Chapter 2
Performance of Digital Communication Over Fading Channels

In this chapter, bit error rate (BER) performance of some of digital modulation schemes and different wireless communication techniques is evaluated in additive white Gaussian noise (AWGN) and fading channels. Further, the BER performance of different diversity techniques such as selective diversity, EGC, and MRC is also evaluated in Rayleigh fading channel.

2.1 BER Performance of Different Modulation Schemes in AWGN, Rayleigh, and Rician Fading Channels

In this section, the effect of fading is evaluated on different modulation schemes. The bit error probability P_{b} often referred to as BER is a better performance measure to evaluate a modulation scheme. The BER performance of any digital modulation scheme in a slow flat fading channel can be evaluated by the following integral

$$P_{\mathrm{b}} = \int_{0}^{\infty} P_{\mathrm{b,\,AWGN}}(\gamma) P_{\mathrm{d}f}(\gamma) \mathrm{d}\gamma \tag{2.1}$$

where $P_{\mathrm{b,\,AWGN}}(\gamma)$ is the probability of error of a particular modulation scheme in AWGN channel at a specific signal-to-noise ratio $\gamma = h^2 \frac{E_{\mathrm{b}}}{N_0}$. Here, the random variable h is the channel gain, $\frac{E_{\mathrm{b}}}{N_0}$ is the ratio of bit energy to noise power density in a non-fading AWGN channel, the random variable h^2 represents the instantaneous power of the fading channel, and $P_{\mathrm{d}f}(\gamma)$ is the probability density function of γ due to the fading channel.

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2.1.1 BER of BPSK Modulation in AWGN Channel

It is known that the BER for M-PSK in AWGN channel is given by [1]

$$\mathrm{BER}_{\mathrm{M-PSK}} = \frac{2}{\max(\log_2 M, 2)} \sum_{k=1}^{\max(M/4,1)} Q\left(\sqrt{\frac{2E_{\mathrm{b}} \log_2 M}{N_0}} \sin\frac{(2k-1)\pi}{M}\right) \tag{2.2}$$

For coherent detection of BPSK, Eq. (2.2) with $M = 2$ reduces to

$$\mathrm{BER}_{\mathrm{BPSK}} = Q\left(\sqrt{\frac{2E_{\mathrm{b}}}{N_0}}\right) \tag{2.3}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{y^2}{2}\right) \mathrm{d}y$$

Equation (2.3) can be rewritten as

$$\mathrm{BER}_{\mathrm{BPSK,\,AWGN}} = \frac{1}{2} \mathrm{erfc}\left(\sqrt{\frac{E_{\mathrm{b}}}{N_0}}\right) \tag{2.4}$$

where erfc is the complementary error function and $\frac{E_{\mathrm{b}}}{N_0}$ is the bit energy-to-noise ratio. The erfc can be related to the Q function as

$$Q(x) = \frac{1}{2} \mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right) \tag{2.5}$$

For large $\frac{E_{\mathrm{b}}}{N_0}$ and $M > 4$, the BER expression can be simplified as

$$\mathrm{BER}_{\mathrm{M-PSK}} = \frac{2}{\log_2 M} Q\left(\sqrt{\frac{2E_{\mathrm{b}} \log_2 M}{N_0}} \sin\frac{\pi}{M}\right) \tag{2.6}$$

2.1.2 BER of BPSK Modulation in Rayleigh Fading Channel

For Rayleigh fading channels, h is Rayleigh distributed, h^2 has chi-square distribution with two degrees of freedom. Hence,

$$P_{\mathrm{d}f}(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \tag{2.7}$$

where $\bar{\gamma} = \frac{E_\mathrm{b}}{N_0} E[h^2]$ is the average signal-to-noise ratio. For $E[h^2] = 1, \bar{\gamma}$ corresponds to the average $\frac{E_\mathrm{b}}{N_0}$ for the fading channel.

By using Eqs. (2.1) and (2.3), the BER for a slowly Rayleigh fading channel with BPSK modulation can be expressed as [2, 3]

$$\mathrm{BER}_{\mathrm{BPSK,\,Rayleigh}} = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right) \tag{2.8}$$

For $E[h^2] = 1$, Eq. (2.8) can be rewritten as

$$\mathrm{BER}_{\mathrm{BPSK,\,Rayleigh}} = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{E_\mathrm{b}}{N_0}}{1+\frac{E_\mathrm{b}}{N_0}}}\right) \tag{2.9}$$

2.1.3 BER of BPSK Modulation in Rician Fading Channel

The error probability estimates for linear BPSK signaling in Rician fading channels are well documented in [4] and is given as

$$P_{\mathrm{b,\,Rician}} = Q_1(a,b) - \frac{1}{2}\left[1 + \sqrt{\frac{d}{d+1}}\right] \exp\left(-\frac{a^2+b^2}{2}\right) I_0(\mathrm{ab}) \tag{2.10}$$

where

$$a = \left[\sqrt{\frac{K_r^2\left[1+2d-2\sqrt{d(d+1)}\right]}{2(d+1)}}\right],\ b = \left[\sqrt{\frac{K_r^2\left[1+2d+2\sqrt{d(d+1)}\right]}{2(d+1)}}\right]$$

$$K_r = \frac{\alpha^2}{2\sigma^2},\ d = \sigma^2 \frac{E_\mathrm{b}}{N_0}.$$

The parameter K_r is the Rician factor. The $Q_1(a,b)$ is the Marcum Q function defined [2] as

$$\begin{aligned} Q_1(a,b) &= \exp\left(-\frac{a^2+b^2}{2}\right) \sum_{l=0}^{\infty} \left(\frac{a}{b}\right)^l I_0(\mathrm{ab}), \quad b \geq a > o \\ Q_1(a,b) &= Q(b-a), \quad b \gg 1 \text{ and } b \gg b-a \end{aligned} \tag{2.11}$$

The following MATLAB program is used to illustrate the BER performance of BPSK in AWGN, Rayleigh, and Rician fading channels.

Program 2.1 Program for computing the BER for BPSK modulation in AWGN, Rayleigh, and Rician fading channels

```
clear all;
clc;
M=2;K=5;DIVORDER= 1;
EbNo = 0:5:35;
BER_Ray = BERFADING(EbNo, 'psk', M, DIVORDER);
BER_Rician = BERFADING(EbNo, 'psk', 2, 1, K);
BER = BERAWGN(EbNo, 'psk', M,'nondiff');
semilogy(EbNo,BER,'o-');
hold on
semilogy(EbNo,BER_Ray,'*-');
semilogy(EbNo,BER_Rician,'+-');grid on
legend('AWGN channel','Rayleighchannel','Rician channel');%, 'Rayleigh-
Simulation');
xlabel('Eb/No, dB');
ylabel('Bit Error Rate');
axis([ 0 35 1e-5 1 ])
```

The BER performance resulted from the above MATLAB program for BPSK in the AWGN, Rayleigh, and Rician ($K = 5$) channels is depicted in Fig. 2.1.

From Fig. 2.1, for instance, we can see that to obtain a BER of 10^{-4}, using BPSK, an AWGN channel requires $\frac{E_b}{N_0}$ of 8.35 dB, Rician channel requires $\frac{E_b}{N_0}$ of 20.5 dB, and a Rayleigh channel requires $\frac{E_b}{N_0}$ of 34 dB. It is clearly indicative of the large performance difference between AWGN channel and fading channels.

2.1.4 BER Performance of BFSK in AWGN, Rayleigh, and Rician Fading Channels

In BPSK, the receiver provides coherent phase reference to demodulate the received signal, whereas the certain applications use non-coherent formats avoiding a phase reference. This type of non-coherent format is known as binary frequency-shift keying (BFSK).

