Relay network under broadband jamming

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RELAY NETWORK UNDER BROADBAND JAMMING

A Thesis by

Jayesh Murlidhar Sonawane

Bachelor of Engineering, Pune University, 2006.

Submitted to the Department of Electrical Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

December 2010

RELAY NETWORK UNDER BROADBAND JAMMING

The following faculty members have examined the copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

Hyuck M. Kwon, Committee Chair

Xiaomi Hu, Committee Member

Yanwu Ding, Committee Member

DEDICATION

To my father and my mother, two people in this world without whom I would be incomplete

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ABSTRACT

In this thesis, the bit error rate (BER) performance of a relay network using binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulation was compared under broadband jamming with a normalized maximum ratio combining (MRC) scheme at various jamming locations. Results show that, among various jamming locations in the relay network, jamming at the destination has more negative effects on BER than jamming at the relay. Other observations show that increasing the jamming power will cause loss in the diversity order of the relay network.

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LIST OF ABBREVATIONS/NOMENCLATURE

AF	Amplify and Forward
a_1	MRC coefficient for Source-Destination link
a_2	MRC coefficient for Relay-Destination link
a_2^J	MRC coefficient with jamming
b^J	Amplification Coefficient
b	Amplification coefficient
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
D	Destination node
E_b/N_J	Bit energy to jamming signal power ratio.
h_{rd}	Channel coefficient in Relay-Destination link
h_{sd}	Channel coefficient in Source-Relay link
h_{sr}	Channel coefficient in Source-Destination link
J	Jamming Signal
MRC	Maximum Ratio Combining scheme
n_{J1}	Noise signal in case of jamming present at R-D link near destination
n_{J2}	Noise signal in case of jamming present at R-D link near relay
n_{JR}	Noise signal in case of jamming present at S-R link near relay
n_{rd}	Noise signal present in R-D link
n_{sd}	Noise signal present in S-D link
n_{sr}	Noise signal present in S-R link

LIST OF ABBREVATIONS/NOMENCLATURE (continued)

N_0	Noise signal power for all link without jamming
N_J	Noise signal power in for jamming signal
N_J'	Noise signal power in case of jamming at S-R link near relay
N_{J1}	Noise signal power in case of jamming at R-D link near destination
N_{J2}	Noise signal power in case of jamming at R-D link near relay
P	Signal power/ Relay power
QPSK	Qudrature Phase Shift Keying
R	Relay
R-D	Relay – Destination link
S	Source
S-D	Source-Destination link
S-R	Source-Relay link
SIR	Signal power to Jamming (Interference) Signal power Ratio
SNR	Signal power to Noise power Ratio
X	Transmitted signal
Y_{rd}	Received signal at destination node from relay node
Y_{rd}^J	Received signal at destination node from relay node in case of jamming at S-R link jamming near real
Y_{rd1}^J	Received signal at destination node from relay node in case of jamming at R-D link near destination
Y_{rd2}^J	Received signal at destination node from relay node in case of jamming at R-D link near relay

LIST OF ABBREVATIONS/NOMENCLATURE (continued)

Y_{sd}	Received signal at destination node from source node
Y_{sr}	Received signal at relay node from source node
Y_{sr}^{J}	Received signal at relay node in case of jamming at S-R link near relay

CHAPTER 1

INTRODUCTION

1.1 Relay Systems

In cooperative communications, independent paths between a source and a base station or destination can be generated via the introduction of a relay channel [1]. A relay channel can be thought of as an auxiliary channel to the direct channel between the source and the destination.

Cooperative communication protocols can be generally categorized into fixed relaying schemes and adaptive relaying schemes. In a fixed relaying scheme, the channel resources are divided between source and relay in a deterministic manner. Processing at the relay differs according to the employed protocol. In a fixed amplify-and-forward (AF) relaying protocol [2], the relay simply scales the received version and transmits the amplified version of it to the destination.

Figure 1 shows a system model of a typical relay network [1] with one source node, one destination node, and one relay node.

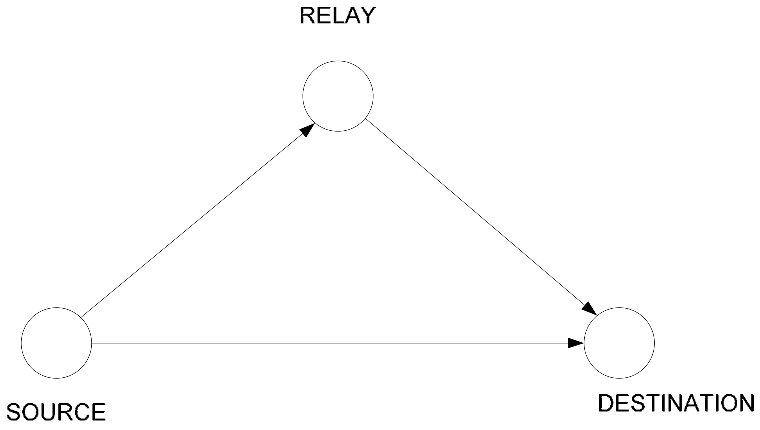

Figure 1. Relay system.

1.2 Jamming Signal

There are many different types of jamming signals such as broadband jamming, partial-band jamming, tone jamming, pulse jamming, etc. Broadband jamming is an effective jamming scheme when the jammer power is sufficient. This thesis considers broadband jamming.

1.3 Thesis Overview

This thesis studies a relay network that has one source (S) node, one destination (D) node, and one intermediate node, which act as a relay (R) node to assist in communication between the source and the destination. This thesis considers a relay network under the Rayleigh fading environment, whereby the destination receives the same information from both the source and the relay nodes. However, the signal received from the relay node is distorted more than the signal received from the source node. This paper assumes an amplify-and-forward relay where the source transmits information to the relay node and the destination node in the first time slot, while, in the second time slot, only the relay node will transmit a received signal from the source node in the first time slot with some amplification. The amplification coefficient is dependent on the signal received at the relay node.

The main objective of this thesis is to study the performance of the relay network under a broadband jamming environment using binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulations.

