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Fuqin Xiong
Cleveland State University, f.xiong@csuohio.edu

S Bgatnyket
Cleveland State University

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Performance of MHPM in Rician and Rayleigh Fading Mobile Channels

Fuqin Xiong and Sachin Bhatmuley

Abstract— **This paper evaluates the error probability of the rectangular frequency pulse multi-h modulation (MHPM) scheme in slowly-fading, frequency-nonselective or frequency-selective Rician and Rayleigh channels. The evaluation is performed with a method combining analysis and computer simulation. Performance degradations are evaluated for various direct-to-reflected signal ratio, Doppler shifts, and relative time delays in Rician fading channels. Compared with minimum shift keying (MSK), MHPM schemes appear to have retained their coding gains.**

Index Terms—**Fading channels, mobile communication.**

I. Introduction

RECENTLY, multi-h phase-coded modulation (MHPM) has attracted a great deal of attention because of its good immunity to the nonlinearity in transmitter, excellent bandwidth efficiency and power efficiency. This paper will evaluate the BER of the full response rectangular frequency pulse MHPM (1REC-MHPM) in Rician and Rayleigh fading channels. This scheme is also known as Multi-h CPFSK. The basic assumption is that maximum likelihood sequence estimation (MLSE) for 1REC-MHPM designed for AWGN channels is used in a fading environment. We are interested in the evaluation of the degradation due to fading.

1REC-MHPM signals can be represented as four dimensional signals by using Gram–Schmidt orthogonalization [1]. Thus, the MLSE detector only needs four correlators followed by a Viterbi decoder. To simplify analysis without loss of generality, it is convenient to set the beginning time of each symbol to zero, thus the ith received 1REC-MHPM signal symbol (without noise) can be written as

$$r(t) = \sqrt{2E/T}\cos(\omega_c t + a_i \pi h_i t/T + \phi_i), \quad 0 \le t \le T \quad (1)$$

where E = symbol energy; T = symbol duration; ω_c = carrier angular frequency; $a_i \in [1, -1]$ is digital information; $[h_i, i = 1, 2, \cdots, K]$ is the a set of modulation indices; ϕ_i = initial phase of the ith interval. By using Gram–Schmidt procedure, $r(t)$ can be expressed as a vector in a four-dimensional (4-D) space spanned by $\psi_i(t)$, $i = 1, \ldots, 4$.

$$r(t) = \sqrt{E}[A_{1,i}\psi_1(t) + A_{2,i}\psi_2(t) + A_{3,i}\psi_3(t) + A_{4,i}\psi_4(t)] \quad (2)$$

where

$$\begin{aligned} A_{1,i} = {} & (\cos\phi_i)(1+a_i)/2 + C_{1,i}(\cos\phi_i)(1-a_i)/2 \\ & + C_{2,i}(\sin\phi_i)(1-a_i)/2 \end{aligned} \quad (3)$$

$$\begin{aligned} A_{2,i} = {} & -(\sin\phi_i)(1+a_i)/2 + C_{2,i}(\cos\phi_i)(1-a_i)/2 \\ & - C_{1,i}(\sin\phi_i)(1-a_i)/2 \end{aligned} \quad (4)$$

$$A_{3,i} = \sqrt{D_i}(\cos\phi_i)(1-a_i)/2 \quad (5)$$

$$A_{4,i} = -\sqrt{D_i}(\sin\phi_i)(1-a_i)/2 \quad (6)$$

and $C_{1,i} = (\sin 2\pi h_i)/(2\pi h_i), C_{2,i} = (1 - \cos 2\pi h_i)/2\pi h_i$, $D_i = 1 - C_{1,i}^2 - C_{2,i}^2$; and

$$\psi_1(t) = \sqrt{2/T}\cos(\omega_c t + \pi h_i t/T) \quad (7)$$

$$\psi_2(t) = \sqrt{2/T}\sin(\omega_c t + \pi h_i t/T) \quad (8)$$

$$\begin{aligned} \psi_3(t) = {} & \left(1/\sqrt{D_i}\right)\left[\sqrt{2/T}\cos(\omega_c t - \pi h_i t/T) \right. \\ & \left. - C_{1,i}\psi_1(t) - C_{2,i}\psi_2(t)\right] \end{aligned} \quad (9)$$

$$\begin{aligned} \psi_4(t) = {} & \left(1/\sqrt{D_i}\right)\left[\sqrt{2/T}\sin(\omega_c t - \pi h_i t/T) \right. \\ & \left. + C_{2,i}\psi_1(t) - C_{1,i}\psi_2(t)\right] \end{aligned} \quad (10)$$

are the four base functions.