The BER for non-coherent BFSK in slow flat fading Rician channel is expressed as [3]

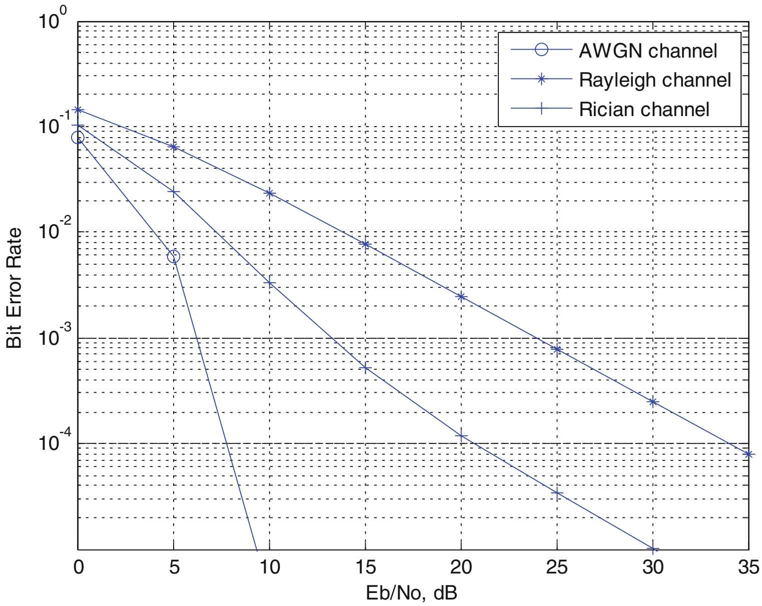

Fig. 2.1 BER performance of BPSK in AWGN, Rayleigh, and Rician fading channels

$$P_{\mathrm{b,\,BFSK(Ric)}} = \frac{1+K_r}{2+2K_r+\bar{\gamma}} \exp\left(-\frac{K_r\bar{\gamma}}{2+2K_r+\bar{\gamma}}\right) \tag{2.12}$$

where K_r is the power ratio between the LOS path and non-LOS paths in the Rician fading channel.

Substituting $K_r = \infty$ in Eq. (2.8), the BER in AWGN channel for non-coherent BFSK can be expressed as

$$P_{\mathrm{b,\,AWGN}} = \frac{1}{2}\exp\left(-\frac{E_\mathrm{b}}{2N_0}\right) \tag{2.13}$$

whereas substitution of $K_r = 0$ leads to the following BER expression for slow flat Rayleigh fading channels using non-coherent BFSK modulation

$$P_{\mathrm{b,\,BFSK(Ray)}} = \frac{1}{2+\bar{\gamma}} \tag{2.14}$$

The following MATLAB program is used to illustrate the BER performance of non-coherent BFSK modulation in AWGN, Rayleigh, and Rician fading channels.

Program 2.2 Program for computing the BER for BFSK modulation in AWGN, Rayleigh and Rician fading channels

```
clear all;
clc;
Eb_N0_dB = [0:5:35];
K=5;
EbN0Lin = 10.^(Eb_N0_dB/10);
theoryBerAWGN = 0.5*exp(-0.5*EbN0Lin); % theoretical ber
for i=1:8
theoryBer(i) = 1/(EbN0Lin(i)+2);
theoryberric(i)=((1+K)/(EbN0Lin(i)+2+2*K))*exp(-
K*EbN0Lin(i)/(EbN0Lin(i)+2+2*K));
end
semilogy(Eb_N0_dB,theoryBerAWGN,'-o','LineWidth',2);
hold on
semilogy(Eb_N0_dB,theoryBer,'-*','LineWidth',2);
semilogy(Eb_N0_dB,theoryberric,'-+','LineWidth',2);
axis([0 35 10^-6 0.5])
grid on
legend('AWGN channel','Rayleighchannel','Rician channel');%, 'Rayleigh-
Simulation');
xlabel('Eb/No, dB');
ylabel('Bit Error Rate');
```

The BER performance resulted from the MATLAB program 2.2 for non-coherent BFSK in the AWGN, Rayleigh, and Rician ($K = 5$) channels is depicted in Fig. 2.2.

2.1.5 *Comparison of BER Performance of BPSK, QPSK, and 16-QAM in AWGN and Rayleigh Fading Channels*

The BER of gray-coded M-QAM in AWGN channel can be more accurately computed by [5]

$$\mathrm{BER}_{16\mathrm{QAM,\,AWGN}} \approx \frac{4}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right)\sum_{i=1}^{\frac{\sqrt{M}}{2}} Q\left(\sqrt{\frac{3\log_2 \mathrm{M}E_b}{(M-1)N_0}}\right) \tag{2.15}$$

In Rayleigh fading, the average BER for M-QAM is given by [6]

$$\mathrm{BER}_{\mathrm{MQAM,\,AWGN}} \approx \frac{2}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right)\sum_{i=1}^{\frac{\sqrt{M}}{2}}\left(1-\sqrt{\frac{1.5(2i-1)^2\bar{\gamma}\log_2 M}{M-1+1.5(2i-1)^2\bar{\gamma}\log_2 M}}\right) \tag{2.16}$$

The following MATLAB program 2.3 is used to compute theoretic BER performance of 4-QAM, 8-QAM, and 16-QAM modulations in AWGN and Rayleigh fading channels.

Program 2.3 Program for computing theoretic BER for 4-QAM, 8-QAM and 16-QAM modulations in AWGN and Rayleigh fading channels

```
clear all;
Eb_N0_dB =   [0:35]; % multiple Eb/N0 values
EbN0Lin = 10.^(Eb_N0_dB/10);
M=4;
BER_4QAM_AWGN = 0.5* erfc( sqrt( EbN0Lin ) ) ;
BER_4QAM_Rayleigh = 0.5.*(1-1*(1+1./EbN0Lin).^(-0.5));
M=8;
BER_8QAM_AWGN = 4/log2(M) * (1-1/sqrt(M) )*( 0.5*erfc (sqrt( 3/2*
log2(M) *EbN0Lin / (M-1) ) ) + ... 0.5 * erfc (3* sqrt( 3/2* log2(M)
*EbN0Lin / (M-1) ) ) );
BER_8QAM_Rayleigh = (2/log2(M)) * (1 - 1/sqrt(M) )*((1-
1*(1+7./(4.5*EbN0Lin)).^(-0.5))+...(1-1*(1+7./(40.5*EbN0Lin)).^(-0.5)));
M=16;
BER_16QAM_AWGN = 4/log2(M) * (1 - 1/sqrt(M) ) * ( 0.5 * erfc ( sqrt(
3/2* log2(M) *EbN0Lin / (M-1) ) ) + ...0.5 * erfc (3* sqrt( 3/2* log2(M)
*EbN0Lin / (M-1) ) ) );
BER_16QAM_Rayleigh = 2/log2(M) * (1 - 1/sqrt(M) )*((1-
1*(1+15./(6*EbN0Lin)).^(-0.5))+...(1-1*(1+15./(54*EbN0Lin)).^(-0.5)));
close all
Figure
semilogy(Eb_N0_dB,BER_16QAM_Rayleigh,'-*','LineWidth',2);
hold on
semilogy(Eb_N0_dB,BER_8QAM_Rayleigh ,'-','LineWidth',2);
semilogy(Eb_N0_dB,BER_4QAM_Rayleigh ,'-x','LineWidth',2);
semilogy(Eb_N0_dB,BER_16QAM_AWGN,'--','LineWidth',2);
semilogy(Eb_N0_dB,BER_8QAM_AWGN,'-v','LineWidth',2);
semilogy(Eb_N0_dB,BER_4QAM_AWGN ,'-d','LineWidth',2);
axis([0 35 10^-8 1])
grid on
legend('16-QAM Rayleigh','8-QAM Rayleigh','4-QAM Rayleigh','16QAM
AWGN','8QAM AWGN', '4-QAM AWGN');
xlabel('Eb/No, dB');
ylabel('BER');
```

The BER performance obtained from the above program is depicted in Fig. 2.3.

