CLOSED-LOOP TRANSMIT DIVERSITY (TRANSMIT BEAMFORMING) FOR MITIGATION OF INTERFERENCE AND MULTIPATH FADING IN WIRELESS COMMUNICATION SYSTEMS

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Abstract

The wireless communication channel suffers from many impairments such as the thermal noise often modeled as Additive White Gaussian Noise (AWGN), the path loss in power as the radio signal propagates, the shadowing due to the presence of fixed obstacles in the radio path, and the fading which combines the effects of multiple propagation paths and the rapid movement of mobile units reflectors. Deploying multiple antennas at the transmitter has been shown to increase diversity and therefore improve signal quality with increased throughput. This paper proposes a transmit diversity scheme, where multiple transmit antennas are used at the transmitter. A feedback path is provided from the receiver to communicate the channel seen by the receiver to the transmitter (closed-loop). When closed-loop transmit diversity is applied, the symbol from each transmit antenna is multiplied with a complex number corresponding to the inverse of the phase of the channel so as to ensure that the signals add constructively at the receiver. From this research it was found that sending the same information on multiple transmit antenna does not always provide diversity gain. However if the transmitted symbols are multiplied by a complex phase to ensure that the phases align at the receiver, there is diversity gain though the bit error rate performance seems to be slightly poorer than the maximal ratio combining case.

Key words: Closed-loop, transmit diversity, transmit beamforming, single-input single-output, multipath fading, mmaximal ratio combining

1.0 Introduction

The performance of a communication system depends on the received signal energy. Higher energy signals are detected more reliably (with fewer errors) than are lower energy signals. In other words, the received signal does the work. On the other hand power, is the rate at which energy is delivered. An electrical signal can be represented as a voltage *v(t)* or a current *i(t)* with instantaneous power *p(t)* across the load (resistor) defined by. (Hourani, 2004).

$$p(t) = \frac{v(t)}{R} = i^{2}(t)R \qquad (1)$$

In communication systems, power is often normalized by assuming the load resistor (R) to be *1Ω,* therefore regardless of whether the signal is a voltage or a current waveform, the normalized convention allows instantaneous power to be expressed as

$$p(t) = v^{2}(t) = i^{2}(t) \qquad (2)$$

$$p(t) = x^{2}(t) \qquad (3)$$

Where *x(t)* is either a voltage or a current signal (Tarokh *et al*, 1998).

The performance of a communication system is generally measured by the bit error rate (BER), which is a function of the signal-to-noise ratio (SNR). Due to unknown location of the mobile station and the unknown medium between the transmitter and the receiver, the wireless channel is best characterized as random. A wireless communication system is fundamentally limited by the random nature of the channel. (Sklar, 2001).

1.1 Challenges in Wireless Signal Transmission.

The wireless communication channel suffers from many impairments such as the thermal noise often modeled as Additive White Gaussian Noise (AWGN), the path loss in power as the radio signal propagates, the shadowing due to the presence of fixed obstacles in the radio path, and the fading which combines the effects of multiple propagation paths and the rapid movement of mobile units reflectors. (Zheng, 2003).

In communications, the additive white Gaussian noise (AWGN) channel model is one in which the information is given a single impairment: a linear addition of wideband or white noise with a constant spectral density and a Gaussian distribution of noise samples. The model does not account for the phenomena of fading, frequency selectivity, interference, nonlinearity or dispersion. However, AWGN produces simple and tractable mathematical models which are useful for gaining insight into the underlying behavior of a system before these other phenomena are considered. (Proakis, 1995).

The wideband Gaussian noise comes from many natural sources, such as the thermal vibrations of electrons in atoms (referred to as thermal noise or Johnson-Nyquist noise), shot (schottky) noise (which arises in an electric current due to discontinuous nature of conduction by electrons), black body radiation from the earth and other warm objects, and from celestial sources such as the sun.

The AWGN channel is represented by a series of outputs Y_i at discrete time event. Y_i is the sum of the input x_i and noise, n_i, where n_i is independently and identically distributed (i.i.d.) and drawn from a zero mean normal distribution with variance ***v.*** The n_i are further assumed not to be correlated with the x_i i.e. $n_i \sim N(0,v)$.

$$Y_i = x_i + n_i \quad \text{.......... (4)}$$

Physical channels such as under water acoustic channels and ionospheric radio channels result in time-variant multipath propagation of the transmitted signal which may be characterized mathematically as time-variant linear filter i.e.

$$y(t) = x(t) * c(\tau;t) + n(t)$$
$$= \int_{-\infty}^{+\infty} c(\tau;t)x(t-\tau)\delta\tau + n(t) \quad \text{.......... (5)}$$

where $c(\tau;t)$ is the impulse response of the linear time-variant filter and * denotes convolution.

