Master's Thesis
석사 학위논문

Improved noise power and SNR estimation in severe fading channels for OFDM systems

Inho Choi (최 인 호 崔 寅 浩)

Department of Information and Communication Engineering
정보통신융합 전공

DGIST

2013

Master's Thesis
석사 학위논문

Improved noise power and SNR estimation in severe fading channels for OFDM systems

Inho Choi (최 인 호 崔 寅 浩)

Department of Information and Communication Engineering

정보통신융합 전공

DGIST

2013

Improved noise power and SNR estimation in severe fading channels for OFDM systems

Advisor : Professor Ji-Woong Choi

Co-advisor : Professor Jaesung Hong

by

Inho Choi

Department of Information and Communication Engineering

DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of information and communication engineering. The study was conducted in accordance with Code of Research Ethics[1]

11(month). 15(day). 2012(year)

Approved by

Professor Ji-Woong Choi (Signature)
(Advisor)

Professor Jaesung Hong (Signature)
(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Improved noise power and SNR estimation in severe fading channels for OFDM systems

Inho Choi

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

12(month). 5(day). 2012(year)

Head of Committee 최지웅 (인)

Prof. Ji-Woong Choi

Committee Member 박경준 (인)

Prof. Kyung-Joon Park

Committee Member 홍재성 (인)

Prof. Jaesung Hong

Degree
학번

최 인호, Inho Choi, The study of wireless communication. Department of Information and communication engineering. 2013. 34p. Advisors Prof. Ji-Woong Choi, Prof. Co-Advisors Jaesung Hong.

ABSTRACT

The purpose of this study is to estimate signal to noise power ratio (SNR) in a severe fading channels. Signal power and SNR estimation is hard to estimate in a severe fading channels because channel variation occurs more extremely. In this situation, noise power estimates are generally higher than the actual values because of channel estimation errors, channel variations, and multipath delays. Moreover, current communication systems reduce pilot density to increase data rate. As a result, accurate SNR estimation is becoming more difficult.

This paper analyses SNR estimation techniques and proposes improved signal and SNR estimation schemes in severe fading channels to reduce estimation error. We analyze representative SNR estimators. The proposed signal power and SNR estimators use a channel estimation filter (CEF) and differential scheme. The simulation results show that the differential scheme SNR estimator provides better performance in severe fading channel. The proposed techniques can reduce error because they select a better condition channel domain.

The proposed SNR estimation technique uses OFDM characteristics in multi-dimensional domain. Channel status is different along the time and frequency domain. Choosing a better domain can reduce error in SNR estimation. The proposed SNR estimator uses SNR information of each domain to choose the proper domain. The simulation result shows that the proposed estimation technique can reduce estimation error up to 5dB in a frequency selective or fast fading channel.

The study result can be applied to contemporary communication system channel estimation such as LTE and WiMax, which provide high data rates with low pilot density with high interference channel or fast fading channel.

Keywords: SNR estimation, noise power estimation, OFDM system, fading channel

Contents

Abstract · i

List of contents · iii

List of figures · iv

Ⅰ. Introduction · 1

Ⅱ. System description

2.1 OFDM system overview · 5

2.2 Channel model for OFDM systems · · · · · · · · · · · · · · · · · 8

2.3 SNR estimation in OFDM systems · · · · · · · · · · · · · · · · · 11

Ⅲ. Comparisons of SNR estimation algorithms

3.1 Maximum likelihood (ML) estimation method in AWGN · · · · · · · · 12

3.2 Minimum mean square error (MMSE) estimation method in AWGN · · 13

3.3 Conventional SNR estimator in fading channel · · · · · · · · · · 14

Ⅳ. Proposed SNR estimation techniques

4.1 Noise power estimator using channel estimation filter (CEF) · · 16

4.2 Signal power estimator using CEF · · · · · · · · · · · · · · · · 17

4.3 Signal power estimator using differential scheme · · · · · · · · 18

4.4 Performance analysis · 19

Ⅴ. Proposed SNR estimation techniques in multi-dimension domain

5.1 Noise power estimator using channel estimation filter (CEF) · · 26

5.2 Performance analysis · 27

Ⅵ. Conclusion and future works · 29

List of Figures

Figure 2.1 OFDM system block · 6

Figure 2.2 Resource block for SISO LTE system · · · · · · · · · · · · · · · · 7

Figure 2.3 Water filling technique using SNR information · · · · · · · · · · · 11

Figure 4.1 SNR estimation error using CEF signal power estimator in fast fading channel · 22

Figure 4.2 SNR estimation error using differential signal power estimator in fast fading channel · 22

Figure 4.3 SNR estimation error using CEF and residual noise reduction signal power estimator in fast fading channel · 23

Figure 4.4 SNR estimation error using CEF signal power estimator in frequency selective fading channel · 24

Figure 4.5 SNR estimation error using differential signal power estimator in frequency selective fading channel · 25

Figure 4.6 SNR estimation error using CEF and residual noise reduction signal power estimator in frequency selective fading channel · · · · · · · · · · · 25

Figure 5.1 SNR estimation error using proposed technique in fast fading channel · 28

Figure 5.2 SNR estimation error using proposed technique in frequency selective channel · 28

I. Introduction

The work here is of a SNR estimation method aiming at high-accuracy estimation at fast fading channel for an orthogonal frequency division multiplexing (OFDM) system. Signal-to-noise power ratio (SNR) is defined as the ratio of signal power to noise power, which indicates the quality of a signal. SNR is simple notation that is closely related to the Shannon capacity, which is an important factor in wireless communication because it represents the theoretically achievable upper bound of information capacity.

OFDM systems are widely-used modulation scheme these days. The OFDM system uses multicarrier transmissions, where data can be transmitted using multiple subcarriers. OFDM systems are more robustness in the frequency selective channel, compared to a single carrier system because the single fading factor or interference can cause the entire system link to fail. However, in the OFDM systems only a single subcarrier or a few nearby multi-carriers will fail [1]. Moreover, due to the improvement of smart phones and multi-media systems, a higher data rate is required today. To meet these requirements, wide spectrum is used to get a high data rate. In a single carrier wide band system, the channel equalization and SNR estimation is more difficult. This difficulty is one of the reasons why the current variety of communication standards adopt OFDM systems such as HYPER-LAN2, IEEE 802.11 Wireless Local Area Network (WLAN), Digital Video Broadcasting (DVB), IEEE 802.16 World Interoperability for Microwave Access (WiMax) and Long Term Evolution (LTE) in 3GPP standard [1].

SNR estimation is a major part of communication systems. Modern wireless communication systems use SNR information to determine coding rates, modulation rates, and pilot density [2]. To achieve good system performance, parameters should be changed according to channel status. The accurate estimation of SNR gives more accurate information about the channel status. Moreover, SNR is used for many other situations, such as channel feedback, and link adaptation. Accurate SNR estimation is necessary to achieve maximum system performance as well.

This paper proposes a scheme based on data aid (DA) estimation scenario which provides accurate estimation results and is widely used in OFDM systems. SNR estimation techniques can be divided into two categories based on the transmission scenario, data-aided (DA) estimation where known transmitted data, known as a pilot or reference signal is used for estimation. The second category is NDA, where unknown transmitted data to estimate the SNR [3]. NDA estimation can achieve more data throughput than DA estimation. However, DA transmission is more general scenarios because it estimates more accurately than NDA scenarios and NDA signal information can be used for other estimations, such as channel estimation and decision boundary. Therefore, scheme based on the NDA scenario is analyzed and proposed. In a mobile communication, LTE adopts a lattice structure reference system architecture to transmit the signal, where repeated every four data signals. Therefore, the DA scenario assumption is reasonable.

Most research was based on flat fading channel [4], [5]. However, Gaussian assumption has many errors in severe fading channels. Fast Doppler shift caused by advanced fast transportation systems and increased interference by complex indoor wireless environments make a severe fading channel in time and frequency domain. It also increases SNR estimation errors by increasing channel estimation error. Admittedly, there is some research on fast fading or frequency selective fading. In a fast fading channel, estimators use rank information and autocorrelation information to estimate SNR [6], [7]. In a frequency channel, some studies considering Rayleigh multipath channel which uses subspace based estimation and minimum mean square error (MMSE) based on colored noise estimation [8], [9]. However, there are few studies that consider both fast fading and frequency selective fading. Moreover, there is very little performance comparison in severe fading channels. Most SNR estimators analyze only in specific situations, such as frequency selective channel or fast fading channel. This paper will analyze SNR estimation schemes in various situations. Therefore, the proposed SNR estimation will be compared in severe channels and an estimation technique for better estimation which is applicable to conventional estimation method is proposed.

