communication system in order to estimate unknown $\boldsymbol{\theta}$ parameter vector as follows:

$$\boldsymbol{y} = F(\boldsymbol{s}, \boldsymbol{\theta}) + \boldsymbol{w}$$

where, $\boldsymbol{y}$ is observation vector, $\boldsymbol{s}$ is nuisance parameter vector and $\boldsymbol{w}$ is additive Gaussian noise vector in that model. A maximum-likelihood estimation of $\boldsymbol{\theta}$ vector is based on maximization of $\boldsymbol{\theta}$ according to $p(\boldsymbol{y}|\boldsymbol{\theta}) = E_s[p(\boldsymbol{y}|\boldsymbol{s}, \boldsymbol{\theta})]$ probability function and can be defined mathematically as follows,

$$\widehat{\theta}_{ML} = \arg\max_{\boldsymbol{\theta}} p(\boldsymbol{y}|\boldsymbol{\theta}) = \arg\max_{\boldsymbol{\theta}} E_s p(\boldsymbol{y}|\boldsymbol{\theta}, \boldsymbol{s}). \tag{3.1}$$

Here, $E_{\boldsymbol{S}}\{.\}$ denotes the expected value with respect to $\boldsymbol{s}$. As seen from (3.1) equation, maximum likelihood estimation can be performed after the following two basic steps,

1) Calculating the statistical average over $\boldsymbol{s}$ nuisance parameter vector, in order to compute the likelihood function. However, this may be analytically intractable

2) Maximization of likelihood function over unknown $\boldsymbol{\theta}$ vector.Even if the likelihood can be obtained analytically, however, it is invariably a nonlinear function of $\boldsymbol{s}$. Therefore, maximization step is computationally infeasible because it must be performed in real time.

In such cases and under some conditions, the EM algorithm based phase noise estimation may provide an implementable solution. There are many different problems are solved by the use of EM algorithm in the literature [32, 33, 34, 35].

3.2 System Model

In this thesis, the transmission of a data block which contains N symbols is considered over an AWGN channel which is affected by a phase noise. The phase noise is modeled as a discrete - time Wiener process which is given by,

$$\begin{aligned} \theta(n) &= \theta(n-1) + u(n), \quad n = 0, 1, \cdots, N\text{–}1 \ , \\ \theta(-1) &= 0, \end{aligned} \tag{3.2}$$

Here, $u(n)$ represents a sequence of independent and identically distributed (i.i.d) zero-mean Gaussian random variables with variance σ_u^2. The resulting received signal model can be defined as,

$$y(n) = e^{j\theta(n)} s(n) + w(n) \ , \quad n = 0, 1, \cdots, N\text{–}1 \ , \tag{3.3}$$

Vectorial definition of this expression can be more easy and more useful in future calculations. Therefore, (3.2) and (3.3) can be defined in vectorial form as,

$$\begin{aligned} \boldsymbol{\theta} &= \boldsymbol{G}\boldsymbol{u} \\ \boldsymbol{y} &= \boldsymbol{\Psi}\boldsymbol{s} + \boldsymbol{w} \ . \end{aligned} \tag{3.4}$$

Where,

$$
\begin{aligned}
\boldsymbol{y} &= [y(0), y(1), \cdots, y(N-1)]^T, \\
\boldsymbol{s} &= [s(0), s(1), \cdots, s(N-1)]^T \sim \mathcal{CN}(\boldsymbol{s}_P, \boldsymbol{\Sigma}_{\boldsymbol{s}}^{(0)}), \\
\boldsymbol{\theta} &= [\theta(0), \theta(1), \cdots, \theta(N-1)]^T \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\Sigma}_{\boldsymbol{\theta}}), \\
\boldsymbol{u} &= [u(0), u(1), \cdots, u(N-1)]^T \sim \mathcal{CN}(\boldsymbol{0}, \sigma_u^2 \boldsymbol{I}_N), \\
\boldsymbol{w} &= [w(0), w(1), \cdots, w(N-1)]^T \sim \mathcal{CN}(\boldsymbol{0}, N_0 \boldsymbol{I}_N),
\end{aligned}
$$

describes received signal vector, source signal vector, phase noise vector, Wiener phase process noise vector and additive white noise vector of channel respectively. Here, $\boldsymbol{I}_N$ denotes $N \times N$ identity matrix. In addition, it is defined as $\boldsymbol{\eta} = [e^{j\theta(0)}, e^{j\theta(1)}, \cdots, e^{j\theta(N-1)}]^T$ and $diag(\cdot)$ operator shows obtaining a diagonal matrix from a given vector. In this case, it is obtained as $\boldsymbol{\Psi} = diag(\boldsymbol{\eta})$. $\boldsymbol{G}$ matrix, which is in (3.4) model, is expressed as,