The coefficients $A_{1,i}, A_{2,i}, A_{3,i}, A_{4,i}$ are sufficient statistics which can be derived by passing the received signal through a bank of four correlators [1]. Note that the actual coefficients obtained from a received signal also have an additive noise term in each of them. The noise terms are statistically independent from each other. Demodulation is accomplished by sending these coefficients through a Viterbi decoder.

II. 1REC-MHPM in Fading Channels

Our attempt to analyze the error performance of MHPM in fading channels proved that it is extremely difficult, if not impossible. Anderson simulated MHPM in AWGN channel with computed correlator coefficients [2]. The same approach is taken in this work. First, the set of correlator coefficients are derived taking fading into consideration. Then simulation is performed using these coefficients. The fading channel models considered in this paper are Rician and Rayleigh which are the most commonly used models for satellite mobile and land mobile channels, respectively. We further assume that the channels are slowly-fading.

Rician Fading: The direct signal experiences a Doppler shift $\Delta\omega$ due to the relative motion between the transmitter and the receiver. For the coherent detection of 1REC-MHPM, the carrier needs to be recovered at the receiver. Since the direct signal is usually dominant, the recovered local carrier frequency is the same as the direct signal frequency. Let's denote it as ω_c (Note that it is different from the transmitted frequency by the Doppler shift $\Delta\omega$). The direct signal arriving at the receiver is

$$r_d(t) = \sqrt{2E/T}\cos(\omega_c t + a_i \pi h_i t/T + \phi_i); \quad 0 \le t \le T. \quad (11)$$

The authors are with the Department of Electrical Engineering, Cleveland State University, Cleveland, OH 44115 USA.

The multipath signal model varies with different environments. In this study, the two-ray multipath model is used [3]. The satellite to ground vehicle channel and the airplane to ground channel, where MHPM schemes are likely to be used, are of this type. In these channels, the principal multipath component is due to reflection of the terrain. It undergoes Rayleigh fading because of the terrain variation [3, p. 710]. The Doppler shift is not explicitly included in the Rayleigh fading signal model since its effect is modeled by the Rayleigh envelope and the random phase [4]. Therefore Rayleigh signal has the same carrier frequency as the transmission, but it is different from ω_c by $\Delta\omega$. There is also a delay τ in $r_r(t)$ with respect to the direct component $r_d(t)$. Further, we assume that the channel is slow-fading. Thus, the reflected signal can be represented as

$$\begin{aligned} r_r(t) = v_i\sqrt{2E/T}\cos((\omega_c+\Delta\omega)(t-\tau) \\ + a_i\pi h_i(t-\tau)/T + (\phi_i+\varphi_i)) \end{aligned} \quad (12)$$

where φ_i is the uniformly distributed phase in $(0, 2\pi)$, v_i is the Rayleigh envelope. Both are constant in a symbol period. Let $\theta_i = \varphi_i - a_i\pi h_i\tau/T - (\omega_c+\Delta\omega)\tau$, which is still a random variable with uniform distribution in $(0, 2\pi)$. The channel is approximately frequency-nonselective for a small delay $(\tau/T \ll 1)$ or large $K = P_d/P_r$, the ratio of direct signal power over multipath signal power, and is frequency-selective for a larger delay or smaller K [5]. The reflected component can be written as

$$\begin{aligned} r_r(t) = & \underbrace{F_1\sqrt{2/T}\cos((\omega_c+\Delta\omega)t+\pi h_i t/T)}_{s_1(t)} \\ & - \underbrace{F_2\sqrt{2/T}\sin((\omega_c+\Delta\omega)t+\pi h_i t/T)}_{s_2(t)} \\ & + \underbrace{F_3\sqrt{2/T}\cos((\omega_c+\Delta\omega)t-\pi h_i t/T)}_{s_3(t)} \\ & - \underbrace{F_4\sqrt{2/T}\sin((\omega_c+\Delta\omega)t-\pi h_i t/T)}_{s_4(t)} \end{aligned} \quad (13)$$