Two representative SNR estimators, ML SNR estimator and MMSE SNR estimator will be analyze in a fading channel, which are based on ensemble average and autocorrelation. A conventional SNR estimator uses signal power estimators or noise power estimator to estimate SNR. SNR estimation using one estimator can give better performance and reduce complexity when the channel is stable. However, SNR estimation error is vulnerable in signal power estimator or noise power estimator error. Therefore, this paper proposes an SNR estimation technique that estimates signal power and noise power separately. We estimate signal power and noise power separately to reduce the performance degradation.

The proposed SNR estimation technique uses multi domain characteristic in OFDM systems. OFDM systems send the data along the time and frequency domain. If we select the proper estimation domain, estimation error can be reduced. The proposed technique uses SNR information to select the proper domain. The variation of the channel will be present as a noise power term which makes lower SNR value than actual SNR value. Higher SNR values give the better estimation domain.

The rest of this paper is organized as follows. Section II introduces a system model of the OFDM system. The basic idea and principle in OFDM system and channel model for frequency selective channel and fast fading channel. Conventional SNR estimators are reviewed in Chapter Ⅲ. In Chapter Ⅳ, the proposed noise power and signal power estimator and its simulation results in severe fading channels are descrived using analytical and numerical method. Although wireless communication has several estimation techniques, there is very little research about the comparison between SNR estimation schemes. The performance analysis will be conducted using analytic comparison and simulation results. The analysis will help to choose an effective SNR estimator according to system performance. In Chapter Ⅴ, an accurate SNR technique for severe fading channels will be proposed. By taking maximum SNR value in times, frequency and time and frequency-domain, an improved SNR estimation technique can be derived. The proposed techniques can be applied in proposed algorithms. We evaluate the performance of estimation technique using proposed estimator. Finally, we discuss our conclusions and comment on possible improvements in SNR estimation in Section Ⅵ.

Ⅱ. System model

In this chapter, the basic principles of OFDM systems, cyclic prefix (CP), and pilot signals will be looked at to explain the system model. In addition, basic knowledge about the channel model for severe fading channels, frequency selective channel and fast fading channel will be introduced. Finally, SNR estimation and its application will be discussed.

2.1 OFDM system overview

OFDM is a promising technique to achieve a high data rate with low complexity equalization. Current communication systems require a high data rate specification. High data rate communication needs high bandwidths compared to low data rate systems. A single carrier communication system needs a complex equalizer according to its larger bandwidth. The channel characteristic is different along the bandwidth. To mitigate the problem, a complex equalizer is required. However, complexity can be reduced using multicarrier systems such as OFDM systems, which transmit data into a number of small subcarriers. If we choose orthogonal subcarriers, data can be separated into small carriers, and sent in parallel.

The basic idea of a multicarrier system is to divide the high rate data into a small rate data and transmit it over a number of subcarriers [1]. The lower rate parallel subcarriers can be robust in multipath fading. If the subcarrier is narrow enough, subcarriers can be regard as flat fading channels even if total band experiences frequency selective fading channel. The OFDM system increases spectral efficiency by allowing subcarriers overlapping in frequency. OFDM systems use orthogonal subcarriers to prevent intercarrier interference (ICI).

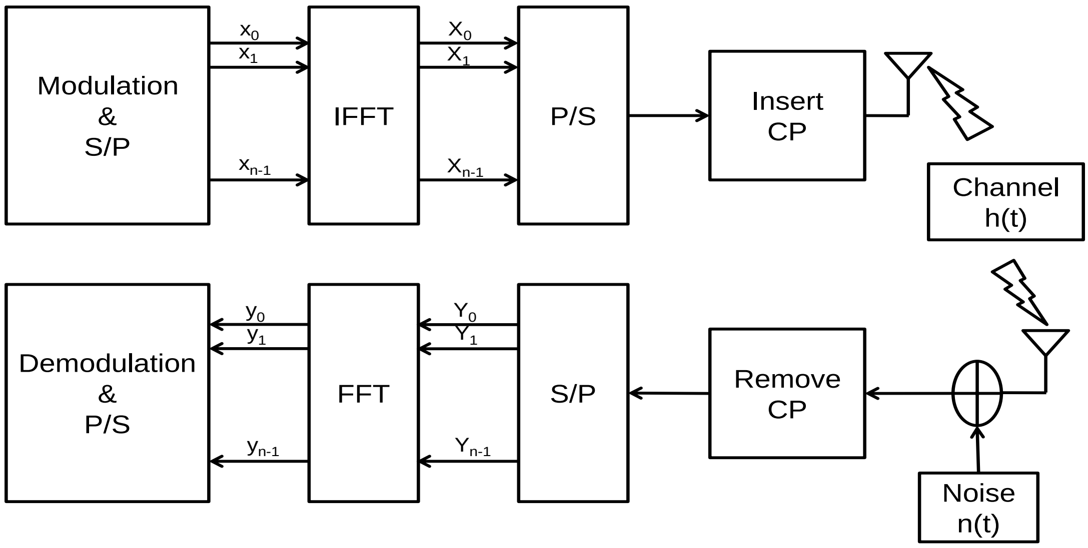

Figure 2.1. OFDM system block.

The baseband model of an OFDM system is illustrated in Fig. 2.1, where the upper path is the transmitter chain and the lower path is the receiver chain. n is the number of subcarriers, x_n, n=0,1,…,n-1 are the transmitted signal, Xn, n=0,1,…,n-1, re-transmit signal after passsing the baseband filter, Yn, n=0,1,…,n-1, are the received signal, and yn, n=0,1,…,n-1, are the demodulation and de-serialized signal after passing through base band filter. Cyclic-prefix (CP) is added before transmission to prevent inter-symbol interference (ISI).

Discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT) is used to make orthogonal subcarriers. The OFDM system could be efficiently implanted using FFT and IFFT [10]. This is one of the main reasons that OFDM systems are used so widely. Flat fading channels can make simple or one tap equalizers, whereas single carrier systems need large tap equalizers. A large tap equalizer needs n^2 complexity, where n is the tap number. However, FFT reduces this complexity, because its block complicity is much smaller than the large tap equalizer, $n\log_2 n$.

Guard time interval could be used in the OFDM system to prevent performance degradation caused by ISI using the transmission of CP. If we set the CP length longer than the maximum excessive delay of the channel and take a window at no ISI effect of the sym-

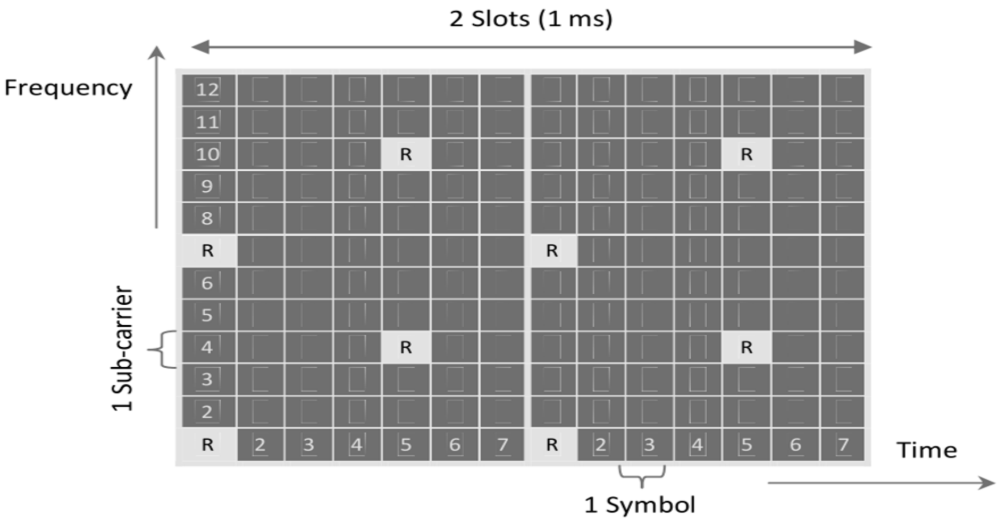

Figure 2.2. Resource block for SISO LTE system [14].

bol, we can remove ISI and ICI. Because of received signal' s cyclic extension characteristic, the received signal can be presented as cyclic convolution between impulse response and OFDM symbol. In this paper, we use cyclic extension CP to reduce ISI event and assume that no ISI. `

Pilot signals transmit a known signal to estimate the information about the channel between a transmitter and a receiver side: for synchronization, equalization, and SNR estimation. This system is also known as a reference signal in LTE systems. If the transmittion signal is known, the signal from the transmitter side can be tracked. This method is how communication parameters can be estimated rather than using un-known signal or data. This paper uses rectangular shape pilot placement, four symbols along to time and frequency domain.

