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A Partially Coherent Detector for OFDM MFSK system in Rapidly Time Varying Channels

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ABSTRACT

In this paper, a partially coherent detector is proposed to improve the performance of Orthogonal Frequency Division Multiplexing (OFDM) Multi-frequency shift keying (MFSK) system in high speed mobile communication environment where the channel changes very quickly. The proposed detection is deduced under maximum likelihood rule and an autoregressive channel model. The maximum likelihood (ML) of partially coherent OFDM-MFSK leads to be a linear combination of coherent and non-coherent detection. Simulation results show that partially coherent detector can achieve a significant performance improvement compared with the coherent and non-coherent detector in time fast fading channel. And the partially coherent detector is robust to Doppler shift. The improvement of the performance is contributed by using the partial channel knowledge.

Keywords: Rapidly varying channels, partially coherent, OFDM MFSK, ML rule.

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1. INTRODUCTION

Wireless channel is subject to rapidly time varying in high speed mobile scenarios, such as high speed trains, aircrafts, etc. The characteristics of channel show time selective fading and frequency selective fading [1-4]. The time selective fading is due to Doppler shift which caused by very high speed movement between the transmitter and receiver. The frequency selective fading is induced by multipath propagating of radio waves for the reflections at buildings or hills around the transceiver. So it is difficult but also a great potential market to provide a high quality broadband wireless access service for thousands of passengers on high speed moving vehicles.

OFDM has been the backbone of modern broadband wireless transmission due to its high spectrum efficiency and strong ability of anti-multipath [5]. There are two kinds of detecting methods for OFDM signals at the receiver. One is coherent detection. The coherent detection can achieve good performance by using perfect channel information to compensate for distortions of received signals. The coherent detection is typically applied to OFDM-QAM scheme which combine OFDM and quadrature amplitude modulation (QAM), OFDM-PSK scheme which combines OFDM and Phase Shift Keying (PSK). The other method is non-coherent detection. The non-coherent detection can demodulate the received signals without the channel information by applying an appropriate modulation scheme for transmitter. Compared with the non-coherent detection, coherent detection with accurate channel information can achieve 3-4 dB gains in signal-to-noise ratio (SNR). However, in rapidly time varying channel, it is hardly to get the accurate channel information by employing a channel estimating algorithm. So the non-coherent detection is more suitable for high speed mobile scenarios than coherent detection. And it is valuable to improve the SNR performance of non-coherent detection.

OFDM-MFSK which can be detected non-coherently was proposed by WETZ for high speed mobile scenarios in [6-7]. It is an association of MFSK and OFDM. The subcarriers of an OFDM symbol is divided into several groups, and MFSK modulation scheme is applied to each of these groups. A simple non-coherent receiving structure which does not need equalization and channel estimation is adopted to perform the demodulation. The OFDM-MFSK can take advantages of both OFDM and MFSK. It shows strong ability of anti-multipath and robustness for Doppler spreads. However, higher SNR is needed for non-coherent detection of OFDM-MFSK to maintain the detection performance.

The performance of non-coherent detection for OFDM-MFSK can be improved by iterative detection [8-9]. The results show that an improvement in the order of 1dB can be achieved compared to a conventional detector. Though the channel state changed very quickly in a rapidly varying channel, it is possible to get partial channel information, and partially coherent detection which is a combination of coherent and non-coherent detection can be performed. A partially coherent detector for single carrier system was proposed in [10]. The simulation indicates that partially detection outperforms both coherent detection and non-coherent detection. The gain achieved from the partial channel information is at most 1dB at low SNR range.

In this paper, we consider partially coherent detection for multi-carrier systems in the environment of rapidly time varying multi-path Rayleigh channel. Based on ML rule, we construct a partial coherent detector for OFDM-MFSK. The partial coherent detector results in a combination of coherent detection and no-coherent detection. Simulation shows that the performance of partially detection is close to coherent detection under poor SNRs and non-coherent at a high SNR. The basic system model and modulation technology are described in Section II and Section III. The partially coherent detection technology is explained in Section IV. Simulation of the technology is given in Section V and we will analyze the simulation results.