where

$$F_1 = \sqrt{E}[V_{1,i}\cos\phi_i(1+a_i)/2 - V_{2,i}\sin\phi_i(1+a_i)/2],$$
$$F_2 = \sqrt{E}[V_{1,i}\sin\phi_i(1+a_i)/2 + V_{2,i}\cos\phi_i(1+a_i)/2],$$
$$F_3 = \sqrt{E}[V_{1,i}\cos\phi_i(1-a_i)/2 - V_{2,i}\sin\phi_i(1-a_i)/2],$$
$$F_4 = \sqrt{E}[V_{1,i}\cos\phi_i(1-a_i)/2 + V_{2,i}\sin\phi_i(1-a_i)/2],$$

where $V_{1,i} = v_i\cos\theta_i$, $V_{2,i} = v_i\sin\theta_i$ which are constant in a symbol period. $V_{1,i}$ and $V_{2,i}$ are independent Gaussian random variables with zero-mean and variance σ^2.

Regardless, the actual value of τ, the misalignment is equivalent to the case of $0 \le \tau \le T$. Thus, without loss of generality, we can assume that $0 \le \tau \le T$. The signal $r_r(t)$ in $(0, \tau)$ has the same form as (13), but is determined by h_{i-1}, a_{i-1}, and ϕ_{i-1}. We denote this signal as $r'_r(t)$ which have four components $s'_1(t)$, $s'_2(t)$, $s'_3(t)$, and $s'_4(t)$ with coefficients F'_1, F'_2, F'_3, F'_4. All the quantities have the same form as those for the signal in $[\tau, T]$ except that h_i, a_i, ϕ_i are replaced by $h_{i-1}, a_{i-1}, \phi_{i-1}$, and $V_{1,i}, V_{2,i}$ are replaced by $V_{1,i-1}, V_{2,i-1}$ which are independent Gaussian random variables with zero-mean and variance σ^2.

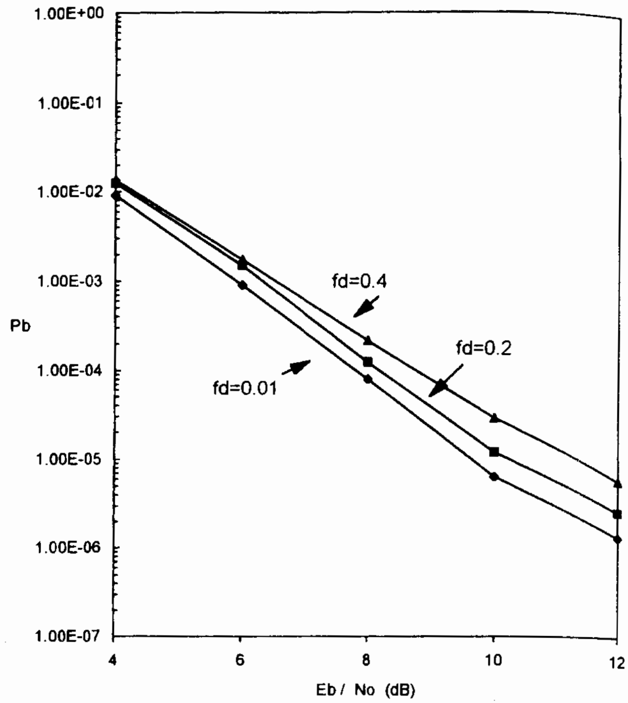

Fig. 1. Performance of 1REC-MHPM $H_2 = (2/4, 3/4)$ in Rician channe for various values of f_d (K =10 dB, $t_d = 0$).

Thus the correlation coefficient of $s_k(t)$ with $\psi_l(t)$ in itl symbol period can be found by

$$A_{l,k,i} = \int_0^\tau s'_k(t)\cdot\psi_l(t)dt + \int_\tau^T s_k(t)\cdot\psi_l(t)dt \quad (14$$

where $l = 1, 2, 3, 4$ and $k = 1, 2, 3, 4$.