This thesis considers that a jamming signal 'J' is present at different locations, which affects the performance of the relay network. This thesis also employs the normalized maximum ratio combining (MRC) scheme for detection of the transmitted symbol. MRC coefficients, including the jamming signal, are derived in this thesis. The case of jamming at the relay node for the source-relay (S-R) link affects the amplification coefficient parameter b. The derivation of amplification coefficient parameter b is shown in the appendix. Based on previous studies [6], the amplification coefficient depends on the received signal at the relay in the first time slot. Hence, the derivation for the right b is important to counter jamming at the relay in the S-R link. The jamming signal affects the choice of the amplification coefficient. Jamming can have significant negative effects on the bit error rate (BER) of the relay system. Jamming near the relay in the relay-destination (R-D) link is more effective than jamming at the source-relay link, which does not show much change in BER performance since the destination receives the strong desired signal from the source-destination (S-D) direct link typically and the signal transmitted from the relay can be already distorted even if the R-D link is not jammed.

1.4 Thesis Outline

In Chapter 2, the system model for the proposed scheme will be explained. Different jamming locations will also be shown in Chapter 2. Chapter 3 provides simulation results. Chapter 4 presents a conclusion and discusses future work. The appendix will show the derivation of an amplification coefficient b.

CHAPTER 2

SYSTEM MODEL

The system studied in this thesis consisted of a simple relay system under broadband jamming for an amplify-and-forward protocol.

2.1 Simple Relay Network without Jamming

The network consisted of a single antenna source node, one relay node, and one destination node, as shown in Figure 2. The amplify-and-forward protocol was used. The destination received signals in two separate time slots. During the first time slot, the relay received the signal transmitted from the source and destination nodes, also received the signal transmitted from the source with signal power P. In the second time slot, the relay transmitted the amplified version of the signal to the destination node. There was no signal transmission from the source to the destination.

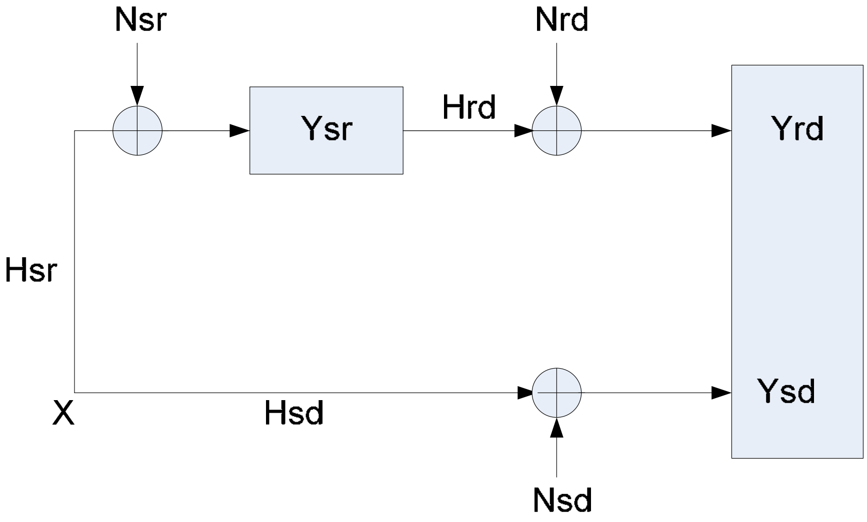

Figure 2. Simple relay-channel model.

At the destination, the received signals at the different time slots for the amplify-and-forward relay network are described below.

2.1.1 Received Signals

At the first time slot, the received signals at the destination and the relay can be written as

$$Y_{sd} = h_{sd}X + n_{sd} \tag{1}$$

$$Y_{sr} = h_{sr}X + n_{sr} \tag{2}$$

At the second time slot, the received signals can be written as

$$Y_{rd} = bY_{sr}h_{rd} + n_{rd} \tag{3}$$

where $n_{sd} \sim \mathcal{N}(0, N_0)$, $n_{sr} \sim \mathcal{N}(0, N_0)$, and $n_{rd} \sim \mathcal{N}(0, N_0)$, are the AWGN noises present in the source-destination link, source-relay link, and relay-destination link, respectively, as shown in Figure 2. The transmitted signal from the source is X, with total power (or energy) P.

2.1.2 Amplification Coefficient

The amplification coefficient b is a very important parameter at the relay in the AF protocol. This parameter was derived from the received signal from the source at the relay for the first time slot. It used power at the relay P to constrain the amplification factor. In this paper, relay power and source power are considered to be P. Hence,

$$b = \frac{\sqrt{P}}{\sqrt{P|h_{sr}|^2 + N_0}} \tag{4}$$

The detailed derivation for this parameter is shown in the appendix.

2.1.3 MRC without Normalization

This thesis also employed the maximum ratio combining scheme at the destination to decode the transmitted signal as

$$Y = a_1Y_{sd} + a_2Y_{rd} \tag{5}$$

where a_1 and a_2 are the MRC coefficients. This thesis derived the MRC coefficients under the jamming conditions. These coefficients should be designed to maximize the combined signal-to-noise ratio (SNR). Since additive white Gaussian noise (AWGN) terms span the entire space, in order to minimize the noise effects, the detector should project the received signals Y_{sd} and Y_{rd} to the desired signal spaces. Hence, Y_{sd} and Y_{rd} should be projected along the directions of $h_{rd}h_{sr}$ and h_{sd}, respectively, as

$$a_1 = \sqrt{P}h_{sd}^* \tag{6}$$

And the expression for the MRC coefficient during the second time slot is given by

$$a_2 = b\sqrt{P}h_{sr}^*h_{rd}^* \tag{7}$$

Equations (6) and (7) give the expressions for the MRC coefficients without the normalization factor.

2.2 Relay Network under Jamming without Normalization

This section describes the relay network under jamming with no normalization

2.2.1 Jamming at Relay-Destination Link Near Destination

In this case, the jamming signal is present near the destination, as shown in Figure 3. A broadband jamming is considered. The jamming signal J is distributed at the same as the noise signal and has considerably strong power, i.e., $\sim\mathcal{N}(0, N_J)$,$N_J > N_0$.

At the destination and the relay, the received signals at the during the first time slot, are equal to (1) and (2), respectively, and at second time slot the received signal in the presence of jamming signal can be written as

$$Y_{rd1}^J = bY_{sr}h_{rd} + n_{rd} + J \tag{8}$$

where $n_{sd}\sim\mathcal{N}(0,N_0)$, $n_{sr}\sim\mathcal{N}(0,N_0)$, $n_{rd}\sim\mathcal{N}(0,N_0)$, and $J\sim\mathcal{N}\left(0,N_J\right)$. The superscript J and the subscript 1 denote the jamming case and the near destination case, respectively. The transmitted signal from the source is X, with power P. Also, b is the amplification coefficient in equation (4).