$$
\boldsymbol{G} = \begin{bmatrix} 1 & 0 \cdots & 0 \\ 1 & \ddots \ddots & \vdots \\ \vdots & \ddots \ddots & 0 \\ 1 & \cdots 1 & 1 \end{bmatrix} \tag{3.5}
$$

and, correspondingly covariance matrix of phase noise vector is calculated as follows,

$$
\boldsymbol{\Sigma}_{\boldsymbol{\theta}} = \sigma_u^2 \boldsymbol{G}\boldsymbol{G}^T = \sigma_u^2 \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & 2 & 2 & \cdots & 2 \\ 1 & 2 & 3 & \cdots & 3 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 2 & 3 & \cdots & N \end{bmatrix} \tag{3.6}
$$

Besides, source signal vector $\boldsymbol{s}$,

$$s(n) = \begin{cases} s_p(n) & , \; n \in \{0, \Delta, 2\Delta, \cdots, (P-1)\Delta\} \\ s_d(n) & , \; \text{otherwise} \end{cases}$$
$$n = 0, 1, \cdots, N-1 \tag{3.7}$$

is obtained by addition of pilot and data vectors, in other words $\boldsymbol{s} = \boldsymbol{s}_p + \boldsymbol{s}_d$. Here, Δ denotes pilot interval and P indicates pilot number in $\boldsymbol{s}$ vector.

3.3 EM Based Phase Noise Estimation Algorithm

The EM algorithm is an iterative method which enables approximating the ML estimation when the direct computation is computationally prohibitive because of missing or hidden data. In other words, EM algorithm is a generalization of ML estimation to the incomplete data case. Each iteration of the algorithm consists of two processes respectively: The *expectation step* (E-Step) and *maximization step* (M-step). In the E-step expectation of log-likelihood function is calculated according to distribution of missing or hidden data in the model. Afterwards, in the M-step, the iteration based update rule is obtained which maximizes the parameter of the expectation of log-likelihood function. These steps can detailed as follows,

3.3.1 Expectation-Step (E-Step)

First step of EM algorithm is guessing a probability distribution over completions of missing data given the current model. Therefore, *E-step* of the algorithm calculates the function given below,

$$Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)}) = E_{\boldsymbol{s}}\{\ln p(\boldsymbol{\theta}|\boldsymbol{y}, \boldsymbol{s})|\boldsymbol{y}, \boldsymbol{\theta}^{(i)}\}. \tag{3.8}$$

Since maximization is performed with respect to $\boldsymbol{\theta}$ in *M-Step*, unnecessary terms which are not dependent on $\boldsymbol{\theta}$ can easily removed and expressed as below,

$$\ln p(\boldsymbol{\theta}|\boldsymbol{y},\boldsymbol{s}) \sim \ln p(\boldsymbol{y}|\boldsymbol{\theta},\boldsymbol{s}) + \ln p(\boldsymbol{\theta}), \tag{3.9}$$

After substituting (3.9) into (3.8), the following expression of $Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)})$ is easily obtained,

$$Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)}) \sim E_{\boldsymbol{S}}\{\ln p(\boldsymbol{y}|\boldsymbol{\theta},\boldsymbol{s})|\boldsymbol{y},\boldsymbol{\theta}^{(i)}\} + \ln p(\boldsymbol{\theta}) \tag{3.10}$$

Expected value of given (3.10) expression's right hand side can be obtained by using the receive signal model in (3.4)and after unnecessary terms which are not dependent on $\boldsymbol{\theta}$ are removed as shown below,

$$E_{\boldsymbol{S}}\{\ln p(\boldsymbol{y}|\boldsymbol{\theta},\boldsymbol{s})|\boldsymbol{y},\boldsymbol{\theta}^{(i)}\} \sim \frac{1}{N_0}\big[\boldsymbol{y}^{\dagger}\boldsymbol{\Psi}\boldsymbol{\mu}_{\boldsymbol{S}}^{(i)} + \boldsymbol{\mu}_{\boldsymbol{S}}^{(i)\dagger}\boldsymbol{\Psi}^{\dagger}\boldsymbol{y}\big] \tag{3.11}$$

Here, $\boldsymbol{\mu}_{\boldsymbol{S}}^{(i)}$ indicates a posteriori expected value of $\boldsymbol{s}$ vector for given $\boldsymbol{\theta}^{(i)}$ and expressed as following,

$$\begin{aligned} \boldsymbol{\mu}_{\boldsymbol{S}}^{(i)} &= E\{\boldsymbol{s}|\boldsymbol{y},\boldsymbol{\theta}^{(i)}\} \\ &= \boldsymbol{s}_p + \frac{1}{N_0}\boldsymbol{\Sigma}_{\boldsymbol{S}}^{(i)}\boldsymbol{\Psi}^{(i)\dagger}\big(\boldsymbol{y} - \boldsymbol{\Psi}^{(i)}\boldsymbol{s}_p\big) \end{aligned} \tag{3.12}$$