The received signal in OFDM systems can be simplified after perfect synchronization [11]. The received samples in a frequency domain can be shown as

$$Y(i,j) = DFT\{y(i,j)\} = H(i,j)X(i,j) + Z(i,j). \tag{2.1}$$

DFT is discrete Fourier transformation of the signal, where $S_m(k)$ is the symbol, $H_m(k)$ is the channel impulse response, and $Z_m(k)$ is the noise term of the received signal. The transmitted signal can be represented, $x_m(n)$, which is transmitted on *i*-th time index of the *j*-th frequency index, and *N* number of subcarriers. IDFT is an inverse transformation of the signal,

$$x(i,j) = IDFT(X(i,j)) = \sum_{k=0}^{N-1} X(i,j) e^{j2\pi nk/N}. \tag{2.2}$$

The received signal in OFDM system can be defined as

$$y_i(j) = \sqrt{B} X(i,j) h(i,j) + \sqrt{N} Z(i,j), \tag{2.3}$$

where i, j is time/frequency index, B and N are the boosting power of the pilot. $X(i,j)$ and $h(i,j)$ are the pilot signal and channel gain. $Z(i,j)$ is noise signal N~C(0, σ^2).

2.2 Channel models for OFDM systems

Wireless systems transfer data using EM waves. As a result, the signal is affected by circumstance, reflection, diffraction (shadowing), and scattering. These phenomena form the channel characteristics. Channel models can be divided into two categories, large-scale fading and small-scale fading. Large scale fading includes the effect of path loss and shadowing, and small scale fading includes the effect of multi-path fading and Doppler shift fading. In this paper, log scale channel gain is assumed to be unity. After normalization of the channel, the system model in Eq 2.1 can be used.

In this paper, a Rayleigh channel model, which is a common modeling technique in single input single output (SISO) modeling in a non-line of sight (LOS) channel situation, is used. To get an accurate channel model, all reflector parameters including position, power, velocity should be known. However, it is difficult to get all this informatio. Therefore, statical models that present typical or average channel situation are used. A Rayleigh channel model is a widely used model in wireless communication systems. Rayleigh probability density function as shown in,

$$p(x) = \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}, \tag{2.4}$$

where x is the amplitude of each subcarrier channel $|H(i,j)|$, i.e. random variable average power is $2\sigma^2$. We can derive the Rayleigh probability density function from the square root of the Gaussian distribution of real and imaginary random sequence.

2.2.1 Fast fading channel

An important channel parameter is the time-scale of the variation of the channel. The variation of the channel is affected by Doppler shift variance. This is called Doppler spread. The channel variation is changed by the moving speed of the receiver or the transmitter. The maximum coherence time T_c of a wireless channel is defined as

$$T_c = \frac{1}{4D_s}, \tag{2.5}$$

where the Doppler spread is $D_s = \max_{i,j} f_c \left| \tau'_i(t) - \tau'_j(t) \right|$, f_c and $\tau'_i(t)$ are carrier frequency and time shift of each path [12]. Coherence time can categorize fast fading and slow fading. Fast fading occurs when the coherence time is much shorter than delays, whereas slow fading occurs when the coherence time is much larger than OFDM symbol duration. A Slow fading channel is a better condition of the channel because the channel changes slowly in the time domain. Fast fading occurs when the transmitter or receiver moves quickly.

2.2.2 Frequency selective fading modeling

Another important channel parameter is multipath delay spread T_d, which is the difference in propagation time between the longest and shortest path. The different characteristic of delay spread, compared to Doppler spread is that it is related to frequency coherence. The coherence bandwidth W_c of wireless channel is defined as

$$W_c = \frac{1}{2T_d}, \tag{2.6}$$

where the time delay is $T_d = \max_{i,j} \left| \tau_i(t) - \tau_j(t) \right|$, $\tau_i(t)$ is propagation time of each path [12]. Coherence frequency can be a standard between frequency-selective fading and flat fading. Frequency selective fading occurs when coherence bandwidth W_c is much smaller than the transmission signal band width. The multi tap response requires a multi-tap equalizer when making a flat fading channel. The system performance is degraded by fading. Frequency selective channel occurs in indoor situations where complex reflector exist in the channel propagation path.

2.3 SNR estimation in OFDM systems

The SNR is defined as

$$\alpha = \frac{Es}{N_0} = \frac{S^2}{\sigma^2}, \tag{2.7}$$

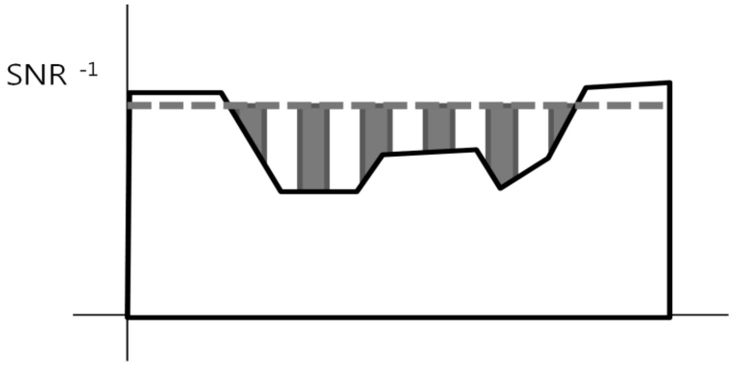

Figure 2.3 Water filling technique using SNR information.

where Es and N_0 are the power of the signal and the power of the noise. If the noise is zero-mean white Gaussian noise, the equation can be simplified. S is the signal amplitude and $\sigma_n{}^2$ is the noise variance.

SNR is a fundamental parameter to determine a digital link's performance. The SNR is widely used because it can be represent the signal condition with simple terms. SNR is widely used for resource allocation, power control, mobile assisted handoff, adaptive modulation, and soft detection and decoding procedures. Figure 2.3 shows how to use SNR information for resource allocation. If we allocate resource power according to inverse of SNR values, we can achieve maximum throughput with a given power [12].

The problem with SNR estimation is that it is difficult to get accurate SNR information in a fading channel [13]. If ideal data information and channel state information (CSI) is used, an accurate SNR value can be obtained. However, channels suffer a great deal of fading and therefore only sparsely separate data and pilot signals can be used to estimate SNR. As a result, an improved SNR estimator is needed. This paper will introduce an SNR estimator that is effective in realistic channels, especially on severe fading channels.

Ⅲ. Conventional SNR estimation methods

This chapter will introduce SNR estimation methods that are important to improve estimation methods further. Conventional SNR estimates are generated by averaging the number of symbol. In the OFDM system, the symbol transferred by each subcarrier has a different channel status. SNR estimator using one symbol can measure instant SNR. However, the performance is degraded by noise. Therefore, SNR estimators are averaged in time and frequency to increase estimation accuracy.

This chapter provides a conventional SNR estimation technique in an OFDM system and its analysis in fading channels. There are two different types of SNR estimation based on pilot calculation: ML estimation and MMSE estimation.

3.1 ML estimation in AWGN noise channel

S. Boumard extended the Maximum Likelihood (ML) SNR estimator of OFDM systems in a time variant linear channel [16], [17]. This estimator is designated ML function. The likelihood function of $\mathbf{y}$ is expressed as

$$\begin{aligned} & f(\mathbf{y};S,N,X_i[j]) \\ & =\frac{1}{\left(\sqrt{2\pi N}\right)^L}\exp\{-\frac{1}{2N}\sum_{j=1}^{L}y_i[j]^2-2SX_i[j]Y_i[j]+SX_i[j]\}, \end{aligned} \tag{3.1}$$

When there are received J pilot signals, the ML estimators $\hat{S}_{ML},\hat{N}_{ML}$ can be found using the following likelihood equations

$$\left.\frac{\partial f(\mathbf{y};S,N,X(i,j))}{\partial S}\right|_{S=S,N=N}=0, \tag{3.2}$$

$$\left.\frac{\partial f(\mathbf{y};S,N,X(i,j))}{\partial N}\right|_{S=S,N=N}=0, \tag{3.3}$$

The ML SNR estimation result can be obtained by

$$\hat{\rho}_{ML}=\hat{S}_{ML}/\hat{N}_{ML} \tag{3.4}$$

$$\begin{aligned}\hat{S}_{ML}&=[\frac{1}{J}\sum_{j=0}^{J-1}\mathrm{Re}\{y(i,j)\hat{h}^*(i,j)x^*(i,j)\}]^2\\ \hat{N}_{ML}&=\frac{1}{J}\sum_{j=0}^{J-1}|y(i,j)|^2-\hat{S}_{ML},\end{aligned} \tag{3.5}$$

where * and $\hat{h}^*(i,j)$ are conjugate signals and channel estimation coefficient. The ML estimation technique uses a statistical model among the sample. The main advantage of ML estimators is better performance than other estimators when the noise characteristic is ensemble and the channel estimation error is small.

