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CHANNEL ESTIMATION ALGORITHMS AND BIT ERROR RATE ANALYSIS OF COGNITIVE RADIO

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ABSTRACT

This paper mathematically proposes channel estimation algorithms for Cognitive Radio (CR) in terms of Mean Square Error (MSE) and analysis of its Bit Error Rate (BER) performance. As cognitive radio associates itself with the family of opportunistic communication for using frequency spectrum efficiently, issues such as spectrum sensing and channel estimation gain attention. When the main issue of spectrum sensing is accomplished through different methods, information needs to be transferred in cognitive radio scenario. The issue of channel estimation is important for information transfer and it plays a role in data detection. Channel estimation is addressed in this paper and the channel estimation algorithms proposed for estimating the wireless channel coefficients in a CR scenario are Least Squares (LS) and Linear Minimum Mean Square Error (MMSE) approaches. Though, LS and LMMSE are existing algorithms, there is no such specific research paper which presents simulation results of MSE performance of both the algorithms for Cognitive Radio. Hence, the unique contribution of this research paper is to derive the channel estimation algorithms for estimating wireless channel coefficients, obtain simulation results in terms of MSE performance and use the estimated coefficients in analyzing BER performance of CR environments. Simulation results show that the LMMSE algorithm shows better MSE performance in comparison to LS algorithm in lower signal to noise ratio (SNR) values and same MSE performance in higher signal to noise ratio values. This performance in higher SNR is due to characteristics of the training sequences used for estimation. To verify the correctness of the claims made in this research paper theoretical Mean Square Error performance is derived to validate channel estimation. The results shown in this paper can be helpful for researchers working in the community of Cognitive Radio and can act as platform for many pioneering research works to evolve in near future.

Keywords: cognitive radio, least squares, linear minimum mean square error, mean square error, bit error rate.

1. INTRODUCTION

Software Defined Radio (SDR) [1], [2] and [6] proposed by Joseph Mitola [1]-[7] are defined as low cost, adaptable wireless communication devices operated in real time using a processor or programmable silicon as hardware base and supported by a software architecture [1]. Further research activities done in SDR lead to the birth of Cognitive Radio[3]-[5], [7] and [10] which are SDR's possessing the ability to sense the environment, making decisions unanimously without any other equipment involvement [2], [5] and [6]. Due to the sensing abilities of cognitive radio, it can change the modulation techniques which lead to efficient communication between a transmitter and a receiver, thereby resulting in an increase in efficient usage of spectrum. Transmitter and receiver of a cognitive radio has a RF section at front end and baseband section at the backend comprising of analog to digital, digital to analog converters, signal generation and signal detection circuitry[6]. Thus CR can be a possible solution to accommodate various developing and forthcoming applications in a heavily occupied spectrum [7].

However, certain issues need to be taken care for successful operation of CR. They are radio based analysis, channel identification; transmit power control and dynamic spectrum management [8] and [9]. Radio based analysis is to determine interference temperature of radio and spot free places in the spectrum. Channel identification identifies channel coefficients in a CR scenario, aids in data detection and predicts capacity of the channel for the transmitter. Minimization of signal to noise at the transmitter and management of the available spectrum efficiently is another issue of importance [9]. Moreover, spectrum management, spectrum sensing, spectrum mobility and spectrum sharing are the other functions of CR systems which gain importance [11].

Though spectrum sensing is the primary issue of importance in CR scenario, it can be done by various methods such as energy detector methods, waveform based methods, cyclostationary methods and by the use of matched filters [12]. After spectrum sensing is done in CR through any one of the above enlisted methods, information needs to be transferred through a wireless channel. Considering this aspect of information transfer, this paper resorts to channel estimation of cognitive radio channels for information transfer between users, irrespective of primary or licensed users and secondary or unlicensed users [13]-[18]. Basically, channel estimation is used for data detection in a CR system for effective information transfer between a transmitter and a receiver.
Research literatures from [13]-[18] present various channel estimation approaches for different cognitive radio scenarios. A linear minimum mean square error algorithm based estimation of cognitive radio channels is analyzed in [13] along with its bit error rate analysis. Considering sensing functionalities, channel estimation is performed for a Bayesian network along with its channel capacity [14]. Channel estimation in cognitive radio systems using orthogonal frequency division multiplexing (OFDM) is done in [15] where it uses pilot signals. In [16]