In this expression, $\boldsymbol{\Sigma}_{\boldsymbol{S}}^{(i)}$ indicates a posteriori covariance matrix of $\boldsymbol{s}$ for given $\boldsymbol{\theta}^{(i)}$ and expressed as shown below,

$$\begin{aligned}\boldsymbol{\Sigma}_{\boldsymbol{s}}^{(i)} &= E\{\boldsymbol{s}\boldsymbol{s}^{\dagger}|\boldsymbol{y},\boldsymbol{\theta}^{(i)}\} \\ &= \boldsymbol{\Sigma}_{\boldsymbol{s}}^{(0)}\left(\boldsymbol{I}_N + \frac{1}{N_0}\boldsymbol{\Sigma}_{\boldsymbol{s}}^{(0)}\right)^{-1}\end{aligned} \tag{3.13}$$

In addition, $\boldsymbol{\Sigma}_{\boldsymbol{s}}^{(0)}$ indicates a priori covariance matrix of $\boldsymbol{s}$ vector. It is also known that $\boldsymbol{\theta} \sim N(0, \boldsymbol{\Sigma}_{\boldsymbol{\theta}})$ from (3.4) and $\boldsymbol{\Sigma}_{\boldsymbol{\theta}}$ matrix is also given in (3.6) expression. Therefore, log-likelihood function $\boldsymbol{\theta}$ can be expressed as,

$$\ln p(\boldsymbol{\theta}) \sim -\boldsymbol{\theta}^T \boldsymbol{\Sigma}_{\boldsymbol{\theta}}^{-1} \boldsymbol{\theta} \tag{3.14}$$

Finally, $Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)})$ function can be obtained by substituting (3.11) and (3.14) expressions into (3.10),

$$Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)}) \sim \frac{1}{N_0}[\boldsymbol{y}^{\dagger}\boldsymbol{\Psi}\boldsymbol{\mu}_{\boldsymbol{s}}^{(i)} + \boldsymbol{\mu}_{\boldsymbol{s}}^{(i)^{\dagger}}\boldsymbol{\Psi}^{\dagger}\boldsymbol{y}] - \boldsymbol{\theta}^T \boldsymbol{\Sigma}_{\boldsymbol{\theta}}^{-1} \boldsymbol{\theta} \tag{3.15}$$

3.3.2 Maximization-Step(M-Step)

In the *M-step* of the algorithm the log-likelihood function is maximized under the assumption that the missing data are known. The estimate of the missing data from the E-step are used instead of the actual missing data. Therefore, in this step, expected value of log-likelihood function in (3.8) is maximized with respect to $\boldsymbol{\theta}$ and updating rule is presented for phase noise estimation.

$$\boldsymbol{\theta}^{(i+1)} = \arg\max_{\boldsymbol{\theta}} Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)}) \tag{3.16}$$

$Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)})$ function which is obtained in (3.15) is maximized with respect to $\boldsymbol{\theta}$ as shown below:

$$
\begin{aligned}
\frac{\partial Q(\boldsymbol{\theta}|\boldsymbol{\theta}^{(i)})}{\partial \boldsymbol{\theta}}\Big|_{\boldsymbol{\theta}=\boldsymbol{\theta}^{(i+1)}} &= -\frac{2}{N_0}\,\mathbb{I}\mathrm{m}\big[\,diag(\boldsymbol{y}^* \odot \boldsymbol{\mu}_{\boldsymbol{s}}^{(i)})\,\boldsymbol{\eta}^{(i+1)}\big] \\
&\quad -2\,\boldsymbol{\Sigma}_{\boldsymbol{\theta}}^{-1}\boldsymbol{\theta}^{(i+1)} \\
&= 0.
\end{aligned} \tag{3.17}
$$

Here, $(\cdot)^*$ denotes complex conjugate operation and $\odot$ denotes element by element multiplication. In addition, it is defined as follows $\boldsymbol{\eta}^{(i+1)} = [e^{j\theta^{(i+1)}(0)}, e^{j\theta^{(i+1)}(1)}, \cdots, e^{j\theta^{(i+1)}(N-1)}]^T$. In general, because of $|\theta(n)| \ll 1$, $\eta(n) = e^{j\theta(n)}$ function can expand to taylor series over $\widehat{\theta}(n)$ for $\theta(n)$. Therefore, it is obtained the linear approach of $\eta(n)$ by taking the first two term of expansion as shown below,

$$
\begin{aligned}
\eta(n) &= e^{j\theta(n)} \quad , \quad n = 0, 1, \cdots, N-1 \\
&\cong e^{j\widehat{\theta}(n)} + j\left[\theta(n) - \widehat{\theta}(n)\right]e^{j\widehat{\theta}(n)} \\
&= [1 - j\widehat{\theta}(n)]e^{j\widehat{\theta}(n)} + je^{j\widehat{\theta}(n)}\,\theta(n),
\end{aligned} \tag{3.18}
$$