2. SYSTEM MODEL

For OFDM system, the relationship between input and output can be written as the following matrix form [12]

$$y(k') = \sum_{k=-\infty}^{\infty} FG_{rp}H(k,k')G_{ap}F^{-1}x(k'-k) + n(k') \tag{1}$$

Where, F is the matrix of Fourier transforms, $G_{rp}=(0_{N\times N_G}\quad I_N)$ is the matrix using to remove cyclic prefix, $H(k,k')$ is the matrix of multipath time delay channels, $G_{ap}=\begin{pmatrix}0_{N\times(N-N_G)} & I_{N_G}\\ \multicolumn{2}{c}{I_N}\end{pmatrix}$ is the matrix using to add cyclic prefix, $n(k')$ is a vector of White Gaussian noise. When a cyclic prefix meets $L-1\le N_G$, (1) can be simplified to a matrix product

$$y(k') = FG_{rp}H(0,k')G_{ap}F^{-1}x(k') + n(k') \tag{2}$$

Defining

$$H_{OFDM}(k') = FG_{rp}H(0,k')G_{ap}F^{-1} \tag{3}$$

For time-varying channel, the channel matrix can be expressed as follows

$$[H_{OFDM}(k')]_{m,n} = \frac{1}{N}\sum_{p=0}^{N-1}\sum_{l=0}^{L-1} h(l,p+N_G+k'(N+N_G))e^{-j\frac{2\pi}{N}(n-1)l}e^{j\frac{2\pi}{N}p(n-m)} \tag{4}$$

Where $h(l,p)$ means a channel with p seconds delay, and then the whole OFDM system can be modeled as follows

$$[y(k')]_m = [H_{OFDM}(k')]_{m,m}[x(k')]_m + \sum_{\substack{n=1\\ n\ne m}}^{N}[H_{OFDM}(k')]_{m,n}[x(k')]_n + [n(k')]_m \tag{5}$$

From the first-order autoregressive equation [13], $h(l,p)$ can be modeled as a form of autoregressive equation

$$h(l,p) = ah(l,p-1) + \sqrt{1-a^2}\,w(l,p) \tag{6}$$

Where $a = J_0(2\pi f_d T_s)$, $J_0(x)$ is the zeroth order Bessel function of the first kind, $f_d = \frac{f_c v}{c} = \frac{v}{\lambda}$ is Doppler frequency offset, T_s is the symbol interval of OFDM, $w(l,p)$ is an independent identically distributed random process with the density function $CN(0,\sigma_h^2)$. We can get

$$\widehat{h}(l,p) \sim CN(a^p h(l,0), 1-a^{2p}) \tag{7}$$

If N is large enough, according to the central limit theorem, $[H_{OFDM}(k')]_{m,m}$ in (5) has a Gauss distribution with probability density function $CN(a^{k'(N+N_G)}H_{OFDM}(0), 1-a^{2k'(N+N_G)})$, and $\sum_{\substack{n=1\\ n\ne m}}^{N}[H_{OFDM}(k')]_{m,n}[x(k')]_n + [n(k')]_m$ in (5) also has a Gauss distribution [14], assuming its probability density function is $CN(\mu,\sigma_H^2)$. We define

$H = H_{OFDM}(k^{'})$ for later discussion. Further, we define $W(k^{'}) = \sum_{\substack{n=1 \\ n\neq m}}^{N} [H_{OFDM}(k^{'})]_{m,n}[x(k^{'})]_n + [n(k^{'})]_m$, and the formulate (5) can be written in matrix form

$$Y = HX + W \tag{8}$$

Where Y is the output vector of size $N \times 1$, X is the input vector of size $N \times 1$, H is the diagonal matrix of channel of size $N \times N$ and W is the noise vector of size $N \times 1$.