ARPN Journal of Engineering and Applied Sciences

minimum mean square error (MMSE) approach and its variants are used to estimate channel impulse response for cognitive radio systems by taking into account estimation errors. Channel estimation for OFDM based cognitive radio systems utilizing cross entropy optimization, analytical pilot power distribution technique to design pilot symbols for minimizing mean square error is shown in [17]. [18] analyzes causal channel estimation methods for wireless cognitive channels with imperfections in channel sensing and correlation.

All the research works reported so far from [13]-[18] dealt with MMSE estimators and its variants but did not provide a complete mathematical derivation of the estimator, nor simulation results to assess LS, LMMSE performance and did not verify the correctness by providing a theoretical MSE to support the simulation results. Hence, this paper derives least squares algorithm and linear minimum mean square error algorithm to estimate wireless channel coefficients in a CR scenario. Further theoretical MSE performance of LS and LMMSE estimators are derived. Based on the obtained simulation results in terms of mean square error, bit error rate analysis using the estimated coefficients is also obtained so as to analyze the impact of estimated channel values in data detection in CR systems.

In this paper section I presents introduction about cognitive radio and the research works carried out related to channel estimation of CR links. Section II mathematically portrays system model of a cognitive radio scenario. Section III presents channel estimation algorithm using Least Squares estimator and Linear Minimum Mean Square Error Estimators. Section IV presents maximum likelihood decoding of CR system for bit error rate analysis. Section V presents simulation results in terms of mean square error and bit error rate and section VI concludes the paper.

Notations and representations: Vectors and scalars are represented as bold face small case and small case respectively. +, *, H, ^ and $\left|\ \right|$ represents the pseudo inverse, conjugate, Hermitian, estimate and norm of the respective elements. Trace of matrix is given by tr{ } and $N\left(\mu,\sigma^2\right)$ represents a normally distributed random variable with mean μ and variance σ^2.

2. SYSTEM MODEL FOR COGNITIVE RADIO

Consider a cognitive radio system model which comprises of a primary transmitter and a primary receiver forming the licensed link and the secondary transmitter and secondary receiver forming the unlicensed link. All the terminals in the CR links are equipped with a single antenna. The wireless channel g_{co} is a circularly symmetric complex Gaussian random variable and it is a Rayleigh flat fading channel where the channel is assumed to be constant for s symbol transmission. Also, the channel values are independent identically distributed (iid) during channel transmissions [13]. When a $s\times 1$ data symbol vector s is transmitted from the secondary transmitter to the primary receiver the $s\times 1$ received signal vector $\mathbf{r}_{co}$ is expressed as

$$\mathbf{r}_{co}=\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{s}+\mathbf{n}_{co} \tag{1}$$

where n_{co} is $s\times 1$ circularly symmetric complex Gaussian noise vector with $N\left(\mu,\sigma^2\right)$ having mean μ and σ^2 is unit variance, with average power constraint $E\left[\left|\mathbf{s}\right|^2\right]\leq 1$ and $\sqrt{\frac{S_i}{N_i}}$ is signal to noise Ratio (SNR) where S_i is the transmitted signal power and N_i represents the noise power.

3. CHANNEL ESTIMATION ALGORITHMS FOR COGNITIVE RADIO

The commonly available algorithms for estimation of wireless channel coefficients in a CR scenario are Least Squares algorithm and Linear Minimum Mean Square Error algorithm.