A good model for multipath signal propagation through physical channels such as the mobile cellular radio channels, is a special case of the above equation in which the time-variant impulse response has the form

$$c(\tau;t) = \sum_{k=1}^{L} a_k(t)\delta(\tau - \tau_k) \quad \text{.......... (6)}$$

where the $a_k(t)$ represent the time variant attenuation factor for the L multipath propagation paths and τ_k are the corresponding time delays. If equation (6) is substituted into equation (5) the received signal has the form

$$y(t) = \sum_{k=1}^{L} a_k\, x(t-\tau_k) + n(t) \quad \text{.......... (7)}$$

Hence the received signal consists of L multipath components, where each component is attenuated by $a_k(t)$ and delayed by τ_k.

Shanon formulated the basic problem of reliable transmission of information in statistical terms, using probabilistic models for information sources and communication channels (Proakis, 1995). He also demonstrated that the effect of a transmitter power constraint, bandwidth (W) constraint and additive noise can be associated with the channel and incorporated into a single parameter called the channel capacity (C).

$$C = W \log_2\left(1 + \frac{P}{WNo}\right) bits/sec \quad \text{.......... (8)}$$

Where *P* is the average transmitted power and N_o is the power spectral density of the additive noise. Therefore if the information rate (R) from the source is less than channel capacity (C), i.e. (R < C) then it is theoretically possible to achieve reliable (error free) transmission through the channel by an appropriate coding. On the contrary, if R > C, reliable transmission is not possible regardless of the amount of signal processing performed at the transmitter and receiver.

2.0 Interference and Multipath Fading in Wireless Communication Systems

2.1 Multipath Propagation of Wireless Signals

In a typical wireless communication environment, multiple propagation paths often exist from a transmitter to a receiver due to scattering by different objects as shown in figure 2.0.

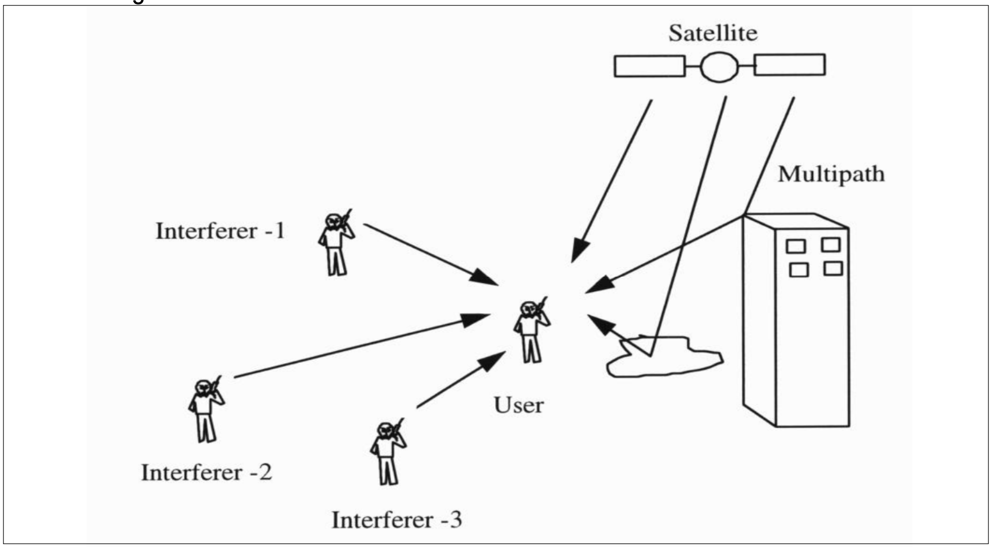

Figure 2: Mobile user in the presence of multipath and interference

Upon the signal transmission, different signal copies following different paths undergo different attenuation, distortion, delays and phase shifts. Multipath fading is known to arise due to the non-coherent combination of signals arriving at the receiver. Interference is caused by deep-fades that occur at a particular point in space, or at a particular time or frequency, and results in severe degradation of the quality of signals at the receiver making it impossible to detect or decode. (Rappaport, 1996).

