IEEE 802.11

Wireless Access Method and Physical Layer Specifications

TITLE: **Performance of DS-SS and SFH Systems with Diversity Reception and BCH FEC over Indoor Multipath Fading Channels**

DATE: November 9, 1992

AUTHOR:

Kwang-Cheng Chen
Department of Electrical Engineering
National Tsing Hua University
Hsinchu, Taiwan 30043,R.O.C.
TEL: +886-35-715131 ext. 4054
FAX: +886-35-715971
E-Mail: chenkc@ee.nthu.edu.tw

Computer and Communication Laboratories
Industrial Technology Research Institute
Bldg. 11, M000, 195 Chung Hsing Rd.,
Section 4, Chutung, Hsinchu,
Taiwan 31015, R.O.C.
TEL: +886-35-917282
FAX: +886-35-941447

Tsung-Cheng Wu
Chi-Chao Chao
Department of Electrical Engineering
National Tsing Hua University
Hsinchu, Taiwan 30043,R.O.C.

Abstract

In this paper, we analyze the performance of spread-spectrum transmission with diversity techniques and BCH forward error correcting codes (FEC) in indoor multipath fading channels. Channel models with clusters of delay paths are considered. Based on the channel models to meet measurement results, bit error probabilities of direct-sequence (DS) and slow frequency hopped (SFH) systems with equal-gain and selective combining diversities are derived and compared over different channel models. BCH codes with single or double error-correcting capability are chosen to further improve the performances of DS and SFH systems. From the numerical results, we demonstrate that these techniques (especially diversity) can improve the performance of DS and SFH systems in indoor multipath fading channels.

I Introduction

Recently, indoor wireless communications has attracted much more attention for the development of personal communication services and wireless data communications. Suffering from severe multipath fading and dynamic changing environments, spread spectrum communications can resist the multipath effects while the choice between DS and SFH systems for the personal communications within indoor environments remains open problem. The bit error probabilities of the DS and SFH systems with additional improving techniques among indoor multipath fading channel are still interesting to us. Diversity reception, one of the effective methods to combat fading, has been studied in [1, 2]. Within those possible diversity combinings, selective or equal-gain combining may be a good choice for it's low complexity to implement the personal communications or wireless data communications. Efforts have been made about the performance analysis of the diversity reception in fading channel [3, 4, 5]. In [7], performance analysis of selective diversity for DS spread spectrum with path number of multipath delay as a parameter in indoor wireless channels was considered. Equal gain diversity in fast frequency hopped communications over Rayleigh fading was studied in [6], which evaluated the bit error probability with the signal-to-interference as a parameter. Selection combining and predetection combining of diversities for DS system with DPSK modulation were analyzed in [15]. The performance study of hybrid DS/SFH systems with diversity techniques and FEC, has been shown in [18]. However, the previous works did not meet the current interested approach, and the channel models for analysis did not exactly meet the measurement results, particularly indoor environments. It is believed that channel models with clusters of arrivals are more likely to approach many practical environment. A simple statistical model with clusters property, has already proposed [12] from the measurement of a 115m $\times$ 14m room. That paper provide only one kind of channel parameters which may not be appropriate for general environments. It is known that diversity reception plus channel coding can improve the performance of DS and SFH systems. Convolutional code, decoded by Viterbi decoder with soft decision, was employed on some applications of mobile communications [17]. Owing to the complexity of convolutional code decoder and most importantly the spectrum efficiency of transmission, we consider a block code, BCH code, in the possible spread spectrum communication systems.

In this paper, we try to establish more general channel parameters as typical cases to meet the practical channels for the performance analyses of the DS and SFH systems with equal-gain or selective combining diversities and single or double error correcting high-rate BCH codes. We will demonstrate the dynamical changes of the performance of the same receiver due to different environments. From the numerical results of this paper, we hope to provide a highlight for the spread spectrum system design. The applied channel model and received signals for DS and SFH systems are given in Section II. The performance derivation for diversity combining are in Section III and IV, selective and equal-gain combinor respectively. Bit error probability both with diversity and BCH code are treated in Section V. The numerical result will be in section VI.

II Channel Model, System Models and Received Signals

A. Channel Model

An equivalent impulse response of multipath fading channel usually includes amplitudes, phases and time delays for each received path. For time delay parameter, uniformly distribution is the most simplest assumption to analysis. Since well curve fitting to the emprical data in urban radio propagation, a modified Poisson process (so-called Δ-K model) of time delay was proposed in [9, 10, 11]. Parameters of the Poisson process of time delay for indoor multipath fading channel were obtained in [14]. However, a modified Poisson process with groups of path arriving property is very complicated to analyze. An alternative multipath model simply to analyze was introduced in [12] to describe the clustering of arriving rays.

This channel model described the arriving clusters as a Poisson process with parameter Λ and rays in each cluster as a independent Poisson process with a different parameter λ. As the statistical model may not represent the real situations, an alternative deterministic model which may be consider as a sample path of the statistical model to develope our performance analysis should be a better way to examine the system performance. Since the indoor channel model is very time-varying, we further introduce a modification to consider the Doppler effect as

$$h(t) = \sum_{n=0}^{\infty}\sum_{k=0}^{\infty} \beta_{nk}\delta(t - T_n - \tau_{nk}) \exp(j\theta_{nk} + j\omega_{d_{nk}} t) \tag{1}$$

where β_{nk} is an amplitude of the kth ray in the nth arrived cluster which follows a Rayleigh distribution. θ_{nk} is the phase difference between the arrived nth-cluster-kth-ray and local oscillator of receiver which is assumed to be well synchronized to the first arrival of the first cluster. $\omega_{d_{nk}}$ denotes the frequency shift for the nth-cluster-kth-ray arrived path relative to the very first arrival, β_{00}. The behavior of path arrivals is depicted in Figure 1.

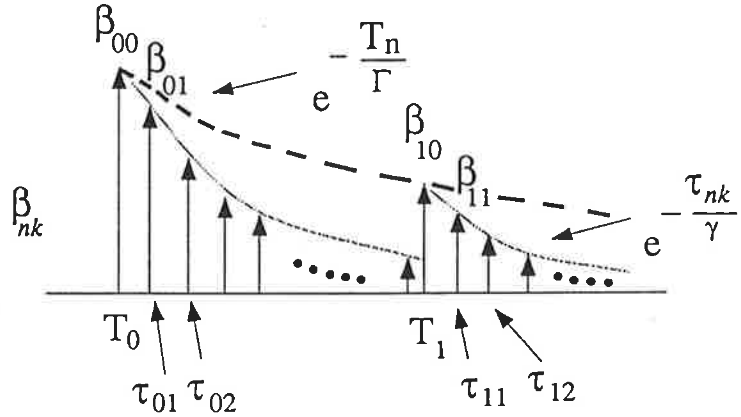

Figure 1: Channel model with cluster arriving paths

We denote the arrival time of the nth cluster to be T_n, $n = 1, 2, \cdots$, after the first arriving cluster. Let the arrival time of the kth ray relative to the beginning of the nth cluster be τ_{nk}, $k = 0, 1, \cdots$. We also assume $T_0 = 0$ and $\tau_{n0} = 0$. The T_n and τ_{nk} are described by the independent interarrival exponential density functions.

$$f(T_n \mid T_{n-1}) = \Lambda \exp[-\Lambda(T_n - T_{n-1})] \quad n > 0 \tag{2}$$

$$f(\tau_{nk} \mid \tau_{n(k-1)}) = \lambda \exp[-\lambda(\tau_{nk} - \tau_{n(k-1)})] \quad k > 0 \tag{3}$$

The mean square value of path amplitudes are exponential decay functions of $\{T_n\}$, $\{\tau_{nk}\}$. That is,

$$\overline{\beta_{nk}^2} = \beta^2(T_n, \tau_{nk}) \tag{4}$$

$$= \overline{\beta^2(0,0)} \exp(-\frac{T_n}{\Gamma}) \exp(-\frac{\tau_{nk}}{\gamma}) \tag{5}$$

where $\overline{\beta^2(0,0)} = \beta_{00}^2$ is the average power of the first ray of the first cluster; Γ, and γ are the decay constants for the clusters and the rays , respectively. We assume that the rays and clusters not overlap such that the rays stop when next cluster occur.

We assume that β_{nk}, θ_{nk}, T_{nk} τ_{nk}, $\omega_{d_{nk}}$ are mutually statistically independent. We consider the behavior of system within $[0,\ T]$, a symbol time interval and assume that the arrivals after 2 symbol periods are small and can be neglected.