3.2 MMSE estimation in AWGN noise channel

The minimum mean square error (MMSE) SNR estimator is defined in [18] and [19].

$$\hat{\rho}_{MMSE}=\hat{S}_{MMSE}/\hat{N}_{MMSE} \tag{3.6}$$

$$\begin{aligned}\hat{S}_{MMSE}&=\frac{1}{J}\sum_{j=0}^{J-1}|y(i,j)|^2-\hat{N}_{MMSE}\\ \hat{N}_{MMSE}&=E[(y(i,j)-\hat{h}(i,j)x(i,j))^2]\\ &=\frac{1}{J}\sum_{j=0}^{J-1}\left|y(i,j)-\hat{h}(i,j)x(i,j)\right|^2,\end{aligned} \tag{3.7}$$

where σ^2 is noise variance and σ_x^2 is variance of the signal. E is the expected value of the signal. The noise MMSE is presented as the square of the mathematical difference of the estimate signal and the received signal. This estimator can minimize error, $E[(y(i,j)-\hat{h}(i,j)a(i,j))^2]$, of SNR estimator.

The MMSE technique estimates the noise power using an MMSE filter technique. As a result, it minimizes noise power estimation errors. The effect of MMSE filter is better tracking of channel variation compared to the ML estimator. Therefore, the MMSE estimator is more robust of channel variation than ML estimator.

3.2 Conventional SNR estimator in fading channel

Conventional SNR estimators offer good performance in flat fading channels. However, in a severe channel where the channel varies fast in time or frequency domain, estimation is increased and incorrectly estimated SNR values occur. In a fading channel, accurate channel status cannot be estimated because of fading in time and/or frequency. Moreover, measurement errors occur in conventional SNR estimation methods because of the interpolated manner that is used to estimate SNR using pilot signals.

A further problem is invalid SNR value in low SNR. Estimated noise power can be larger than the estimated signal power in low SNR regions because of estimation errors. In this case, the SNR value is represented by a negative value or an infinite value. For instance, if the noise power is measured to be larger than the received power, the signal power term is presented as a negative number as seen as Eq 3.7. This result increases errors in SNR estimation. Therefore, an SNR estimator using different and distinct estimators for signal power and noise power will be proposed.

Ⅳ. Proposed SNR estimation techniques in one dimension domain

Conventional SNR estimators have some drawbacks in severe fading channels because of error propagation and invalid SNR values. A noise power estimator and signal estimator with consideration of fading channel will propose in this chapter. Performance evaluation is performed for each SNR estimator in fast fading channel and frequency selective channel based on IEEE 802.11 standard. The proposed scheme is applicable in one dimension domain, such as time, frequency, time-frequency domain. The combination of signal estimator using a differential scheme and noise power estimator offers the best result in severe fading channels.

4.1 Noise power estimator using channel estimation filter (CEF)

The proposed noise power estimator uses a channel estimation filter to estimate noise power. If we have channel information and transmit signal information, we can seperate noise power from the received signal. The proposed noise power estimator is

$$\begin{aligned}\hat{P}_Z &= \frac{\sum_{m=0}^{N_S-1}\sum_{k\in P_m}\left|Y_m[k]-X_m[k]\hat{H}_m[k]\right|^2}{N_S}, \\ &= \sigma_Z^2+\alpha_H^{"}P_S \ , \ \alpha_H^{"}\geq 0\end{aligned} \tag{4.1}$$

where the channel estimator is $\hat{H}_m[k]=\frac{1}{N_S N_P}\sum_{m=0}^{N_S-1}\sum_{k\in P_m}Y_m[h]/X_m[h]$, $\hat{P}_Z$ is the estimated noise power and P_S is thesignal power. σ_Z^2 and $\alpha_H^{"}$ are effective noise power and channel distortion factor. N_S is the number of available OFDMA pilot symbols to estimate noise power. Least square (LS) channel estimators are used to get channel information [15]. The estimated noise term can be represented as the sum of noise power and channel distortion term. The variation of the channel is determined as $\alpha_H^{"}$, which causes noise power increase. The proposed noise power estimator is accurate when channel errors are small. However, estimation errors can be amplified by channel variation. Therefore, noise power is larger than the actual value in a severe fading channel.

4.2 Signal power estimator using channel estimation filter

The proposed signal power estimator uses channel estimation parameters to estimate signal power. If channel information and transmission signal information are known, signal power can be estimated by using CE at the noise power estimator. The signal power estimator using CEF is represented as

$$\begin{aligned}\hat{P}_S &= \frac{\sum_{m=0}^{N_S-1}\sum_{k\in P_m}\left|\hat{H}_m[k]X_m[k]\right|^2}{N_S} \\ &\approx P_S\,\mathrm{Re}\left\{\sum_{k=\lfloor M/2\rfloor-M+1}^{\lfloor M/2\rfloor}\sum_{h=\lfloor M/2\rfloor-M+1}^{\lfloor M/2\rfloor}\left(r_f(k-h)\right)\right\}+\sigma_Z^2 \\ &= (1-\alpha_H)P_S+\beta_H\sigma_Z^2,\end{aligned} \tag{4.2}$$

where $\hat{P}_S$ is the estimated signal power and the actual noise power. N_S is the number of available OFDMA pilot symbols. The channel estimator $\hat{H}_m[k]$ is $\sum_{h=\lfloor M/2\rfloor-M+1}^{h=\lfloor M/2\rfloor} Y_m[h]/X_m[h]$. α_H is the error due to channel distortion, and dependent CEF, β_H is residual noise dependent on CEF.

Note that, α_H and β_H affect the signal power error. Channel variation increases α_H , and thus decreases estimated signal power while, β_H increases signal power.

According to equation 4.2, channel estimation error is propagating to the signal power and increase the signal power. Similar to the noise power estimator, signal estimator using CEF offers good performance when the channel estimator error is small and the noise has ensemble characteristic. Estimated signal power can be smaller than actual SNR in severe fading channels because of α_H . Severe fading channel has more dynamic variation characteristics than flat and slow fading channel. As a result, estimated signal power is decreased than actual signal power. In low SNR, β_H is a more critical factor in estimation error. Noise power σ_Z^2 becomes a large value in low SNR. Therefore residual noise compensation is necessary in low SNR.

A signal power estimator using CE considers residual noise and can compensate that noise, which is measured from the noise power estimation. As shown in equation 4.2, residual noise increases errors in low SNR. The proposed signal power estimator considering residual noise is

$$\begin{aligned}\hat{P}_S &= \frac{\sum_{m=0}^{N_S-1}\sum_{k\in P_m}\left|\hat{H}_m[k]X_m[k]\right|^2}{N_S N_P} - \beta_H \hat{P}_Z \\ &\approx (1-\alpha_H - \beta_H \alpha_H^{''})P_S \\ &= (1-\alpha_H^{'})P_S,\end{aligned} \tag{4.3}$$

where $\alpha_H^{'}$ and $\alpha_H^{''}$ are $\alpha_H + \beta_H \alpha_H^{''}$ and $1/SNR$.

From Chapter 4.2, removing residual noise term is important in low SNR regions because residual noise is presented proportionally to noise power. If β_H can be accurately estimated, the effect of residual noise can be removed.

However, estimating β_H is hard in severe fading channels. Moreover, adaptive β_H estimation needs a great deal of calculation power. This paper uses fixed β_H from a simulation result. 0.05 is used in β_H to reduce residual noise. This method is less effective in severe fading channels or flat fading channel. But according to the simulation result, it works well in fading channel. Therefore, the newly introduced signal power estimator performs better than the Eq. 4.2 estimator.