Several mathematical models have been developed to describe such channels, taking into account, the phenomenon of multipath fading and correlation between sub-channels. Common models employ Rayleigh, Rice and Nakagami-m distributions to approximate actual channel conditions. (Rappaport, 1996). The Rayleigh flat fading channel is commonly used to describe multipath fading channels when there is no line-of-sight (LOS) component. (Proakis, 1995; Nakagami, 1960).

The performance of the systems (in terms of error rate) can be severely degraded by fading. In mobile communications, multiple propagation paths exist, and are time-varying. The result is a time-varying fading channel. Communication through these channels is difficult and special techniques may be required to achieve satisfactory performance. (Hourani, 2004).

2.2 Overcoming Challenges in Wireless Signal Transmission

Equalisation, diversity, and channel coding are the three techniques which can be used independently or in tandem to improve received signal quality and link performance over small scale times and distances. Equalisation compensates for intersymbol interference (ISI) created by multipath propagation within time dispersive channels. Channel coding improves the small-scale link performance by adding redundant data bits in the transmitted message so that if an instantaneous fade occurs in the channel, the data may still be recovered at the receiver. Diversity technique is used to compensate for fading channel impairments, and is usually implemented by using two or more transmitting and/or receiving antennas. (Rappaport, 1996).

Diversity technique is a widely known technique in combating channel impairments arising due to multipath fading. In diversity, several replicas of the same information carrying signal are received over multiple channels with comparable strengths and exhibit independent fading. (Zheng, 2003). Diversity techniques improves the quality of a wireless communications link without altering the common air interface, and without increasing the transmitted power or bandwidth. (Rappaport, 1996). Diversity is usually employed to reduce the depth and duration of the fades experienced by a receiver. Diversity techniques are often employed at both the transmitter (Transmit Diversity) and/or the receiver (Receive Diversity). For a broad class of interference-dominated wireless systems including mobile, personal communications, and wireless LAN networks, a significant increase in systems capacity can be achieved by use of multiple antennas. (Winters, 1998). Use of diversity is made more compelling by decrease in the cost of digital signal processing hardware and the advances in adaptive signal processing. There are different kinds of diversity commonly employed in wireless communication systems; frequency diversity, time diversity, and space diversity. (Winters, 1998).

In frequency diversity, the information signal is modulated through different carriers. Each carrier should be separated from the others by at least the coherence bandwidth $(\Delta f)_c$ as shown in figure 2.1 below, so that different copies of the signal undergo independent fading. The fact that waves transmitted on different frequencies induce different multipath structure in the propagation media is exploited. Thus replicas of the transmitted signal are provided to the receiver in the form of redundancy in the frequency domain.

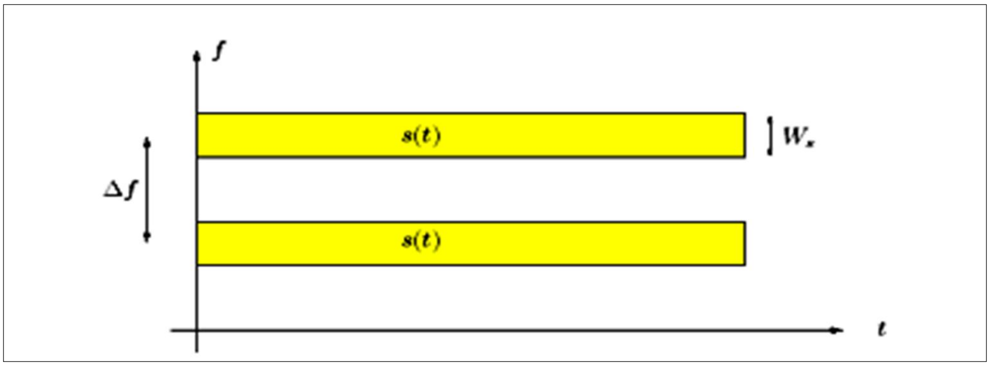

Figure 2.1 Frequency Diversity

Time diversity is achieved by transmitting the desired signal through different periods of time i.e. each symbol is transmitted ***m*** times. The interval between transmissions of the same symbol should be at least the coherence time ***(Δt)c*** as shown in figure 2.2 below so that different copies of the same symbol undergo independent fading. Thus replicas of the transmitted signal are provided to the receiver in the form of redundancy in time domain. (Hourani, 2004).