3. OFDM-MFSK MODULATION SCHEME

OFDM-*M*FSK [15] is a kind of modulation combining OFDM and *M*FSK. It splits the N OFDM subcarriers into groups of M and transmit information by assigning energy to one of the M subcarriers while leaving other $M-1$ subcarriers empty. Its schematic diagram is shown in figure 1. In this paper, we will take $M=2$ as an example. The OFDM subcarriers are segmented into groups of 2 subcarriers. Each group will be modulated in the form of 2FSK. Only one subcarrier will be chosen (solid lines) and its amplitude will be set to one while others (dashed lines) will be set to zero at one time, like this, each group will has two options and $m = \log_2(2)$ bits information can be transmitted per group. OFDM-MFSK is a simple and robust transmission method that combines the advantages of OFDM and MFSK. MFSK can be received using non-coherent signal detection, making channel estimation obsolete.

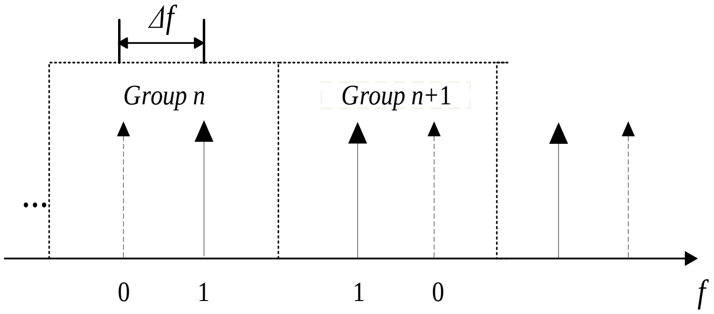

Figure 1. Theory of OFDM-MFSK with M=2

Mapping relationships of OFDM-2FSK are shown in table 1. $f_1 f_2$ are two subcarriers in one group, "1" means the subcarrier's power is one watt while "0" means the subcarrier`s power is zero.

Table 1: Mapping relationships of OFDM-2FSK

Information (bit)	$f_1 f_2$
0	01
1	10

Take $(0,1,\cdots,0)$ as an example, expression of the signal can be written as follows in frequency domain

$$\left(0, e^{j\phi_1(n)}, e^{j\phi_2(n)}, 0, \cdots, 0, e^{j\phi_{\frac{N}{2}}(n)}\right) \tag{9}$$

$\left(0, e^{j\phi_1(n)}\right)$ is group 1, $\left(e^{j\phi_2(n)}, 0\right)$ is group 2, and by this analogy, $\left(0, e^{j\phi_{\frac{N}{2}}(n)}\right)$ is group $\frac{N}{2}$.

Let S be the range of the mapping symbol, it is equal to the second column of table 1. S_i is the mapped symbol of group i, it is equal to one row of the second column of table 1. It is obvious that $S_i \in S$. Let P_i be the index of a subcarrier, for example, $S_i = 1$ then $P_i = \{2\}$. From the above, the expression of S_i in the time domain can be written as follows:

$$s_i(t) = \sum_{k \in P_i} \exp(j\omega_{i,k} t) \qquad 0 \le t \le T_s \tag{10}$$

Where $j=\sqrt{-1}$, $\left\{\omega_{i,k}\right\}$ is the angular frequency of the kth subcarrier in group i , T_s is interval of one OFDM symbol. And then, a symbol of OFDM-2FSK can be written as

$$\begin{aligned} x(t) &= \sum_{i=1}^{N/2} s_i(t) \\ &= \sum_{i=1}^{N/2}\sum_{k\in P_i}\exp(j\omega_{i,k}t) \qquad 0\le t\le T_s \end{aligned} \tag{11}$$