Let $T_{min} = \min(T, T_m)$ where T_m is the multipath spread. If $T_m \leq T$, then T_{min} equal to T_m, the multipath arrived withwin $[0,\ T_m]$ and there will be no intersymbol-interference.

According to different indoor environments and transmitting data rate, delay paths with clusters can be described into four kinds of behavior in Figure 2 by adjusting the parameters $1/\lambda$, $1/\Lambda$, γ, and Γ. Therefore, this channel model are flexible and appropriate to most operating indoor fading environments.

B. System Models

We consider that DS spread spectrum is modulated with BPSK and SFH with BFSK. The receiver structure of the diversity methods are shown in Figure 3, for both DS and SFH systems. In Figure 3, $s_i(t)$, $i = 1, \cdots, M$, denote the spreading sequence for DS system, or the dehopping signal for SFH system.

There are M diversity branches in the receiver, whose detector is coherent correlator for DS system and noncoherent envelope detector for SFH system shown in Figure 4.

We assume that the fading processes among the M diversity branches are mutually statistically independent and have the same variance. The AWGN in each branch are also assumed to be mutually statistically independent. Following the diversity branches, a combinor circuit combines those diversity inputs to become a decision variable, which decide "1" or "0" to be the transmitted signal. There are three well-known combining methods, Maximum-Ratio-Combining (MRC), equal-gain combining (EGC) and selective combining (SC). MRC is the sum of weighted diversity branches, $a_1 r_1 + a_1 r_2 + \cdots + a_M r_M$, where r_i is the output of branch prior to combinor, and a_i is the weighting which need to estimate faded amplitude and phases. The equal-gain combinor is similar to MRC except a_i=1 for all i. The selective combining is to choose the maximum output of those diversity branches. For the complexity of faded amplitude estimation, MRC may not be appropriate for many cost-sensitive indoor wireless communications due to the requirement of high performance implementation. In the following sections, we will derive the error probability of selective and equal-gain combinings.

C. Received Signals

(1) DS system

We denote the well synchronized first arrival of each branch as $\beta_{j,00}$, where '00' means the the first ray of the first cluster of jth diversity branch. The received signal of DS system before combinor for the jth diversity branch deriverd in [8] is

$$r_j = d_0\sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}} g_{j,nk}\beta_{j,nk}\cos\phi_{j,nk} + \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}} p_{j,nl}\beta_{j,nl}\cos\varphi_{j,nl} + \eta_j \quad (6)$$

where
$$g_{j,nk} = d_0 R_c(T_n + \tau_{nk}) + (d_0^{'} - d_0)\theta_c(T_n + \tau_{nk}) \quad (7)$$
$$\phi_{j,nk} = (\omega_0 - \omega_{d_{nk}})(T_n + \tau_{nk}) + \theta_{nk} \quad (8)$$
$$p_{j,nl} = d_0^{'} R_c(T_n + \tau_{nl} - T) + (d_0^{''} - d_0^{'})\theta_c(T_n + \tau_{nl} - T) \quad (9)$$
$$\varphi_{j,nl} = (\omega_0 - \omega_{d_{nl}})(T_n + \tau_{nl} - T) + \theta_{nl} \quad (10)$$

and E is the signal energy. η_j is a zero mean Gaussian random variable with variance $N_0/2$. Let $d_0^{''}, d_0^{'}, d_0$ be the three consecutive data bits; d_0 is the current data bit.

$R_c(T_n + \tau_{nk})$ is the autocorrelation function of spreading sequences. We define $\theta_c(T_n + \tau_{nk})$ to be
$$\theta_c(T_n + \tau_{nk}) := \frac{1}{T}\int_0^{T_n+\tau_{nk}} c(t)c(t - T_n - \tau_{nk})dt$$

The details of the derivation for received signal can be found in [8]. We know that those r_j are Gaussian random variables with mean $\beta_{j,00} d_0 \sqrt{E}$, variance $Var^{(i)}(r_j)$ and mutually independent. We assume equal variances for each diversity branch. $\overline{\beta_{j,00}^2} = \overline{\beta_{00}^2}$ for $j = 1, \cdots, M$. Due to multipath effects, different $d_0^{''}$, $d_0^{'}$, d_0 combinations contribute different values of variances. If data "1" is transmitted, there are four kinds of variances shown in the following.

$$\begin{aligned}
Var^{(1)}(r_j) &= E\rho_0^2\{\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}} R_c^2(T_n + \tau_{nk})\exp(-\frac{T_n}{\Gamma} - \frac{\tau_{nk}}{\gamma}) \\
&\quad + \sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}} R_c^2(T_n + \tau_{nl} - T)\exp(-\frac{T_n}{\Gamma} - \frac{\tau_{nl}}{\gamma})\} + N_0/2 \\
&= E\rho_0^2 K_1(\underline{T}_n, \underline{\tau}_{nk}) + N_0/2 \quad \text{for } d_0 = 1,\ d_0^{'} = 1,\ d_0^{''} = 1 \qquad (11)
\end{aligned}$$

$$\begin{aligned}
Var^{(2)}(r_j) &= E\rho_0^2\{\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}} R_c^2(T_n + \tau_{nk})\exp(-\frac{T_n}{\Gamma} - \frac{\tau_{nk}}{\gamma} \\
&\quad + \sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}} [R_c(T_n + \tau_{nl} - T) - 2\theta_c(T_n + \tau_{nl} - T)]^2\exp(-\frac{T_n}{\Gamma} - \frac{-\tau_{nl}}{\gamma})\} + N_0/2 \\
&= E\rho_0^2 K_2(\underline{T}_n, \underline{\tau}_{nk}) + N_0/2 \quad \text{for } d_0 = 1,\ d_0^{'} = 1,\ d_0^{''} = -1 \qquad (12)
\end{aligned}$$

$$Var^{(3)}(r_j) = E\rho_0^2\{\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}} [R_c(T_n + \tau_{nk}) - 2\theta_c(T_n + \tau_{nk} - T)]^2\exp(-\frac{T_n}{\Gamma} - \frac{\tau_{nk}}{\gamma})$$

$$+\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}[R_c(T_n+\tau_{nl}-T)+2\theta_c(T_n+\tau_{nl}-T)]^2$$

$$\cdot\exp(-\frac{T_n}{\Gamma}-\frac{\tau_{nl}}{\gamma})\}+N_0/2$$

$$= E\rho_0^2K_3(\underline{T}_n,\underline{\tau}_{nk})+N_0/2 \quad \text{for } d_0=1,\ d_0'=-1,\ d_0''=1 \tag{13}$$

$$Var^{(4)}(r_j) = E\rho_0^2\{\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}}[R_c(T_n+\tau_{nk})-2\theta_c(T_n+\tau_{nk})]^2\exp(-\frac{T_n}{\Gamma}-\frac{\tau_{nk}}{\gamma})$$

$$+\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}R_c^2(T_n+\tau_{nl}-T)\exp(-\frac{T_n}{\Gamma}-\frac{\tau_{nl}}{\gamma})\}+N_0/2$$

$$= E\rho_0^2K_4(\underline{T}_n,\underline{\tau}_{nk})+N_0/2 \quad \text{for } d_0=1,\ d_0'=-1,\ d_0''=-1 \tag{14}$$

where $T_{min}=\min(T,\ T_m)$; $\rho_0^2=\frac{1}{2}\overline{\beta_{j,00}^2}$;

$$N_{c1} = \lfloor\Lambda T\rfloor,\quad N_{c2}=\lfloor 2\Lambda T\rfloor \tag{15}$$

$$N_{r1} = \begin{cases}1 & \text{if } N_{c1}=0\\ 0 & \text{if } N_{c1}>0\end{cases} \tag{16}$$

$$N_{r2} = \begin{cases}\lfloor\lambda T_{min}\rfloor & \text{if } N_{c1}=0\\ \lfloor\lambda(T_{min}-N_{c1}\Lambda)\rfloor & \text{if } N_{c1}>0 \text{ and } n=N_{c1}\\ \lfloor\frac{\lambda}{\Lambda}\rfloor & \text{if } N_{c1}>0 \text{ and } n<N_{c1}\end{cases} \tag{17}$$

$$N_{r3} = \begin{cases}\lfloor\lambda T\rfloor+1 & \text{if } N_{c1}=0\\ \lfloor(T-\frac{N_{c1}}{\Lambda})\lambda\rfloor+1 & \text{if } N_{c1}>0\end{cases} \tag{18}$$

$$N_{r4} = \begin{cases}\lfloor 2\lambda T\rfloor & \text{if } N_{c2}=0\\ \lfloor(2T-\frac{N_{c2}}{\Lambda})\lambda\rfloor & \text{if } N_{c2}>0\end{cases} \tag{19}$$

and $\rho_0^2=\frac{1}{2}\overline{\beta_{00}^2}$; $N_0/2$ is the two-side spectral density of AWGN.

