Partially Coherent Detection in Rapidly Time Varying Channels

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Abstract— **We investigate the performance degradation of basic modulation schemes in a rapidly time varying channel using a first order autoregressive channel model. We propose a partially coherent detector for both noncoherent frequency shift keying (FSK) and differential phase shift keying (PSK) that exploits partial channel knowledge to enable the receiver to operate effectively in both fast and slow fading. The maximum likelihood rule (ML) obtained for the partially coherent FSK turns out to be a linear combination of coherent and noncoherent detection rule. Results demonstrate that significant performance improvement can be achieved over the best of coherent and noncoherent FSK detection in fast fading. We also propose a few adaptive schemes that vary the modulation scheme in response to degrading quality of the channel estimate between successive training symbols.**

I. Introduction

With the rapid growth of wireless networks and multimedia applications, next generation wireless systems are not only expected to support very high data rates, but also very high quality of service, stressing the need for robustness under all channel conditions. These systems must be able to operate reliably in rapidly fading environments and therefore the detrimental effects of mobility must be mitigated. A mobile traveling at a speed of 75mph (miles per hour) and operating at a carrier frequency of 5 GHz can give rise to a Doppler shift as high as 550 Hz. There are also scenarios in which an even higher Doppler is encountered such as in satellite communications and some military applications like unmanned airborne vehicles (UAV). This poses a major impediment to many existing wireless systems which would breakdown under such a large Doppler shift. As even higher carrier frequencies are being considered for future wireless systems, the high Doppler scenario will become increasingly relevant. Some of the effects of mobility on major communication blocks are studied in [1].

In this paper, we consider the problems posed by a rapidly time varying channel on modulation and detection in simple receivers. Almost all modulation schemes operating in the band limited region [2] either require accurate channel estimate at the receiver or at least require the channel to remain invariant for a certain time duration. However these requirements might be very hard to satisfy in a rapidly time varying channel. For a coherent scheme to operate well in a time varying channel, the channel has to be estimated quite frequently leading to spectral efficiency loss. Thus noncoherent schemes like differential phase shift keying (DPSK) and noncoherent frequency shift keying (FSK) are preferred in a fast fading channel, as the cost and complexity associated with channel estimation becomes prohibitive. However, even differential schemes suffer from an error floor in rapidly fading environment when the channel does not remain constant across adjacent symbols. For most schemes, the rapid channel variations translate to loss in effective SNR.

Most of the works in the literature [2]–[5] approach the detection problem in fading channels under two extreme cases: the coherent case with perfect channel knowledge available at the receiver, and the noncoherent case with absolutely no knowledge of the channel. As the second case is more pertinent in time varying channels, non coherent detection has been a unanimous choice for data detection in time selective channels. However the channel knowledge at the receiver in practical wireless channels lies in between these two extremes. It is not unrealistic to assume partial CSIR even in a rapidly varying channel and then perform a combination of coherent and noncoherent detection. Partially coherent detection was first proposed in [6] for AWGN channels in the presence of phase noise arising from the phase locked loop (PLL). The receiver has imperfect phase estimates with the phase errors assuming Tikhonov densities. This is extended to fading channels in [7] and optimal decision rule found. In both these cases, the optimal rule turns out to be be a linear combination of coherent and noncoherent detection rule. In Section III, we propose partially coherent detectors for BFSK and DPSK that utilizes channel information consisting of both amplitude and phase uncertainties. Interestingly, for BFSK, the optimal maximum likelihood (ML) rule for the proposed partially coherent detector turns out to be a linear combination of coherent and noncoherent ML detectors similar to [6].

Throughout this paper, we identify the parameters that different modulation schemes are sensitive to, and propose some adaptive strategies in a time varying scenario. The choice of the modulation scheme critically depends on the rate at which the channel varies. The varied performances of coherent, differential and noncoherent schemes provide us the opportunity to use these schemes effectively depending on the channel conditions. In Section IV, we propose two ways of adapting the modulation scheme at the transmitter, namely *Intra-block adaptation* and *Inter-block adaptation*. Results are provided to substantiate the merits of the schemes. Finally, we conclude with Section V.