And N is the number of subcarriers used in this OFDM system. Each group has two subcarriers and N is an integral multiple of two. After sampling with the interval of T_s / N , we can get

$$x(n)=\sum_{i=1}^{N/2}\sum_{k\in P_i}\exp(j2\pi n(2i-k)/N) \tag{12}$$

Let $2i-k=m$, then

$$x(n)=\sum_{k=0}^{N-1}\exp(j2\pi nm/N) \qquad 2i-m\in P_i, i=1,2,\cdots,N/2 \tag{13}$$

(13) is the expression formula of base band for a modulated signal in the frequency domain. From formula (8), the received vector can be written as

$$Y=HX+W \tag{14}$$

Let

$$Y=\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{N/2}\end{bmatrix},\ X=\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{N/2}\end{bmatrix}, W=\begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_{N/2}\end{bmatrix},\ H=\begin{bmatrix} H_1 & & & \\ & H_2 & & \\ & & \ddots & \\ & & & H_{N/2}\end{bmatrix}$$

For each group, we can get

$$Y_i=H_iX_i+W_i \qquad i=1,2,\cdots,\tfrac{N}{2} \tag{15}$$

The input symbol X_i represents the binary data d_k . $X_i=[X_i^1,X_i^2]=[0,\sqrt{E_s}]^T$ or $[\sqrt{E_s},0]^T$, $Y_i=[Y_i^1,Y_i^2]^T$.

4. PARTIALLY COHERENT DETEVTION FOR OFDM-MFSK

Considering transfer sequence and partial channel knowledge, the received symbols are not independent of each other, so, the optimal rule need to be implemented will be the maximum likelihood sequence estimation [16]. The sequence X_i is selected among sequence 2^M to maximize the probability of the formula below

$$P_r(Y_i\mid X_i,a,H_0)=\frac{1}{\pi^N\det(K)}\exp[-(Y_i-AX_i)^TK^{-1}(Y_i-AX_i)] \tag{16}$$

Where $Y_i=[Y_i^1,Y_i^2,...,Y_i^M]$, A is a diagonal matrix with diagonal elements $A_{ii}=a^iH_0$. Equation $\exp(x)$ represents the exponent of scalar x , $\det(K)$ is the determinant of matrix K . Covariance matrix $K=B+N_0I_N$, and matrix B with elements $B_{ij}=a^{|i-j|}(1-a^{2(\min(i,j))})E_s$. If the receiver knows the channel statistic a , the channel estimate H_0 and the binary data position k , a partially coherent detection can be performed. The ML rule can be written as

$$\begin{aligned} &P_r(Y_k^1,Y_k^2\mid a,H_0,d_k=0)\ \overset{0}{\underset{1}{¤}}\ P_r(Y_k^1,Y_k^2\mid a,H_0,d_k=1) \\ &P_r(Y_k^1,Y_k^2\mid a,H_0,d_k)=\prod_{i=1}^{2}P_r(Y_k^i\mid a,H_0,X_k^i) \end{aligned} \tag{17}$$

Where d_k is the input binary data, we can get the density function as follows:

$$P_r(Y_k^1 \mid a, H_0, d_k = 1) \sim N(a^{k(N+N_G)} H_0 \sqrt{E_s}, (1-a^{2k(N+N_G)})\sqrt{E_s} + N_0)$$
$$P_r(Y_k^2 \mid a, H_0, d_k = 1) \sim N(\mu, N_0)$$
$$P_r(Y_k^1 \mid a, H_0, d_k = 0) \sim N(\mu, N_0)$$

$$P_r(Y_k^2 \mid a, H_0, d_k = 0) \sim N(a^{k(N+N_G)} H_0 \sqrt{E_s}, (1-a^{2k(N+N_G)})\sqrt{E_s} + N_0) \qquad (18)$$