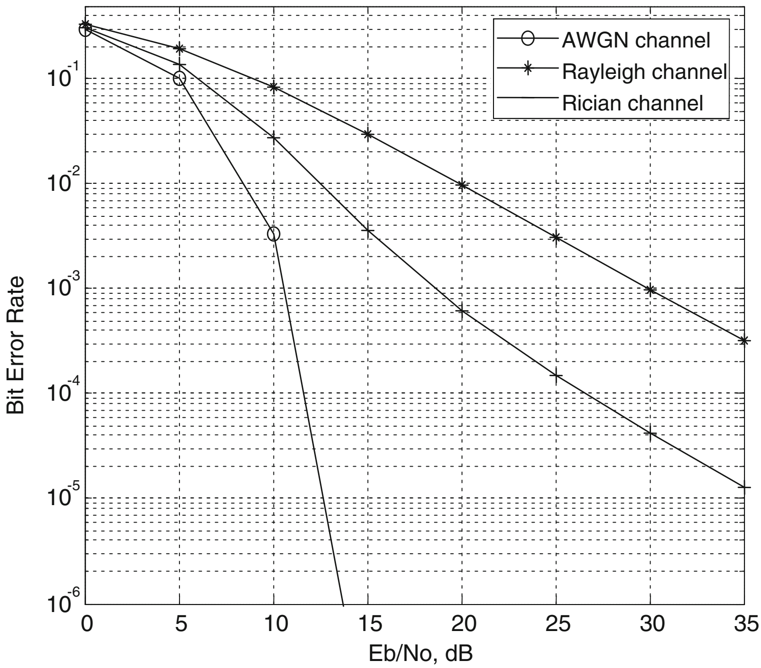

Fig. 2.2 BER performance of BFSK in AWGN, Rayleigh, and Rician fading channels

2.2 Wireless Communication Techniques

The most known wireless communication techniques are:

Direct sequence code division multiple access (DS-CDMA)
Frequency hopping CDMA (FH-CDMA)
Orthogonal frequency division multiplexing (OFDM)
Multicarrier CDMA (MC-CDMA)

2.2.1 DS-CDMA

In code division multiple access (CDMA) systems, the narrow band message signal is multiplied by a very high bandwidth signal, which has a high chip rate, i.e., it accommodates more number of bits in a single bit of message signal. The signal with a high chip rate is called as spreading signal. All users in the CDMA system use the same carrier frequency and transmit simultaneously. The spreading signal or pseudo-noise code must be random so that no other user could be recognized.

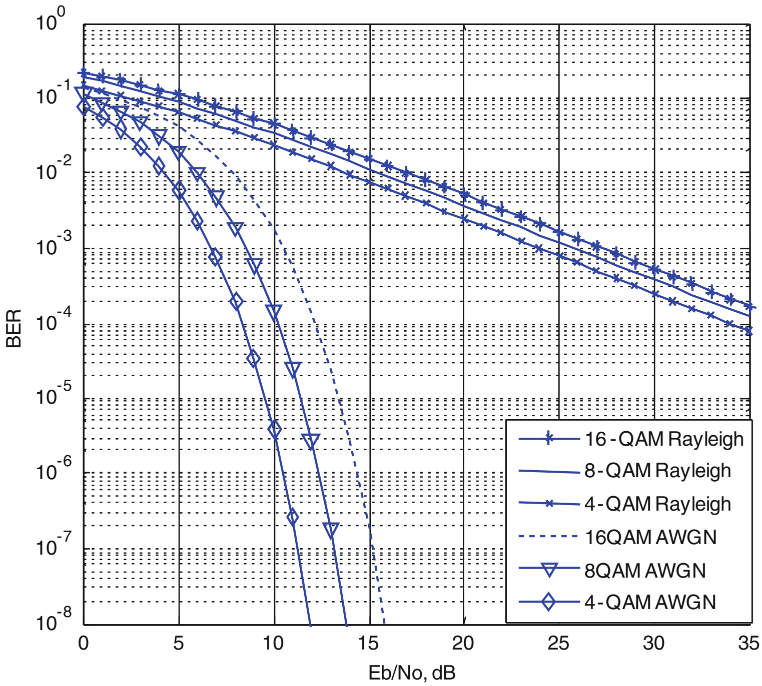

Fig. 2.3 BER performances of 4-QAM, 8-QAM, and 16-QAM in AWGN and Rayleigh fading channels

The intended receiver works with same PN code which is used by the corresponding transmitter, and time correlation operation detects the specific desired codeword only and all other code words appear as noise. Each user operates independently with no knowledge of the other users.

The near-far problem occurs due to the sharing of the same channel by many mobile users. At the base station, the demodulator is captured by the strongest received mobile signal raising the noise floor for the weaker signals and decreasing the probability of weak signal reception. In most of the CDMA applications, power control is used to combat the near-far problem. In a cellular system, each base station provides power control to assure same signal level to the base station receiver from each mobile within the coverage area of the base station and solves the overpowering to the base station receiver by a nearby user drowning out the signals of faraway users.

In CDMA, the actual data are mixed with the output of a PN coder to perform the scrambling process. The scrambled data obtained after scrambling process are then modulated using BPSK or QPSK modulator as shown in Fig. 2.4. The BPSK or QPSK modulated data are then transmitted.

2.2.1.1 BER Performance of DS-CDMA in AWGN and Rayleigh Fading Channels

Let us consider a single cell with K users with each user having a PN sequence length N chips per message symbol. The received signal will consist of the sum of the desired user, $K-1$ undesired users transmitted signals and additive noise. Approximating the total multiple access interference caused by the $K-1$ users as a Gaussian random variable, the BER for DS-CDMA in AWGN channel is given [3] by

$$P_{\mathrm{b,CDMA\,(AWGN)}} = Q\left(\frac{1}{\sqrt{\frac{K-1}{3N}+\frac{N_0}{2E_\mathrm{b}}}}\right) \tag{2.17}$$

The BER for DS-CDMA in Rayleigh fading channel can be expressed [7] as

$$P_{\mathrm{b,CDMA(Ray)}} = \frac{1}{2}\left(1-\frac{1}{\sqrt{1+\frac{N_0}{2E_\mathrm{b}\sigma^2}+\frac{K-1}{3N}}}\right) \tag{2.18}$$

where σ^2 is the variance of the Rayleigh fading random variable.

The following MATLAB program is used to compute theoretic BER of DS-CDMA in AWGN and Rayleigh fading channels.

Program 2.4 Program to compute BER performance of DS-CDMA in AWGN, and Rayleigh fading channels

```
clearall;clc;close all;
Eb_N0_dB=10;
EbN0Lin = 10.^(Eb_N0_dB/10);
N=31;
for k=3:30
xx(k)=1/sqrt(((k-1)/(3*N))+0.5*1/(EbN0Lin));
xxf(k)=sqrt(1+((k-1)/N)+0.5*1/(EbN0Lin));
bercdma(k)=0.5*erfc(xx(k)/sqrt(2));
bercdmaf(k)=0.5-0.5/xxf(k);
end
semilogy(3:30,bercdma(3:30),'-*')
hold on
semilogy(3:30,bercdmaf(3:30),'-+')
legend('AWGN channel','Rayleigh channel');
xlabel('Number of users');
ylabel('Bit Error Rate');
```