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II. SYSTEM MODEL

We assume complex baseband notation throughout the paper. Consider a communication link consisting of a single antenna transmitter and receiver that operates in a time selective and frequency nonselective Rayleigh fading environment modeled by a first order autoregressive process.

$$h_k = a h_{k-1} + \sqrt{1-a^2} w_k, \tag{1}$$

where a is the correlation parameter, $0 < a \leq 1$ and w_k, the varying component of the channel is an independent and identically distributed (i.i.d.) random process with density $\mathcal{CN}(0, \sigma_h^2)$. It is indicated in [8] [9] that the first order Markov model is a good approximation to the actual fading process. It can be noticed from (1) that the lower the value of a, the greater is the channel variation rate. The channel realizations become i.i.d. when $a = 0$ while $a = 1$ models quasi-static fading. The relationship between the Doppler frequency and a can be approximated using Jakes autocorrelation model [3] and it is given by

$$a = \mathcal{J}_0(2\pi f_d T_s),$$

where $\mathcal{J}_0(x)$ is the zeroth order Bessel function of the first kind, $f_d = \frac{f_c v}{c} = \frac{v}{\lambda}$ is the Doppler shift and T_s is the symbol duration. The input-output relationship of this single antenna link is

$$y_k = h_k x_k + n_k, \tag{2}$$

where n_k is complex additive white Gaussian noise (AWGN) with power spectral density N_0. We assume that an accurate estimate of the channel is obtained at the receiver after every N data symbols. With this information, the channel knowledge at the receiver can be described as a complex Gaussian random process,

$$\widehat{h}_k \backsim \mathcal{CN}(a^k h_0, 1 - a^{2k}). \tag{3}$$

Note that $a = 1$ indicates perfect CSI while $a = 0$ denotes no CSI at the receiver. We have not assumed any error in estimating h_0. In general, if the estimation error has to be included in the model, the linear MMSE estimator will be $\widehat{h}_0 = \frac{\sigma_h^2 \sqrt{E_s}}{\sigma_h^2 E_s + N_0} y(0)$.

III. PARTIAL CHANNEL KNOWLEDGE

A fast fading channel can be broadly modeled as $h = h_c + \Delta h$ where h_c is the estimate of the channel obtained through training and Δh denotes the estimation error. Most receivers ignore h_c when employing noncoherent which is commonly associated with a performance penalty(3 dB). On the other hand, a very high channel estimation rate is required to operate coherently, which ultimately results in a spectral efficiency loss.

In a fast fading channel, the channel estimate obtained via training gets outdated so quickly that coherent detection cannot be performed. Nevertheless the outdated channel information can still be utilized in the detection process if it would result in a considerable performance improvement. The channel information in this context (3) has both amplitude and phase uncertainties. In this section, we explore ways to utilize this partial channel knowledge in basic noncoherent schemes like FSK and DPSK, without increasing the complexity. Ideally we require the receiver to perform symbol by symbol detection taking into account the channel knowledge. It is obvious that the additional channel knowledge will improve the system performance but what remains interesting to know is the amount of gain that can be obtained and the extra complexity it entails. For simplicity we consider binary modulation schemes in this work.

Conditioned on the transmitted sequence and partial channel knowledge, the individual received symbols are not independent and therefore the optimal rule to employ will be the maximum likelihood sequence estimation [10]. The sequence $\mathbf{x}_j$ is selected among 2^N sequences to maximize the following probability.

$$\Pr(\mathbf{y}|\mathbf{x}_j, a, h_0) = \frac{1}{\pi^N \det(\mathbf{K})} \exp\left[-(\mathbf{y} - \mathbf{A}\mathbf{x}_j)^\dagger \mathbf{K}^{-1} (\mathbf{y} - \mathbf{A}\mathbf{x}_j)\right], \tag{4}$$

where $\mathbf{y}^N = [y_1, y_2, ..., y_N]$ and $\mathbf{A}$ is a diagonal matrix with diagonal elements $\mathbf{A}_{ii} = a^i h_0$. The function $\exp(x)$ refers to the exponential of scalar x and $\det(\mathbf{K})$ is the determinant of matrix $\mathbf{K}$. The covariance matrix is obtained as $\mathbf{K} = \mathbf{B} + N_0 \mathbf{I_N}$ with the elements of $\mathbf{B}$ given by $\mathbf{B}_{ij} = a^{|i-j|}\left(1 - a^{2(\min(i,j))}\right) E_s$. The complexity associated with this decision rule grows exponentially in N. Such a decision rule cannot be implemented in simple receivers and therefore the need arises for symbol by symbol detection, even though it is suboptimal.