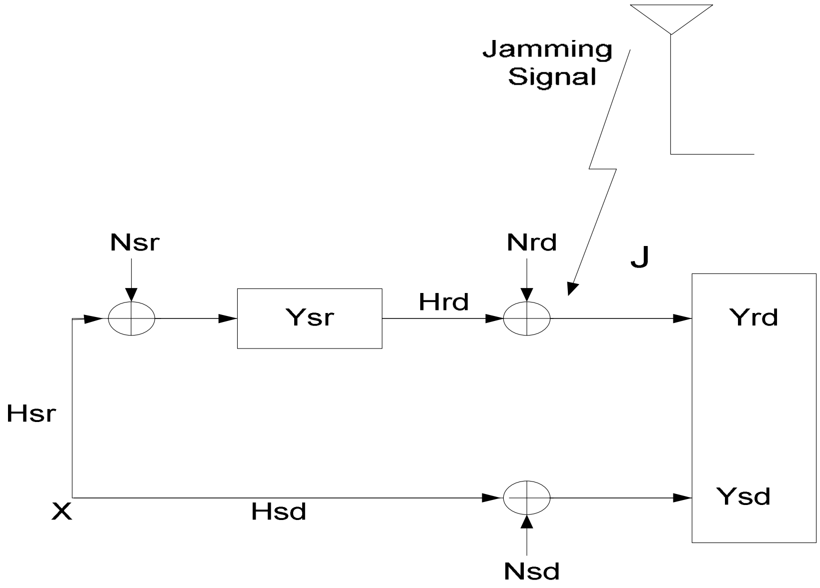

Figure 3. Jamming present at relay-destination link near destination.

Assume that the relay also has power P. Then, the amplification coefficient depends on the received signal power at the relay during the first time slot as shown in equation (4). Y_{rd1}^{J} can be rewritten as

$$\begin{aligned} Y_{rd1}^{J} &= b(h_{sr}X+n_{sr})h_{rd}+n_{rd}+J \\ &= bh_{rd}h_{sr}X+bh_{rd}n_{sr}+n_{rd}+J \\ &= bh_{rd}h_{sr}X+n_{J1} \end{aligned} \tag{9}$$

where n_{J1} represents the overall equivalent noise including the jamming signal. The equivalent noise can be written as

$$\begin{aligned} N_{J1} = {} & E\left[\left(n_{J1}\right)\left(n_{J1}\right)^{*}\right] = (bh_{rd}n_{sr}+n_{rd}+J)(bh_{rd}n_{sr}+n_{rd}+J)^{*} \\ = {} & (bh_{rd}n_{sr})(bh_{rd}n_{sr})^{*}+(n_{rd}n_{rd}{}^{*})+(JJ^{*}) \end{aligned}$$

$$= b^2|h_{rd}|^2 N_0 + N_0 + N_J \tag{10}$$

Hence, the overall equivalent noise distribution is given by $n_{J1} \sim N(0, N_{J1})$.

In this thesis, the MRC scheme was used at the destination to decode the transmitted signal as

$$Y = a_1 Y_{sd} + a_2 Y_{rd1}^{J} \tag{11}$$

where a_1 and a_2 are the MRC coefficients.

Referring to equations (6) and (7), the MRC scheme chose a_1 and a_2 as

$$a_1 = \sqrt{P} h_{sd}^{*}$$

$$a_2 = b\sqrt{P} h_{sr}^{*} h_{rd}^{*}$$

The signals were not normalized at the destination.

Therefore, this scheme was called the not-normalized jamming environment. The signal Y was then decoded. The performance of this network was studied and is discussed and plotted in Chapter 3.

2.2.2 Jamming at Relay-Destination Link Near Relay

In this case, the broadband jamming signal was present in the relay-destination link near the relay with $J \sim \mathcal{N}(0, N_J)$. At the destination, the received signals at different time slots for the amplify-and-forward case can be written as

$$Y_{sd} = h_{sd} X + n_{sd}$$

$$Y_{sr} = h_{sr} X + n_{sr}$$

During the second time slot,

$$Y_{rd2}^{J} = (bY_{sr} + J) h_{rd} + n_{rd} \tag{12}$$

where $n_{sd} \sim \mathcal{N}(0, N_0)$, $n_{sr} \sim \mathcal{N}(0, N_0)$, and $n_{rd} \sim \mathcal{N}(0, N_0), J \sim \mathcal{N}(0, N_J)$, as shown in Figure 4. The subscript 2 denotes the jamming signal near the relay in the relay-destination link. The transmitted signal from the source is X, with total power P.

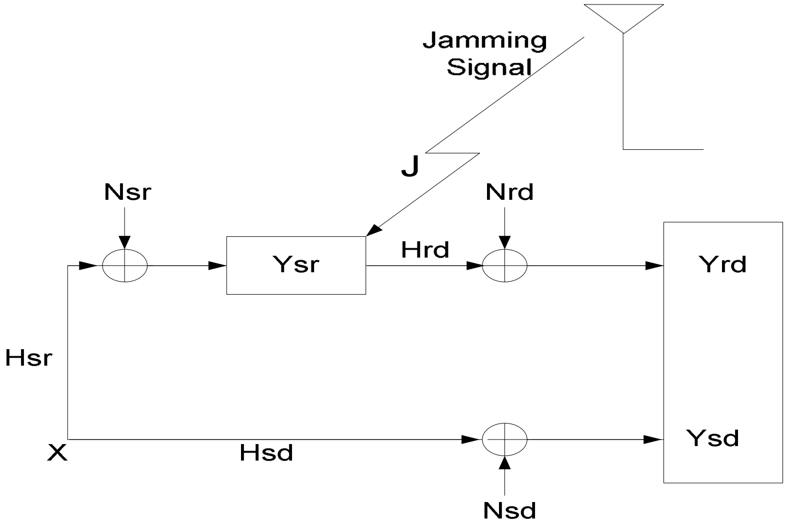

Figure 4. Jamming present at relay-destination link near relay.

Also, b is the amplification coefficient which is written as

$$b = \frac{\sqrt{P}}{\sqrt{P|h_{sr}|^2 + N_0}}$$

The relay power is P.

Y_{rd2}^{J} can be written as

$$\begin{aligned} Y_{rd2}^{J} &= (b(h_{sr}X + n_{sr}) + J)h_{rd} + n_{rd} \\ &= bh_{rd}h_{sr}X + bh_{rd}n_{sr} + Jh_{rd} + n_{rd} \\ &= bh_{rd}h_{sr}X + n_{J2} \end{aligned} \tag{13}$$

where n_{J2} is the equivalent noise including jamming signal.