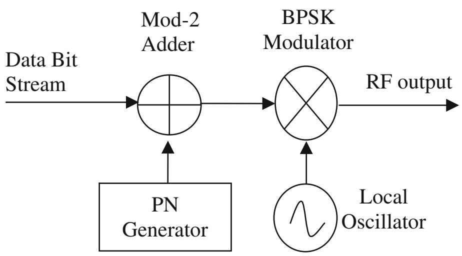

Fig. 2.4 Scrambler system using BPSK modulation

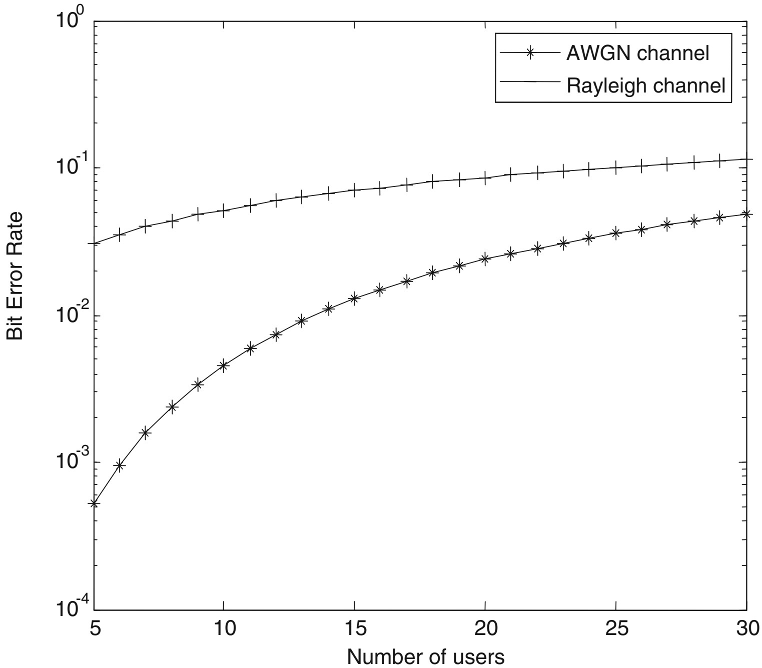

Fig. 2.5 BER performance of DS-CDMA in AWGN and Rayleigh fading channels for $N = 31$, $\sigma^2 = 1$, and $\frac{E_b}{N_0} = 10\,\text{dB}$

The BER performance from the above program for DS-CDMA in the AWGN and Rayleigh channels for $N = 31$, $\sigma^2 = 1$, and $\frac{E_b}{N_0} = 20\,\text{dB}$ is depicted in Fig. 2.5.

From Fig. 2.5, it is observed that the BER performance of DS-CDMA is better in AWGN channel as compared to Rayleigh fading channel. Further, with an increased number of users, the BER performance decreases in both the channels.

2.2.2 *FH-CDMA*

In FH-CDMA, each data bit is divided over a number of frequency-hop channels (carrier frequencies). At each frequency-hop channel, a complete PN sequence of length N is combined with the data signal. Applying fast frequency hopping (FFH) requires a wider bandwidth than slow frequency hopping (SFH). The difference between the traditional slow and FFH schemes can be visualized as shown in Fig. 2.6. A slow hopped system has one or more information symbols per hop or slot. It is suitable for high-capacity wireless communications. A fast hopped system has the hopping rate greater than the data rate. During one information symbol, the system transmits over many bands with short duration. It is more prevalent in military communications.

In FH-CDMA, modulation by some kind of the phase-shift keying is quite susceptible to channel distortions due to several frequency hops in each data bit. Hence, an FSK modulation scheme is to be chosen for FH-CDMA.

The hop set, dwell time, and hop rate with respect to FHCDMA are defined as

Hop set It is the number of different frequencies used by the system.

Dwell time It is defined as the length of time that the system spent on one frequency for transmission.

Hop rate It is the rate at which the system changes from one frequency to another.

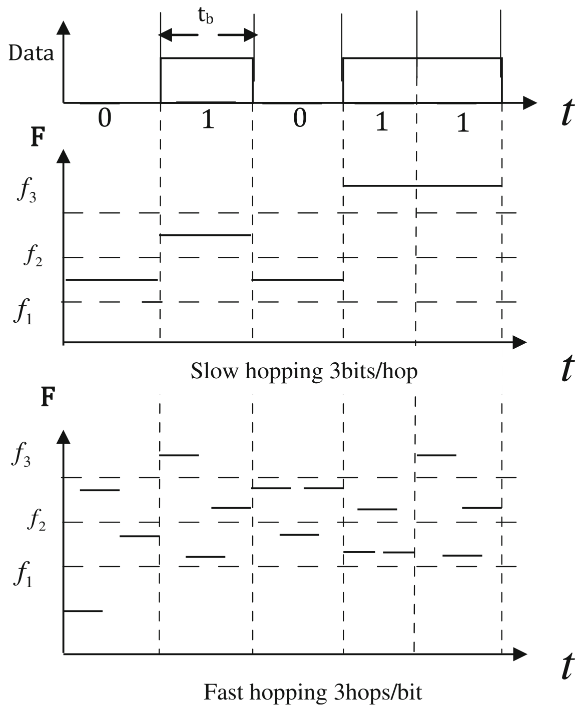

Fig. 2.6 Slow and fast hopping

2.2.2.1 BER Expression for Synchronous SFH-CDMA

Consider a SFH-*CDMA* channel with K active users and q (frequency) slots. The hit probability is the probability that a number of interfering users are transmitting on the same frequency-hop channel as the reference user. This probability will be referred to as $P_{\mathrm{h}}(K)$ where K is the total number of active users.

The probability of hitting from a given user is given by [8]

$$P = \frac{1}{q}\left(1 + \frac{1}{N_b}\right) \tag{2.19}$$

where N_b is the number of bits per hop and q stands for the number of hops. The primary interest for our analysis is the probability P_{h} of one or more hits from the $K - 1$ users is given by

$$P_{\mathrm{h}} = 1 - (1 - P)^{K-1} \tag{2.20}$$

By substituting "P" value from Eq. (2.19) in Eq. (2.20), we get the probability of hit from $K - 1$ users as

$$P_{\mathrm{h}}(K) = 1 - \left(1 - \frac{1}{q}\left(1 + \frac{1}{N_b}\right)\right)^{K-1} \tag{2.21}$$

If it is assumed that all users hop their carrier frequencies synchronously, the probability of hits is given by

$$P_{\mathrm{h}} = 1 - \left(1 - \frac{1}{q}\right)^{K-1} \tag{2.22}$$

For large q,

$$P_{\mathrm{h}}(K) = 1 - \left(1 - \frac{1}{q}\right)^{K-1} \approx \frac{K-1}{q} \tag{2.23}$$

The probability of bit error for synchronous MFSK SFH-CDMA when the K number of active users is present in the system can be found by [9]

$$P_{\mathrm{SFH}}(K) = \sum_{k=1}^{K} \binom{K-1}{k} P_{\mathrm{h}}^{k}(1 - P_{\mathrm{h}})^{K-1-k} P_{\mathrm{MFSK}}(K) \tag{2.24}$$

where $P_{\mathrm{MFSK}}(K)$ denotes the probability of error when the reference user is hit by all other active users. Equation (2.24) is the upper bound of the bit error probability of the SFH-CDMA system. The $P_{\mathrm{MFSK}}(K)$ for the AWGN and flat fading channels can be expressed as [10]

$$P_{\text{MFSK}}(K) = \begin{cases} \sum_{i=1}^{M-1} \frac{(-1)^{i+1}}{i+1} \binom{M-1}{i} \exp\left(-\frac{i\frac{E_b}{N_0}}{i+1}\right) \text{AWGN} \\ \sum_{i=1}^{M-1} \frac{(-1)^{i+1}}{1+i+i\frac{E_b}{N_0}} \binom{M-1}{i} \quad \text{Rayleigh fading} \end{cases} \tag{2.25}$$

The following MATLAB program computes theoretic BER of SFH-CDMA in AWGN and Rayleigh fading channels.

Program 2.5 Program to compute BER performance of SFH-CDMA in AWGN, and Rayleigh fading channels

```
clearall;clc;
snr1=10;Eb_N0_dB=10;
EbN0Lin = 10.^(Eb_N0_dB/10);
 q=32;
pe=0.5*exp(-(EbN0Lin /2));
for K=3:30
ph=(K-1)/q;
  pe1=0;
for k=1:(K-1)
    pe1=pe1+nchoosek(K-1,k)*(ph)^k*(1-ph)^(K-1-k);
end
pesfh(K)=pe1*pe;
end
disp(pesfh);
semilogy(3:30,pesfh(3:30),'-*');
hold on;
pe=1/(2+EbN0Lin );
for K=3:30
ph=(K-1)/q;
  pe1=0;
for k=1:(K-1)
    pe1=pe1+nchoosek(K-1,k)*(ph)^k*(1-ph)^(K-1-k);
end
pesfhr(K)=pe1*pe;
end
disp(pesfhr);
semilogy(3:30,pesfhr(3:30),'-+');
hold on;
legend('AWGN' ,' Rayleigh');
xlabel('Number of users');
ylabel('Bit Error Rate');
```

The BER performance from the above program for SFH-CDMA in the AWGN and Rayleigh channels with $q = 32$ and $M = 2$ (BFSK) at $\frac{E_b}{N_0} = 10\,\text{dB}$ is depicted in Fig. 2.7.