(2) SFH system

Similarly, for SFH system, there are four kinds of combination of received signal before combinor due to different d_0'', d_0', d_0. We assume that data "1" is modulated by ω_1 band, data "0" by ω_2 band, and the system transmits signal with ω_1 band. After some algebraic manipulations similar to those in [8], we have

case 1 for $d_0=1,\ d_0'=1,\ d_0''=1$

$$y_{c1} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=0}^{N_{r2}}h_{j,nk}^{(1)}+\sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}q_{j,nl}^{(1)}+\eta_1 \tag{20}$$

$$y_{c2} = \eta_2 \tag{21}$$

case 2 for $d_0 = 1,\ d_0' = 1,\ d_0'' = -1$

$$y_{c1} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=0}^{N_{r2}} h_{j,nk}^{(1)} + \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}(2-\frac{T_n}{T}-\frac{\tau_{nl}}{T})q_{j,nl}^{(1)} + \eta_1 \quad (22)$$

$$y_{c2} = \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}(\frac{T_n}{T}+\frac{\tau_{nl}}{T}-1)q_{j,nl}^{(2)} + \eta_2 \quad (23)$$

case 3 for $d_0 = 1,\ d_0' = -1,\ d_0'' = 1$

$$y_{c1} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=0}^{N_{r2}}(1-\frac{T_n}{T}-\frac{\tau_{nk}}{T})h_{j,nk}^{(1)} + \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}(\frac{T_n}{T}+\frac{\tau_{nl}}{T}-1)q_{j,nl}^{(1)} + \eta_1 \quad (24)$$

$$y_{c2} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}}(\frac{T_n}{T}+\frac{\tau_{nk}}{T})h_{j,nk}^{(2)} + \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}}(2-\frac{T_n}{T}-\frac{\tau_{nl}}{T})q_{j,nl}^{(2)} + \eta_2 \quad (25)$$

case 4 for $d_0 = 1,\ d_0' = -1,\ d_0'' = -1$

$$y_{c1} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=0}^{N_{r2}}(1-\frac{T_n}{T}-\frac{\tau_{nk}}{T})h_{j,nk}^{(1)} + \eta_1 \quad (26)$$

$$y_{c2} = \sqrt{E}\sum_{n=0}^{N_{c1}}\sum_{k=N_{r1}}^{N_{r2}}(\frac{T_n}{T}+\frac{\tau_{nk}}{T})h_{j,nk}^{(2)} + \sqrt{E}\sum_{n=N_{c1}}^{N_{c2}}\sum_{l=N_{r3}}^{N_{r4}} q_{j,nl}^{(2)} + \eta_2 \quad (27)$$

where

$$h_{j,nk}^{(i)} = \beta_{j,nk}\cdot\cos[(\omega_0+\omega_i+\omega_{d_{nk}})(T_n+\tau_{nk})-\theta_{nk}], \quad (28)$$

$$q_{j,nl}^{(i)} = \beta_{j,nl}\cdot\cos[(\omega_0+\omega_i+\omega_{d_{nl}})(T-T_n-\tau_{nl})-\theta_{nl}] \quad (29)$$

and η_1, η_2 are Gaussian random variables with zero mean and variance $N_0/2$, where $N_0/2$ is the two-side spectral density of AWGN. Therefore, y_{c1} and y_{s1} are Gaussian random variables with zero mean and equal variances, so are y_{c2} and y_{s2}.

Without any diversity technique, the envelope detector output $e_1 = y_{c1}^2 + y_{s1}^2$ for ω_1 band, $e_2 = y_{c2}^2 + y_{s2}^2$ for ω_2 band, where y_{s1} is the same as y_{c1} except that $\cos(\cdot)$ is replaced by $\sin(\cdot)$ within $h_{j,nk}^{(i)}$ and $q_{j,nl}^{(i)}$. For the same reason, y_{s2} is similar to y_{c2}. When diversity techniques are considered in the receiver structure, we will denote the received signal before combinor as $e_{j,1}$ and $e_{j,2}$ for the jth diversity branch.

III Selective Combining Diversity

A. DS System with Selective Combinor

Because of the coherent correlator of DS system, each diversity branch output before the combinor is a specified signal, $\beta_{j,00}$, with a Gaussian noise. A selective combinor chooses the maximum output from those M diversity branches, described by $\beta_{max} = \max(\beta_{1,00}, \beta_{2,00}, \ldots, \beta_{M,00})$. The average error probability is

$$P_e = \frac{1}{4}\int_{\mathcal{I}_k}\int_{\beta^2_{max}} P_{b|\beta^2_{max},\tau_k} f(\beta^2_{max}) f(\mathcal{I}_k)\, d\beta^2_{max}\, d\mathcal{I}_k \tag{30}$$

From the derivation of conditional error probability in [8], we know that

$$\begin{aligned} P_{b|\beta^2_{max},\tau_k} &= \sum_{i=1}^{4}\frac{1}{2}erfc(\sqrt{\frac{\beta^2_{max}E}{2Var^{(i)}(r)}}) \\ &= \sum_{i=1}^{4}\frac{1}{2}erfc(\sqrt{\alpha_i}) \end{aligned} \tag{31}$$

where r is the output of chosen diversity branch, and $r = max(r_0, r_1, \ldots, r_M)$.

Furthermore,

$$P_e = \frac{1}{4}\int_{\mathcal{I}_k}\sum_{i=1}^{4}\int_{\alpha_i} P_{b|\alpha_i,\mathcal{I}_k} f(\alpha_i) f(\mathcal{I}_k)\, d\alpha_i\, d\mathcal{I}_k, \quad \alpha_i = \frac{\beta^2_{max}E}{2Var^{(i)}(r)} \tag{32}$$

The p.d.f of α_i that will be derived from [1] is

$$f(\alpha_i) = M\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{(k+1)b'_i}\exp(-\frac{\alpha_i}{b'_i}) \tag{33}$$

where

$$b'_i = \frac{\overline{\alpha_i}}{k+1}$$

Consequently, the error probability is

$$P_e = \frac{1}{4}\int_{\mathcal{I}_k}\sum_{i=1}^{4}\int_{\alpha_i}\frac{1}{2}erfc(\sqrt{\alpha_i})M\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{(k+1)b'_i}\exp(-\frac{\alpha_i}{b'_i})f(\mathcal{I}_k)\, d\alpha_i\, d\mathcal{I}_k$$

From [2], we know

$$\int_0^\infty \frac{1}{2}erfc(\sqrt{\gamma_b})\frac{1}{b}\exp(-\frac{\gamma_b}{b}) = \frac{1}{2}[1-\sqrt{\frac{b}{1+b}}]$$

$$\text{Then } P_e = \frac{M}{4}\int_{\mathcal{I}_k}\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{(k+1)}\sum_{i=1}^{4}\frac{1}{2}[1-\sqrt{\frac{b_i'}{1+b_i'}}]f(\mathcal{I}_k)d\mathcal{I}_k \tag{34}$$

That is,

$$P_e = \frac{M}{8}\int_{\mathcal{I}_k}\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{(k+1)}\sum_{i=1}^{4}\{1-\sqrt{\frac{2\frac{E}{N_0}\rho_0^2}{2\frac{E}{N_0}\rho_0^2[1+(k+1)K_i(\mathcal{I}_k)]+k+1}}\}f(\mathcal{I}_k)d\mathcal{I}_k \tag{35}$$

B. SFH System with Selective Combinor

The outputs of SFH system receiver before combinor for jth diversity branch are $e_{j,1}$ and $e_{j,2}$. The selective combinor is equivalent to choosing the largest output of those envelope detectors in ω_1, ω_2 bands respectively in Figure 5.