4.3 Signal power estimator using differential scheme

Instead of using CE, the proposed signal power estimator uses a differential scheme. Assume that transmit pilot signal power is unity, $\left|X_m[k]\right|^2 = 1$, then differential scheme as,

$$\begin{aligned}\hat{P}_S &= \frac{\left|\sum_{m=0}^{N_S-1}\sum_{k\in P_m} Y_m[k]Y_m^*[k+\Delta k]\frac{X_m[k]X_m^*[k+\Delta k]}{\left|X_m[k]X_m^*[k+\Delta k]\right|}\right|}{N_S(N_P-1)} \\ &= \frac{\left|\sum_{m=0}^{N_S-1}\sum_{k=0}^{N_P-2}\tilde{H}_m[k]\tilde{H}_m^*[k+\Delta k]\right|}{N_S(N_P-1)} \\ &\approx P_S\left|r_f(\Delta k)\right|,\end{aligned} \tag{4.4}$$

where Δk is the number of symbols between the pilot and $*$ is the conjugate operation of the signal. $r_f(\Delta k)$ is the auto-correlation of the received signals shifted by Δk subcarriers.

Assuming ensemble average, there is no residual noise. Compared to equation 4.2, there is no noise enhancement term, β_H. Therefore, a differential scheme estimator provides better performance than signal power estimation using CE. The channel variation compensation term is absent from the estimator which is caused by CE are absention in the estimation scheme.

The differential scheme has benefits in sever fading channels because it does not use a channel estimation filter. Channel estimation errors are increased in severe fading channels. Signal power estimation using the differential scheme does not need a channel estimator which is the cause of error propagation.

4.4 Performance analysis

In this chapter, the prosed scheme will be compared using analytic comparison and computer simulation in frequency selective channel or fast fading channel.

4.4.1 Analytic comparison

Three different kinds of signal power estimators are compared using analytic comparison. Signal power estimator can be divided into two types, using channel estimation filter and differential schemes. Signal power estimation using CEF is more accurate than differential scheme in flat fading channel because of finite sample errors and coherent addition. Moreover, signal power estimator considering residual noise can estimate signal power accurately.

However, CEF estimator is vulnerable in severe fading channels, because finite average is not equal to ensemble average in practice, especially on severe fading channels. The channel variation makes many errors in CEF and degrades the performance of the estimator. Therefore, a differential scheme may be better than the above CEF scheme for signal power estimation.

4.4.2 Simulation results

The simulation is conducted based on an IEEE 802.11 WLAN system in frequency selective and fast fading channel. Computer simulation is performed using a MATLAB^{TM} communication toolbox. The simulation shows the mean and standard deviation of SNR estimation. Simulation is conducted in fast fading channel and near-flat fading with 555Hz Doppler frequency and frequency selective channel and moderate speed with 3Hz Doppler frequency.

The system parameters we considered are as follows.

- 2.4GHz carrier frequency, 4μsec symbol time per symbol
- FFT size N= 64, 1/8 cyclic prefix length
- Pilot spacing is 4 (time/frequency)
- Time-frequency domain, 3 Tap filter for channel estimator
- Rayleigh channel using Jakes Doppler model
- Perfect time and frequency sychronization and no inter-symbol interference (ISI)
- 50 times iterations

4.5.2.1 Fast fading channel

SNR estimator performance simulations are conducted in fast fading channel with maximum Doppler shift (f_d) is 555Hz. Path delays and average path gains are 0, 0.02μsec, 0.04μsec(Sec), and 0, -10, -30 (dB). Different signal power estimators and noise power estimator are used which proposed in Chapter 4.1, 4.2, and 4.3 are tested. Figures 4.1, 4.2 and 4.3 show that mean and standard deviations of SNR estimator. The line represents the mean of estimated SNR error and the bar represents standard deviation. A lower mean of

SNR estimation error represents higher accuracy of the estimator. Less standard deviation means a stability of estimator.

According to the simulation result, SNR estimator using differential scheme, Figure 4.2, offers the best in terms of SNR estimation error and standard deviation. The differential estimation error is 5dB less than using the CEF estimator. The Doppler spread affect to the CEF and it increase estimation error. In a fast fading channel, channel is fast changing than slow fading channel. CEF is hard to estimate in fast fading channels because it uses the average between large symbol times. The simulation results show 8dB estimation error in Figure 4.1. Differential estimator is better performance in fast fading channel condition in Figure 4.2. Figure 4.3 shows that, considering residual noise, we can reduce 3dB estimation error. Moreover, a small deviation can be achieved using differential SNR estimator. As a result, differential estimator gives 5 dB better estimation performances in severe fading channels. Considering residual noise gives a 3 dB gain in estimation performance. Removing residual term also reduces standard deviation. Therefore, removing residual noise with fixed value is effective in fast fading channel.

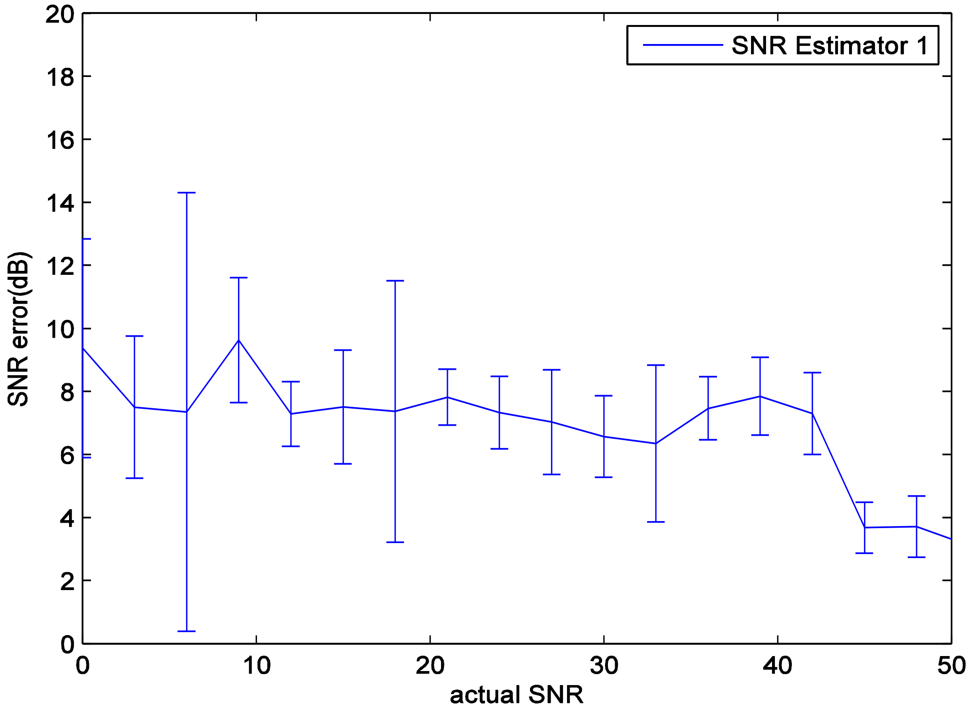

Figure 4.1 SNR estimation error using CEF signal power estimator in fast fading channel.

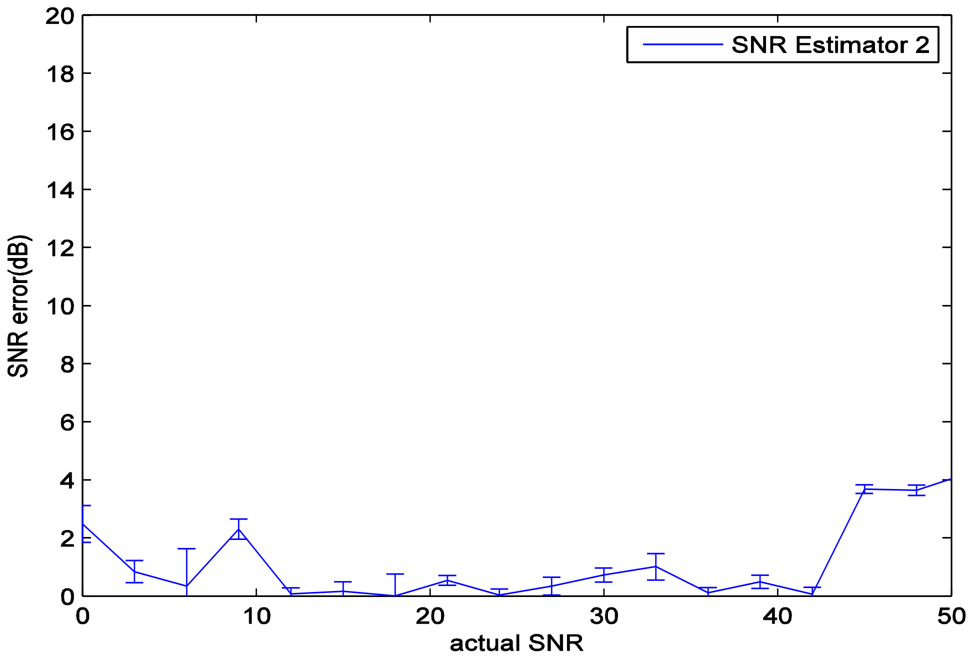

Figure 4.2 SNR estimation error using differential signal power estimator in fast fading channel.