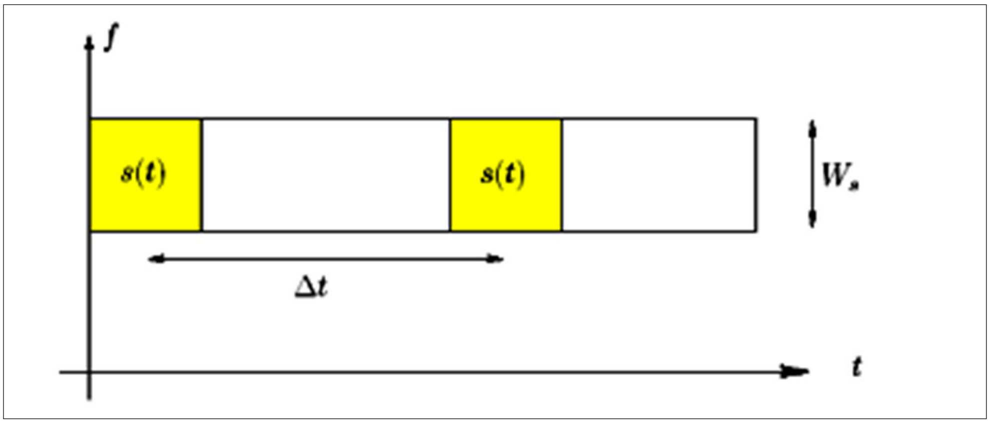

Figure 2.2: Time diversity

2.3 Spatial Diversity Techniques

Spatial diversity is the most common diversity technique**.** In space diversity, multiple antennas are strategically spaced and connected to a common transmitting and/or receiving system. Spatial diversity provides an attractive means for improving the performance of wireless communication systems. Spatial diversity can be employed to combat both frequency selective fading and time selective fading. (Hourani, 2004; Rappaport, 1996).

Unlike frequency diversity where additional bandwidth may be required and time diversity where additional time may be required, in spatial diversity no additional bandwidth or transmission time is required. Spatial diversity can be implemented at the receiver (Receive diversity) and/or the transmitter (transmit diversity). Transmit and receive diversity have emerged as effective means of achieving higher throughput in wireless communication systems. (Winters, 1998).

3.0 Theoretical Analysis

Multiple antenna systems have been known to increase diversity to combat channel fading. Each pair of transmit and receive antennas provides a signal path from the transmitter to the receiver. By sending signals that carry the same information through different paths, multiple independently faded replicas of the data symbol can be obtained at the receiver end; hence more reliable reception is achieved. (Alamouti, 1998). In a slow Rayleigh fading environment with one transmit and ***n*** receive antennas, the transmitted signal is passed through ***n*** different paths. If the fading is independent across antenna pairs, a maximal diversity gain of ***n*** can be achieved. (Rappaport, 1996; Foschini). The average error probability is known to decay by $1/SNR^n$ at high (Signal to Noise Ratio) ***SNR*** in contrast to SNR^{-1} for the single input single output (SISO) system. With multiple transmit antennas, ***m*** and one receive antenna, the underlying idea is still averaging over multiple path gains to increase the reliability. It has been shown that with ***m*** transmit antennas and one receive antenna, a diversity gain within 0.1dB that of ***n*** receive antennas with one transmit antenna can be achieved. (Zheng, 2003).

3.1 Closed-loop Transmit Diversity (CLTD) Scheme

In closed-loop Transmit diversity scheme, the transmitter has the knowledge of the channel as there is a feedback path required from the receiver to communicate the channel seen by the receiver to the transmitter. The channel experienced by each receive antenna is randomly varying in time. For the i^{th} receive antenna, each transmitted symbol gets multiplied by a randomly varying complex number $\boldsymbol{h_i}$ The channel is a flat fading Rayleigh channel, the real and imaginary parts of $\boldsymbol{h_i}$ are Gaussian distributed having mean $\boldsymbol{\mu_{h_i}} = \mathbf{0}$ and variance $\boldsymbol{\sigma^2_{h_i}} = \frac{1}{2}$. The channel experienced by each transmit antenna to receive antenna is independent from the channel experienced by other transmit antennas. On the receive antenna, the noise $\boldsymbol{n}$ has the Gaussian probability density function with $\mu = 0$ and $\sigma^2 = \frac{N_o}{2}$.

A 2 transmit 1 receive antenna case is depicted in figure 3.0 below.