We represent the combinor as

$$e_1 = max(e_{1,1}, e_{2,1}, \ldots, e_{M,1}) \quad e_2 = max(e_{2,1}, e_{2,2}, \cdots\cdots\cdots, e_{M,2}) \tag{36}$$

where $e_{j,1}$, $e_{j,2}$ both are chi-square random variables with degree of freedom 2, Their p.d.f.s are

$$f(e_{j,1}) = \frac{1}{2\sigma_1^2}\exp(-\frac{e_{j,1}}{2\sigma_1^2}), \quad f(e_{j,2}) = \frac{1}{2\sigma_2^2}\exp(-\frac{e_{j,2}}{2\sigma_2^2})$$

Then the p.d.f. of e_1 and e_2 can be derived as (33).

$$f(e_1) = M\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{2\sigma_1^2}\exp(-\frac{e_1(k+1)}{2\sigma_1^2}) \tag{37}$$

$$f(e_2) = M\sum_{n=0}^{M-1}\binom{M-1}{n}\frac{(-1)^n}{2\sigma_2^2}\exp(-\frac{e_2(n+1)}{2\sigma_2^2}) \tag{38}$$

The error probability is derived by

$$\begin{aligned} f(e_2 > e_1) &= \int_{e_1=0}^{\infty}\int_{e_2=e_1}^{\infty} f(e_1, e_2)\, de_2\, de_1 \\ &= M^2\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{2\sigma_1^2}\sum_{n=0}^{M-1}\binom{M-1}{n}\frac{(-1)^n}{2\sigma_2^2} \\ &\quad \cdot\int_{e_1=0}^{\infty}\int_{e_2=e_1}^{\infty}\exp(-\frac{e_2(n+1)}{2\sigma_2^2})\exp(-\frac{e_1(k+1)}{2\sigma_1^2})\, de_2\, de_1 \\ &= M^2\sum_{k=0}^{M-1}\binom{M-1}{k}\frac{(-1)^k}{k+1}\sum_{n=0}^{M-1}\binom{M-1}{n}\frac{(-1)^n}{n+1}\frac{\frac{\sigma_2^2}{n+1}}{\frac{\sigma_1^2}{k+1}+\frac{\sigma_2^2}{n+1}} \end{aligned} \tag{39}$$

For example, M=2

$$
\begin{aligned}
P_e &= 4\sum_{k=0}^{1}\frac{(-1)^k}{k+1}\sum_{n=0}^{1}\frac{(-1)^n}{n+1}\frac{\frac{\sigma_2^2}{n+1}}{\frac{\sigma_1^2}{k+1}+\frac{\sigma_2^2}{n+1}} \\
&= 5\frac{\sigma_2^2}{\sigma_1^2+\sigma_2^2} - 2\frac{\sigma_2^2}{2\sigma_1^2+\sigma_2^2} - 4\frac{\sigma_2^2}{\sigma_1^2+2\sigma_2^2} \qquad (40)
\end{aligned}
$$

IV Equal-Gain Combining Diversity

A. DS System with Equal-gain Combinor

The output of equal-gain combinor is $r = r_1 + r_2 + \ldots + r_M$, where r_j, $j = 1, \ldots, M$, are the outputs of coherent correlation receiver before the combinor for each diversity branch. We assume that signal in each branch must be coherent in phase before combinor. That is, signal needs to pass through a cophasing circuit to keep coherence. The analysis is complicated for $M > 2$. Being most interested in obtaining the performance of systems with two diversities, we derive the error probability for $M = 2$. Let $z = \beta_{1,00} + \beta_{2,00}$, where $\beta_{1,00}$, $\beta_{2,00}$ denote the coherent received first arrival in the two diversities. The error probability will be

$$
P_e = \sum_{i=1}^{4}\int_{z=0}^{\infty}\frac{1}{2}erfc(\sqrt{\frac{Ez^2}{4Var^{(i)}(r)}})f(z)\,dz \qquad (41)
$$

where

$$
f(z) = \int_0^\infty \frac{(z-w)}{\rho_1^2}\cdot\exp(-\frac{(z-w)^2}{2\rho_1^2})\cdot\frac{w}{\rho_2^2}\exp(-\frac{w^2}{2\rho_2^2})\cdot u(z-w)\,dw \qquad (42)
$$

and $\rho_1^2 = \frac{1}{2}\overline{\beta_{1,00}^2}$, $\rho_2^2 = \frac{1}{2}\overline{\beta_{2,00}^2}$. $u(t)$ is the step function, $u(t) = 1$ for $t > 1$.

B. SFH System with Equal-gain Combinor

The equal-gain combining for SFH system is to sum all the ω_1 band outputs, $e_{j,1}$, where $j = 1, 2, \cdots, M$, to become z_1, so are the ω_2 band outputs. Figure 6 depicts this structure.

$$z_1 = \sum_{j=1}^{M} e_{j,1} \quad z_2 = \sum_{j=1}^{M} e_{j,2}$$

We know that those $e_{j,1}$, and $e_{j,2}$, $j = 1, 2, \ldots, M$, are chi-square distributions with degree of freedom 2, such that z_1, z_2 are chi-square distributions with degree of freedom $2M$. That is,

$$f(e_{j,h}) = \frac{1}{2\xi_{j,h}^2} \exp(-\frac{e_{j,h}}{2\xi_{j,h}^2}), \quad h = 1, 2 \text{ denoting the } h\text{th frequency band}$$

Let $\xi_1^2 = \sum_{j=1}^{M} \xi_{j,1}^2$, be the sum of variances, where $\xi_{j,1}^2$ is the variance of the I or Q channel output of the jth diversity with respect to the ω_1 band, and $\xi_2^2 = \sum_{j=1}^{M} \xi_{j,2}^2$. Let

$$z_1' = \frac{z_1}{2\xi_1^2}, \quad z_2' = \frac{z_2}{2\xi_2^2}$$

To derive the bit error probability, we need to know the probability of $z_1 - z_2 < 0$. The inequality is equivalent to the ratio $z_1/z_2 < 1$, such that

$$\frac{z_1'}{z_2'} < \frac{\xi_2^2}{\xi_1^2}$$

Let $R = z_1'/z_2'$. The random variable R is a central F-distribution random variable. The p.d.f. is

$$f_F(R = r) = \frac{\Gamma(2M)}{\Gamma(M)\Gamma(M)} \frac{r^{M-1}}{(1+r)^{2M}} = \frac{(2M-1)!}{(M-1)!^2} \frac{r^{M-1}}{(1+r)^{2M}} \tag{43}$$

where $\Gamma(M) = (M-1)!$. Then,

$$P_e = \int_{\underline{\mathcal{I}}_k} \int_{r=0}^{\frac{\xi_2^2}{\xi_1^2}} \frac{(2M-1)!}{\{(M-1)!\}^2} \frac{r^{M-1}}{(1+r)^{2M}} f(\underline{\mathcal{I}}_k)\, dr\, d\underline{\mathcal{I}}_k \tag{44}$$

For M=2 that is most interesting to us, we get

$$P_e = \frac{3\xi_1^2(\xi_2^2)^2 + (\xi_2^2)^3}{(\xi_1^2 + \xi_2^2)^3} \tag{45}$$

V Diversity Techniques Plus BCH Codes

BCH (255, 247) code with one error-correcting and BCH (511, 493) code with two error-correcting are investigated in this paper. Their code rates which 0.968 for BCH(255, 247) and 0.965 for BCH(511, 493) are almost the same. Since BCH code is used to correct random errors, the possible burst errors which naturally come from Rayleigh fading channels need the interleaving technique to overcome. We assume that the interleaver has infinity depth for the simplicity of analysis.

For an $(n,\ k)$ block code, where n denotes code length and k the information bits. The error probability of information bit, P_b, is

$$P_b \simeq \frac{1}{n} \sum_{i=t+1}^{n} i \begin{pmatrix} n \\ i \end{pmatrix} P_e^i (1 - P_e)^{n-i}$$

where P_e is the error probability of encoded channel code; t is the minimum error-correcting capability. We already derived the P_e for diversity techniques in the preceding sections.

VI Numerical Results

We assume that the data bit rate ranges from 1 Mbps to 10 Mbps and the spreading sequences are maximum-length sequences with periods $L = 15$ and 127 while these lengths are popular for some wireless personal communication applications, especially those bandwidth efficient applications

We establish these codes to evaluate $\theta_c(\tau_k)$, defined on spreading sequence delay along with the autocorrelation function. We assume ρ_0^2=0.5 according to [13] such that $\overline{\beta_{j,00}^2}$=1.

The average error probability P_e of DS and SFH systems involve integration over $\{\underline{T}_n\}$, $\{\underline{\tau}_{nk}\}$ which is difficult to numerically evaluate the multiple integrals. However, we numerically illustrate the analytic performance of both systems by choosing some "typical" channel parameters. Then, we substitute the expected value of each time delay T_n, τ_{nk} to observe the error probabilities of DS and SFH systems.