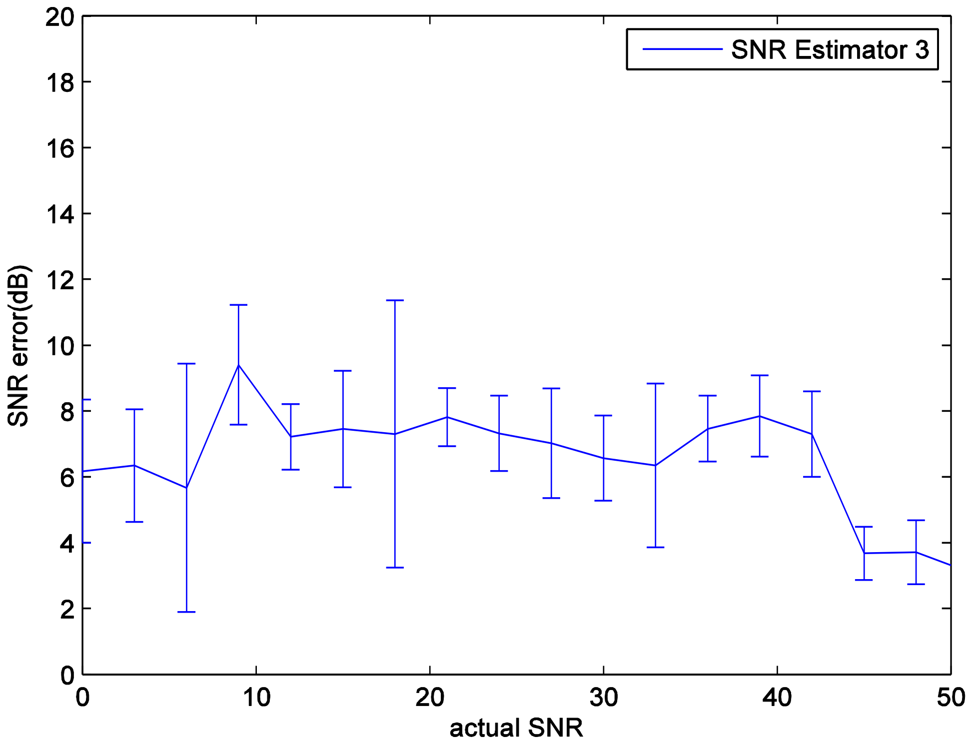

Figure 4.3 SNR estimation error using CEF and residual noise reduction signal power estimator in fast fading channel.

4.5.2.2 Frequency selective channel

Simulations are conducted in a frequency selective channel with 6 ray multi path channel. Multi path delays and path gains are 0 0.02μsec 0.04μsec 0.08μsec 0.25μsec 0.40μsec (delay) and 0, -4, -6, -10, -12, -30 (dB). ISI effects did not occured in the simulation because all multi-paths occurred inside in CP duration.

According to the simulation result, the SNR estimator using differential scheme, provides the best result in terms of SNR estimation error and standard deviation in frequency selective channel. The differential estimation error is 5dB less than using a CEF estimator. The frequency selective channel variation affect to the CEF which increase estimation error. In a frequency selective fading channel, the channel changes more than the flat fading channel in frequency domain. In this situation, CEF is hard to estimate channel variation between frequency symbols. Figure 4.4 show that 9dB error is occurred using CEF estimator. Therefore, differential estimator provides best performance in frequency selective fading channel. From our simulation result, 5dB errors are reduced using differential SNR estimator in Figure 4.5. Considering residual noise estimator reduces 3dB estimation errors than CEF signal power estimator in figure 4.6.

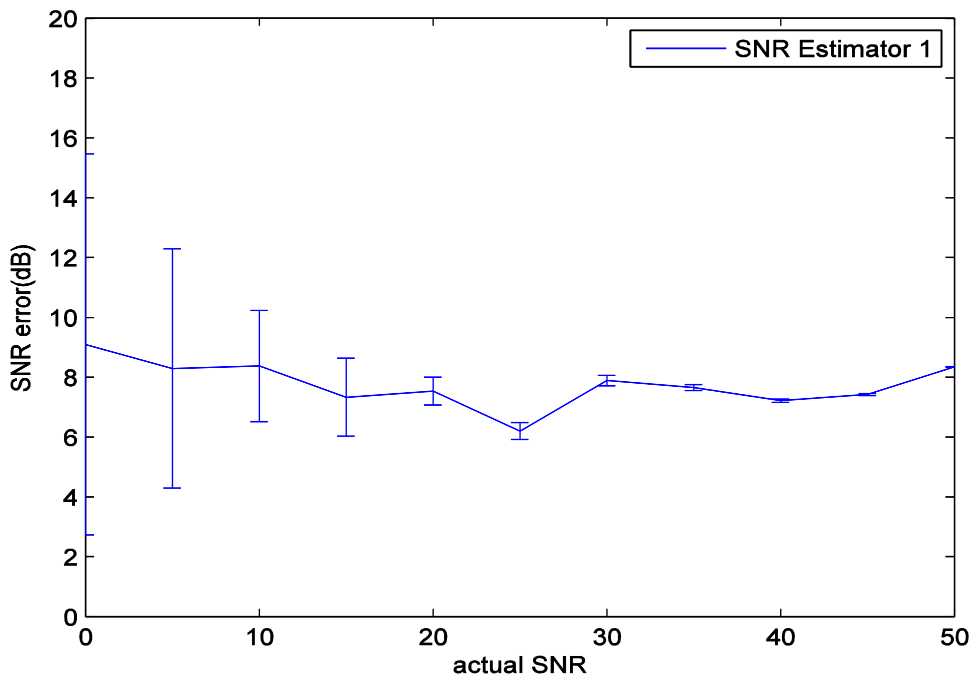

Figure 4.4 SNR estimation error using CEF signal power estimator in frequency selective fading channel.

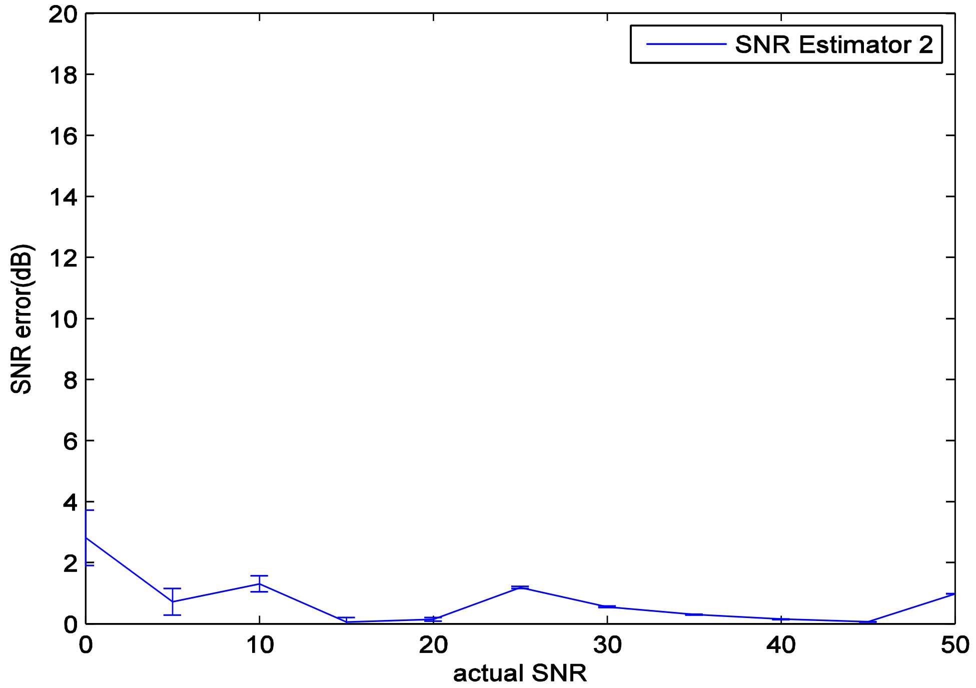

Figure 4.5 SNR estimation error using differential signal power estimator in frequency selective fading channel.