The variance of n_{J2} can be written as

$$N_{J2} = \left(b^2|h_{rd}|^2 + 1\right)N_0 + |h_{rd}|^2 N_J \tag{14}$$

The derivation of this equivalent noise variance is the same as the one calculated in the previous section. The MRC scheme to decode the transmitted signal is

$$Y = a_1 Y_{sd} + a_2 Y_{rd2}^{J} \tag{15}$$

where a_1 and a_2 are the same coefficients in equations (6) and (7), respectively, for the no-normalization case. Performance of this scheme will be shown in Chapter 3.

2.2.3 Jamming at Source-Relay Link at Relay Input

In this case, the jamming signal was present at the relay input in the source-relay link. The broadband jamming J was considered again, with distribution $J \sim \mathcal{N}(0, N_J)$. Here the relay received the transmitted signal with the jamming signal. Figure 5 shows the block diagram for this case.

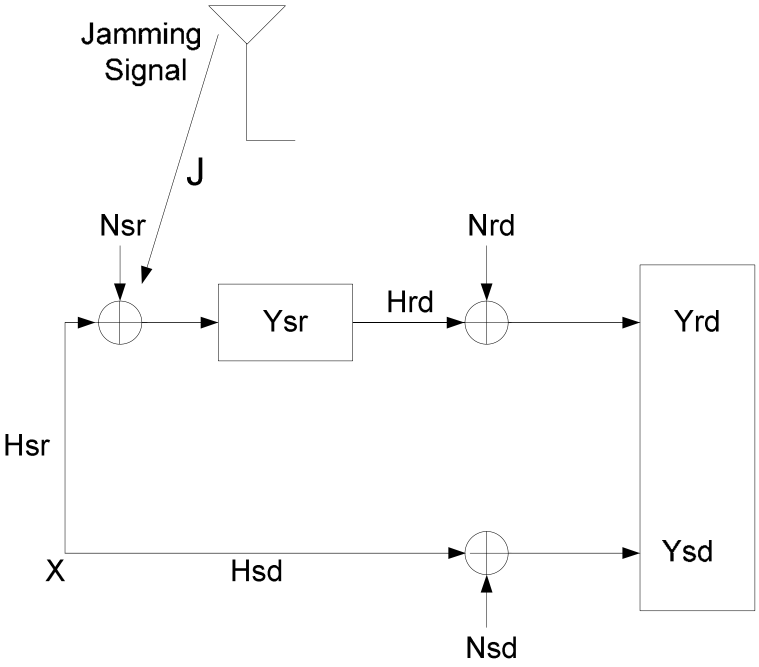

Figure 5. Jamming present at source-relay link near relay.

At the destination, the received signals at different time slots for the amplify-and-forward relay can be written as

$$Y_{sd} = h_{sd} X + n_{sd}$$

$$Y_{s,r}^J = h_{sr}X + n_{sr} + J \tag{16}$$

During the first time slot,

$$Y_{rd}^J = (b\, Y_{s,r}^J)h_{rd} + n_{rd} \tag{17}$$

where $n_{sd} \sim \mathcal{N}(0, N_0)$, $n_{sr} \sim \mathcal{N}(0, N_0)$, and $n_{rd} \sim \mathcal{N}(0, N_0)$, $J \sim \mathcal{N}\left(0, N_J\right)$, the transmitted signal from the source is X, with total power P, as shown in the Figure 5. Also b is the amplification coefficient, which can be written as

$$b^J = \frac{\sqrt{P}}{\sqrt{P|h_{sr}|^2 + N_0 + N_J}} \tag{18}$$

because the relay transmits power that is equal to P. Proof of this amplification coefficient is given in the appendix.

Y_{rd}^J can be rewritten as

$$\begin{aligned} Y_{rd}^J &= b^J(h_{sr}X + n_{sr} + J)h_{rd} + n_{rd} && (19) \\ &= b^J h_{rd} h_{sr} X + b^J h_{rd} n_{sr} + b^J h_{rd} J + n_{rd} \\ &= b^J h_{rd} h_{sr} X + n_{JR} && (20) \end{aligned}$$

where n_{JR} is the equivalent noise including jamming with variance equal to

$$N_J' = \left((b^J)^2 |h_{rd}|^2 + 1\right) N_0 + \left(b^J\right)^2 |h_{rd}|^2 N_J \tag{21}$$

The derivation of this noise variance is the same as the calculated one in equation (10). The MRC scheme uses the same equation (6) for a_1, but a_2 in equation (7) changed due to the change in the expression of b to b^J:

$$a_2^J = b^J \sqrt{P} h_{sr}^* h_{rd}^* \tag{22}$$

Again, equation (22) is not normalized. The derivation of the noise variance is the same as the one calculated in equation (10). Referring to equation (15), the MRC scheme was performed to decode the transmitted signal as

$$Y = a_1 Y_{sd} + a_2^J Y_{rd}^J$$

Performance of this scheme will be presented in Chapter 3.

2.3 Normalized Jamming Environment

The previous sections have discussed the MRC scheme without normalization. In other words, the link from relay to destination and the link from source to destination were treated equivalently. In this section, they are treated differently, according to the quality of each link.

2.3.1 Jamming at Relay-Destination Link Near Destination

For the case shown in the Figure 3, the normalized received signal at the destination can be written as

$$Y = a_1 Y_{sd} + a_2^J Y_{rd1}^J$$

where a_1 and a_2^J are the normalized MRC coefficients. These coefficients should be designed to maximize the combined SNR. For the source-destination link during the first time slot, the coefficients were normalized by the variance of each link as

$$a_1 = \frac{\sqrt{P} h_{sd}^*}{N_0} \tag{23}$$

since the noise variance is equal to N_0. The normalized coefficient during the second time slot is given by

$$a_2^J = \frac{b\sqrt{P} h_{sr}^* h_{rd}^*}{(b^2|h_{rd}|^2+1)N_0+N_J} \tag{24}$$

because the variance of the received signal during the second time slot is $(b^2|h_{rd}|^2+1)N_0+N_J$. This normalization improves the BER performance significantly. The performance of this channel will be shown in Chapter 3.