(3.18) expression can be rearranged by taking $\theta(n) = \theta^{(i+1)}(n)$ and $\widehat{\theta}(n) = \theta^{(i)}(n)$ in this approach with given definitions $a^{(i)}(n) = [1 - j\theta^{(i)}(n)]e^{j\theta^{(i)}(n)}$, $b^{(i)}(n) = je^{j\theta^{(i)}(n)}$:

$$
\eta^{(i+1)}(n) \cong a^{(i)}(n) + b^{(i)}(n)\,\theta^{(i+1)}(n). \tag{3.19}
$$

(3.19) expression can be obtained as a vector with the given definitions $\boldsymbol{a}^{(i)} = [a^{(i)}(0), a^{(i)}(1), \cdots, a^{(i)}(N-1)]^T$ and $\boldsymbol{b}^{(i)} = [b^{(i)}(0), b^{(i)}(1), \cdots, b^{(i)}(N-1)]^T$ as follows:

$$
\boldsymbol{\eta}^{(i+1)} \cong \boldsymbol{a}^{(i)} + diag(\boldsymbol{b}^{(i)})\,\boldsymbol{\theta}^{(i+1)}. \tag{3.20}
$$

Finally, updating rule for phase noise estimation is obtained by substituting (3.20) expression into (3.17) expression as shown below:

$$\boldsymbol{\theta}^{(i+1)} = -\boldsymbol{T}^{(i)^{-1}}\boldsymbol{v}^{(i)}. \tag{3.21}$$

Here, $T^{(i)}$ matrix and $\boldsymbol{v}^{(i)}$ vector are defined as,

$$\begin{aligned}
\boldsymbol{T}^{(i)} &= \Big(\mathbb{Im}\big[diag(\boldsymbol{y}^* \odot \boldsymbol{\mu}_{\boldsymbol{S}}^{(i)} \odot \boldsymbol{b}^{(i)})\big] + N_0\boldsymbol{\Sigma}_{\boldsymbol{\theta}}^{-1}\Big)^{-1}, \\
\boldsymbol{v}^{(i)} &= \mathbb{Im}\big[diag(\boldsymbol{y}^* \odot \boldsymbol{\mu}_{\boldsymbol{S}}^{(i)})\,\boldsymbol{a}^{(i)}\big]
\end{aligned} \tag{3.22}$$

3.3.3 Initialization

At first step, the pilot symbols are employed as observations. To obtain an initial estimate, phase noise values are calculated at receiver as shown below,

$$\boldsymbol{\theta}^{(0)}(n) = arg\Big(\frac{y(n)}{s_p(n)}\Big),\; n \in \{0, \Delta, 2\Delta, \cdots, (P-1)\Delta\}. \tag{3.23}$$

Therefore, initial phase noise values in data positions are determined by cubic interpolation of initial pilot position values which are given in (3.23).

Chapter 4

Simulation Results

As mentioned in first chapter, there are various methods are proposed in literature for phase noise estimation. However, researches on this problem still continue because obtained results are not satisfactory. Therefore, after theoretical framework is provided for suggested algorithm, performance of this algorithm is presented by computer simulations in this chapter. In order to evaluate the performance of phase noise estimation and source detection algorithms, MSE curves were used. For the simulations in this project, MATLAB was employed with its Communications Toolbox for all data runs.

Three different concept are studied in following simulations. Firstly performance of phase noise estimator and source detector which are main objective of this thesis and also optimum pilot interval selection. Selected simulation parameters are shown in table 4.1. Here N indicates symbol number, σ_u is standard deviation of phase noise and Δ is pilot interval. These parameters are assumed as constant for each simulation.

Parameter	**Specification**
N	256
σ_u	$3°$
Δ	4

Table 4.1: Simulation Parameters

4.1 Phase Noise Estimator Performance

In this section, the performance of the proposed algorithm in terms of the MSE of the phase estimation is shown by computer simulations. It is assumed the transmission of a block of N symbols over an AWGN channel in the presence of Wiener phase noise $\theta(n)$ which is described in (3.2)

As shown in figure 4.1, despite the strong phase noise($\sigma_u = 3°$), error rate is decreased dramatically in the first iteration step and it decreased at each step and converged an error border in 4th iteration. In addition, clearly, by SNR values are increased, error rate is decreased as it is expected. It can be concluded that this algorithm works well for phase noise estimation in the presence of strong phase noise.