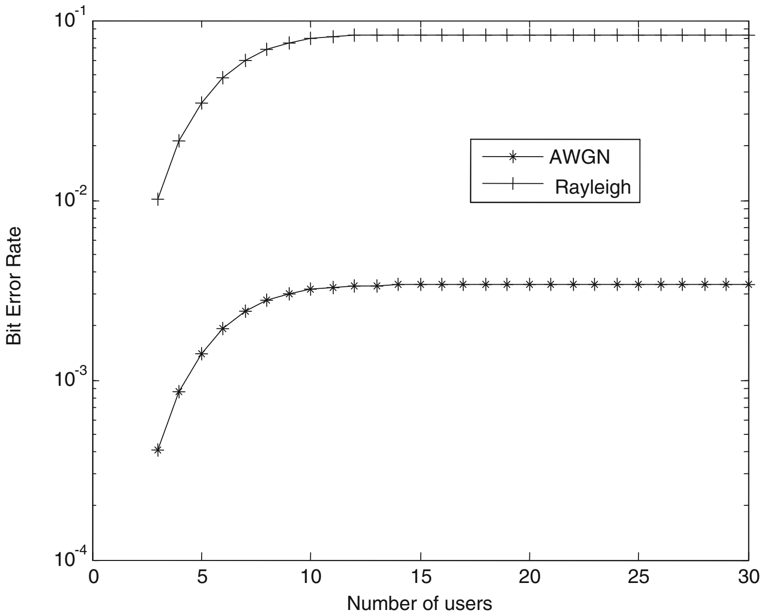

Fig. 2.7 BER performance of SFH-CDMA in AWGN and Rayleigh fading channels with $q = 32$ and $M = 2$(BFSK) at $\frac{E_b}{N_0} = 10\,\mathrm{dB}$

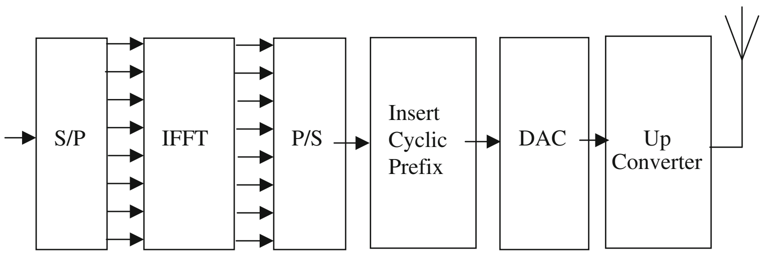

Fig. 2.8 Schematic block diagram of OFDM transmitter

2.2.3 OFDM

The block diagram of OFDM transmitter is shown in Fig. 2.8. In OFDM, the input data are serial-to-parallel converted (the S/P block). Then, the inverse fast Fourier transform (IFFT) is performed on the N parallel outputs of the S/P block to create an OFDM symbol.

The complex numbers in the output of the IFFT block are parallel-to-serial converted (P/S). Then, the cyclic prefix is inserted in order to combat the

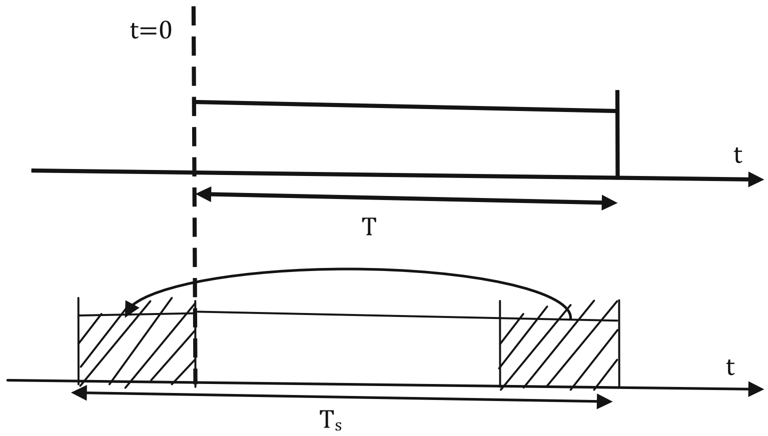

Fig. 2.9 Inserting cyclic prefix

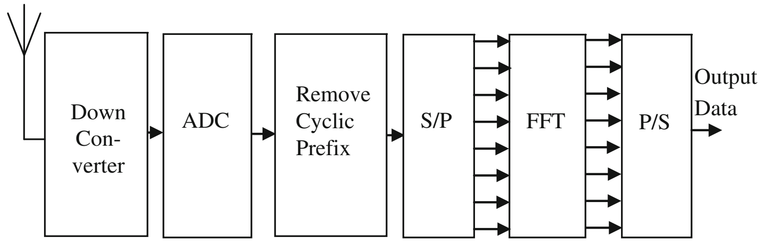

Fig. 2.10 Schematic block diagram of OFDM receiver

intersymbol interference (ISI) and intercarrier interference (ICI) caused by the multipath channel. To create the cyclic prefix, the complex vector of length at the end of the symbol duration T is copied and appended to the front of the signal block as shown in Fig. 2.9. The schematic block diagram of the OFDM receiver is shown in Fig. 2.10. It is the exact inverse of the transmitter shown in Fig. 2.8.

2.2.4 MC-CDMA

MC-CDMA is a combination of OFDM and CDMA having the benefits of both OFDM and CDMA. In MC-CDMA, frequency diversity is achieved by modulating symbols on many subcarriers instead of modulating on one carrier like in CDMA.

In MC-CDMA, the same symbol is transmitted through many subcarriers in parallel, whereas in OFDM, different symbols are transmitted on different subcarriers. The block diagram of the MC-CDMA system transmitter is shown in Fig. 2.11. The block diagram of the MC-CDMA system receiver is shown in Fig. 2.12. In the

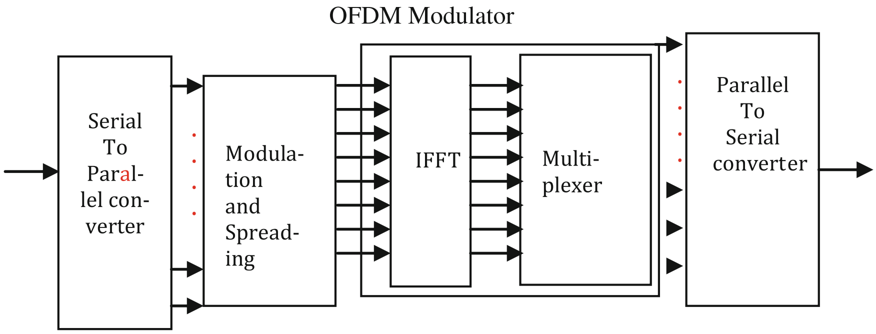

Fig. 2.11 Block diagram of MC-CDMA transmitter

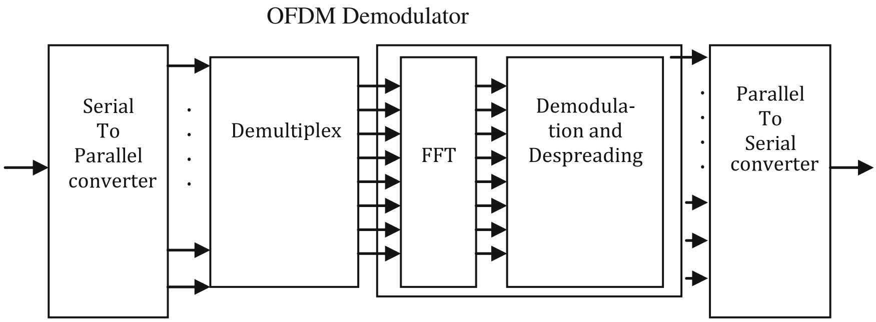

Fig. 2.12 Block diagram of MC-CDMA receiver

receiver, the cyclic prefix is removed and FFT is performed to obtain the signals in the frequency domain.