2.3.2 Jamming at Relay-Destination Link Near Relay

Referring to equation (15), the normalized received signal at the destination can be written the same as for the case shown in Figure 4 as

$$Y = a_1 Y_{sd} + a_2^J Y_{rd2}^J$$

where a_1 and a_2^J are the normalized MRC coefficients. Again, the coefficients are normalized by the variance of each link as

$$a_1 = \frac{\sqrt{P}h_{sd}^*}{N_0} \tag{25}$$

for the source-destination link during the first time slot because the variance is equal to N_0. And the normalized MRC coefficients during the second time slot are given as

$$a_2^J = \frac{b\sqrt{P}h_{sr}^* h_{rd}^*}{\left(b^2|h_{rd}|^2+1\right)N_0+|h_{rd}|^2 N_J} \tag{26}$$

because the noise variance of the received signal during the second time slot is

$$(b^2|h_{rd}|^2+1)N_0+|h_{rd}|^2 N_J$$

This normalization improves BER performance. The performance of this network will be shown in Chapter 3.

2.3.3 Jamming at Source-Relay Link Near Relay

The system model for this case is shown in Figure 5. The normalized MRC output can be written as

$$Y = a_1 Y_{sd} + a_2^J Y_{rd}^J$$

where a_1 and a_2^J are the normalized MRC coefficients, which can be written as

$$a_1 = \frac{\sqrt{P}h_{sd}^*}{N_0} \tag{27}$$

during the first time slot, and

$$a_2^J = \frac{b^J\sqrt{P}h_{sr}^*h_{rd}^*}{\left(\left(b^J\right)^2|h_{rd}|^2+1\right)N_0+(b^J)^2|h_{rd}|^2N_J} \tag{28}$$

during second time slot.

Again, normalization improves the BER performance, which will be shown in Chapter 3.

CHAPTER 3

SIMULATION RESULTS

3.1 Assumptions

This section discusses the performance of the relay network under different jamming scenarios. All simulations were taken for 1,000,000 bits. The employed modulation was either BPSK or QPSK. All channel coefficients, $h_{s,d}$, $h_{r,d}$, and $h_{s,r}$, had a zero mean and unit variance. And all AWGN noises had a zero mean and unit variance. The transmitted signal had unit energy. And the ratio of signal power to jamming signal power was set to 10 dB and -10 dB. For simplicity, only the broadband jamming was considered. Finally, normalized and no-normalized MRC schemes were employed.

3.2 Jamming Near Destination in Relay-Destination Link

3.2.1 BPSK Modulation without Normalization

Figure 6 shows BER performance where the R-D link jammed near the destination for the BPSK modulation with no-normalization. Figure 7 shows the BER performance of the R-D link jammed near the destination for the BPSK modulation with normalization. Clearly, it can be seen that under a jamming scenario, the BER performance is poor.

3.2.2 BPSK Modulation with Normalization

Figure 7 shows that as the power of the jamming signal increased, BER performance worsened. At a BER of 10^{-4}, approximately 5 dB loss was observed for the SIR of 10 dB. Also, for SIR of -10 dB, there was a loss in diversity gain.

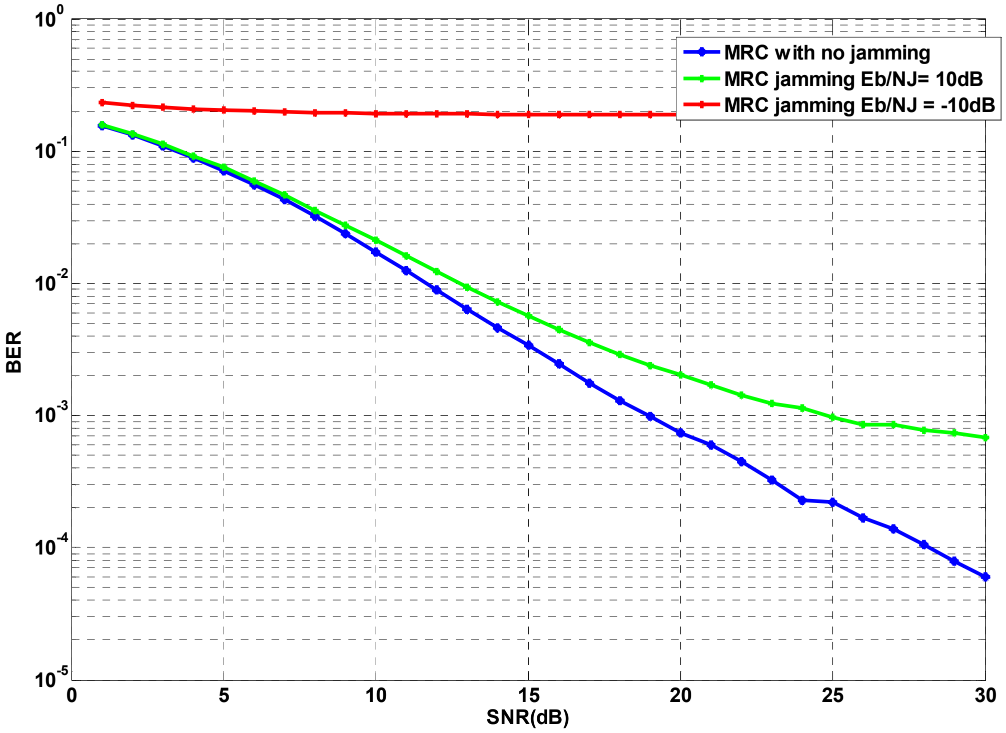

Figure 6. BER performance of R-D link jammed near destination with BPSK modulation without normalization.