To simplify the expressions of these coefficients, we defin

$$\begin{aligned}
\Phi_{1,i} &= \Delta\omega T + \pi(h_{i-1} - h_i), \\
\Phi_{2,i} &= \Delta\omega\tau + \pi(h_i - h_i)\frac{\tau}{T}, \\
\Phi_{3,i} &= \Delta\omega T, \\
\Phi_{4,i} &= \Delta\omega\tau, \\
\Phi_{5,i} &= \Delta\omega T + \pi(h_{i-1} + h_i), \\
\Phi_{6,i} &= \Delta\omega\tau + \pi(h_{i-1} + h_i)\frac{\tau}{T}, \\
\Phi_{7,i} &= \Delta\omega T + 2\pi h_i, \\
\Phi_{8,i} &= \Delta\omega\tau + 2\pi h_i\frac{\tau}{T}, \\
\Phi_{9,i} &= \Delta\omega T - \pi(h_{i-1} + h_i), \\
\Phi_{10,i} &= \Delta\omega\tau - \pi(h_{i-1} + h_i)\frac{\tau}{T}, \\
\Phi_{11,i} &= \Delta\omega T - 2\pi h_i, \\
\Phi_{12,i} &= \Delta\omega\tau - 2\pi h_i\frac{\tau}{T}, \\
\Phi_{13,i} &= \Delta\omega T - \pi(h_{i-1} - h_i), \\
\Phi_{14,i} &= \Delta\omega\tau - \pi(h_{i-1} - h_i)\frac{\tau}{T}.
\end{aligned}$$

Then total 16 coefficients due to the reflected signal $r_r(t$ are found as follows:

$$\begin{aligned} A_{1,1,i} = (F'_1/\Phi_{1,i})\sin\Phi_{2,i} + (F_1/\Phi_{3,i}) \\ \times(\sin\Phi_{3,i} - \sin\Phi_{4,i}) \end{aligned}$$

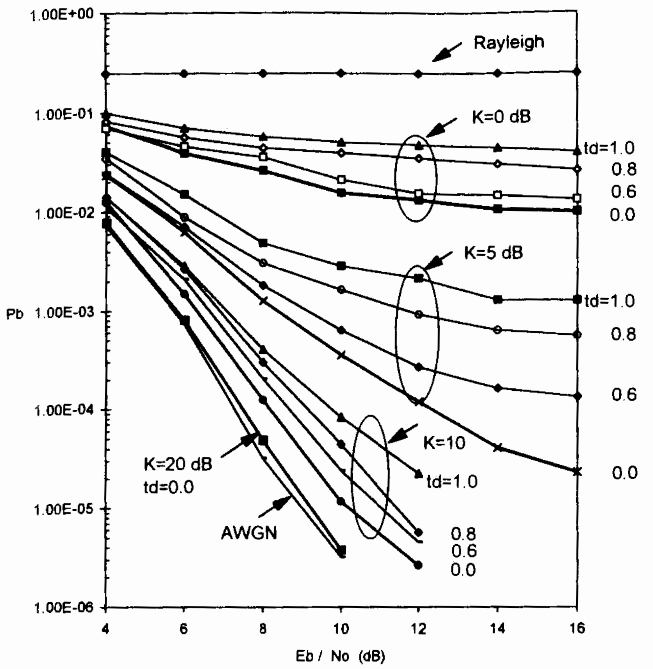

Fig. 2. Performance of 1REC-MHPM $H_2 = (2/4, 3/4)$ in Rayleigh, Rician and AWGN channels for various values of K and t_d ($f_d = 0.2$). Rayleigh channel is approximated by $K = -200$ dB, and no synchronization is done for the Rayleigh fading signal.