A. Least Squares (LS) algorithm

To estimate the wireless channel coefficients between a secondary transmitter and a primary receiver using least squares algorithm [19], it is necessary to transmit a known training sequence vector t of length of $t\times 1$ from secondary transmitter to the primary receiver. The $t\times 1$ received signal vector $\mathbf{r}_{co}$ at the primary receiver takes the form as

$$\mathbf{r}_{co}=\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{t}+\mathbf{n}_{co} \tag{2}$$

where $\sqrt{\frac{S_i}{N_i}}$ is SNR, t is the $t\times 1$ training signal vector and n_{co} is the $t\times 1$ noise vector at the primary receiver. To derive the LS estimate [19] for $t\times 1$ received signal vector in (2), consider the objective function Q to determine the scalar channel coefficient g_{co}. To derive the estimate consider Q to be the objective function

$$Q=\left(\mathbf{r}_{co}-\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{t}\right)^2 \tag{3}$$

Now, partially differentiating (3) with respect to g_{co} it results in

$$\frac{\partial Q}{\partial g_{co}}=2\left(\mathbf{r}_{co}-\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{t}\right)\left(-\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right) \tag{4}$$

ARPN Journal of Engineering and Applied Sciences

Equating the resultant to the least value which is zero in (4) it is rewritten as

$$0 = 2\left(\mathbf{r}_{co} - \sqrt{\frac{S_i}{N_i}}\hat{g}_{coLS}\mathbf{t}\right)\left(-\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right) \quad (5)$$

Further (5) is rearranged and it is given as

$$0 = \mathbf{r}_{co} - \sqrt{\frac{S_i}{N_i}}\hat{g}_{coLS}\mathbf{t} \quad (6)$$

Further rearranging (6) it results in the LS estimator as given by (7) and (8)

$$0 + \sqrt{\frac{S_i}{N_i}}\hat{g}_{coLS}\mathbf{t} = \mathbf{r}_{co} \quad (7)$$

$$\hat{g}_{coLS} = \mathbf{r}_{co}\frac{1}{\sqrt{\frac{S_i}{N_i}}\mathbf{t}} \quad (8)$$

The LS estimate [19] of g_{co} is determined as

$$\hat{g}_{coLS} = \left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\mathbf{r}_{co} \quad (9)$$

To verify the correctness of the derived estimator in (9) theoretical Mean Square Error (MSE) performance needs to be derived. To derive theoretical MSE of Least Squares (LS) estimation algorithm consider

$$MSE_{LS} = tr\left\{E\left\{(g_{co} - \hat{g}_{coLS})(g - \hat{g}_{coLS})^{H}\right\}\right\} \quad (10)$$

Considering (9) and replacing (2) in (9) it is given as

$$\hat{g}_{coLS} = \left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\left(\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{t} + \mathbf{n}_{co}\right) \quad (11)$$

Further (11) is expanded as

$$\hat{g}_{coLS} = \left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\sqrt{\frac{S_i}{N_i}}g_{co}\mathbf{t} + \left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\mathbf{n}_{co} \quad (12)$$

Where the second term in (12) constitutes noise and the error $e = (g_{co} - \hat{g}_{coLS})$ is given as

$$e_{LS} = \left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\mathbf{n} \quad (13)$$

Now considering (10), MSE in terms of error is given as

$$MSE_{LS} = tr\left\{E\left\{ee^{H}\right\}\right\} \quad (14)$$

$$MSE_{LS} = tr\left\{E\left\{\left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\mathbf{n}\left(\left(\sqrt{\frac{S_i}{N_i}}\mathbf{t}\right)^{+}\mathbf{n}\right)^{H}\right\}\right\} \quad (15)$$

B. Linear Minimum Mean Square Error (LMMSE) algorithm

To derive the linear minimum mean square error estimation algorithm for cognitive radio scenario consider the optimization for $\hat{g}_{co} = \mathbf{b}^{H}\mathbf{r}_{co}$ where $\hat{g}_{co}$ is the estimated value of g_{co} and error is given as $e = g_{co} - \hat{g}_{co}$. The optimization problem is given as

$$\min_{c} E[ee^{*}] = \min_{c} E[(g_{co} - \mathbf{b}^{H}\mathbf{r}_{co})(g_{co} - \mathbf{b}^{H}\mathbf{r}_{co})^{*}] \quad (16)$$