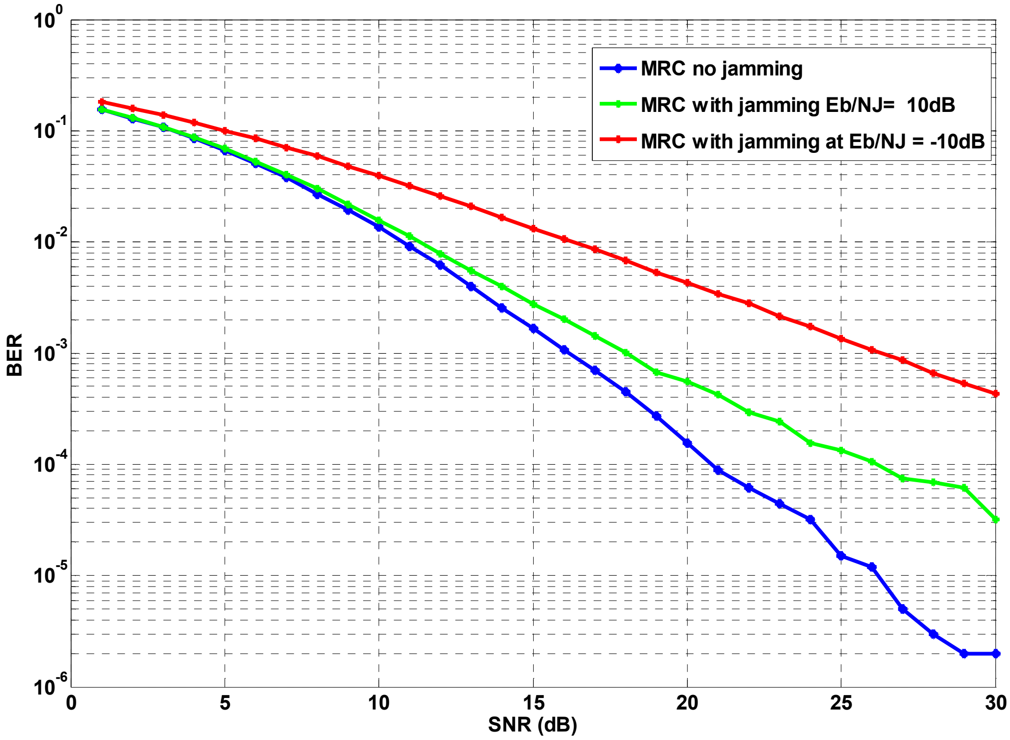

Figure 7. BER performance of R-D link jammed near destination with BPSK modulation with normalization.

Comparing Figures 6 and 7, it can be seen that normalization improves the BER of the network significantly. For example, with a BER of 10^{-3}, an approximately 4 dB gain can be achieved.

3.2.3 QPSK Modulation without Normalization

Figure 8 shows the BER performance of the R-D link jammed near the relay for QPSK modulation without normalization.

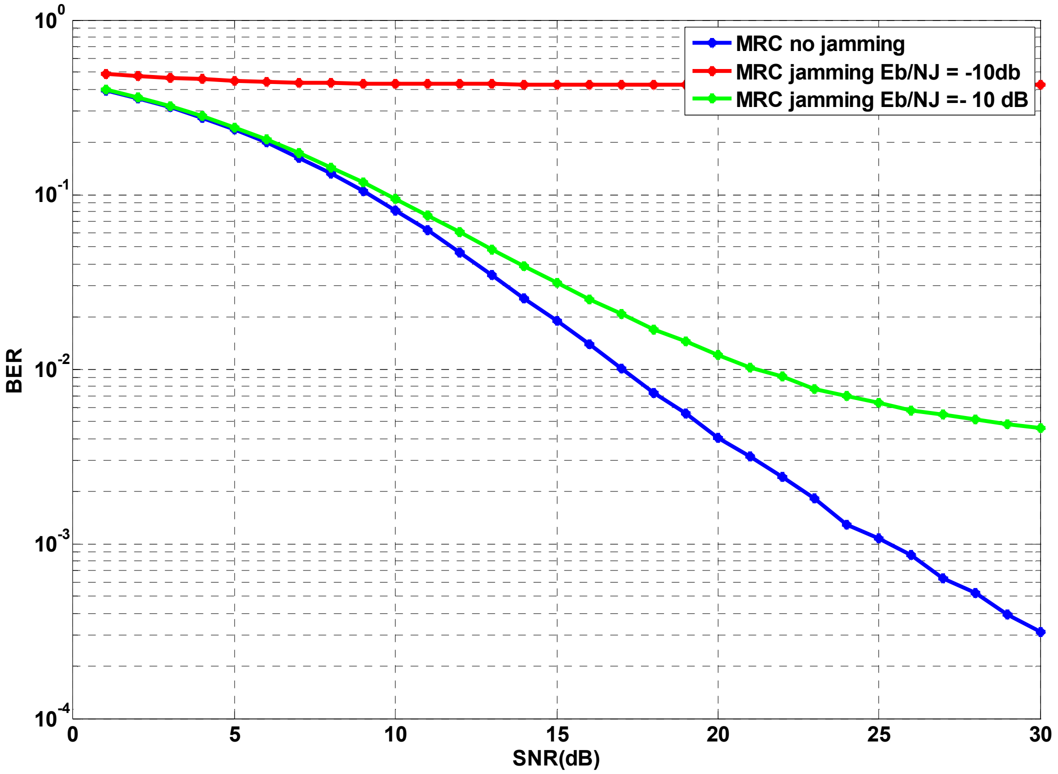

Figure 8. BER performance of R-D link jammed near destination with QPSK modulation without normalization.

3.2.4 QPSK Modulation with Normalization.

Figure 9 shows the BER performance of the R-D link jammed near the relay for QPSK modulation with normalization. At a BER of 10^{-2}, an approximately 4 dB loss was observed for the bit-energy-to-jamming-power (E_b/N_J) of 10 dB. Also, for the E_b/N_J of -10 dB, no diversity gain could be observed.