$$\begin{aligned}
A_{2,1,i} &= -(F_1'/\Phi_{1,i})(1-\cos\Phi_{2,i}) \\
&\quad + (F_1/\Phi_{3,i})(\cos\Phi_{3,i} - \cos\Phi_{4,i}) \\
A_{3,1,i} &= \left(1/\sqrt{D_i}\right)[(F_1'/\Phi_{5,i})\sin\Phi_{6,i} \\
&\quad + (F_1/\Phi_{7,i})(\sin\Phi_{7,i} - \sin\Phi_{8,i}) \\
&\quad - C_{1,i}A_{1,1,i} - C_{2,i}A_{2,1,i}] \\
A_{4,1,i} &= \left(1/\sqrt{D_i}\right)[-(F_1'/\Phi_{5,i})(1-\cos\Phi_{6,i}) \\
&\quad + (F_1/\Phi_{7,i})(\cos\Phi_{7,i} - \cos\Phi_{8,i}) \\
&\quad + C_{2,i}A_{1,1,i} - C_{1,i}A_{2,1,i}] \\
A_{1,2,i} &= -(F_2'/\Phi_{1,i})(1-\cos\Phi_{2,i}) \\
&\quad + (F_2/\Phi_{3,i})(\cos\Phi_{3,i} - \cos\Phi_{4,i}) \\
A_{2,2,i} &= -(F_2'/\Phi_{1,i})\sin\Phi_{2,i} - (F_2/\Phi_{3,i}) \\
&\quad \times (\sin\Phi_{3,i} - \sin\Phi_{4,i}) \\
A_{3,2,i} &= \left(1/\sqrt{D_i}\right)[(-F_2'/\Phi_{5,i})(1-\cos\Phi_{6,i}) \\
&\quad + (F_2/\Phi_{7,i})(\cos\Phi_{7,i} - \cos\Phi_{8,i}) \\
&\quad - C_{1,i}A_{1,2,i} - C_{2,i}A_{2,2,i}] \\
A_{4,2,i} &= \left(1/\sqrt{D_i}\right)[(-F_2'/\Phi_{5,i})\sin\Phi_{6,i} \\
&\quad - (F_2/\Phi_{7,i})(\sin\Phi_{7,i} - \sin\Phi_{8,i}) \\
&\quad + C_{2,i}A_{1,2,i} - C_{1,i}A_{2,2,i}] \\
A_{1,3,i} &= (F_3'/\Phi_{9,i})\sin\Phi_{10,i} + (F_3/\Phi_{11,i}) \\
&\quad \times (\sin\Phi_{11,i} - \sin\Phi_{12,i}) \\
A_{2,3,i} &= -(F_3'/\Phi_{9,i})(1-\cos\Phi_{10,i}) \\
&\quad + (F_3/\Phi_{11,i})(\cos\Phi_{11,i} - \cos\Phi_{12,i}) \\
A_{3,3,i} &= \left(1/\sqrt{D_i}\right)[(F_3'/\Phi_{13,i})\sin\Phi_{14,i} \\
&\quad + (F_3/\Phi_{15,i})(\sin\Phi_{3,i} - \sin\Phi_{4,i}) \\
&\quad - C_{1,i}A_{1,3,i} - C_{2,i}A_{2,3,i}]
\end{aligned}$$

$$\begin{aligned}
A_{4,3,i} &= \left(1/\sqrt{D_i}\right)[-(F_3'/\Phi_{13,i})(1-\cos\Phi_{14,i}) \\
&\quad + (F_3/\Phi_{3,i})(\cos\Phi_{3,i} - \cos\Phi_{4,i}) \\
&\quad + C_{2,i}A_{1,3,i} - C_{1,i}A_{2,3,i}] \\
A_{1,4,i} &= -(F_4'/\Phi_{9,i})(1-\cos\Phi_{10,i}) \\
&\quad + (F_4/\Phi_{11,i})(\cos\Phi_{11,i} - \cos\Phi_{12,i}) \\
A_{2,4,i} &= -(F_4'/\Phi_{9,i})\sin\Phi_{10,i} - (F_4/\Phi_{11,i}) \\
&\quad \times (\sin\Phi_{11,i} - \sin\Phi_{12,i}) \\
A_{3,4,i} &= \left(1/\sqrt{D_i}\right)[-(F_4'/\Phi_{13,i})(1-\cos\Phi_{14,i}) \\
&\quad + (F_4/\Phi_{3,i})(\cos\Phi_{3,i} - \cos\Phi_{4,i}) \\
&\quad - C_{1,i}A_{1,4,i} - C_{2,i}A_{2,4,i}] \\
A_{4,4,i} &= \left(1/\sqrt{D_i}\right)[-(F_4'/\Phi_{13,i})\sin\Phi_{14,i} \\
&\quad - (F_4/\Phi_{3,i})(\sin\Phi_{3,i} - \sin\Phi_{4,i}) \\
&\quad + C_{2,i}A_{1,4,i} - C_{1,i}A_{2,4,i}].
\end{aligned}$$