To obtain the solution for the problem in (16) expanding it as

$$\min_{c} E\begin{bmatrix}[g_{co}g_{co}^{*}] - \left[g_{co}\mathbf{b}^{H}\mathbf{r}_{co}^{H}\right] - [\mathbf{b}^{H}\mathbf{r}_{co}g_{co}^{*}] - \\ [\mathbf{b}^{H}\mathbf{r}_{co}\mathbf{b}^{H}\mathbf{r}_{co}^{*}]\end{bmatrix} \quad (17)$$

where the first term in the expression in (17) is given as

$$E[g_{co}g_{co}^{*}] = \gamma_{gg} \quad (18)$$

where γ_{gg} represents the correlation between the wireless channel coefficients. Similarly, the second term is expanded

as $E[g_{co}\mathbf{b}^{H}\mathbf{r}_{co}^{*}] = E[g_{co}(\sqrt{\frac{S_i}{N_i}}\; g_{co}\mathbf{t} + \mathbf{n}_{co})^{*}\mathbf{b}^{H^{*}}]$ and it is found to be

$$E[\mathbf{b}^{H}\mathbf{r}_{co}^{*}g_{co}] = \sqrt{\frac{S_i}{N_i}}\mathbf{t}^{*}E[g_{co}g_{co}^{*}]\mathbf{b}^{H^{*}} \quad (19)$$

Further, the third term in the expression in (16) is $E[\mathbf{b}^{H}\mathbf{r}_{co}g_{co}] = E[g_{co}^{*}(\sqrt{\frac{S_i}{N_i}}\; g_{co}\mathbf{t} + n_{co})\mathbf{b}^{H}]$ and it reaches to

$$E[\mathbf{r}_{co}g_{co}^{*}\mathbf{b}^{H}] = \sqrt{\frac{S_i}{N_i}}\mathbf{t}E[g_{co}g_{co}^{*}]\mathbf{b}^{H} \quad (20)$$

Finally, the fourth term in the expression is

$$E[\mathbf{b}^H \mathbf{r}_{co} \mathbf{b}^H \mathbf{r}_{co}^*] = E[\mathbf{b}^H (\sqrt{\frac{S_i}{N_i}}\, g_{co}\mathbf{t} + \mathbf{n}_{co})\mathbf{b}^{H^*} (\sqrt{\frac{S_i}{N_i}}\, g_{co}\mathbf{t} + \mathbf{n}_{co})^*] \quad (21)$$

On further simplification of (20) it is

$$E[\mathbf{b}^H \mathbf{r}_{co} \mathbf{b}^{H^*} \mathbf{r}_{co}^*] = \mathbf{b}^H \frac{S_i}{N_i}\mathbf{t}E[g_{co} g_{co}^*]\mathbf{t}^* \mathbf{b}^{H^*} + \mathbf{b}^H E[n_{co} n_{co}^*]\,\mathbf{b}^{H^*} \quad (22)$$

Now substituting (18), (19), (20) and (22) it results in the intermediate function specified by J

$$J = \gamma_{gg}^* - \sqrt{\frac{S_i}{N_i}}\, E[g_{co} g_{co}^*]\mathbf{t}^* \mathbf{b}^H - \mathbf{b}^H \sqrt{\frac{S_i}{N_i}}\mathbf{t}E[g_{co} g_{co}^*] - \frac{S_i}{N_i}\mathbf{b}^H \mathbf{t}E[g_{co} g_{co}^*]\mathbf{t}^* \mathbf{b}^H + \mathbf{b}^H E[\mathbf{n}_{co} \mathbf{n}_{co}^*]\mathbf{b}^H \quad (23)$$

Now (23) is further rewritten as

$$J = \gamma_{gg} - \sqrt{\frac{S_i}{N_i}}\, \gamma_{gg}\mathbf{t}^* \mathbf{b}^H - \mathbf{b}^H \mathbf{t}\sqrt{\frac{S_i}{N_i}}\gamma_{gg} - \mathbf{b}^H [\frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^* + \sigma_n^2 \gamma_{nn}]\,\mathbf{b}^H \quad (24)$$