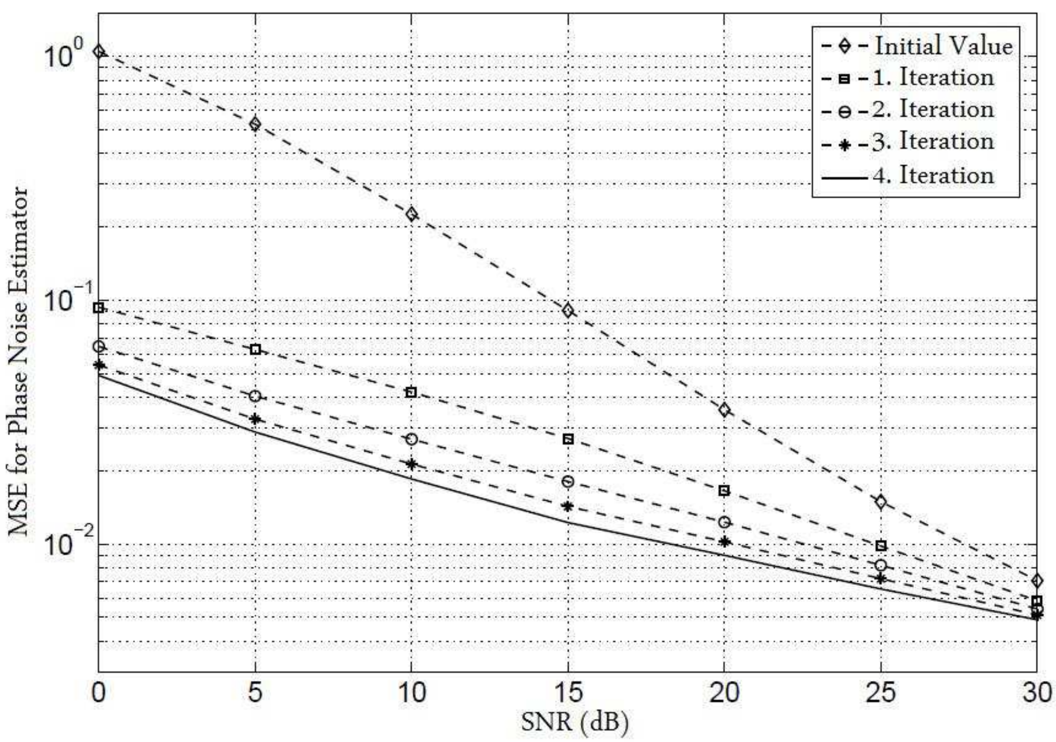

Figure 4.1: MSE Performance of Phase Noise Estimator.

4.2 Source Detector Performance

In this section, source detector performance is evaluated in terms of MSE by computer simulations. It is beneficial to indicate that same system parameters and same transmission scheme is used in this simulation which are described above. It is assumed the transmission of 256 symbols and pilot interval is set as 4.

It is clearly seen in figure 4.2 that MSE is decreased for each iteration steps. However, this decrement is not dramatic as phase noise estimator. Moreover, after first iteration a slight change is appeared between each iteration steps but error rate is converged an error border in 4th iteration as phase noise estimator. Therefore, it can be concluded that 4 iteration is sufficient for algorithms convergence.