The output of the correlator consists of both the coefficients due to $r_d(t)$ and the coefficients due to $r_r(t)$. In total, the coefficients are

$$\begin{aligned}
A_{1,i} &= A_{1,d,i,} + A_{1,1,i} + A_{1,2,i} + A_{1,3,i} + A_{1,4,i} \\
A_{2,i} &= A_{2,d,i} + A_{2,1,i} + A_{2,2,i} + A_{2,3,i} + A_{2,4,i} \\
A_{3,i} &= A_{3,d,i} + A_{3,1,i} + A_{3,2,i} + A_{3,3,i} + A_{3,4,i} \\
A_{4,i} &= A_{4,d,i} + A_{4,1,i} + A_{4,2,i} + A_{4,3,i} + A_{4,4,i}
\end{aligned} \tag{15}$$

where $(A_{1,d,i}, A_{2,d,i}, A_{3,d,i}, A_{4,d,i})$ are determined by (3) to (6).

Rayleigh Fading: In this case, since there is only one signal, the relative delay need not be considered. The Doppler deviation also need not be considered as we mentioned before. Therefore, we proceed with identical mathematical treatment as in the case of the two-ray model, except that we let $\tau = 0$ and $\Delta\omega = 0$. The results obtained are now summarized:

$$\begin{aligned}
&A_{1,i} \\
&= \sqrt{E}\{V_{1,i}(\cos\phi_i)(1+a_i)/2 - V_{2,i}(\sin\phi_i)(1+a_i)/2 \\
&\quad + C_{1,i}[V_{1,i}(\cos\phi_i)(1-a_i)/2 - V_{2,i}(\sin\phi_i)(1-a_i)/2] \\
&\quad + C_{2,i}[V_{2,i}(\cos\phi_i)(1-a_i)/2 + V_{1,i}(\sin\phi_i)(1-a_i)/2]\}
\end{aligned} \tag{16}$$

$$\begin{aligned}
&A_{2,i} \\
&= \sqrt{E}\{-V_{2,i}(\cos\phi_i)(1+a_i)/2 - V_{1,i}(\sin\phi_i)(1-a_i)/2 \\
&\quad + C_{2,i}[V_{1,i}(\cos\phi_i)(1-a_i)/2 - V_{2,i}(\sin\phi_i)(1-a_i)/2] \\
&\quad + C_{1,i}[-V_{2,i}(\cos\phi_i)(1-a_i)/2 - V_{1,i}(\sin\phi_i)(1-a_i)/2]\}
\end{aligned} \tag{17}$$

$$\begin{aligned}
A_{3,i} &= \sqrt{E}\sqrt{D_i}\{V_{1,i}(\cos\phi_i)(1-a_i)/2 \\
&\quad - V_{2,i}(\sin\phi_i)(1-a_i)/2\}
\end{aligned} \tag{18}$$

$$\begin{aligned}
A_{4,i} &= \sqrt{E}\sqrt{D_i}\{-V_{2,i}(\cos\phi_i)(1-a_i)/2 \\
&\quad - V_{1,i}(\sin\phi_i)(1-a_i)/2\}.
\end{aligned} \tag{19}$$