2.2.4.1 BER Expression for Synchronous MC-CDMA

Assuming a synchronous MC-CDMA system with K users, N subcarriers, and binary phase-shift keying (BPSK) modulation, the BER for MC-CDMA in slowly varying Rayleigh fading channel can be calculated using the residue method by [11]

$$P_{\mathrm{MC-CDMA,\,Rayleigh}}(K) = \frac{(2c)^{N_c}}{[(N_c-1)!]^2} \sum_{k=0}^{N_c-1} \binom{N_c-1}{k} (N_c-1-k)!$$

$$(N_c-1-k)!(c+d)^{-(N_c-k)}(2d)^{-(N_c+k)} \tag{2.26}$$

where k stands for the number of users, N_c denotes the number of subcarriers, and the parameters c and d are defined by

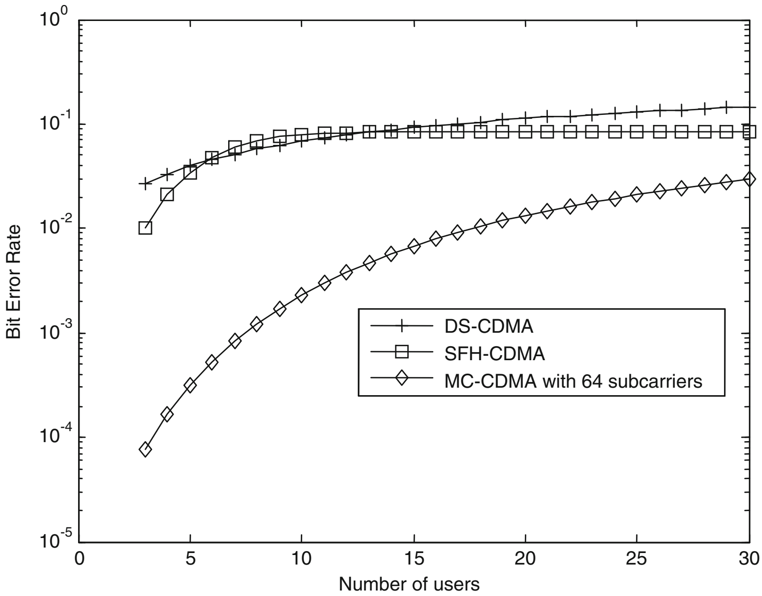

Fig. 2.13 BER performance of DS-CDMA, SFH-CDMA, and MC-CDMA in Rayleigh fading channels at $\frac{E_b}{N_0} = 10\,\text{dB}$

$$\frac{1}{2c} = \frac{N_c}{4E_b/N_0} + \frac{k+1}{4}, \quad d = \sqrt{c^2 + 2c} \tag{2.27}$$

A theoretical BER performance comparison of DS-CDMA, SFH-CDMA, and MC-CDMA in Rayleigh fading channels at $\frac{E_b}{N_0} = 10\,\text{dB}$ is shown in Fig. 2.13.

From Fig. 2.13, it is observed that MC-CDM outperforms both the DS-CDMA and SFH-CDMA.

2.3 Diversity Reception

Two channels with different frequencies, polarizations, or physical locations experience fading independently of each other. By combing two or more such channels, fading can be reduced. This is called diversity.

On a fading channel, the SNR at the receiver is a random variable, the idea is to transmit the same signal through r separate fading channels. These are chosen so as to provide the receiver with r independent (or close-to-independent) replicas of the same signal, giving rise to independent SNRs. If r is large enough, then at any time instant, there is a high probability that at least one of the signals received from the

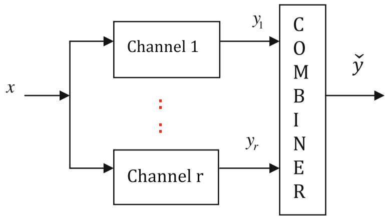

Fig. 2.14 Diversity and combining

r "diversity branches" is not affected by a deep fade and hence that its SNR is above a critical threshold. By suitably combining the received signals, the fading effect will be mitigated (Fig. 2.14).

Many techniques have been advocated for generating the independent channels on which the diversity principle is based, and several methods are known for combining the signals $y_1, \ldots, y_r$ obtained at their outputs into a single channel $\breve{y}$. Among the categorized techniques, the most important ones are as follows:

1. Space diversity
2. Polarization diversity
3. Frequency diversity
4. Time diversity
5. Cooperative diversity

Space diversity: To obtain sufficient correlation, the spacing between the r separate antennas should be wide with respect to their coherent distance while receiving the signal. It does not require any extra spectrum occupancy and can be easily implemented.

Polarization diversity: Over a wireless channel, multipath components polarized either horizontally or vertically have different propagation. Diversity is provided when the receiving signal uses two different polarized antennas. In another way, two cross-polarized antennas with no spacing between them also provide diversity. Cross-polarized are preferred since they are able to double the antenna numbers using half the spacing being used for co-polarized antennas. Polarized diversity can achieve more gain than space diversity alone in reasonable scattering areas, and hence, it is deployed in more and more BSs.

Frequency diversity: In order to obtain frequency diversity, the same signal over different carrier frequencies should be sent whose separation must be larger than the coherence bandwidth of the channel.

Time diversity: This is obtained by transmitting the same signal in different time slots separated by a longer interval than the coherence time of the channel.

Cooperative diversity: This is obtained by sharing of resources by users or nodes in a wireless network and transmits cooperatively. The users or nodes act like an antenna array and provide diversity. This type of diversity can be achieved by combining the signals transmitted from the direct and relay links.

2.3.1 Receive Diversity with N Receive Antennas in AWGN

The received signal on the *i*th antenna can be expressed as

$$y_i = h_i x + \eta_i \tag{2.28}$$

where
y_i is the symbol received on the *i*th receive antenna,
h_i is the channel gain on the *i*th receive antenna,
x is the input symbol transmitted, and
η_i is the noise on the *i*th receive antenna.
The received signal can be written in matrix form as

$$y = hx + n$$

where
$y = [y_1 y_2 \ldots y_N]^{\mathrm{T}}$ is the received symbol from all the receive antenna,
$h = [h_1 h_2 \ldots h_N]^{\mathrm{T}}$ is the channel on all the receive antenna,
x is the transmitted symbol, and
$\eta = [\eta_1 \eta_2 \ldots \eta_N]^{\mathrm{T}}$ is the AWGN on all the receive antenna.

Effective $\frac{E_{\mathrm{b}}}{N_0}$ with N receive antennas is N times $\frac{E_{\mathrm{b}}}{N_0}$ for single antenna. Thus, the effective $\frac{E_{\mathrm{b}}}{N_0}$ for N antennas in AWGN can be expressed as

$$\left[\frac{E_{\mathrm{b}}}{N_0}\right]_{\mathrm{eff},N} = \frac{\mathrm{NE_b}}{N_0} \tag{2.29}$$

So the BER for N receive antennas is given by

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{\mathrm{NE_b}}{N_0}}\right) \tag{2.30}$$

2.4 Diversity Combining Techniques

The three main combining techniques that can be used in conjunction with any of the diversity schemes are as follows:

1. Selection combining
2. Equal gain combining (EGC)
3. Maximal ratio combining

2.4.1 Selection Diversity

In this combiner, the receiver selects the antenna with the highest received signal power and ignores observations from the other antennas.