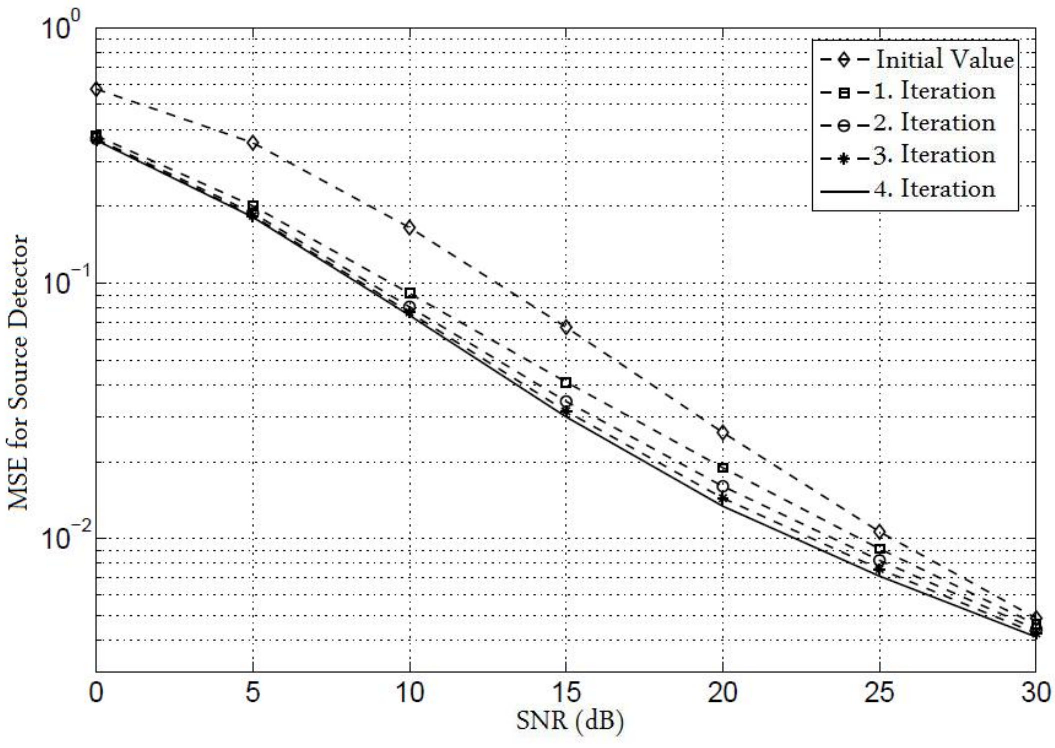

Figure 4.2: MSE Performance of Source Detector.

4.3 Optimum Pilot Interval

In figure 4.3., MSE performance of phase noise estimator is given for various pilot intervals for 3 different SNR values which are 10dB, 15 dB and 20 dB. Relation between pilot interval and system performance is clearly seen from figure 4.3. Namely, if pilot interval is increased, the overall performance of system is decreased. In addition, it is observed that error is increased linearly for larger pilot intervals more than 8. Therefore, it is concluded from here that, to choose pilot interval as 8 for this system is appropriate.

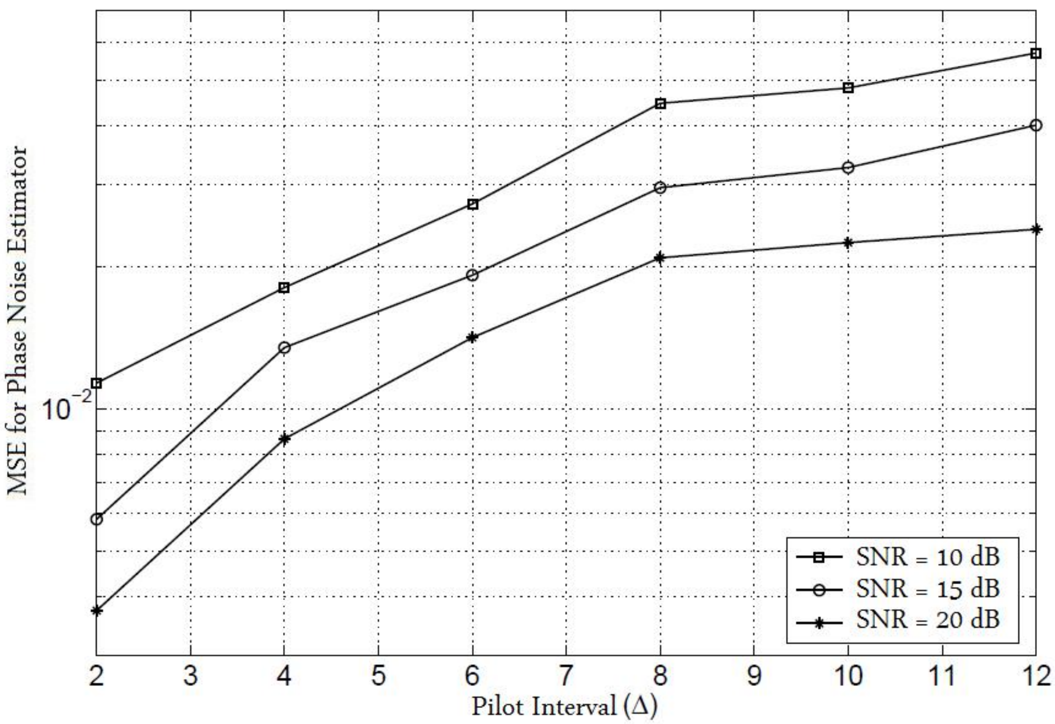

Figure 4.3: MSE Performance of Phase Noise Estimator vs Pilot Interval.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The increment of user demands toward to high data rate services without regard to location, has directed the research of future of communication on high speed wireless systems. However, wireless channels have some disadvantages and it is quite difficult to achieve this goal under these circumstances. Most of these disadvantages are discussed in literature and a lot of techniques are proposed in order to cope with them. Nevertheless, one of the major problem is phase noise sensitivity for all proposed techniques.