Solving (17) and simplifying the terms, we can get the final decision rule

$$\widehat{l}_k = 2a^{k(N+N_G)} N_0 Re(H_0^*(y_k^1 - y_k^2)) + (1-a^{2k(N+N_G)})(\left|y_k^1\right|^2 - \left|y_k^2\right|^2) \underset{1}{\overset{0}{\gtrless}} 0 \qquad (19)$$

The above detection rule is a linear combination of the ML rules coherent and non-coherent detection. The weight is decided by the rate of channel changing and SNR. The decision rule is like MRC combining as that coherent detection is often using in the environment of slow fading and low SNR while non-coherent detection is superior in fast fading and high SNR. It can be pointed that, $a = 1$ will lead to a purely coherent detection while $a = 0$ results in a completely non-coherent detection. This rule is suited for all orthogonal signal transmission scheme. In order to implement this rule, we have to know the channel statistic a and N_0 which can be got by monitoring the reverse link. One of the significant advantages of this detection rule is that quality of the channel estimate will not drastically affect the system performance.

5. SIMULATION AND ANALYSIS

In order to verify the effectiveness of the proposed method, we have some simulations. In this simulation, frequency of the carrier is 5.8 GHz, bandwidth is 80 MHz, and each OFDM symbol has 256 subcarriers.

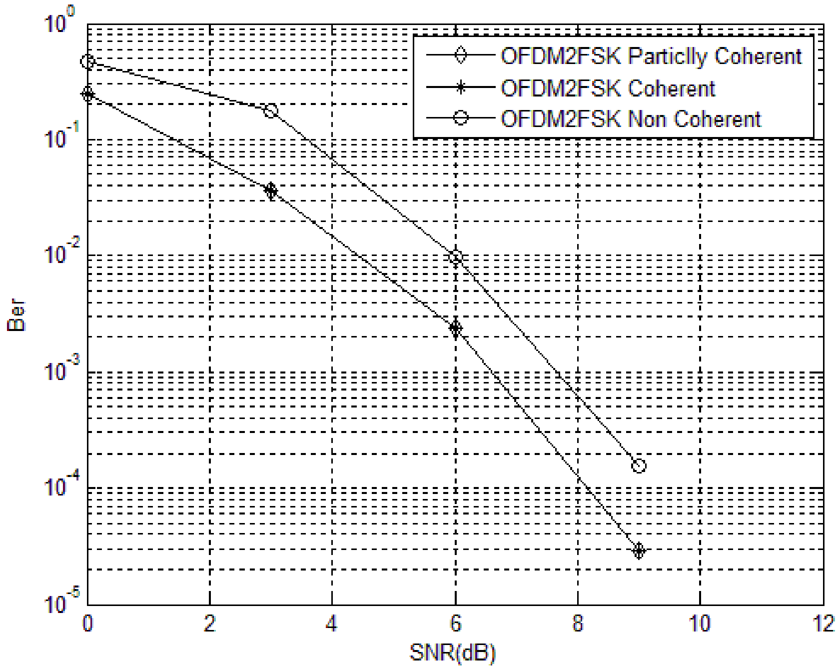

Figure 2. Performance of partially coherent detection compared with Traditional detection for OFDM-2FSK system with Gauss channel.

It is shown in Figure 2 that the performance of this partially detection method compared with traditional coherent and non-coherent detection for OFDM-2FSK system. The channel used is Gauss channel, and move speed of the receiver is zero. From the figure, we can see that, partially coherent detection is same as coherent detection and better than non-coherent detection. Compared with non-coherent detection, partially coherent detection and coherent detection get about 2-3db performance improvement over a wide range of SNR.