A. FSK Modulation

For BFSK, over the two orthogonal bands, the received vector $\mathbf{y_k}$ can be written as

$$\mathbf{y_k} = h_k \mathbf{x_k} + \mathbf{n_k}, \tag{5}$$

where h_k is the time varying flat fading scalar channel modeled as in (1). The input symbol $\mathbf{x_k}$ represents the binary data d_k and assumes one of the two possible states $\mathbf{x_k} = \left[x_k^1, x_k^2\right]^T = \left[0, \sqrt{E_s}\right]^T$ or $\left[\sqrt{E_s}, 0\right]^T$ and $\mathbf{y_k} = \left[y_k^1, y_k^2\right]^T$. Receivers for FSK have a unique advantage of operating coherently and noncoherently as the transmission is same for both the schemes. The estimate available at the receiver is h_0. Suppose the receiver operates coherently (ignoring Δh), the detection rule will be

$$\mathfrak{Re}\left(h_0^* \left(y_k^1 - y_k^2\right)\right) \gtrless_1^0 0, \tag{6}$$

where $\mathfrak{Re}(x)$ denotes the real part of the complex value x. Note that the noise is enhanced due to imperfect channel knowledge. The instantaneous post detection SNR γ_k is given by

$$\gamma_k = \frac{a^{2k}|h_0|^2 E_s}{(1 - a^{2k})E_s + 2N_0}. \tag{7}$$

The effective SNR depends on the symbol location and it decreases with time until a new channel estimate is obtained. Each symbol in the block has different average error probability. The closer it is to the training symbol the lower the probability of symbol error. After averaging the probability of error for the k^{th} symbol position over h_0, we obtain

$$P_e^C(k) = \frac{1}{2}\left(1 - a^k \sqrt{\frac{E_s}{E_s + 2N_0}}\right). \tag{8}$$

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The overall average BER for the N-symbol block is

$$\overline{P_e} = \frac{1}{N}\sum_{k=1}^{N} P_e\left(k\right). \tag{9}$$

This yields

$$\overline{P_e}^{C} = \frac{1}{2}\left[1 - \frac{a}{N}\left(\frac{1-a^N}{1-a}\right)\sqrt{\frac{E_s}{E_s+2N_0}}\right]. \tag{10}$$

The error floor in coherent FSK for ignoring Δh is

$$\overline{P_e}^{C} = \frac{1}{2}\left[1 - \frac{a}{N}\left(\frac{1-a^N}{1-a}\right)\right]. \tag{11}$$

Discarding the outdated channel estimate, the noncoherent detection rule is

$$\left(|y_k^1|^2 - |y_k^2|^2\right) \gtrless_1^0 0, \tag{12}$$

where $|x|$ denotes the absolute value of the complex number x. The average probability of error [11] is given by

$$\overline{P}_e^{NC} = \frac{1}{2+\frac{E_s}{N_0}}, \tag{13}$$

B. Partially Coherent FSK detection

If the receiver is aware of the channel statistic a, the channel estimate h_0 and the symbol position k, a partially coherent detection can be performed. The ML rule is

$$\Pr\left(y_k^1, y_k^2 | a, h_0, d_k = 0\right) \gtrless_1^0 \Pr\left(y_k^1, y_k^2 | a, h_0, d_k = 1\right). \tag{14}$$

$$\Pr\left(y_k^1, y_k^2 | a, h_0, d_k\right) = \Pr\left(y_k^1 | a, h_0, x_k^1\right)\ \Pr\left(y_k^2 | a, h_0, x_k^2\right)$$

It is straightforward to arrive at the following densities.

$$\begin{aligned}
\Pr\left(y_k^1 | a, h_0, d_k = 1\right) &\sim \mathcal{N}(a^k h_0\sqrt{E_s}, (1-a^{2k})E_s + N_0) \\
\Pr\left(y_k^2 | a, h_0, d_k = 1\right) &\sim \mathcal{N}(0, N_0) \\
\Pr\left(y_k^1 | a, h_0, d_k = 0\right) &\sim \mathcal{N}(0, N_0) \\
\Pr\left(y_k^2 | a, h_0, d_k = 0\right) &\sim \mathcal{N}(a^k h_0\sqrt{E_s}, (1-a^{2k})E_s + N_0)
\end{aligned}$$