In this thesis phase noise estimation problem is discussed. In chapter 2 phase noise problem and its reasons are introduced and mathematical modeling process is shown in detail. As shown in this chapter phase noise is an important factor which degrades the error performance of overall communication system and must be eliminated.

Therefore, an EM based phase noise estimation algorithm is proposed in order to cope with this problem for single carrier transmission. In addition, source detection is also performed by this algorithm. As it is shown in chapter 3, proposed algorithm has reduced computational complexity and easy to implement. Initialization for algorithm is performed by interpolation of pilot symbols.

From the simulation results which are obtained in chapter 4, it can be concluded that the proposed algorithm works well. Simulations are performed under strong phase noise

($\sigma_u = 3^\circ$) and decrement of MSE, especially in lower SNR values, can clearly observed for phase noise estimator and also for source detector. In addition, MSE performance is examined due to pilot interval and an optimal pilot interval is also determined for this system.

5.2 Future Works

There is a relevant suggestion regarding the future work. The proposed algorithm works well for single carrier transmission systems. However, OFDM is a well-known concept which suffers from phase noise because its sensitivity to phase differences. Therefore, extended version of this algorithm may applied for OFDM based communication schemes. This algorithm is appropriate for this extension, therefore, results would be satisfactory.

References

[1] http://www.itu.int/ITU-D/ict/statistics/ Accessed:26.06.2010

[2] T. Rappaport, *Wireless Communications*, Saddle River, NJ:Prentice Hall,2002.

[3] K. Santhi, V. Srivastava, G. Senthil, and A. Butare., "Goals of true broad bands wireless next wave (4G-5G)," *IEEE Vehicular Technology Conference*, vol.4, Oct.2003, pp.2317-2321

[4] D. Tse, P. Wiswanath, *Fundamentals of Wireless Communications*, Cambridge University Press, 2005.

[5] R. Chang, "Synthesis of band limited Orthogonal Signals for multichannel data transmission ," *BSTJ*, vol. 46, pp. 1775-1796, December 1966.

[6] Burc A. Kaleli, Habib Senol and Erdal Panayirci, "Ortak faz gurultusu kestirimi ve kaynak sezimlemesi," *IEEE Signal Processing and Communication Applications (SIU'10) conference*, Diyarbakir, Turkey, April.2010.

[7] F.M.gardner, *Phaselock Techniques, 2nd Ed.*, New York, U.S.A.: John Wiley and Sons, 1979.

[8] H. Meyr, M. Moeneclaey and S. A. Fechtel, *Digital Communication Receivers: Synchronization, Channel Estimation, and Signal Processing*, New York, U.S.A.: John Wiley, 1997.

[9] L. Benvenuti, L. Giugno, V. Lottici, and M. Luise, "Code-aware carrier phase noise compensation on turbo-coded spectrally-efficient highorder modulations," *8th Intern. Work. on Signal Processing for Space Communication*, pp. 177-184, September 2003.

[10] V. Simon, A. Senst, M. Speth and H. Meyr, "Phase Noise Estimation via Adapted Interpolation," *Proc. of the IEEE Global Comm. Conference (GLOBECOM 2001)*, San Antonio, TX, USA, Nov. 2001.

[11] K.P.Ho, *Phase-Modulated Optical Communication Systems*, New York, U.S.A.: Springer, 2005, Chapter 4.

[12] N. Hadaschik, M. Dorpinghaus, A. Senst, O. Harmjanz, U. Kaufer, G. Ascheid, H. Meyr, "Improving MIMOPhase Noise Estimation by Exploiting Spatial Correlations," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 3, pp. 833-836, 2005.

[13] L. Zhao and W. Namgoong, "Novel Phase-Noise Compensation Scheme for Communication Receivers," *IEEE Transactions on Communications*, vol. 54, no. 3, pp. 532-542, March 2006.

[14] H. Fu and P. Y. Kam , "MAP/ML Estimation of the Frequency and Phase of a Single Sinusoid in Noise," *IEEE Transactions on Signal Processing*, vol. 55, no. 3, pp. 834-845, March 2007.

[15] G. Ferrari, G. Colavolpe and R. Raheli, "Linear Predictive Detection for Communications With Phase Noise and Frequency Offset," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 4, pp. 2073-2085, July 2007.

[16] Peter Moters and Yural Peres *Brownian Motion*, Draft Version as of May 25, 2008. available at http://www.stat.berkeley.edu/users/peres/bmbook.pdf

[17] H. Fu and P. Y. Kam , "Improved Weighted Phase Averager for Frequency Estimation of Single Sinusoid in Noise," *IET Electronics Letters*, vol. 44, no. 3, pp. 247-248,January 2008.

[18] G. Colavolpe, A. Barbieri, and G. Caire, "Algorithms for iterative decoding in the

presence of strong phase noise," *IEEE Journal on selected areas in communications*, vol. 23, pp. 1748-1757, September 2005.