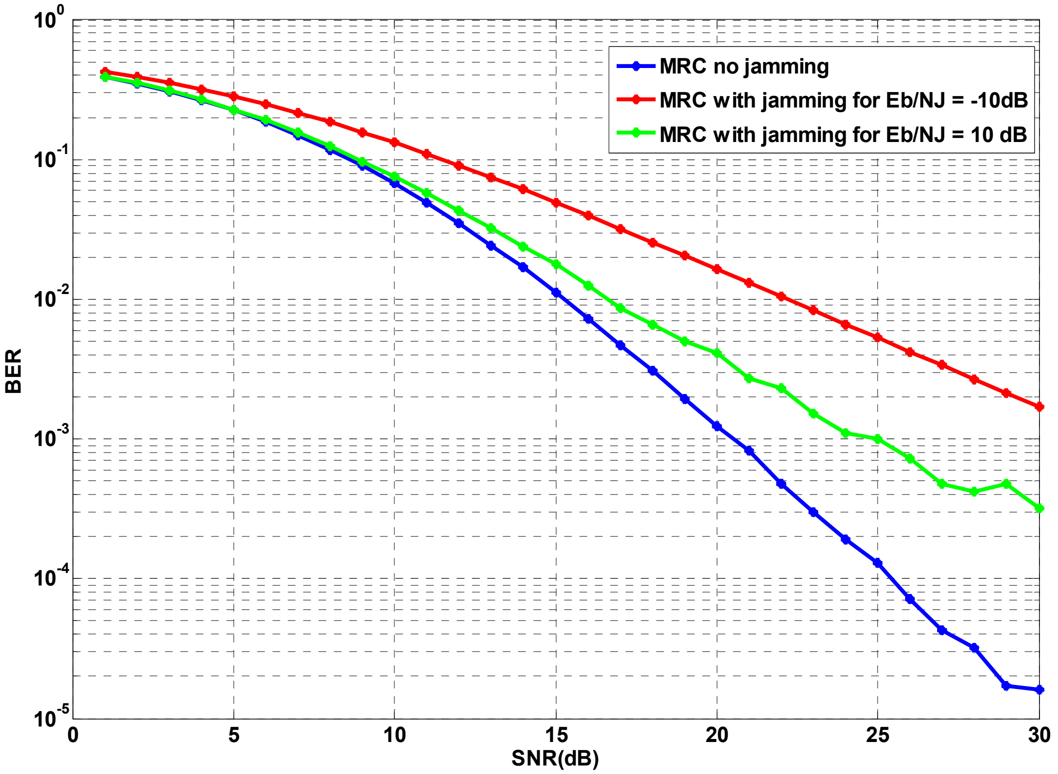

Figure 9. BER performance of R-D link jammed near destination with QPSK modulation with normalization.

Comparing Figures 8 and 9, normalization improves the BER of the system significantly. For example, with a BER of 10^{-2}, an approximately 4 dB of gain was achieved. And, in the case of jamming, an approximately 4 dB gain was also achieved.

3.3 Jamming Near Relay in Relay-Destination Link

3.3.1 BPSK Modulation without Normalization

Figure 10 shows BER performance of the R-D link jammed near the relay for BPSK modulation without normalization.

3.3.2 BPSK Modulation with Normalization.

Figure 11 shows BER performance of the R-D link jammed near the relay for BPSK modulation with normalization.

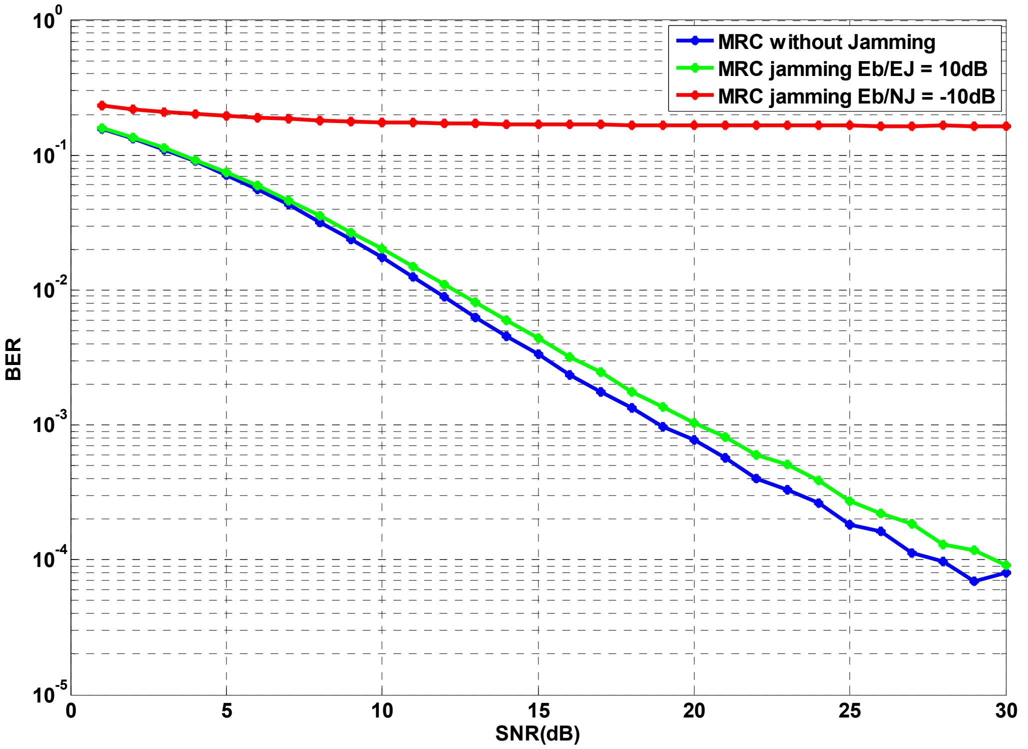

Figure 10. BER performance of R-D link jammed at relay with BPSK modulation without normalization.

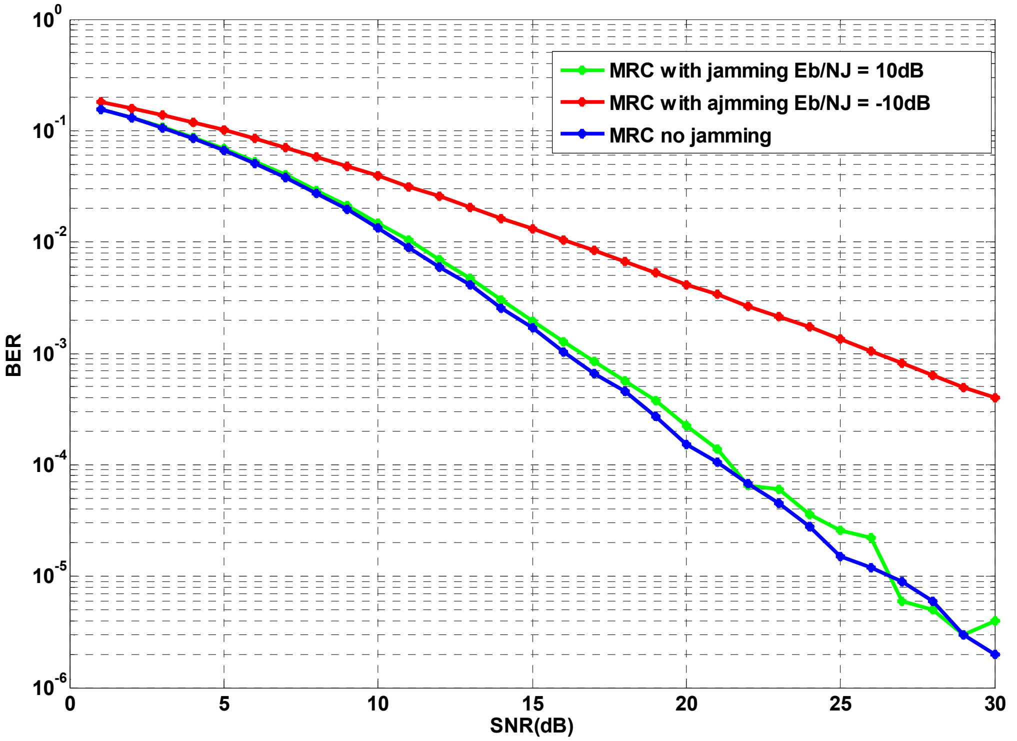

Figure 11. BER performance of R-D link jammed at relay with BPSK modulation with normalization.