The final decision rule obtained after solving (14) and simplifying the terms is

$$\begin{aligned}
\widehat{l}_k = 2a^k N_0 \mathfrak{Re}\left(h_0^*(y_k^1 - y_k^2)\right) + \\
(1-a^{2k})\sqrt{E_s}(|y_k^1|^2 - |y_k^2|^2) \gtrless_1^0 0.
\end{aligned} \tag{15}$$

The detection rule obtained above is a linear combination of the ML rules coherent and noncoherent detection with the weights determined by the channel variation rate and SNR. The decision rule is analogous to MRC combining as coherent detection is given more emphasis at slow fading and at low SNR while noncoherent detection is prominent at fast fading and high SNR, which is consistent with intuition. It can be noted that $a = 1$ results in a purely coherent detection while complete noncoherent detection takes place at $a = 0$. For the intermediate values of a, a combination of coherent and noncoherent detection takes place. This rule is applicable to all orthogonal signalling schemes including pulse position modulation (PPM) with partial channel state information at the receiver. The knowledge of the channel statistic a and N_0 is required for implementing this rule, which can be obtained by monitoring the reverse link. A significant advantage of this detection rule is that the quality of the channel estimate i.e. the amount of coherence, does not drastically affect the system performance, unlike PSK systems.

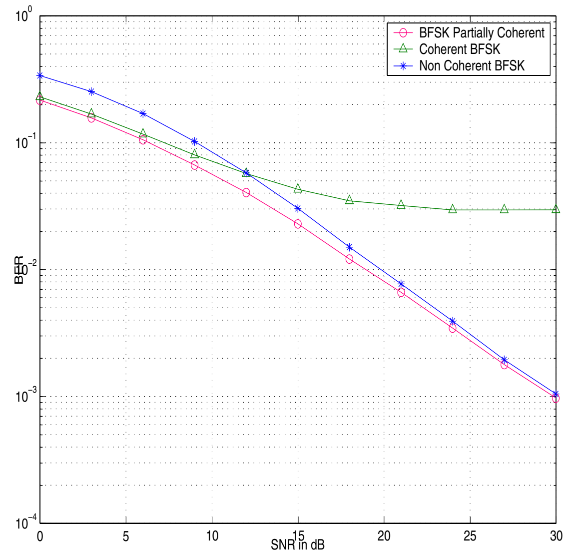

Fig. 1. Performance improvement in FSK with partial CSI for a=0.999 and N=100.

The performance of this system along with the conventional coherent and noncoherent BFSK system is shown in Fig. 1. It can be seen the scheme outperforms the best of coherent and noncoherent BFSK for all SNRs. A gain of 2 dB is obtained over a wide range of SNR. The gain is about 3 dB at the BER where noncoherent and coherent curves cross each other. However the gain diminishes with increase in SNR after that point. A very tight upper bound for the probability of error for this detector can be readily obtained by noting that the detector performs better than the best of coherent and noncoherent detection for any a and N.

$$\begin{aligned}
\overline{P_e}(k) &\leq \min\left(\overline{P_e}^{C}(k), \overline{P_e}^{NC}\right) \\
&\leq \min\left(\frac{1}{2}\left(1 - a^k\sqrt{\frac{E_s}{E_s+2N_0}}\right), \frac{1}{(2+\frac{E_s}{N_0})}\right)
\end{aligned}$$

As the quality of the channel estimate degrades with k, noncoherent FSK will outperform coherent FSK after k reaches a threshold. The probability of error $\overline{P_e}(k)$ averaged over k yields

$$\overline{P_e} \leq \frac{N-N_t}{N}\left(\frac{N_0}{2N_0+E_s}\right) + \frac{N_t}{2N} - \frac{a}{N}\left(\frac{1-a^{N_t}}{1-a}\right)\sqrt{\frac{E_s}{E_s+2N_0}}. \tag{16}$$

The value of N_t is chosen such that

$$\overline{P}_e^{C}\left(N_t\right) = \overline{P}_e^{NC}\left(N_t\right). \tag{17}$$

An adaptive scheme based on this upper bound is discussed in Section IV. For M-ary FSK, the partially coherent detector chooses the symbol j that has the maximum loglikelihood ratio.

$$\widehat{l}_k^m = 2a^k N_0 \mathfrak{Re}\left(h_0^* y_k^m\right) + (1-a^{2k})\sqrt{E_s}|y_k^m|^2 \tag{18}$$

where $m = 1$ to M, the set of all possible symbols.