We propose three kinds of channel models in Table 1 to evaluate the performances. Model A describe the multipaths arriving without clusters, shown in Figure 2 (d). Model B describe the multipaths with a cluster about 100ns time-delay. Model C describe the multipaths with three clusters which occur at 50, 100, 150ns time-delays. The comparison of attenuation dB for arriving paths and number of receiced paths to three channel models are listed in Table 2. By the precise description of delay paths in the three models, we can understand much more about the differences of bit error probability according to different indoor environments.

In Figure 7, comparing SC to EGC of 10 Mbps uncoded DS system with two diversity, EGC has about 3 dB gain to SC over Model A, B, C. In Figure 8, because of a delay path arrived within a chip time, Model C degrade obviously the performance of 1 Mbps DS system even that the period of spreading sequence is 127. In Figure 9, 10M bps SFH system with SC or EGC diversity get nearly the same performance. However, 1 Mbps SFH system with SC has better performance than EGC at low signal-to-noise ratio, shown in Figure 10. For SFH system with 1M bps bit rate, more denser or more clustering arrivals do not defintely bring worser performance at low signal-to-noise ratio in Figure 10.

Figure 11 and Figure 13 demonstrated coded 10 Mbps DS system with SC or EGC diversity obviously improve their performance over Model A, B, C. Specially, DS system with diversity, L=127 and BCH (511, 493) code have bit error probability lower than 10^{-9} at high signal-to-noise ratio. Also, we notice that DS system with double error-correcting BCH (511, 493) code has much better performance than coded one with single error-correcting BCH (255, 247) code while both have almost equal code rate. In Figure 12 and Figure 14, coded 1 Mbps DS system have higher bit error probabilities for Model C.

From Figure 15 to Figure 18 show the improved performance of coded SFH system for 1 Mbps and 10 Mbps. Similarly, 1 Mbps SFH systems with BCH (511,493) code possess significant performance improvement . The 10 Mbps SFH system, which suffers from intersymbol-interference, retains the bit error probability around 10^{-2} even with diversity techniques.

VII Conclusion

Performance of DS and SFH systems with diversity reception and BCH code has been investigated. We have derived the bit error probabilities of DS and SFH systems with EGC and SC diversities respectively. The numerical results demonstrate that employing BCH (511, 493) code provides much improvement in bit error probability while DS and SFH systems transmit 1 Mbps and 10 Mbps. From severe to light multipath fading, BCH (511, 493) with EGC or SC diversities still have much better performance. When DS system with low processing gain, for example L=15, diversity techniques can still improve performance. However, from the numerical results, EGC and SC diversities have nearly the same error probability curves over Rayleigh multipath fading channels. We also demonstrated that DS system with higher processing gain, for example 127, will much degrade the performance while any delay path arriving within a chip time.

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Table 1: Channel Models Parameters

	$\frac{1}{\lambda}$	$\frac{1}{\Lambda}$	γ	Γ
Model A	10 ns		20 ns	
Model B	10 ns	100 ns	20 ns	43 ns
Model C	5 ns	50 ns	20 ns	36 ns

Table 2: Attenuation and path numbers; a denote the attenuation dB of the received path at time delay= 50, 100, 150 and 200ns, N_L denote the numbers of path received at each time delay.

	50ns		100ns		150ns		200ns		The attenuation of the first cluster, $\overline{\beta_{10}^2}$
	a	N_L	a	N_L	a	N_L	a	N_L	
Model A	-10.85	5	-21.71	10	-32.57	15	-43.43	20	
Model B	-10.85	5	-10.1	10	-20.96	15	-31.81	20	-10.1 dB
Model C	-6.3	10	-12.06	20	-18.9	30	-29.75	100	-6.3 dB

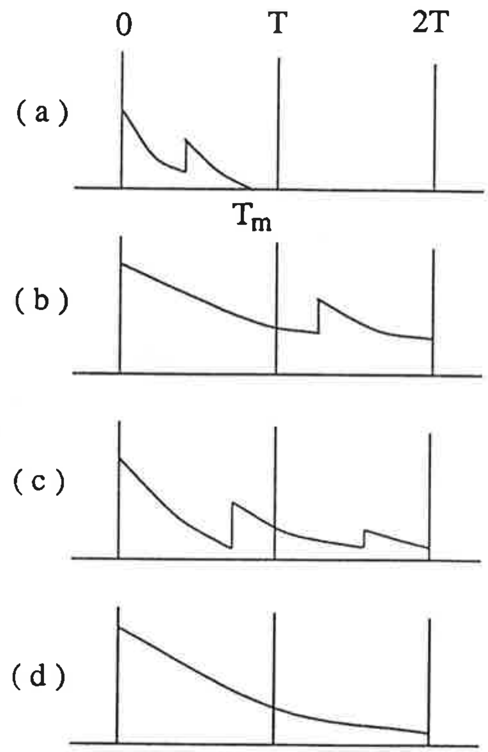

Figure 2: Descriptions of clusters, (a) multipath delay within a symbol time, (b) clusters arrived within $[T, 2T]$, (c) clusters arrived in $[0, T]$, (d) no clusters arrived.