2.4.1.1 Expression for BER with Selection Diversity

Consider N independent Rayleigh fading channels, each channel being a diversity branch. It is assumed that each branch has the same average signal-to-noise ratio

$$\bar{\gamma} = \frac{E_\mathrm{b}}{N_0} E\left[h^2\right] \tag{2.31}$$

The outage probability is the probability that the bit energy-to-noise ratio falls below a threshold (γ). The probability of outage on ith receive antenna can be expressed by

$$P_{\mathrm{out},\gamma_i} = P[\gamma_i < \gamma] = \int_0^\gamma \frac{1}{\bar{\gamma}} \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}} d\gamma_i = 1 - \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}} \tag{2.32}$$

The joint probability is the product of the individual probabilities if the channel on each antenna is assumed to be independent; thus, the joint probability with N receiving antennas becomes

$$\begin{aligned} P_\mathrm{out} &= P[\gamma_1 < \gamma] P[\gamma_2 < \gamma] \cdots P[\gamma_N < \gamma] \\ &= \left[1 - \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}}\right]^N \end{aligned} \tag{2.33}$$

where $\gamma_1, \gamma_2, \cdots, \gamma_N$ are the instantaneous bit energy-to-noise ratios of the 1st, 2nd, and so on till the nth receive antenna.

Equation (2.33) is in fact the cumulative distribution function (CDF) of γ. Then, the probability density function (PDF) is given by the derivate of the CDF as

$$P(\gamma) = \frac{\mathrm{d}P_\mathrm{out}}{\mathrm{d}\gamma} = \frac{N}{\bar{\gamma}} \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}} \left[1 - \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}}\right]^{N-1} \tag{2.34}$$

Substituting Eq. (2.34) in Eq. (2.1), BER for selective diversity can be expressed by

$$\mathrm{BER_{SEL}} = \int_0^\infty \frac{1}{2} \mathrm{erfc}(\sqrt{\gamma}) \frac{N}{\bar{\gamma}} \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}} \left[1 - \mathrm{e}^{-\frac{\gamma_i}{\bar{\gamma}}}\right]^{N-1} \mathrm{d}\gamma \tag{2.35}$$

Assuming $\alpha^2 = 1$, the above expression can be rewritten as [12]

$$\mathrm{BER}_{\mathrm{SEL}} = \frac{1}{2}\sum_{k=0}^{N}(-1)^k\binom{N}{k}\left(1+\frac{k}{\left(\frac{E_\mathrm{b}}{N_0}\right)}\right)^{-\frac{1}{2}} \tag{2.36}$$

2.4.2 Equal Gain Combining (EGC)

In EGC, equalization is performed on the ith receive antenna at the receiver by dividing the received symbol y_i by the a priori known phase of channel h_i. $|h_i|\mathrm{e}^{j\theta_i}$ represents the channel h_i in polar form. The decoded symbol is obtained by

$$\hat{y} = \sum_i \frac{y_i}{\mathrm{e}^{j\theta_i}} = \sum_i \frac{|h_i|\mathrm{e}^{j\theta_i}x + \eta_i}{\mathrm{e}^{j\theta_i}} = \sum_i |h_i|x + \tilde{\eta}_i \tag{2.37}$$

where

$\hat{y}$ is the sum of the phase compensated channel from all the receiving antennas and

$\tilde{\eta}_i = \frac{\eta_i}{\mathrm{e}^{j\theta_i}}$ is the additive noise scaled by the phase of the channel coefficient.

2.4.2.1 Expression for BER with Equal Gain Combining

The BER with EGC with two receive antennas can be expressed with BPSK and BFSK modulations as [13]

$$\mathrm{BER}_{\mathrm{EGC,BPSK}} = \frac{1}{2}\left[1 - \frac{\sqrt{E_\mathrm{b}/N_0(E_\mathrm{b}/N_0+2)}}{E_\mathrm{b}/N_0+1}\right] \tag{2.38}$$

$$\mathrm{BER}_{\mathrm{EGC,BFSK}} = \frac{1}{2}\left[1 - \frac{\sqrt{E_\mathrm{b}/N_0(E_\mathrm{b}/N_0+4)}}{E_\mathrm{b}/N_0+2}\right] \tag{2.39}$$

2.4.3 Maximum Ratio Combining (MRC)

2.4.3.1 Expression for BER with Maximal Ratio Combining (MRC)

For channel h_i, the instantaneous bit energy-to-noise ratio at ith receive antenna is given by

$$\gamma_i = \frac{|h_i|^2 E_\mathrm{b}}{N_0}, \tag{2.40}$$

If h_i is a Rayleigh distributed random variable, then h_i^2 is a chi-squared random variable with two degrees of freedom. Hence, the $\mathrm{p_{df}}$ of γ_i can be expressed as

$$P_{df}(\gamma_i) = \frac{1}{(E_\mathrm{b}/N_0)} \mathrm{e}^{\frac{-\gamma_i}{(E_\mathrm{b}/N_0)}} \tag{2.41}$$

Since the effective bit energy-to-noise ratio γ is the sum of N such random variables, the $\mathrm{p_{df}}$ of γ is a chi-square random variable with $2N$ degrees of freedom. Thus, the $\mathrm{p_{df}}$ of γ is given by

$$P_{df}(\gamma) = \frac{1}{(N-1)!(E_\mathrm{b}/N_0)^N} \gamma^{N-1} \mathrm{e}^{\frac{-\gamma}{(E_\mathrm{b}/N_0)}}, \quad \gamma \geq 0 \tag{2.42}$$

Substituting Eq. (2.42) in Eq. (2.1), BER for maximal ratio combining can be expressed by

$$\begin{aligned} \mathrm{BER_{MRC}} &= \int_0^\infty \frac{1}{2} \mathrm{erfc}(\sqrt{\gamma}) P_{df} p(\gamma) \mathrm{d}\gamma \\ &= \int_0^\infty \frac{1}{2} \mathrm{erfc}(\sqrt{\gamma}) \frac{1}{(N-1)!(E_\mathrm{b}/N_0)^N} \gamma^{N-1} \mathrm{e}^{\frac{-\gamma}{(E_\mathrm{b}/N_0)}} \mathrm{d}\gamma \end{aligned} \tag{2.43}$$

The above expression can be rewritten [12] as

$$\mathrm{BER_{MRC}} = P^N \sum_{k=0}^{N-1} \binom{N-1+k}{k} (1-P)^k \tag{2.44}$$

where

$$P = \frac{1}{2} - \frac{1}{2}\left(1 + \frac{1}{E_\mathrm{b}/N_0}\right)^{-1/2}$$

The following MATLAB program computes the theoretic BER for BPSK modulation in Rayleigh fading channels with selective diversity, EGC, and MRC.

Program 2.6 Program for computing the theoretic BER for BPSK modulation in a Rayleigh fading channel with selection diversity, EGC and MRC

```
clear all;
Eb_N0_dB =   [0:20]; % multiple Eb/N0 values
EbN0Lin = 10.^(Eb_N0_dB/10);
theoryBer_nRx1 = 0.5.*(1-1*(1+1./EbN0Lin).^(-0.5));
theoryBer_sel_nRx2          =          0.5.*(1-2*(1+1./EbN0Lin).^(-0.5)          +
(1+2./EbN0Lin).^(-0.5));
theoryBer_EG_nRx2 =0.5*(1- sqrt(EbN0Lin.*(EbN0Lin+2))./(EbN0Lin+1) );
p = 1/2 - 1/2*(1+1./EbN0Lin).^(-1/2);
theoryBer_MRC_nRx2 = p.^2.*(1+2*(1-p));
semilogy(Eb_N0_dB,theoryBer_nRx1,'*','LineWidth',2);
hold on
semilogy(Eb_N0_dB,theoryBer_sel_nRx2,'-','LineWidth',2);
semilogy(Eb_N0_dB,theoryBer_EG_nRx2 ,'-+','LineWidth',2);
semilogy(Eb_N0_dB,theoryBer_MRC_nRx2,'--','LineWidth',2);
axis([0 20 10^-5 0.5])
gridon
legend('Rayleigh','selection(nRx=2) ', ' EGC(nRx=2)', 'MRC(nRx=2)');
xlabel('Eb/No, dB');
ylabel('BER');
```

The BER performance from the above program with two receive antennas is shown in Fig. 2.15. From Fig. 2.15, it is observed that the BER with MRC is better than selective diversity and EGC and outperforms the single antenna case.