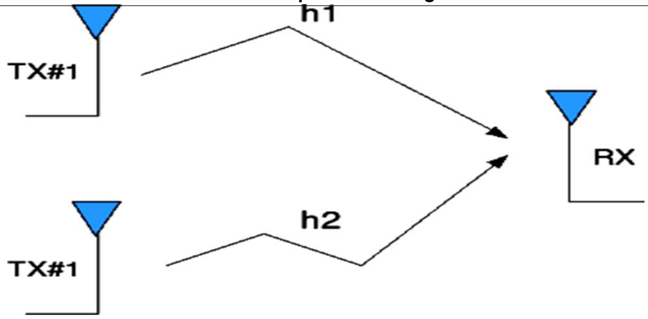

Figure 3.2: Transmit 1 receive beam steering

On the receive antenna RX, the received signal is,

$$\boldsymbol{y_i} = [\boldsymbol{h_1}\ \boldsymbol{h_2}]\begin{bmatrix}\boldsymbol{x}\\ \boldsymbol{x}\end{bmatrix} + \boldsymbol{n} = (\boldsymbol{h_1} + \boldsymbol{h_2})\boldsymbol{x} + \boldsymbol{n} \qquad \text{.......................... (9)}$$

where $\boldsymbol{y}_i$ is the received symbol, $\boldsymbol{h_i}$ is the channel on the i^{th} transmit antenna, $\boldsymbol{x}$ is the transmitted symbol and $\boldsymbol{n}$ is the noise on the receive antenna. When transmit beamforming (closed-loop) is applied, the symbol from each transmit antenna is multiplied by a complex number corresponding to the inverse of the phase (the channel effect are reversed) of the channel so as to ensure that the signals add constructively at the receiver. In this scenario, the received signal is,

$$\boldsymbol{y} = [\boldsymbol{h_1}\ \boldsymbol{h_2}]\begin{bmatrix}\boldsymbol{e}^{-j\theta_1}\\ \boldsymbol{e}^{-j\theta_2}\end{bmatrix}\boldsymbol{x} + \boldsymbol{n} \qquad \text{.. (10)}$$

where,

$$\boldsymbol{h_1} = |\boldsymbol{h_1}|\,\boldsymbol{e}^{j\theta_1} \qquad \text{and} \qquad \boldsymbol{h_2} = |\boldsymbol{h_2}|\,\boldsymbol{e}^{j\theta_2}$$

In this case, the signal at the receiver is,

$$y = \underbrace{(|h_1| + |h_2|)}\,x + n \qquad \text{....................................(11)}$$

For equalization, we need to divide the received symbol $\boldsymbol{y}$ with the new effective channel, i.e.

$$\breve{y} = \frac{\boldsymbol{y}}{[|\boldsymbol{h_1}|\quad|\boldsymbol{h_2}|]} = \boldsymbol{x} + \frac{\boldsymbol{n}}{[|\boldsymbol{h_1}|\quad|\boldsymbol{h_2}|]} \qquad \text{...................... (12)}$$

4.0 Discussion and Conclusion

From this research, it was found that sending the same information on multiple transmit antenna does not provide diversity gain. This is depicted in figure 4.0 by the graphs for *1tx – 1rx* (theory) and *2tx – 1rx* (no beamforming – simulated). Intuitively, this is due to the fact that the effective channel $h_1 + h_2$ in a 2 transmit antenna case is again a Rayleigh channel; hence the Bit Error Rate (BER) performance is identical to 1 transmit 1 receive Rayleigh channel case. However if the transmit symbols are multiplied by a complex phase (closed loop) to ensure that the phases align at the receiver, there is diversity gain though the BER performance seems to be slightly poorer than the 1 transmit (tx) 2 receive (rx)

Maximal Ratio Combining (MRC) case as in figure 4.0 (*1tx-1rx* mrc theory and *2tx-1rx* beamforming simulated graphs). This is because the noise is scaled by $|h_1| + |h_2|$ in the case of transmit beamforming.