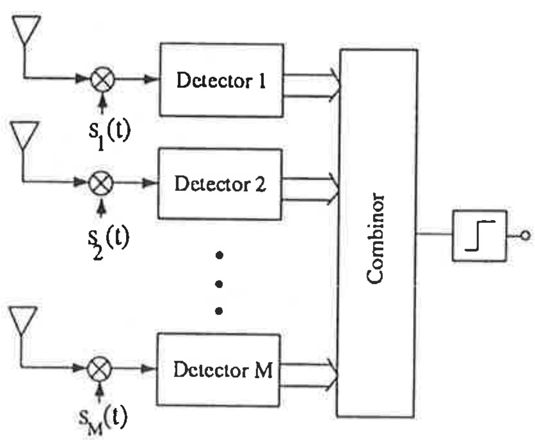

Figure 3: Receiver structure for ~~DS~~ and SFH systems

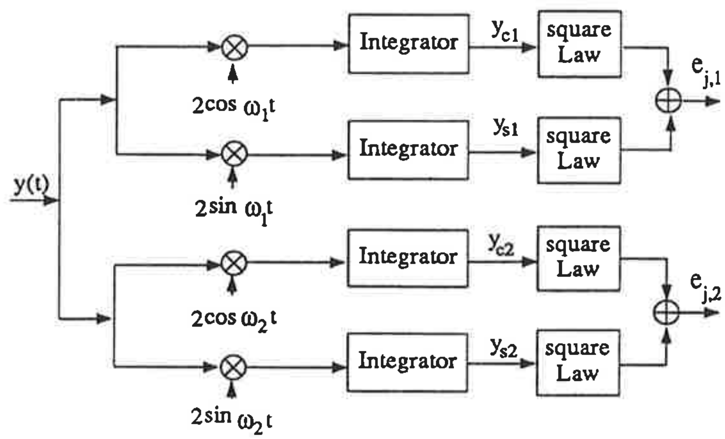

Figure 4: Envelope detector for SFH system

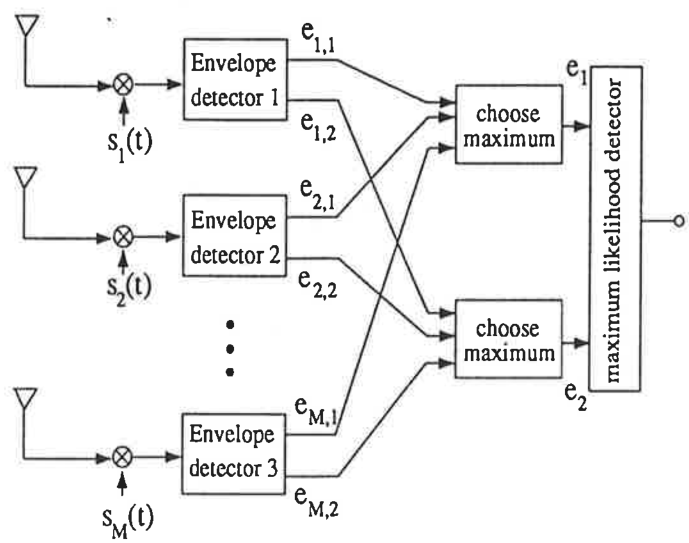

Figure 5: Selective diversity combining for SFH system

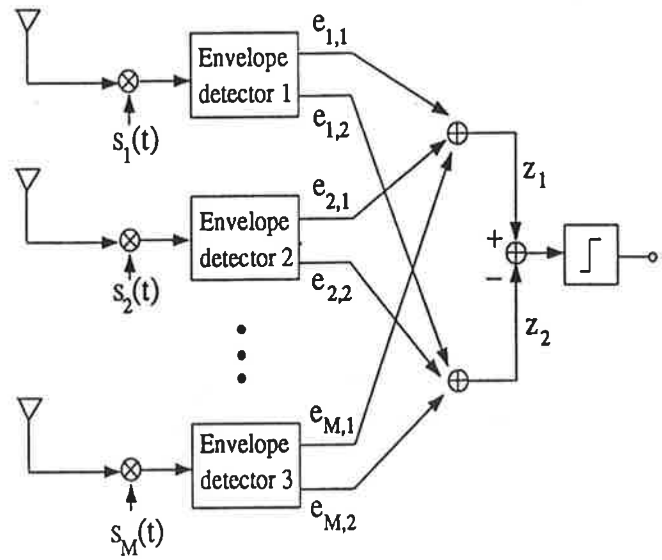

Figure 6: Equal-gain diversity combining for SFH system

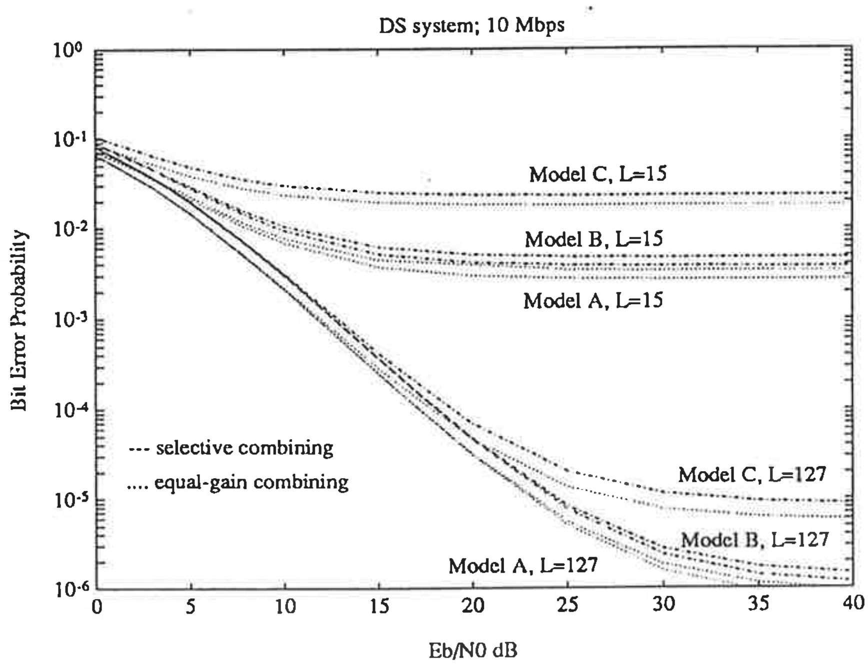

Figure 7: Bit error probability of DS system with selective and eaual-gain diversities for bit rate 10 Mbps over Model A, B, C. L is the period of spreading sequence of DS system. M=2 branches of diversity.

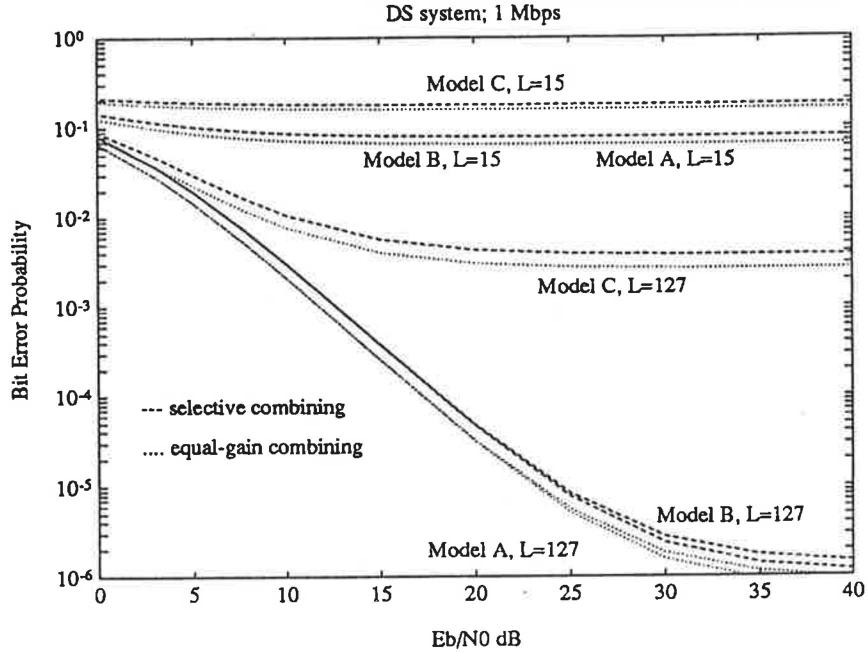

Figure 8: Bit error probability of DS system with selective and eaual-gain diversities for bit rate 1 Mbps over Model A, B, C. L is the period of spreading sequence of DS system. M=2 branches of diversity.

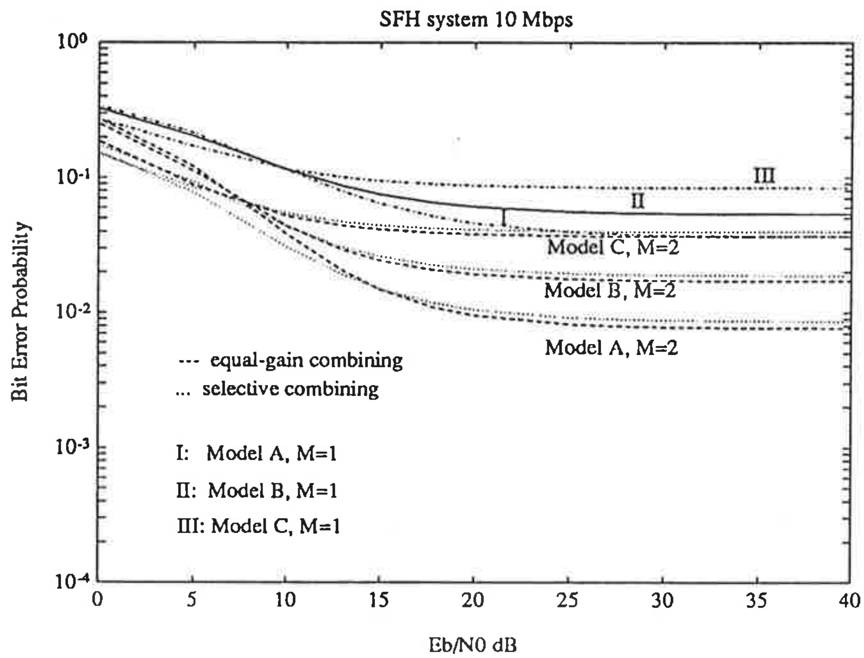

Figure 9: Bit error probability of SFH system with selective and equal-gain diversities for bit rate 10 Mbps over Model A, B, C. M=2 branches of diversity.

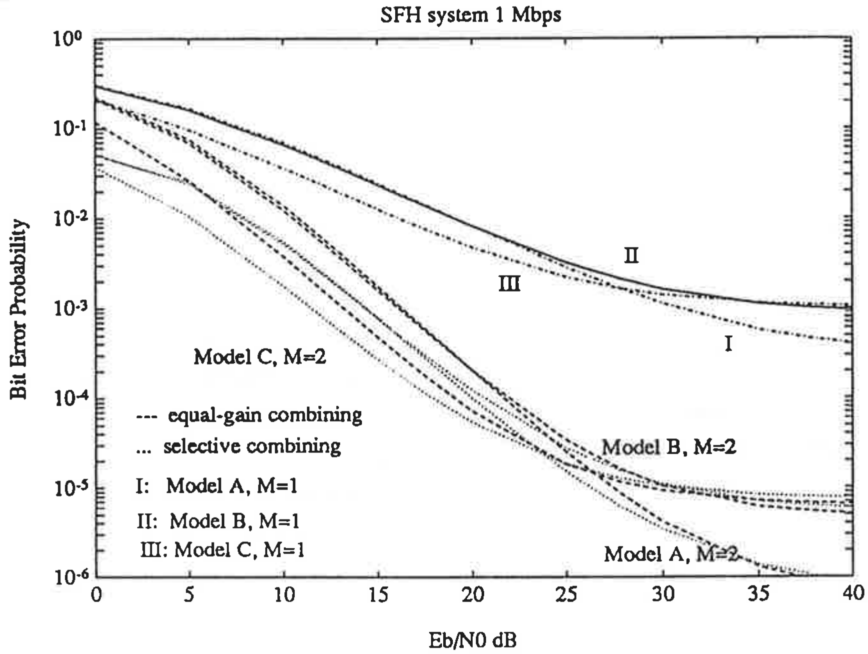

Figure 10: Bit error probability of DS system with selective and equal-gain diversities for bit rate 1 Mbps over Model A, B, C. M=2 branches of diversity.