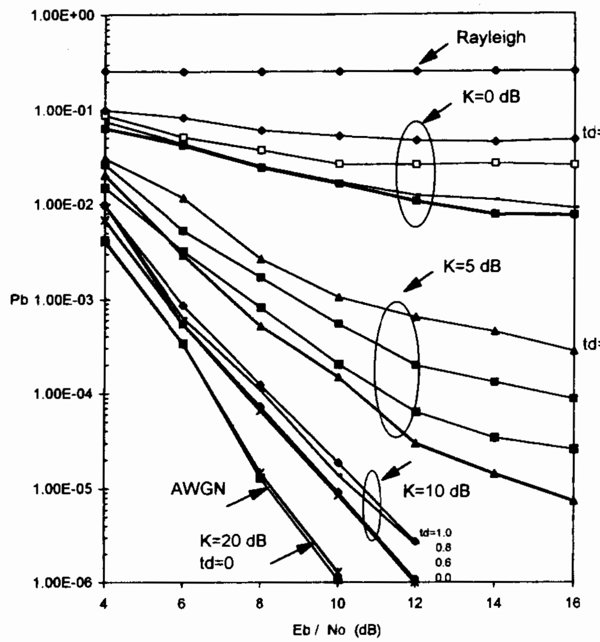

Fig. 3. Performance of 1REC-MHPM $H_3 = (4/8, 5/8, 6/8)$ inRayleigh, Rician and AWGN channels for various values of K and t_d ($f_d = 0.2$). Rayleigh channel is approximated by $K = -200$ dB, and no synchronization is done for the Rayleigh fading signal.

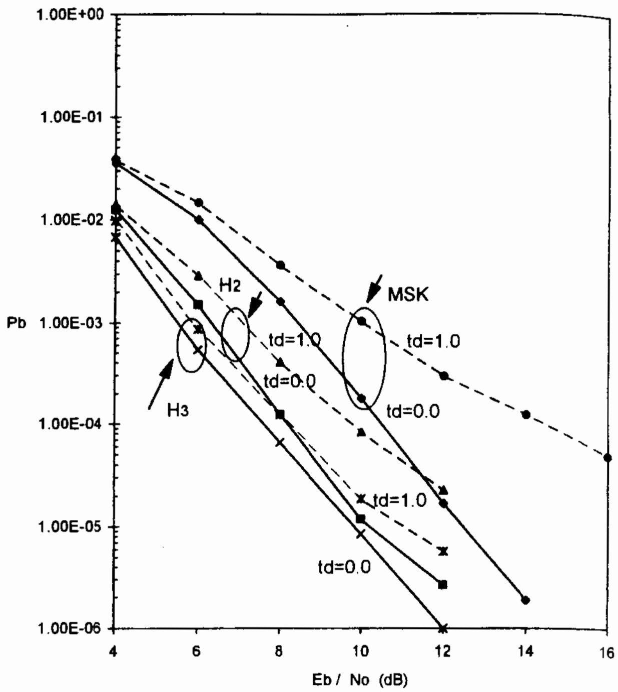

Fig. 4. Comparison of MSK, $H_2 = (2/4, 3/4)$, and $H_3 = (4/8, 5/8, 6/8)$ in Rician channel ($K = 10$ dB, $f_d = 0.2$).

III. Simulation Results and Findings

Based on above coefficients simulation has been done to deduce the performance degradation experienced by a 1REC-MHPM signal in various fading media. The performance improvement of 1REC-MHPM over MSK in fading channels is also evaluated.

In the simulation, the two independent Gaussian processes $V_{1,i}$ and $V_{2,i}$ which represent the Rayleigh fading process are bandlimited by a 6th order Butterworth low pass filter. It has a bandwidth of the fading process determined by the Doppler spread of the channel which, in turn, is determined by the mobile speed. In the simulation the noise power is characterized by E_b/N_o, which is the ratio of bit energy of the direct path signal over the one side power spectral density of the additive white Gaussian noise. The multipath signal power is characterized by $K = P_d/P_r$, which is the power ratio between the direct signal and the reflected signal. In the simulation, P_d is fixed, P_r is varied for different K.

In the simulation, we found that variation of Doppler shift has some, but insignificant effect on P_b as shown in Fig. 1, where $f_d = \Delta f T$, varies from 0.01 to 0.4. It is seen that P_b increases with the increase of f_d slightly. However, the effect of f_d is not as significant as that of other parameters. Therefore, when we exam the effect of other parameters, we set $f_d = 0.2$, which gives average value of P_b in the practical range of f_d.