Example 2.1 What is the BER for $E_b/N_0 = 8\,\text{dB}$ at the receiver output in an AWGN channel if coherently demodulated BPSK modulation is used and if no error control coding is used.

Solution For BPSK modulation in AWGN channel, BER is given by

$$\text{BER}_{\text{BPSK, AWGN}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$\frac{E_b}{N_0} = 10^{(8/10)} = 6.3096$$

Thus,

$$\text{BER}_{\text{BPSK, AWGN}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{6.3096}\right) = 0.0001909.$$

Example 2.2 Using the system in the problem1, compute the coding gain that will be necessary if the BER is to be improved to 10^{-6}.

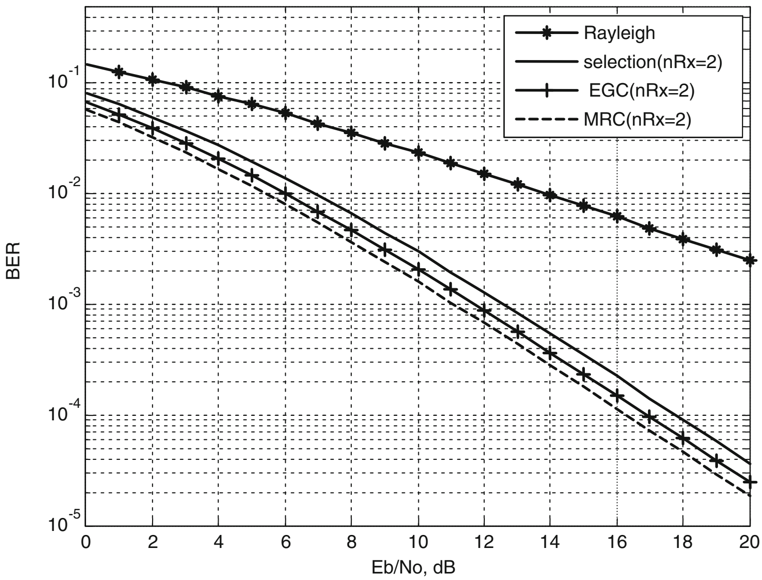

Fig. 2.15 Theoretic BER for BPSK modulation in a Rayleigh fading channel with selection diversity, EGC, and MRC

Solution Here,

$$0.000001 = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$\sqrt{\frac{E_\mathrm{b}}{N_0}} = \mathrm{erfcinv}(0.000002) = 3.3612$$

$$\frac{E_\mathrm{b}}{N_0} = (3.3612)^2 = 11.29;\ \frac{E_\mathrm{b}}{N_0}(\mathrm{dB}) = 10\log_{10}(11.29) = 10.5269$$

Hence, necessary coding gain = 10.5269 − 8.0 = 2.5269 dB.

Example 2.3 Determine the coding gain required to maintain a BER of 10^{-4} when the received Eb/No is fixed, and the modulation format is changed from BPSK to BFSK.

Solution For BPSK in AWGN channel,

$$0.0001 = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$\sqrt{\frac{E_b}{N_0}} = \operatorname{erfcinv}(0.0002) = 2.2697$$

$$\frac{E_b}{N_0} = (2.2697)^2 = 6.9155; \ \frac{E_b}{N_0}(\mathrm{dB}) = 10\log_{10}(6.9155) = 8.3982$$

For BFSK in AWGN channel:

$$\mathrm{BER}_{\mathrm{BFSK,\,AWGN}} = 0.0001 = \frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right)$$

$$\frac{E_b}{N_0} = -2\ln(0.0002) = 17.0344; \quad \frac{E_b}{N_0}(\mathrm{dB}) = 10\log_{10}(17.0344) = 12.3133$$

Hence, necessary coding gain $= 12.3133 - 8.3982 = 3.9151\,\mathrm{dB}$.

Example 2.4 Determine the coding gain required to maintain a BER of 10^{-3} when the received Eb/No remains fixed and the modulation format is changed from BPSK to 8-PSK in AWGN channel.

Solution For BPSK in AWGN channel,

$$0.001 = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$\sqrt{\frac{E_b}{N_0}} = \operatorname{erfcinv}(0.002) = 2.1851$$

$$\frac{E_b}{N_0} = (2.1851)^2 = 4.7748; \ \frac{E_b}{N_0}(\mathrm{dB}) = 10\log_{10}(4.7748) = 6.7895$$

From Eq. (2.6), for 8-PSK in AWGN channel,

$$\mathrm{BER}_{8-\mathrm{PSK}} = \frac{2}{3}Q\left(\sin\left(\frac{\pi}{8}\right)\sqrt{\frac{6E_b}{N_0}}\right)$$

$$0.001 = \frac{2}{3}Q\left(\sin\left(\frac{\pi}{8}\right)\sqrt{\frac{6E_b}{N_0}}\right) = \frac{2}{3}Q\left(0.3827\sqrt{\frac{6E_b}{N_0}}\right)$$

Since,

$$Q(x) = \frac{1}{2}\operatorname{erfc}\left(\frac{x}{\sqrt{2}}\right)$$

$$\frac{0.003}{2} = \frac{1}{2}\operatorname{erfc}\left(\frac{0.3827}{\sqrt{2}}\sqrt{\frac{6E_\mathrm{b}}{N_0}}\right)$$

$$0.003 = \operatorname{erfc}\left(0.6629\sqrt{\frac{6E_\mathrm{b}}{N_0}}\right)$$

$$\sqrt{\frac{E_\mathrm{b}}{N_0}} = \frac{1}{0.6629}\operatorname{erfcinv}(0.003) = \frac{2.0985}{0.6629} = 3.1656$$

$$\frac{E_\mathrm{b}}{N_0} = (3.1656)^2 = 10.0210; \frac{E_\mathrm{b}}{N_0}(\mathrm{dB}) = 10\log_{10}(10.0210) = 10.0091$$

Hence, necessary coding gain = 10.0091 – 6.7895 = 3.2196 dB.

2.5 Problems

1. An AWGN channel requires $\frac{E_\mathrm{b}}{N_0} = 9.6\,\mathrm{dB}$ to achieve BER of 10^{-5} using BPSK modulation. Determine the coding gain required to achieve BER of 10^{-5} in a Rayleigh fading channel using BPSK.
2. Using the system in Problem 1, determine the coding gain required to maintain a BER of 10^{-5} in Rayleigh fading channel when the modulation format is changed from BPSK to BFSK.
3. Determine the necessary $\frac{E_b}{N_0}$ for a Rayleigh fading channel with an average BER of 10^{-5} in order to detect (i) BPSK and (ii) BFSK.
4. Determine the necessary $\frac{E_b}{N_0}$ in order to detect BFSK with an average BER of 10^{-4} for a Rician fading channel with Rician factor of 5 dB.
5. Determine the probability of error as a function of $\frac{E_b}{N_0}$ for 4-QAM. Plot $\frac{E_b}{N_0}$ vs probability of error and compare the results with BPSK and non-coherent BFSK on the same plot.
6. Obtain an approximations to the outage capacity in a Rayleigh fading channel: (i) at low SNRs and (ii) at high SNRs.
7. Obtain an approximation to the outage probability for the parallel channel with M Rayleigh branches.
8. Assume three-branch MRC diversity in a Rayleigh fading channel. For an average SNR of 20 dB, determine the outage probability that the SNR is below 10 dB.

2.6 MATLAB Exercises

1. Write a MATLAB program to simulate the BER versus number of users performance of SFH-CDMA in AWGN and Rayleigh fading channels at different $\frac{E_b}{N_0}$.
2. Write a MATLAB program to simulate the performance of OFDM in AWGN and Rayleigh fading channels.
3. Write a MATLAB program to simulate the BER versus number of users performance of MC-CDMA in AWGN and Rayleigh fading channels for different number of subcarriers at different $\frac{E_b}{N_0}$.
4. Write a MATLAB program to simulate the performance of selection diversity, equal gain combiner, and maximum ratio combiner and compare the performance with the theoretical results.

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