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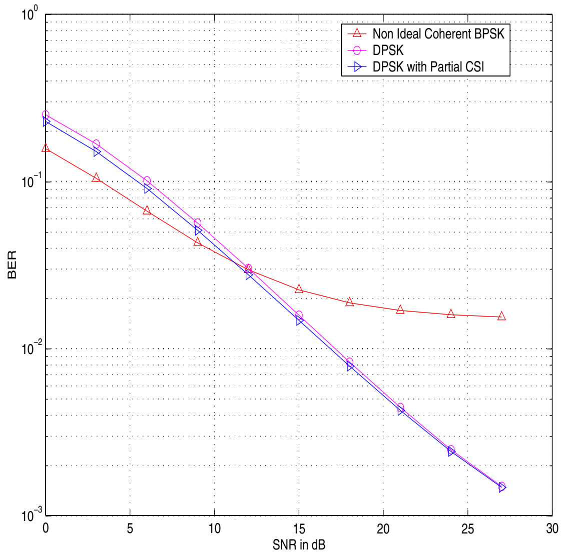

Fig. 2. Performance improvement in DPSK with partial CSI for a=0.999.

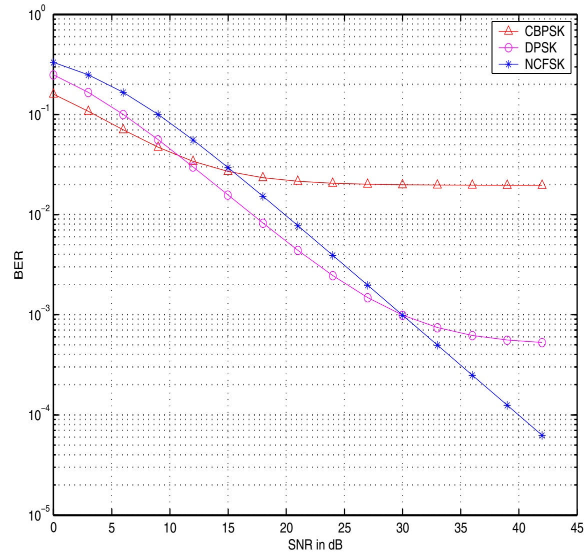

Fig. 3. BER performance of the schemes at a=0.999 & N=100.

C. PSK Modulation

The symbol transmitted at the k^{th} duration is

$$x_k = \sqrt{E_s} e^{j\phi_k}, \tag{19}$$

where $\phi_k \in [\pi, -\pi]$, is the transmitted phase and E_s is the symbol energy. The received symbol at k^{th} symbol duration corrupted by AWGN noise of power spectral density N_0 is given by (2). For symbol by symbol detection, the optimal rule turns out to be co-phasing of the received symbols with the noisy estimate h_0.

$$\frac{h_0^*}{|h_0|} y_k = a^k |h_0|^2 x_k + z_k. \tag{20}$$

Then the instantaneous SNR γ_k is given by

$$\gamma_k = \frac{a^{2k}|h_0|^2 E_s}{(1-a^{2k})E_s + N_0}. \tag{21}$$

The average effective SNR for the k^{th} symbol position Γ_k is

$$\Gamma_k = \frac{a^{2k} E_s}{(1-a^{2k})E_s + N_0}. \tag{22}$$

The probability of error of the k^{th} symbol position for a coherent BPSK system is given by

$$\overline{P_e(k)} = \frac{1}{2}\left(1 - a^k \sqrt{\frac{E_s}{E_s + N_0}}\right). \tag{23}$$

The overall average BER for the N-symbol block is then given by

$$\overline{P_e} = \frac{1}{2}\left[1 - \frac{a}{N}\left(\frac{1-a^N}{1-a}\right)\sqrt{\frac{E_s}{E_s+N_0}}\right]. \tag{24}$$

The error floor of coherent BPSK due to constrained channel estimation rate can be calculated from (24) above and is given by

$$\overline{P_e} = \frac{1}{2}\left[1 - \frac{a}{N}\left(\frac{1-a^N}{1-a}\right)\right]. \tag{25}$$

From the above equation it can be said that, with very high channel estimate rate coherent schemes can perform well even in a rapidly varying channel while in a slow fading channel they can still perform poorly if the channel estimation rate is very low. As noncoherent detection of PSK signals is not possible, partially coherent detection invariably leads to coherent detection with a noisy estimate. Thus we analyze the performance of differential PSK systems with partial CSI.