[19] J. Bhatti and M. Moeneclaey, "Influence of pilot symbol configuration on data-aided phase noise estimation from a DCT basis expansion," *Proceedings of INCC 2008*, Lahore, Pakistan, pp. 79 - 84, May 2008.

[20] J. Bhatti and M. Moeneclaey, "Feedforward data-aided phase noise estimation from a DCT basis expansion," *EURASIP Journal on Wireless Communications and Networking*, Special Issue on Synchronization in Wireless Communications, January 2009.

[21] J. Bhatti and M. Moeneclaey, "Iterative-soft-decision directed phase noise estimation from a DCT basis expansion," *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Tokyo, Japan, pp. 3228 - 3232, September 2009.

[22] K. Nikitopoulos and A. Polydoros, "Compensation schemes for phase noise and residual frequency offset in OFDM systems," *IEEE Global Telecommunications Conference*, San Antonio, Texas, November 2001.

[23] S. Wu and Y. Bar-Ness, "A Phase Noise Suppression Algorithm for OFDM-Based WLANs," *IEEE Communications Letters*, vol.6, no. 12, pp. 535-537, December 2002.

[24] R. A. Casas, S. L. Biracree and A. E. Youtz, "Time Domain Phase Noise Correction for OFDM Signals," *IEEE Transactions on Broadcasting*, vol. 48, no. 3, pp. 230-236, September 2002.

[25] D. D. Lin, R.A. Pacheco, T. J. Lim and D. Hatzinakos, "Joint Estimation of Channel Response, Frequency Offset, and Phase Noise in OFDM," *IEEE Transactions on Signal processing*, vol.54, No.9, September 2006

[26] S. Wu, P. Liu and Y. Bar-Ness, "Phase Noise Estimation and Mitigation for OFDM

Systems," *IEEE Transactions on Wireless Communications*, vol.5, No.12, December 2006.

[27] Q. Zou, A. Tarighat and A.H. Sayed, "Compensation of Phase Noise in OFDM Wireless Systems," *IEEE Transactions on Signal Processing*, vol.55, No.11, November 2007.

[28] J. Salz, "Coherent Ligtwave Communication," *AT & T Technical Journal*, vol.64, No.10 , pp. 2153-2209, December 1985.

[29] C. H. Henry, "Theory of Linewidth of Semiconductor Lasers," *IEEE Journal of Quantum Electronics*, vol QE-18, pp. 259-264, February 1982.

[30] J. Ruthman and F.L. Walls, "Characterization of Frequency Stability in Precision Frequency Sources," *Proceedings of The IEEE*, vol.79, No.6, pp. 952-960, June 1991.

[31] S.M.Kay, *Fundamentals of Statistical Signal Processing: Estimation Theory*, New Jersey,U.S.A.: Prentice Hall, 1993.

[32] H.V. Poor, "On parameter estimation in DS/SSMA formats," *Proc. Advances in Communications and Control Systems, Baton Rouge*, LA, October 1988.

[33] G.K. Kaleh, "Joint decoding and phase estimation via the expectation-maximization algorithm," *Proc. Int. Symp. on Information Theory*, San Diego, CA, January 1990.

[34] C. N. Georghiades and D. L. Snyder, "The expectation-maximization algorithm for symbol unsynchronized sequence detection," *IEEE Trans.Commun.*, vol.39, pp. 54-61, January 1991.

[35] S. M. Zabin and H. V. Poor, "Efficient estimation of class A noise parameters via the EM algorithm," *IEEE Trans. Inform. Theory*, vol.37, pp. 60-72, January 1991.

Curriculum Vitae

Burç Arslan Kaleli was born on September 24, 1985 in Istanbul.He received his BS degree in Electronics Engineering and Industrial Engineering (Double Major) in 2008 from Kadir Has University. He worked as a research assistant at the department of Electronics Engineering of Kadir Has University from 2008 to 2010. During this time has been affiliated NEWCOM++ project which is supported within the context of European Union Seventh Framework Programme. His research interests include communication theory, wireless communication and estimation theory.

Publications

[1] Serhat Erküçük and Burç Arslan Kaleli, *"IEEE 802.11.4a Standardında Sistemlerin Birlikte Varolabilmeleri için Darbelerin Doğrusal Birleşimi", IEEE 17th Signal Processing and Communications Applications Conference(SIU)"*, 9-11 April 2009, Antalya, TURKEY

[2] Burç Arslan Kaleli, Erdal Panayırcı and Habib Şenol, *"Ortak Faz Gürültüsü Kestirimi ve Kaynak Sezimlemesi", IEEE 18th Signal Processing and Communications Applications Conference(SIU)"*, 22-24 April 2010, Diyarbakır, TURKEY