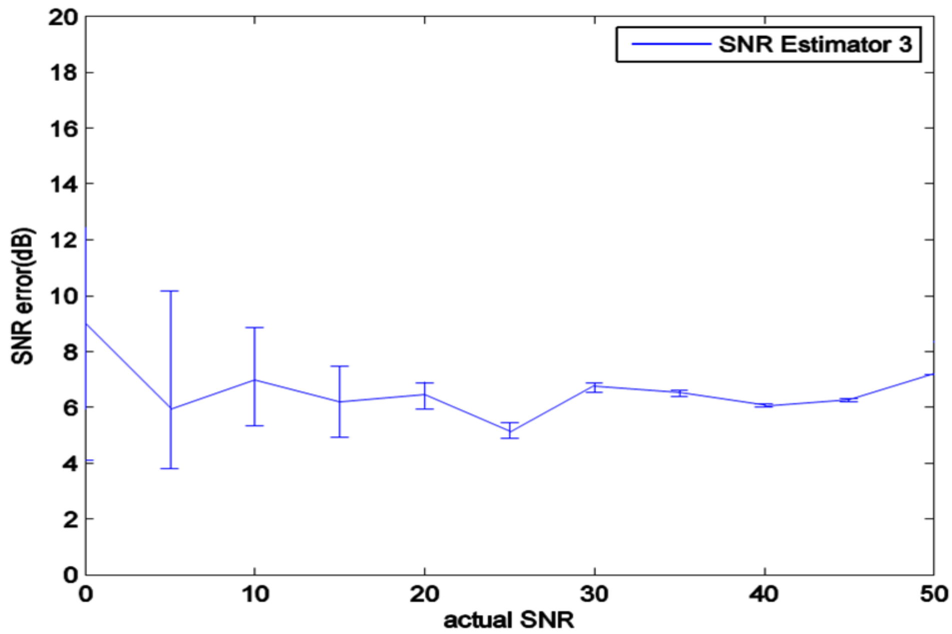

Figure 4.6 SNR estimation error using CEF and residual noise reduction signal power estimator in frequency selective fading channel.

Ⅴ. Proposed SNR estimation techniques in multi dimension domain

Conventional methods usually consider predetermined filters for channel estimation. Noise estimation errors become enormous in conventional methods when the channel varies in time or frequency. The proposed estimation method performs well by choosing a stable domain in the filtering window. The selection of a stable domain using SNR information is proposed.

5.1 Proposed estimation technique

The Direct method uses estimated SNR information, directly by choosing best SNR domain in time, frequency and time-frequency domain.

$$\begin{aligned} &SNR\_est \\ &\quad = \max(SNR\_time\ domain,\ SNR\_freq\ domain) \end{aligned} \tag{5.1}$$

A High SNR means good channel condition compared to the other domain because estimation error is increased by bad channel conditions. The error of SNR estimation can be reduced by choosing a proper domain, which increase errors of the estimator. The proposed scheme is effective to reduce error in a fast-fading channel and a frequency selective channel; whereas time domain method increases estimation error in a fast fading channel and frequency domain method increases estimation error in a frequency selective channel. The simulation result shows that proposed method reduces estimation error.

5.2 Performance of proposed SNR estimation technique

Simulations are conducted in fast fading channel and near-flat fading with 555Hz Doppler frequency and frequency selective channel and moderate speed with 3Hz Doppler frequency. As seen in Figure 5.1 and 5.2, the simulation results show that conventional schemes have enormous errors when channel estimation is performed across severe domain where finding is either fast or highly frequency selective. SNR estimation error increases in fast fading channel in Figure 5.1, whereas the frequency domain estimation error increases in frequency selective fading channel in Figure 5.2. However, if we select flat fading channel or slow fading channel, the result shows that we can reduce the SNR estimation error. If we select the proper domain, we can select flat fading channel or slow fading channel. As a result, we can reduce estimation error domain. We can reduce 5dB error when apply this technique.

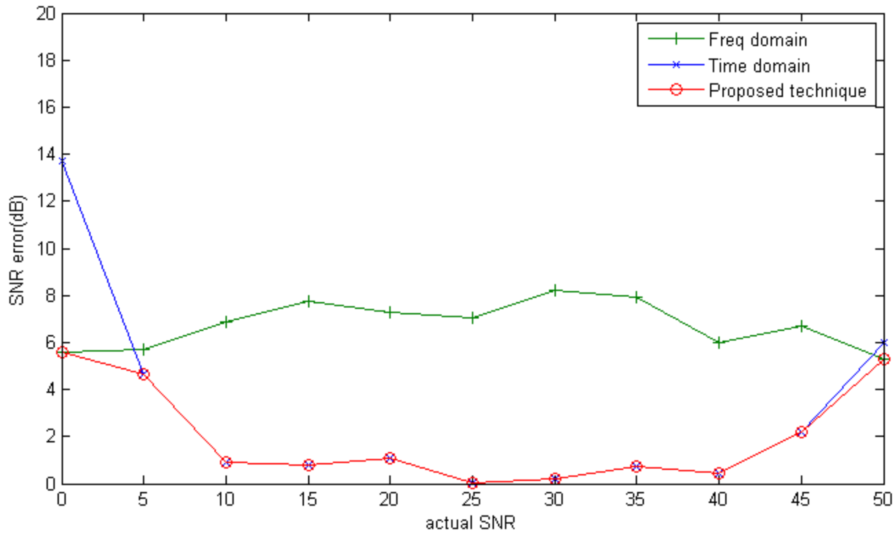

Figure 5.1 SNR estimation error using proposed technique in fast fading channel.

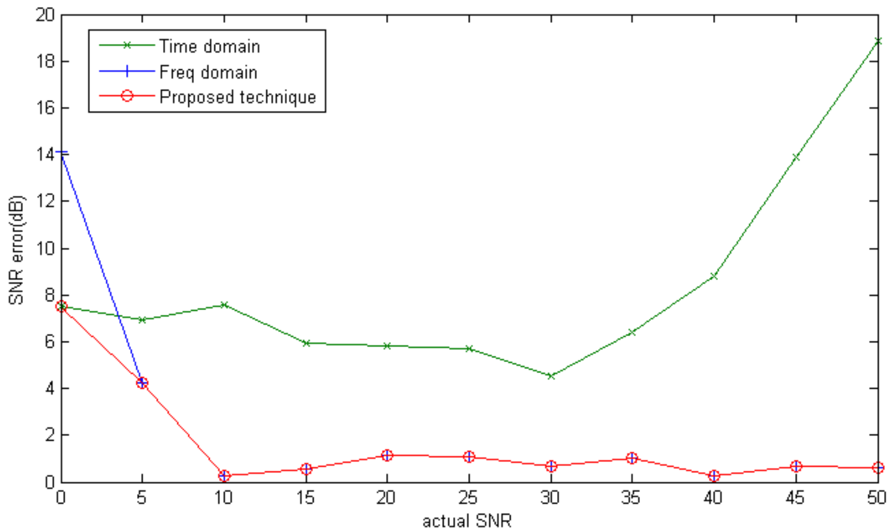

Figure 5.2 SNR estimation error using proposed technique in frequency selective channel.

Ⅵ. Conclusion & Future work

In this paper, efficient SNR estimation schemes are proposed in a severe fading channels, fast fading channel or frequency selective channel for the OFDM system. The proposed three signal power estimator and one noise power estimator are analyzed its performance in fast fading and frequency selective channel. Noise power estimator uses channel estimation filter to estimate noise power. And we proposed three signal power estimators, signal power estimator using CEF, using differential scheme, and using CEF considering residual noise. Differential scheme is more efficient than other schemes in severe fading channel. According the simulation result, we can reduce 5dB SNR estimation error using differential scheme in severe fading channels.

A multi-domain SNR estimation technique is also proposed in Chapter Ⅴ. The estimated SNR would be decreased in a severe fading channels, because channel estimation filter error and channel variation increases noise power. An OFDM system is composed with small symbols along time and frequency domain. Choosing better estimation domain in time, frequency can estimate SNR accurately. The proposed technique uses SNR value to choose in multi domain. A high SNR can be represents the better condition of the channel. According to simulation results, we can reduce errors using the proposed estimation technique in frequency selective of fast fading channel.

The paper result can be applied to fast moving train systems and indoor environments to estimate SNR. SNR is widely used for change modulation order, coding rate, and resource allocation. The proposed SNR estimator and technique in a severe fading channels can be applied in mobile wireless communications.