D. Differential PSK modulation

For a differential PSK system, the phase of the transmitted symbol during the k^{th} symbol duration is encoded as $\phi_k = \phi_{k-1} + \theta_k$ where θ_k is a point in the BPSK signal constellation. The following operation is performed at the receiver to obtain the decision variable.

$$\begin{aligned} y_k^* y_{k+1} &= (h_k^* x_k^* + n_k^*)(h_{k+1}x_{k+1} + n_{k+1}) \\ &= (h_k^* x_k^* + n_k^*)\left((ah_k + \sqrt{1-a^2}w_k)x_{k+1} + n_{k+1}\right) \\ &= a|h_k|^2 u_{k+1} + z_{k+1}, \end{aligned}$$

where u_{k+1} is the actual data symbol and z_{k+1} contains all the noise terms. We neglect the product of Gaussian random variables $w_k n_k^*$ and $n_{k+1} n_k^*$ as in [2], in the calculation of the SNR and the error probability. The instantaneous post detection SNR γ_{dif} is,

$$\gamma_{\text{dif}} = \frac{a^2 |h_k|^2 E_s}{(1-a^2)E_s + (1+a^2)N_0}.$$

Unlike coherent schemes, the SNR here is independent of the position of the symbol and thus all symbols in the block have the same SNR. The probability of error is given by

$$\overline{P_e} = \frac{1}{2}\left(1 - \frac{2a^2 E_s}{(1+a^2)(E_s+N_0)}\right). \tag{26}$$

From the above expression, the error floor caused due to channel variation within successive symbol durations in DPSK can be obtained as

$$\overline{P_e} = \frac{1}{2}\left(\frac{1-a^2}{1+a^2}\right). \tag{27}$$

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For a transmit diversity system employing differential space time codes [12], that requires the channel to be constant for two codewords, the effect of rapid variations in channel will be more pronounced.

E. DPSK with partial CSI

With the knowledge of a and h_0 at the receiver, the ML detection rule is

$$\Pr\left(y_k, y_{k+1}|a, h_0, u_{k+1} = -1\right) \gtrless_{1}^{-1} \text{Prob}\left(y_k, y_{k+1}|a, h_0, u_{k+1} = 1\right). \quad (28)$$

Now the required probability is written as a mixture of two gaussian distributions,

$$\Pr\left(y_k, y_{k+1}|a, h_0, u_{k+1} = s_m\right) = \frac{1}{2}\Pr\left(y_k, y_{k+1}|a, h_0, u_{k+1} = s_m, x_k = 1\right) + \frac{1}{2}\Pr\left(y_k, y_{k+1}|a, h_0, u_{k+1} = s_m, x_k = -1\right).$$

The joint probability distribution of the received vector conditioned on u_{k+1}, x_k, h_0 and a is given by

$$\Pr\left(\mathbf{y}^k|u_{k+1}, x_k, h_0, a\right) = \frac{1}{\pi \det\left(K_y\right)} e^{-\left[\left(\mathbf{y}^k - \mathbf{m}^k\right)^{\dagger} K_y^{-1}\left(\mathbf{y}^k - \mathbf{m}^k\right)\right]} \quad (29)$$

where $\mathbf{y}^k = \left[y_k, y_{k+1}\right]^T$ and $\mathbf{m}^k = \left[a^k h_0 x_k, a^{k+1} h_0 x_k u_{k+1}\right]^T$. The covariance matrix K_y^k is obtained as

$$K_y^k = \begin{bmatrix} 1 - a^{2k} + N_0 & \left(a - a^{2k+1}\right) u_{k+1} \\ \left(a - a^{2k+1}\right) u_{k+1} & 1 - a^{2k+2} + N_0 \end{bmatrix}.$$

The detection rule in (28) cannot be simplified further and is therefore quite complex to implement. The performance of a DPSK system employing this detection rule is shown in Fig. 2. Although the performance is better than the conventional DPSK for all SNR and fading rate a, the gain achieved from the channel knowledge is at most 1 dB at low SNR range.