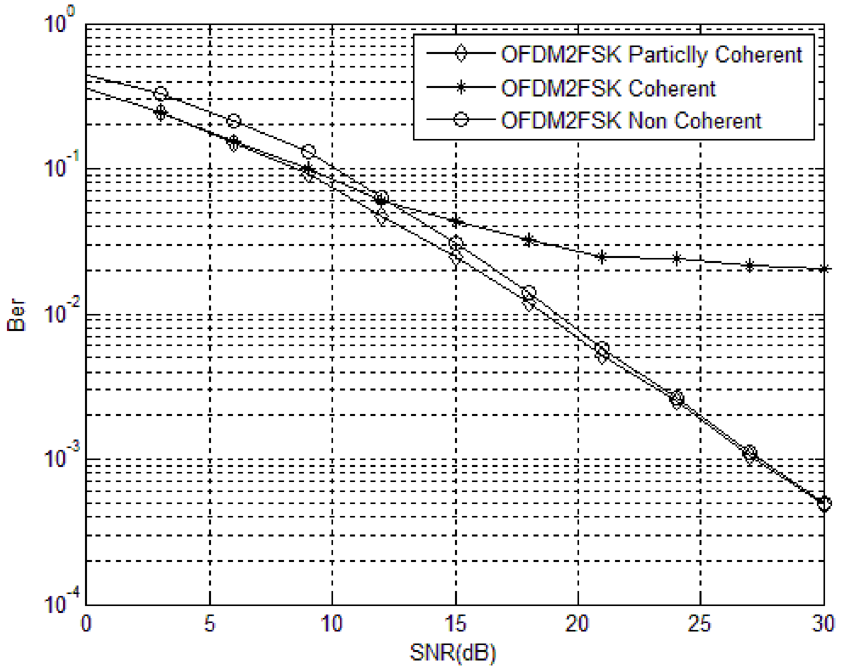

Figure 3. Performance of partially coherent detection compared with traditional Detection for OFDM-2FSK system with Rayleigh fading channel at speed of 600km/h.

A performance comparison is shown in Figure 3 under the Rayleigh fading channel. The comparison is made between the performance of proposed partially coherent detection method, traditional coherent and no-coherent detection for OFDM-2FSK system. Move speed of the receiver is 600km per hour. The figure show that performance of this detection is better than traditional coherent and non-coherent detection for all SNRs. It gets about 1db performance improvement over a wide range of SNR and 3db at the BER where non-coherent and coherent curves cross each other. After that point, the gain diminishes with increase in SNR.

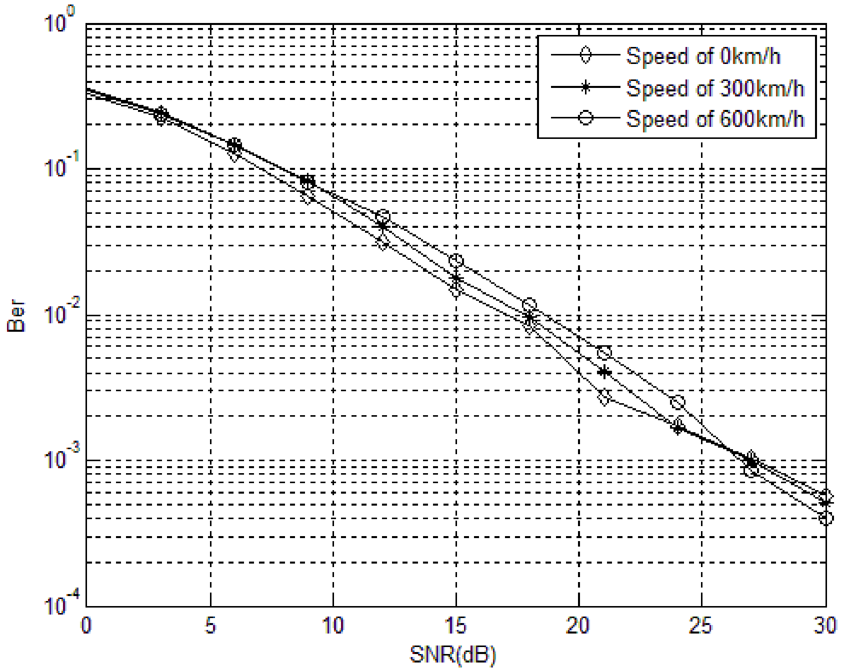

Figure 4. Performance of partially coherent detection with different Speed for OFDM-2FSK system with Rayleigh fading channel.