Now partially differentiating (24) with respect to $\mathbf{b}^H$ it results in

$$\frac{\partial J}{\partial \mathbf{b}^H} = 0 - \sqrt{\frac{S_i}{N_i}}\, \gamma_{gg}\mathbf{t}^* - \mathbf{t}\sqrt{\frac{S_i}{N_i}}\gamma_{gg} + 2[\frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^* + \sigma_n^2 \gamma_{nn}]\mathbf{b}^H \quad (25)$$

On further rearranging (25) to find the parameter $\mathbf{b}^H$ it is given by (27)

$$\sqrt{\frac{S_i}{N_i}}\, \gamma_{gg}\mathbf{t}^* = [\frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^* + \sigma_n^2 \gamma_{nn}]\mathbf{b}^{\mathbf{H}} \quad (26)$$

$$\mathbf{b}^H = \frac{\sqrt{\frac{S_i}{N_i}}\, \gamma_{gg}\mathbf{t}^*}{[\frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^* + \sigma_n^2 \gamma_{nn}]} \quad (27)$$

Where σ_n^2 is noise variance and γ_{nn} is the noise correlation. Now substituting (27) in $\hat{g}_{co} = \mathbf{b}^H \mathbf{r}_{co}$, the linear minimum mean square error estimator is given by (29)

$$\hat{g}_{coLMMSE} = \frac{\sqrt{\frac{S_i}{N_i}}\, \gamma_{gg}\mathbf{t}^*}{(\frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^* + \sigma_n^2 \gamma_{nn})} r_{co} \quad (28)$$

$$\hat{g}_{coLMMSE} = \frac{\sqrt{\frac{S_i}{N_i}}\gamma_{gg}\mathbf{t}^*}{\left(1 + \frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^*\right)} r_{co} \quad (29)$$

Also, to verify the correctness of the derived estimator in (29) theoretical MSE performance needs to be derived. Following similar procedure as that with MSE_{LS}, MSE of Linear Minimum Mean Square Error (LMMSE) estimation algorithm is defined as

$$MSE_{LMMSE} = tr\left\{E\left\{(g_{co} - \hat{g}_{coLMMSE})(g - \hat{g}_{coLMMSE})^H\right\}\right\} \quad (30)$$

The error value e_{LMMSE} is found to be as

$$e_{LMMSE} = \frac{\sqrt{\frac{S_i}{N_i}}\gamma_{gg}\mathbf{t}^* n_{co}}{\left(1 + \frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^*\right)} \quad (31)$$

Further considering (31), MSE in terms of error is found to be given by (33)

$$MSE_{LS} = tr\left\{E\left\{e_{LMMSE}\, e_{LMMSE}{}^H\right\}\right\} \quad (32)$$

$$MSE_{LS} = tr\left\{E\left\{\left(\frac{\sqrt{\frac{S_i}{N_i}}\gamma_{gg}\mathbf{t}^* n_{co}}{\left(1 + \frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^*\right)}\right)\left(\frac{\sqrt{\frac{S_i}{N_i}}\gamma_{gg}\mathbf{t}^* n_{co}}{\left(1 + \frac{S_i}{N_i}\mathbf{t}\gamma_{gg}\mathbf{t}^*\right)}\right)^H\right\}\right\} \quad (33)$$

4. MAXIMUM LIKILIHOOD BASED DECODING OF COGNITIVE RADIO SYSTEM

To analyze the bit error rate performance of a cognitive radio system, consider the received signal as given in (1). Using Binary Phase Shift Keying (BPSK), modulation technique the maximum likelihood (ML) decision rule at the receiver for a received signal is to select signal d_i [20] iff

$$v^2(r_{Ray0}, g_{Ray0}s_i) + v^2(r_{Ray1}, g_{Ray1}s_i) \le vv^2(r_{Ray0}, g_{Ray0}s_k) + v^2(r_{Ray1}, g_{Ray1}s_k), \qquad \forall i \ne k \quad (34)$$

where $v^2(a,b)$ is the squared Euclidean distance [13] between *a* and *b* calculated by the following expression