References

[1] R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications,* Artech House, 2000.
[2] K. Balachandran, S. R. Kadaba, and S. Nanda, "Channel quality estimation and rate adaptation for cellular mobile radio," *IEEE J. Select Areas Commun.,* vol. 17, pp. 1244–1256, Jul, 1999.
[3] A. Wiesel , J. Goldberg and H. Messer–Yaron "SNR estimation in time–varying fading channels", *IEEE Trans. Commun.,* vol. 54, pp.841, May. 2006
[4] D. R. Pauluzzi and N. C. Beaulieu, "A comparison of SNR estimation techniques for the AWGN channel," *IEEE Trans. Commun.,* vol. 48, pp. 681–1691, Oct. 2000.
[5] D. R. Pauluzzi, "Signal–to–noise ratio and signal–to–impairment ratio estimation in AWGN and wireless channels," Ph.D. dissertation, Queen's Univ., Kingston, ON, Canada, Sep. 1997.
[6] H. Xu, G. Wei, and J, Zhu, "A novel SNR estimation algorithm for OFDM," in *Proc. IEEE Vehicular Technology Conf.,* May 2005, pp. 3068-3071.
[7] A. Wiesel, J. Goldberg, and H. Messer–Yaron, "SNR estimation in time varying fading channels," *IEEE Trans. Commun.,* vol. 54, no. 5, pp. 841-848, May 2006.
[8] X. Xu, Y. Jing, and X.Yu, "Subspace–based noise variance and SNR estimation for OFDM systems," in *Proc. IEEE Wireless Commun. Netw. Conf.*, New Orleans, LA, vol. 1, pp. 23-26, Mar. 2005,
[9] T. Y ¨ ucek and H. Arslan, "MMSE noise plus interference power estimation in adaptive OFDM systems," *IEEE Trans. Veh. Technol.,* vol. 56, pp. 3857–3863, Nov. 2007
[10] S.B. Weinstein, "Data transmission by frequency division multiplexing using the discrete fourier transform," *IEEE Trans. Commun. Technol.,* vol. 19, pp. 628–634, Oct. 1971.
[11] N. S. Alagha, "Cramer–Rao bounds for SNR estimates for BPSK and QPSK modulated signals," *IEEE Commun. Lett.*, vol. 5, pp. 10-12, Jan. 2001.
[12] D. N. C. Tse and P. Viswanath, *Fundamentals of Wireless Communications.* Cambridge, U.K.: Cambridge Univ. Press, 2005.
[13] D. Bai, C. Park, J. Lee, H. Nguyen, J. Singh, A. Gupta, Z. Pi,
T. Kim, C. Lim, M. Kim, and I. Kang, "LTE–Advanced modem design: challenges and perspectives," *IEEE Commun. Mag.*, vol. 50, pp. 178–186, Feb. 2012.
[14] Frank Rayal, "LTE in a Nutshell: System Overview," Jun. 2010.

[15] M. Noh, Y. Lee, and H. Park, “Low complexity LMMSE channel estimation for OFDM,” *IEE Proc.−Commun*, vol. 153, no. 5, pp. 645-650, Oct. 2006.
[16] F. Rice, B. Cowley, B. Moran, and M. Rice, "Cramer−Rao lower bounds for QAM phase and frequency estimation," *IEEE Trans. Com−mun*, vol. 49, pp. 1582−1591, Sep. 2001.
[17] R. Matzner, F. Engleberger, and R. Siewert, “Analysis and de−sign of a blind statistical SNR estimator,” in *Proc. AES 102nd Conv.*, Munchen, Germany, Mar. 1997.
[18] J. J. van de Beek, M. Sandell, andP. O. Borjesson, B “ML esti−mation of timing and frequency offset in OFDM systems,” *IEEE Trans. Signal Proc.*, vol. 45, no. 7,pp. 1800-1805, Jul. 1997.
[19] H. Arslan and S. Reddy, “Noise power and SNR estimation for OFDM based wireless communication systems,” in *IASTED Int. Conf. on Wireless and Optical Commu.*, May. 2003.
[20] Yong Soo Cho, Jaekwon Kim, Won Young Yang, Chung G. Kang, *MIMO−OFDM Wireless Communications with MATLAB*, John Wiley & Sons (Asia) Pte Ltd., 2010.
[21] J.−W. Choi and Y.−H. Lee, “Design of a channel−aware OFDM transceiver,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, pp. 1813−1822, May 2007.

요 약 문

OFDM 시스템에서 극한 페이딩 채널 특성에 강인한 향상된 잡음 전력, 신호대 잡음비 추정 기법 연구

본 논문은 OFDM 통신 시스템에서 극한 페이딩 채널 환경 하에서 보다 나은 잡음 전력과 신호대 잡음비 (SNR)을 추정하는 기법을 제안한다. 정확한 잡음 전력과 SNR 값 추정은 통신 시스템 파라메터 설정과 파일럿 선택에 있어서 중요한 파라메터이다. 하지만 극한 페이딩 채널에서는 채널의 변화, 다중 전파 경로 지연, 채널 추정 오차가 극심하므로 정확한 잡음 전력과 SNR 추정이 힘들다.

이를 해결하기 위해서 본 논문에서는 채널 추정 필터를 이용한 잡음 전력 추정기와 채널 추정 필터, 파일럿 사이의 상관 함수 (correlation)를 이용한 신호 전력 추정기를 이용한 SNR 추정기를 제안한다. 기존의 SNR 추정기의 경우에는 신호 혹은 잡음 전력 추정기 하나만을 사용하고, 페이딩 환경에 대한 고려가 적어 오차가 많았다. 본 논문에서는 신호 전력과 잡음 전력을 따로 추정하여 추정 오차의 전파를 막아 보다 정밀한 측정이 가능하였다. 또한 상관함수를 사용한 추정기가 기존의 SNR 추정기보다 5dB 오차를 줄일 수 있었으며, 신호 추정에 따른 잡음 전력 오차를 고려한 추정기를 이용했을 때 3dB 정도의 오차를 줄일 수 있음을 시변 채널 환경과 주파수 선택적 페이딩 환경에서의 시뮬레이션 결과를 통해 알 수 있었다.

또한 OFDM 시스템의 다중 캐리어 특성을 이용하여, 다중 도메인에서의 SNR 값을 추정하고, 이를 비교하여, 적합한 도메인 선택을 통한 오차 감소 기법을 제시하였다. 채널의 변화는 채널 추정 필터나 잡음 전력 추정의 증가를 가져와 실제 SNR 값보다 낮은 SNR 추정치를 만들어 낸다. 이러한 특성을 이용하여 신호, 주파수와 같은 다중 도메인에서 높은 SNR 값을 가지는 도메인을 선택하여 추정함으로써 SNR 추정 오차를 줄일 수 있었다.

본 논문의 결과는 현재 광범위하게 사용되는 LTE, WiMax 등 OFDM 통신시스템에서 적용하여 적합한 SNR 추정을 통한 효율적인 통신 방식에 이용할 수 있다.

핵심어: 신호대 잡음비 추정, 노이즈파워 추정, OFDM 시스템, 페이딩 채널

Acknowledgement

주) * 활자크기 : 제목 14pt, 기타 10pt.(글자체의 크기는 약간씩 조정 가능함)
* 감사의 글 작성은 선택사항임.
☞작성후 주)부분 전부삭제

Curriculum Vitae

Name: Inho Choi

Birth Date: Feb.09.1984

Education

Mar/11 – Feb/13- M.S. in Information and Communication Engineering, DGIST, Daegu, Korea

Mar/02 - Feb/09- B.S. in Electronic, Electrical and Computer Science, KNU, Daegu, Korea

Work Experience

Jan/09 - Feb/11 - Research Engineer, LIG nex1, Avionics R&D Lab, Daejeon, Korea

Professional Activities

Publications

[1] Inho Choi, Jungyeol Kim, Daebeom Seoug, "Switching Mode LED Backlight Luminance Control Circuit for Avionics Display," *ADD 40th Anniversary Conference*, pp 336 – 338 Aug. 2010.

[2] Inho Choi, Ji-Woong Choi, "Improved Noise Power and SNR Estimation using Time & Frequency Fading Characteristics in OFDM Systems," *한국통신학회 하계종합학술발표회*, June. 2012.

[3] Jeong Hee Shin, Jaehan Im, Sang Sik Shin, Inho Choi, Ji-Woong Choi, and Jae Eun Jang, "Asymmetric tunneling metal-insulator-metal diode for high frequency application," *IRMMW2012*, Aug. 2012