IV. Adaptive Schemes

It is quite clear from the previous sections that the performance of modulation schemes is very sensitive to many parameters that include the channel variation rate a, channel estimation frequency N and SNR. The varied performance of the modulation schemes in a time varying channel provides us the opportunity to adapt the modulation schemes to the channel conditions. Due to the time varying nature of the channel, the quality of the channel estimate in coherent schemes degrades with symbol position, thereby making the probability of error dependent on the symbol position. This motivates us to employ coherent modulation for certain number of symbols in the block till the channel estimate quality is good and operate noncoherently for the rest of the symbols in the block . We call this as an *Intra Block Adaptation*. From the BER plots in Fig. 3 and from the ML rule in (15), it is clear that an ideal modulation scheme should exhibit the performance of a coherent scheme at low SNR and low Doppler while noncoherent behavior is desired at high SNR or high Doppler. This is the basis for adaptation in *Inter-Block Adaptation*.

A. Intra-Block Adaptation

The transmission strategy is to send first N_t symbols with a coherent modulation, where the channel estimate is good and the remaining $(N - N_t)$ symbols with noncoherent modulation.

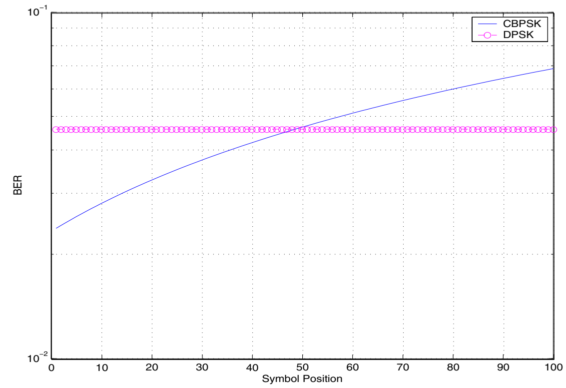

Fig. 4. Error Probability of individual symbols at a=0.999 and SNR=5 dB.

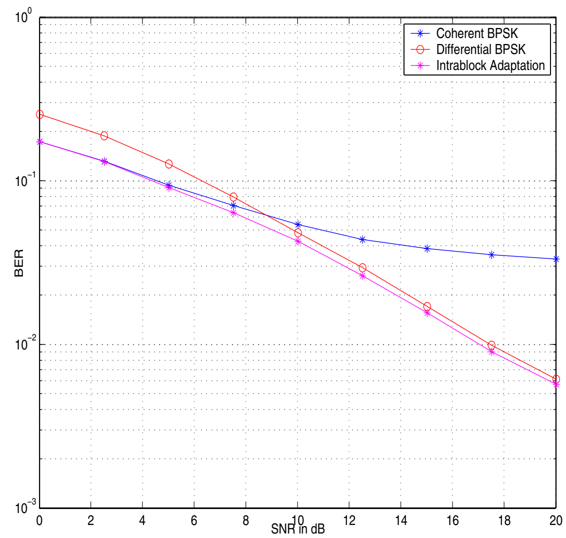

Fig. 5. Performance of the intra block adaptation scheme at a=0.999 and N=100.

Considering BPSK and DPSK, we have

$$\phi_k = \begin{cases} \theta_k & k \leq N_t \\ \phi_{k-1} + \theta_k & k > N_t \end{cases} \quad (30)$$

The value of N_t is chosen such that

$$\overline{P}_e^{BPSK}\left(N_t\right) = \overline{P}_e^{DPSK}\left(N_t\right) \quad (31)$$

The average symbol error probability is then given by

$$\overline{P_e} = \frac{\sum_{i=1}^{N_t} P_e^{BPSK}(i) + \left(N - N_t\right) P_e^{DPSK}}{N} \quad (32)$$

Upon substituting (24) and (26), the average probability of error of the intra block adaptation scheme (32) becomes

$$\overline{P_e} = \frac{1}{2}\left[1 - \frac{a}{N}\left(\frac{1 - a^{N_t}}{1 - a}\right)\sqrt{\frac{E_s}{E_s + N_0}} - \frac{\left(N - N_t\right) a^2 E_s}{N\left(1 + a^2\right)\left(1 + N_0\right)}\right] \quad (33)$$