Fig. 2 shows various P_b plots of Rician fading for different K and $t_d = \tau/T$ for the 1REC-MHPM scheme with $H_2 = (2/4, 3/4)$. When K goes to zero, the channel becomes Rayleigh. In the simulation, we approximate the Rayleigh channel by assigning a very small value to K, namely $K = -200$ dB. Since P_d is fixed, P_r is very large in this case. The actual signal-to-noise ratio (SNR) is the labeled E_b/N_o, plus K. It is seen from the plot of Rayleigh fading that the bit-error rate (BER) P_b is very high (0.25–0.26) in spite of the high SNR. This can be attributed to the fact that there is no steady phase reference available at the receiver for the coherent detection of the signal. The coherent detection of a Rayleigh faded signal proves meaningless unless some kind of channel tracking scheme is incorporated in the system. When the content of P_d is increased, i.e., when a carrier is recovered at the receiver from the direct signal component, a significant improvement in P_b is observed (see plots for $K = 0$, 5, 10, 20 dB). The P_b at $K = 20$ dB is comparable to that in the presence of only AWGN. For $P_b = 10^{-6}$, the performance degradation at $K = 10$ dB and $t_d = 0$, with respect to the AWGN channel, is about 2 dB. Due to the Rayleigh component in the signal these plots show error floors. However, they can be largely removed if channel state tracking mechanism is incorporated. Fig. 2 also shows the effect of t_d on the P_b. It is seen that when t_d increases P_b increases steadily, especially when $t_d \geq 0.6$. This is due to the fact that when t_d is much larger than 0, the channel becomes frequency-selective, which causes additional distortion of the signal on top of fading and AWGN. This in turn increases the P_b.

Fig. 3 is similar to Fig. 2 except that it is for $H_3 = (4/8, 5/8, 6/8)$. Again, we see that the direct to reflected signal ratio K and t_d have significant impact on P_b.

The performance comparison of MSK and 1REC-MHPM schemes in Rician fading is plotted in Fig. 4, for $K = 10$ dB and $t_d = 0$ and 1.0. This figure compares the MSK, $H_2 = (2/4, 3/4)$, and $H_3 = (4/8, 5/8, 6/8)$. The solid lines are for $t_d = 0$ case, and the dotted lines are for $t_d = 1.0$ case. The performance of $H_2 = (2/4, 3/4)$ is found to be superior to MSK by about 2 dB for $t_d = 0$ throughout the E_b/N_o range. This coding gain is slightly larger than that in AWGN channel

(1.4 dB) [6]. Comparing $H_3 = (4/8, 5/8, 6/8)$ with MSK, the coding gain is around 3 dB for $t_d = 0$ which is slightly larger than that of AWGN channel (2.8 dB). For $t_d = 1.0$, MSK suffers from more loss in P_b than MHPM schemes. This indicates that these 1REC-MHPM schemes have retained their coding gain over MSK in fading channels and are subject to less loss in error performance when delay spread increases.

IV. Conclusion

In this paper, the performance of binary 1REC- MHPM scheme has been evaluated in Rayleigh and Rician fading channels. Without any channel tracking mechanism, the coherent detection of 1REC-MHPM signal in Rayleigh fading channels proves to be meaningless. However, in Rician fading channels the performance degradation of 1REC-MHPM is reduced to some extent, depending on the ratio of direct signal to reflected signal. The BER was found to deteriorate slightly with the increase of the Doppler shift but significantly with the increase of delay spread of the multipath signal. 1REC-MHPM was found to still perform better than MSK in a Rician fading channel.

References

[1] V. R. Bhargava, D. Haccoun, R. Matyas, and P. P. Nuspl, *Digital Communications by Satellite*. New York: Wiley, 1981.

[2] J. B. Anderson, "Simulated error performance of multi-h phase codes," *IEEE Trans. Inform. Theory*, vol. IT-27, pp. 357–362, May 1981.

[3] J. G. Proakis, *Digital Communications*. New York: McGraw-Hill, 1989.

[4] T. Aulin, "A modified model for the fading signal at a mobile radio channel," *IEEE Trans. Vehicular Technol.*, vol. VT-28, pp. 182–203, Aug. 1979.

[5] M. Miller, B. Vucetic, and L. Bery, *Satellite Communications, Mobile and Fixed Services*. Boston, MA: Kluwer, 1993.

[6] S. G. Wilson, J. H. Highfill III, and C.-D. Hsu, "Error bounds for multi-h phase codes," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 650–665, July 1982.