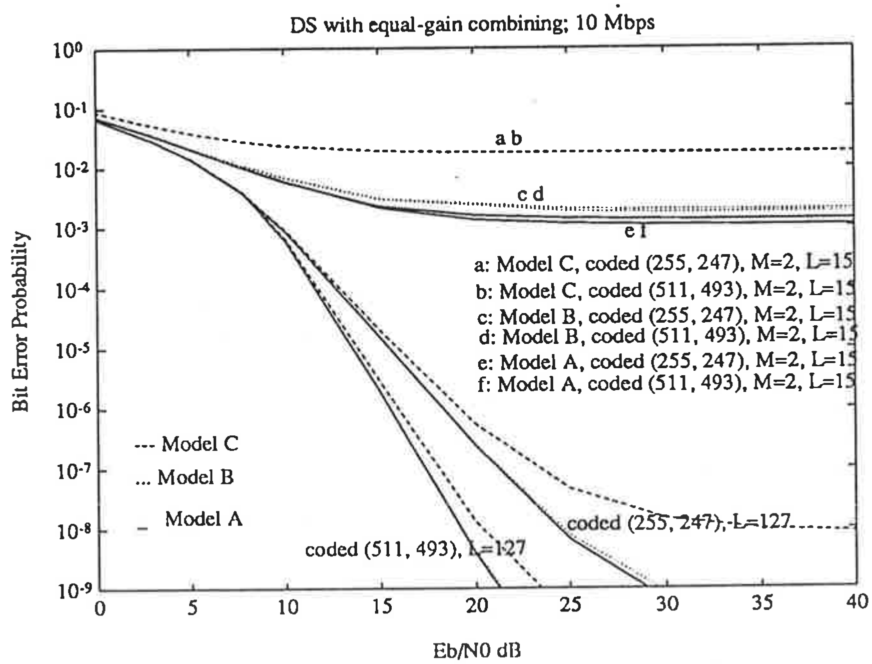

Figure 11: Bit error probability of DS system with equal-gain diversity and FEC for bit rate 10 Mbps over Model A, B, C. L is the period of spreading sequence. M=2 branches of diversity.

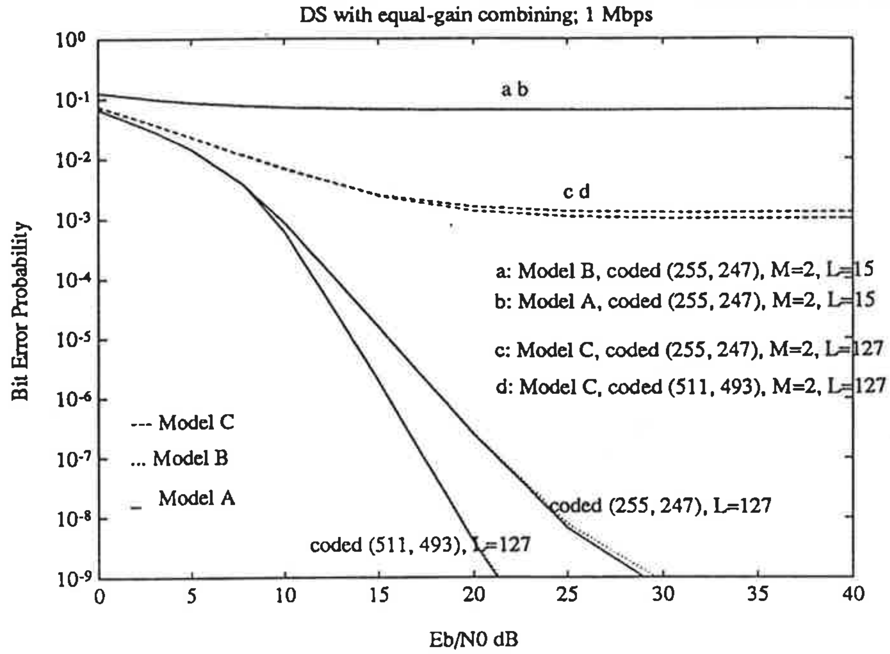

Figure 12: Bit error probability of DS system with equal-gain diversity and FEC for bit rate 1 Mbps over Model A, B, C. L is the period of spreading sequence. M=2 branches of diversity.

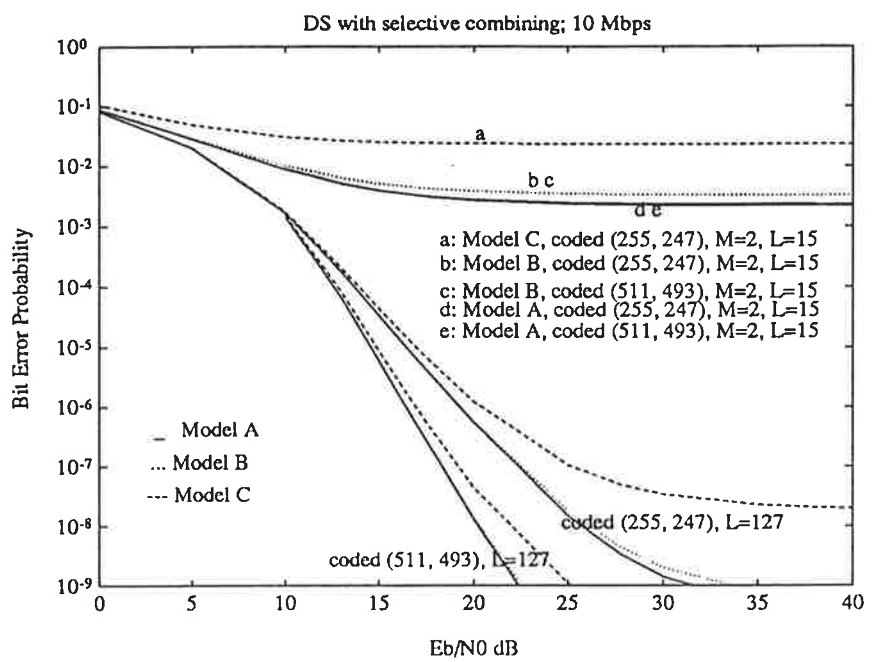

Figure 13: Bit error probability of DS system with selective diversity and FEC for bit rate 10 Mbps over Model A, B, C. L is the period of spreading sequence. M=2 branches of diversity.

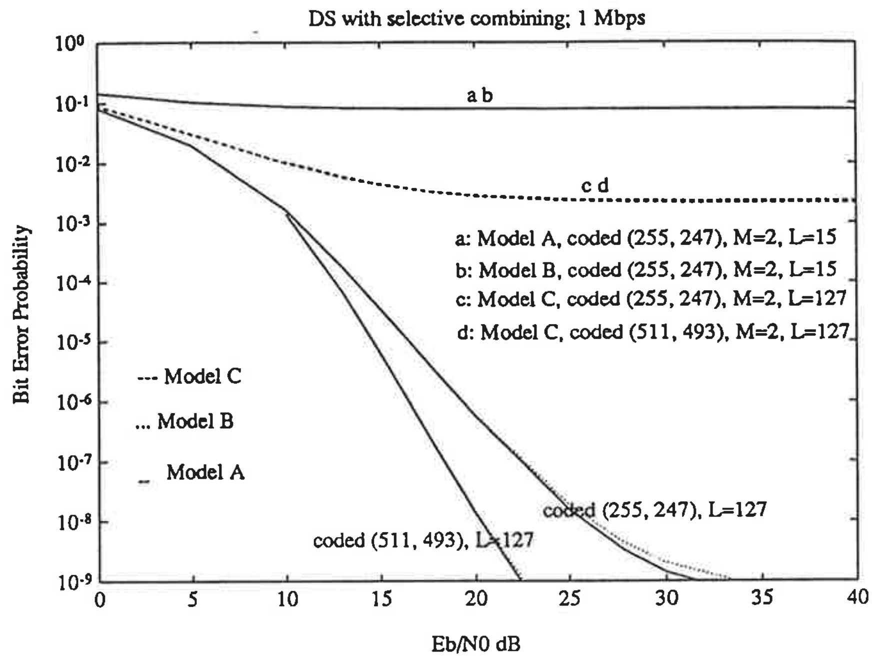

Figure 14: Bit error probability of DS system with selective diversity and FEC for bit rate 1 Mbps over Model A, B, C. $L$is the period of spreading sequence. M=2 branches of diversity.