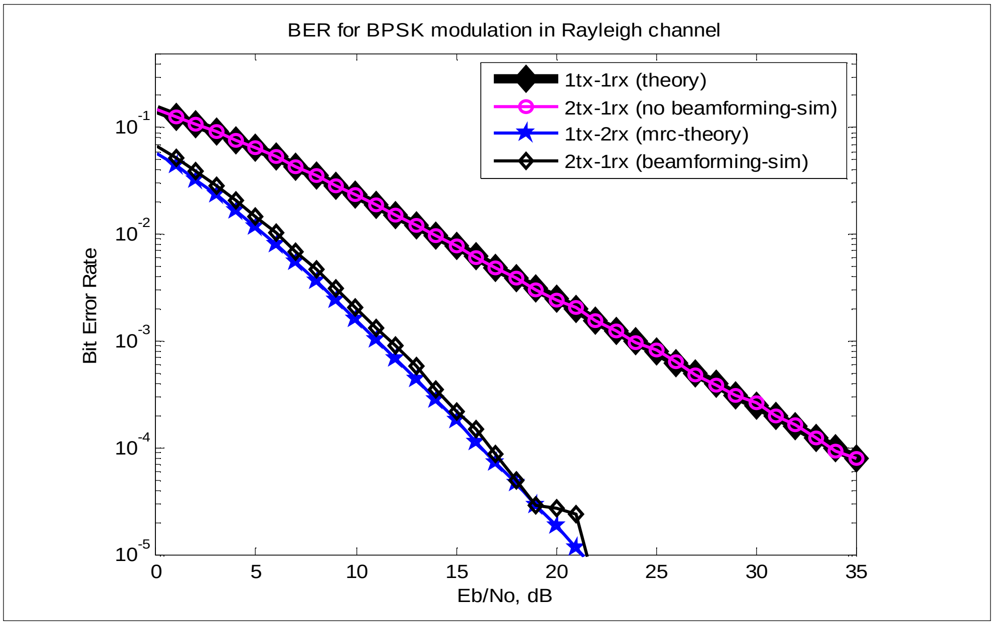

Fig. 4: BER plot for 2 transmit 1 receive CLTD for Binary Phase Shift Keying (BPSK) in Rayleigh channel

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Appendices

Appendix A

Script for computing the BER for BPSK modulation in a Rayleigh fading channel with and without transmit beamforming.

```
clear
N = 10^6 % number of bits or symbols

% Transmitter
ip = rand(1,N)>0.5; % generating 0,1 with equal probability
s = 2*ip-1; % BPSK modulation 0 -> -1; 1 -> 0
nTx = 2;

Eb_N0_dB = [0:35]; % multiple Eb/N0 values

for ii = 1:length(Eb_N0_dB)

  n = 1/sqrt(2)*[randn(1,N) + j*randn(1,N)]; % white gaussian noise, 0dB variance
  h = 1/sqrt(2)*[randn(nTx,N) + j*randn(nTx,N)]; % Rayleigh channel

  sr = (1/sqrt(nTx))*kron(ones(nTx,1),s);

  % Channel and noise Noise addition
  hEff = h.*exp(-j*angle(h));
  y1 = sum(h.*sr,1) + 10^(-Eb_N0_dB(ii)/20)*n;
  y2 = sum(hEff.*sr,1) + 10^(-Eb_N0_dB(ii)/20)*n;

  % equalization
  y1Hat = y1./sum(h,1);
  y2Hat = y2./sum(hEff,1);

  % receiver - hard decision decoding
  ip1Hat = real(y1Hat)>0;
  ip2Hat = real(y2Hat)>0;

  % counting the errors
  nErr1(ii) = size(find([ip- ip1Hat]),2);
  nErr2(ii) = size(find([ip- ip2Hat]),2);

end

simBer1 = nErr1/N; % simulated ber (no beam forming)
```

```
simBer2 = nErr2/N; % simulated ber (with beam forming)
theoryBerAWGN = 0.5*erfc(sqrt(10.^(Eb_N0_dB/10))); % theoretical ber
EbN0Lin = 10.^(Eb_N0_dB/10);
theoryBer = 0.5.*(1-sqrt(EbN0Lin./(EbN0Lin+1)));
p = 1/2 - 1/2*(1+1./EbN0Lin).^(-1/2);
theoryBer_nRx2 = p.^2.*(1+2*(1-p));

close all
figure
semilogy(Eb_N0_dB,theoryBer,'bp-','LineWidth',2);
hold on
semilogy(Eb_N0_dB,simBer1,'ys-','LineWidth',2);
semilogy(Eb_N0_dB,theoryBer_nRx2,'gp-','LineWidth',2);
semilogy(Eb_N0_dB,simBer2,'mx-','LineWidth',2);
axis([0 35 10^-5 0.5])
grid on
legend('1tx-1rx (theory)','2tx-1rx (no beamforming-sim)','1tx-2rx (mrc-theory)','2tx-
1rx (beamforming-sim)');

xlabel('Eb/No, dB');
ylabel('Bit Error Rate');
title('BER for BPSK modulation in Rayleigh channel');
```