A similar adaptive scheme with coherent FSK and noncoherent FSK can be seen in Section III, where it was employed to find an upper bound to the probability of error of a partially coherent FSK detector. If we do not consider the data rate mismatch [13] between PSK and FSK, an intra-block adaptive scheme between BPSK and NCFSK can be designed. This will

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be useful when DPSK suffers from an error floor.

$$\overline{P_e} = \frac{\sum_{i=1}^{N_t} P_e^{CBPSK}(i) + (N - N_t) P_e^{NCFSK}}{N}. \quad (34)$$

Upon substituting (13) and (24), we have

$$\overline{P_e} = \frac{N - N_t}{N}\left(\frac{N_0}{2N_0 + E_s}\right) + \frac{N_t}{2N} - \frac{a}{2N}\left(\frac{1 - a^{N_t}}{1 - a}\right)\sqrt{\frac{E_s}{E_s + N_0}}. \quad (35)$$

Fig. 4 plots the BER of individual symbol positions with coherent BPSK following (23) and DPSK following (26). Fig. 5 shows the performance of intra-block adaptive scheme versus the individual modulation schemes. A gain of about 1 dB is achieved over a wide range of SNR values.

B. Inter-Block Adaptation

Even though the modulation schemes like BPSK and DPSK are susceptible to error floors in a fast fading channel, they are optimal at low SNR when the noise power is comparable to the SNR loss caused due to channel decorrelation. Thus the knowledge of the received SNR is crucial in employing optimal modulation strategies. Therefore an adaptive scheme should also consider shadowing, which causes deviations in received SNR. A model to include shadowing [14] is

$$h(k) = \sqrt{\overline{G}(k)} r(k).$$

where $\overline{G}(k)$ is the local mean received power which varies due to shadowing and $r(k)$ is due to the fast fade that follows the distribution $\mathcal{N}(0, 1)$. We assume a lognormal distribution for the shadowing in which an entire block of N symbols experience a particular realization of lognormal shadowing and the shadowing parameter for the next block is totally independent of the previous block. Shadowing results in the average received power to slowly vary and can be tracked by the transmitter using the reverse transmission link. Fig. 6 shows the performance of inter-block adaptive scheme versus the individual modulation schemes for a standard deviation of 7 dB for the log-normal distribution. The performance gain is maximum near the cross over of the curves, as shadowing alters the order of the performance of the modulation schemes. The inter-block adaptive scheme in general can also include intra block adaptation. An easier form of adaptation would be to choose the best modulation scheme for each communication session, deciding only based on mobility.

V. CONCLUSION

Rapid channel variations, caused by mobility lead to loss in effective SNR for modulation schemes operating in the bandlimited region of the capacity curve [2], resulting in an error floor. This is true even for differential schemes that do not require channel knowledge at the receiver. The performance loss due to mobility is less with orthogonal modulation schemes like FSK that can operate noncoherently, compared to differential or coherent schemes. As noncoherent schemes are increasingly being deployed in many wireless systems, there is a scope for significant performance improvement in these systems when the role of partial channel knowledge is considered. The partially coherent detector that we derived for FSK is simple and at the same time provides significant performance improvement over the best of coherent and noncoherent FSK detection. We also showed that an opportunistic adoption of various modulation schemes within a block or between blocks or sessions will result in substantial performance improvements.

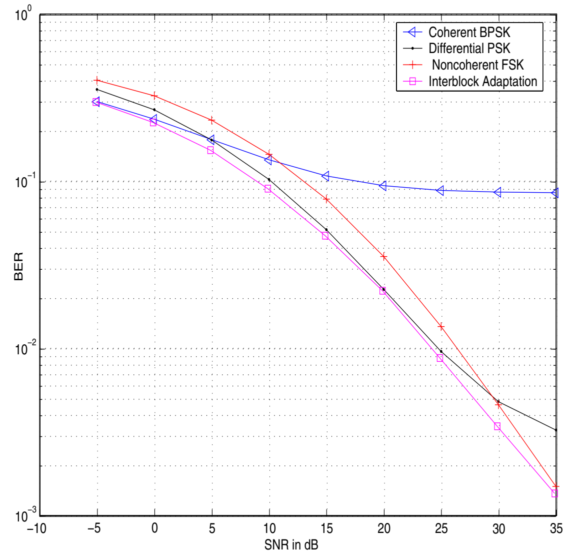

Fig. 6. Interblock Adaptation for a=0.999 and N=100 σ=7 dB.

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