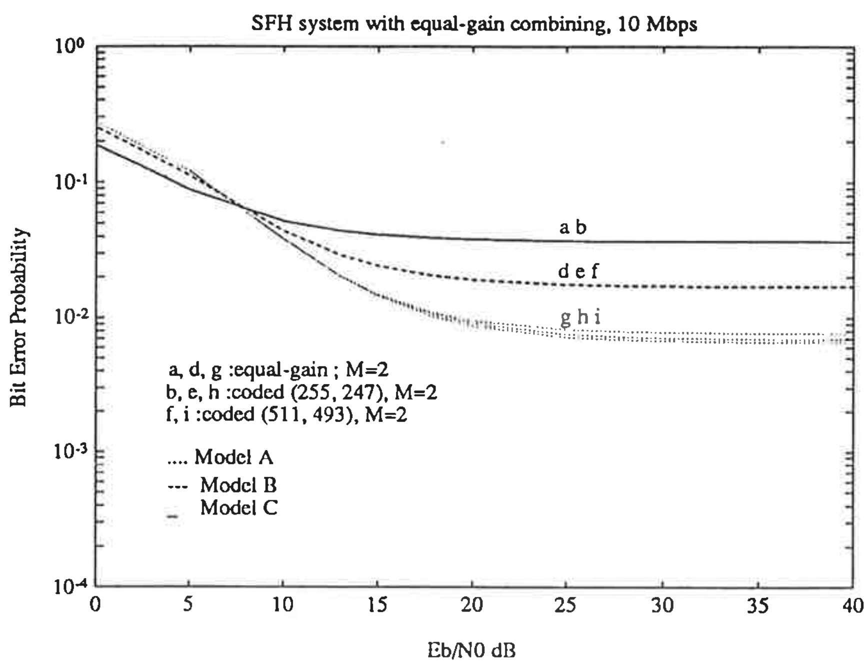

Figure 15: Bit error probability of SFH system with equal-gain diversity and FEC for bit rate 10 Mbps over Model A, B, C. M=2 branches of diversity.

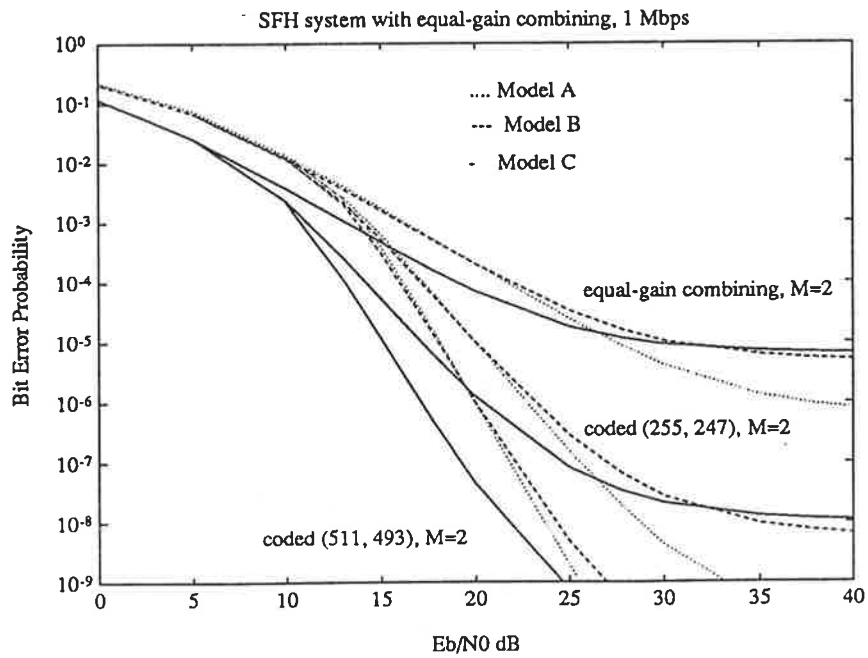

Figure 16: Bit error probability of SFH system with equal-gain diversity and FEC for bit rate 1 Mbps over Model A, B, C. M=2 branches of diversity.

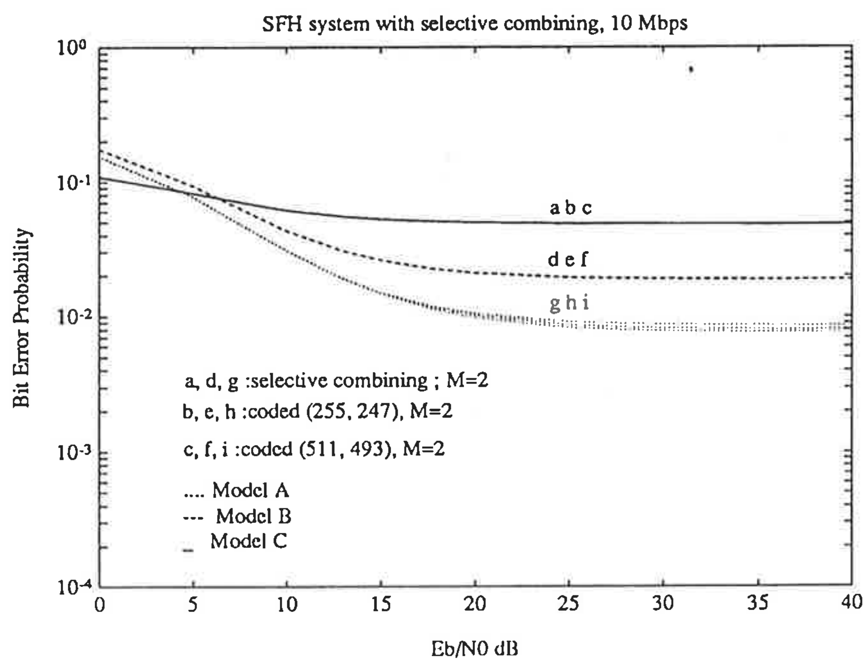

Figure 17: Bit error probability of SFH system with selective diversity and FEC for bit rate 10 Mbps over Model A, B, C. M=2 branches of diversity.

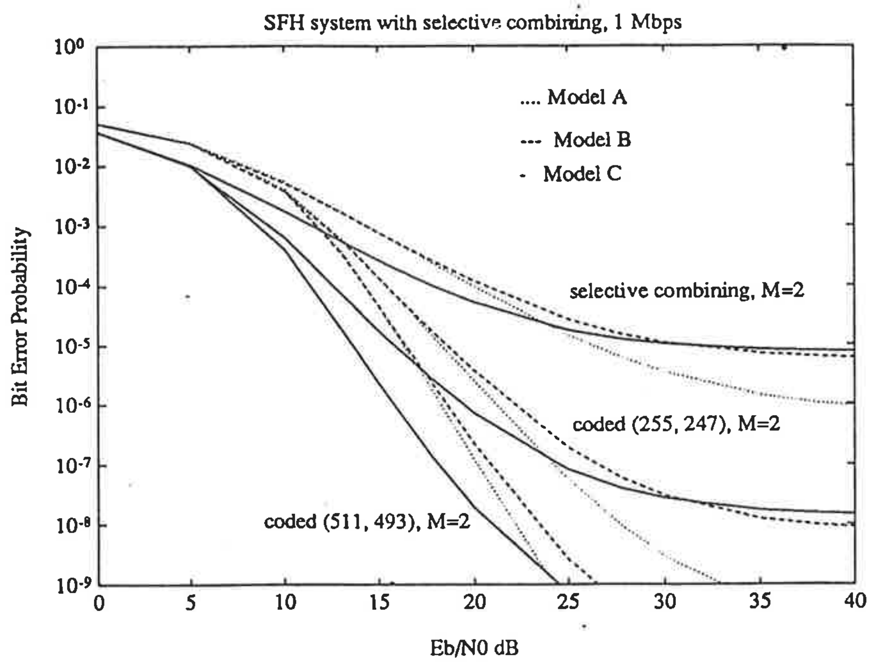

Figure 18: Bit error probability of SFH system with selective diversity and FEC for bit rate 1 Mbps over Model A, B, C. M=2 branches of diversity.