ARPN Journal of Engineering and Applied Sciences

$v^2(a,b)=(a-b)(a^*-b^*)$, r_{Ray0} is the received signal passed through Rayleigh flat fading channel [20]. For a BPSK based cognitive radio system the decision rule for deciding the transmitted symbol s_0, for either +1 or -1 is to select s_i if

$$v^2(\tilde{r}_{Ray0}, s_i) \le v^2(\tilde{r}_{Ray0}, s_k); \quad \forall i \neq k. \tag{35}$$

Similarly, for the other symbol s_1, decision rule is to select signal s_i when

$$v^2(\tilde{r}_{Ray1}, s_i) \le v^2(\tilde{r}_{Ray1}, \tilde{s}_k), \qquad \forall i \neq k \tag{36}$$

ML decoding performed for a CR system takes into the channel impulse response in the given CR system model in (2) where it is estimated by using a training sequence transmitted from the secondary transmitter to the primary receiver. The training sequence considered in this paper is Zadoff-Chu sequence [21] which is defined mathematically by the expression

$$z(n)=\begin{cases} e^{-j\frac{\pi Qn(n+2q)}{N}} & ;n=01,2....N-1; \quad N \text{ is even} \\ e^{-j\frac{\pi Qn(n+1+2q)}{N}} & ;n=01,2....N-1; \quad N \text{ is odd} \end{cases} \tag{37}$$

where q and Q are integers in which Q is relatively prime to N. Zadoff Chu (ZC) training sequences have very good autocorrelation and periodicity properties [21]. Using the derived LS and LMMSE estimator as given by (9) and (29) the bit error rate performance analysis is found by using ML decoding [22] which is represented as

$$\arg\max P(\mathbf{r}_{co}/\mathbf{s}_k) = \arg\min_{\mathbf{s}_k} \left\| \mathbf{r}_{co} - \sqrt{\frac{S_i}{N_i}} \hat{g}_{co}\mathbf{s} \right\|^2 \tag{38}$$

5. SIMULATION RESULTS

In this section, mean square error against signal to noise ratio performance and bit error rate against signal to noise ratio performance of a cognitive radio system comprising of a secondary transmitter and receiver is analyzed. Wireless channel coefficient g_{co} and noise at the primary receiver are considered as independent identically distributed (i.i.d) complex Gaussian random variables. Signal to noise ratio is $\frac{S_i}{N_i}$.

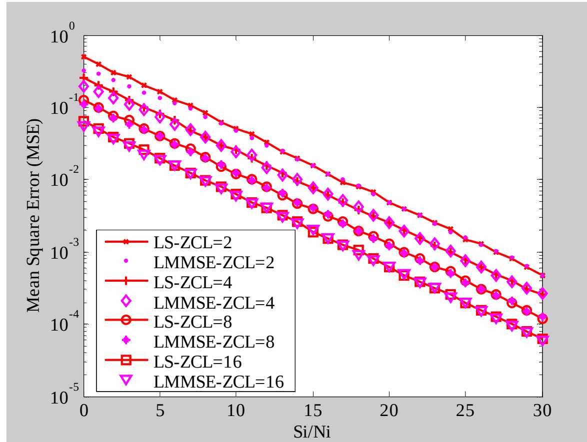

Figure-1. MSE vs SNR performance of LS and LMMSE algorithm for different training sequence lengths.

Figure-1, shows the MSE performance of Least Squares (LS) algorithm and Linear Minimum Mean Square Error (LMMSE) algorithm for various training signal lengths of L=2, 4, 8 and 16 using Zadoff-Chu (ZC) sequences [21]. When training signal length increases mean square error decreases for increased signal to noise ratio values. To achieve a mean square error value of 10^{-1} training signal length of 2 takes greater than 7dB for LS algorithm, and less than 7dB for LMMSE algorithm. However, as SNR increases LS and LMMSE show similar performance which is due to characteristics of training sequences used for estimation. Also, increase in length of training sequence also attributes to improved performance. This shows the importance in increasing the length of the training sequences.