Figure 4 shows the performance of partially coherent detection for OFDM-2FSk system. Speeds of movement are 0km per hour, 300km per hour and 600km per hour. The channel used is Rayleigh channel. We can see that performance of partially coherent detection at low speed is better than the performance at a higher speed at low SNRs and it is inverse at high SNRs. That means, the detection we proposed is robustness to Doppler shift.

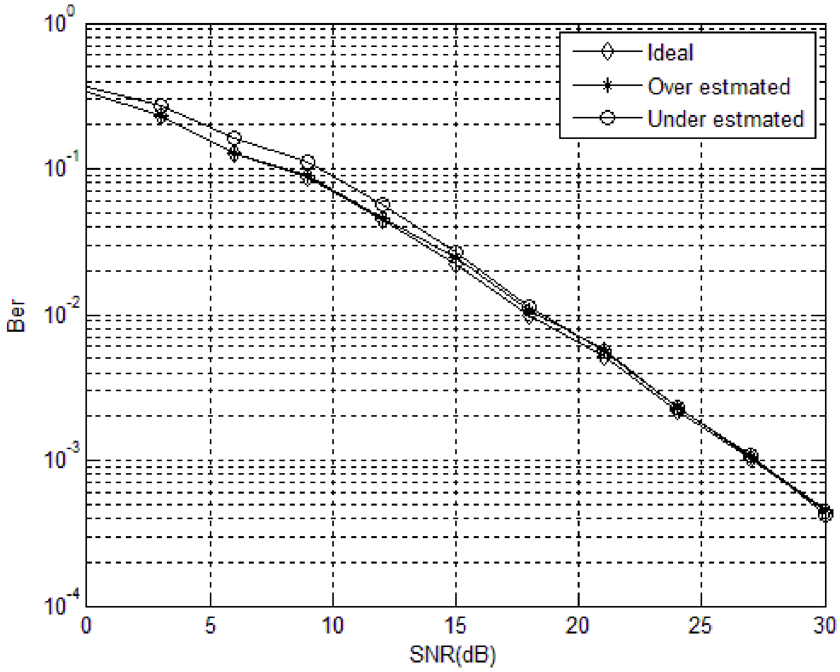

Figure 5. Performance of partially coherent detection with ideal estimate of a (0.985) Compared with over-estimated a (0.999) and under-estimated a (0.955) for OFDM-2FSK system with Rayleigh fading channel.

Figure 5 shows the performance of partially coherent detection for OFDM-2FSk system with imperfect estimate of a. When a is over-estimated by 0.014, the performance degradation of partially coherent detection is less than 1db compared with ideal estimate of a over a wide range of SNR. When a is under-estimated by 0.03, the performance degradation of partially coherent detection is less than 2db compared with ideal estimate of a at low SNRs and less than 1db at a high SNR. That means the performance of partially coherent detection is robust even a is estimated imperfectly. From the above, we can see the effectiveness of the detection we proposed in this paper. And this detection is more applicable for mobile communication environment.

6. CONCLUSION

It is hardly to get accurate channel information in high mobility environments. Coherent detection with inaccurate channel information will lead to an error floor in term of bit error performance. Non-coherent detection doesn't require channel knowledge, however it would result in a loss in SNR performance. In this paper, we have proposed a partially coherent detector for OFDM-MFSK in high mobility environments. The proposed detector can be considered as a combination of coherent detection and non-coherent detection. So it overcame the disadvantages of both coherent detection and non-detection. We found that the performance has been improved when the partial knowledge of the channel is considered. The partially coherent detection has been shown robustness to Doppler shift and imperfect channel information.

7. ACKNOWLEDGMENT

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