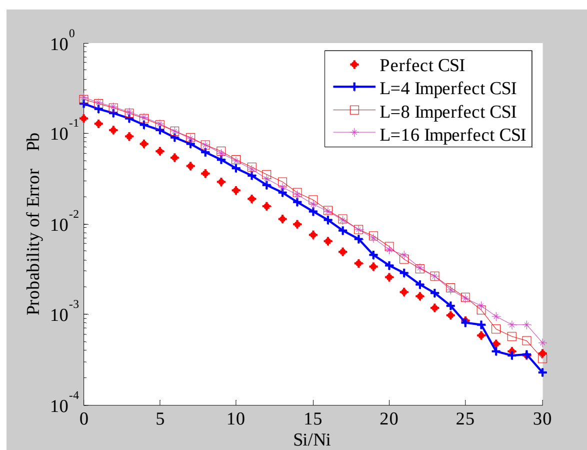

Figure-2. Bit Error Rate vs Signal to Noise Ratio performance of Least Squares algorithm for perfect CSI and imperfect CSI.

Figure-2, shows the bit error rate performance under imperfect channel state information and perfect channel state information using least squares algorithm for various training signal lengths for L=4,8 and 16 using

Zadoff Chu sequences. To obtain a bit error rate of 10^{-2} a length 4, Zadoff Chu sequence requires 17 dB, while length 8 sequence requires 19 dB and length 16 sequence takes greater than 19 dB. Thereby, increasing the length of training sequence increases bit error rate as signal to noise ratio value is very less. However, on increasing the signal to noise ratio the bit error rate reduces which is obvious due to the impact created by SNR value which in turn analyzes the performance of a cognitive radio system. Perfect CSI is also shown here for reference. The MSE and BER simulation parameters are summarized in Table-1. Similarly LMMSE performance can also be analyzed in the same fashion from Figure-2.

Table-1. MSE and BER analysis.

Simulation parameters	Simulation values
Information bits	1000 bits
Estimation algorithm	Least Squares (LS) Linear Minimum Mean Square Error (LMMSE)
BER analysis MSE analysis modulation scheme	Binary phase shift keying
Monte Carlo simulations	1000 runs
Cognitive radio channel	Rayleigh flat fading channel

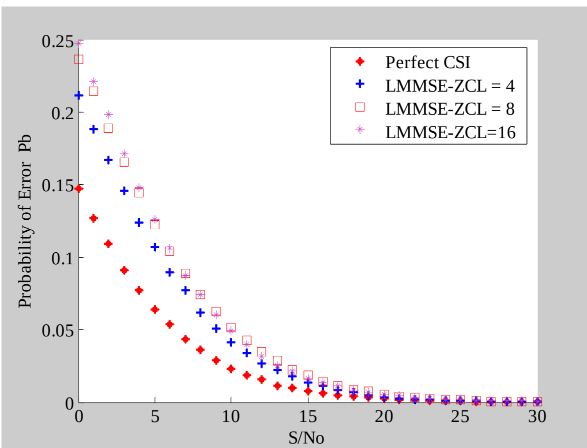

Figure-3. Probability of Error vs Signal to Noise Ratio performance of LMMSE algorithm for perfect CSI and imperfect CSI.

CONCLUSIONS

In this paper channel estimation algorithms and bit error rate performance analysis is done for cognitive radio LMMSE algorithms shows better MSE performance in comparison to LS algorithm in lower SNR values and the performance are equal in high SNR ranges which is due to characteristics exhibited by training signals used for estimation. Bit error rate performance also shows the impact of estimated channel coefficients on the CR system. The obtained simulation results and derived mathematical representations will aid researchers working in the field of cognitive radios.

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