It can be seen in Figures 10 and 11 that the high E_b/N_J does not degrade BER much, compared to the no-jamming case when jamming is near the relay output.

3.3.3 QPSK Modulation without Normalization

Figure 12 shows BER performance of the R-D link jammed near the relay for QPSK modulation without normalization.

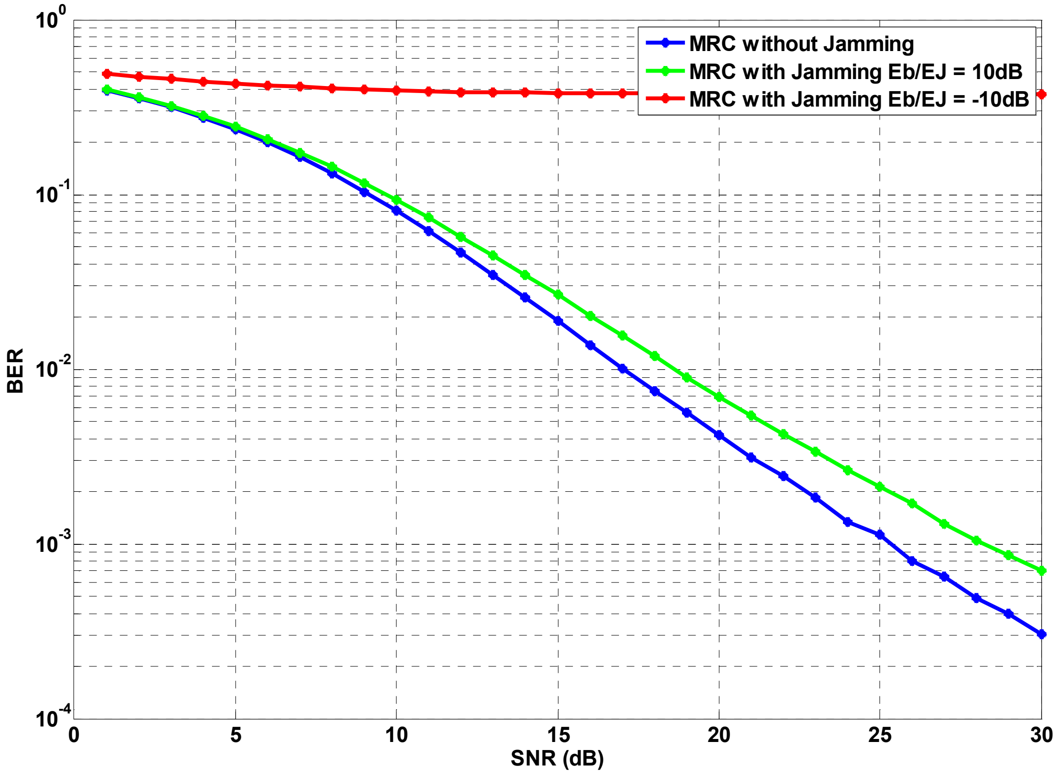

Figure 12. BER performance of R-D link jammed near relay with QPSK modulation without normalization.

3.3.4 QPSK Modulation with Normalization

Figure 13 shows the corresponding BER with normalization.

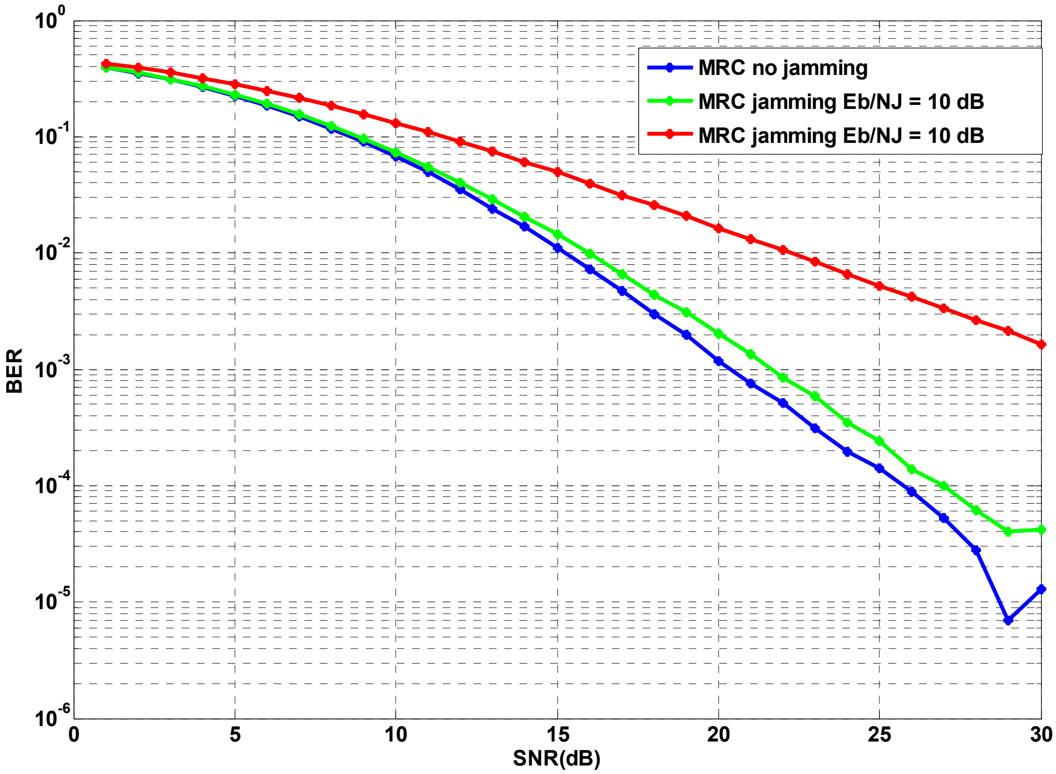

Figure 13. BER performance of R-D link jammed near relay with QPSK modulation with normalization.

It can be observed that for low E_b/N_J, the diversity gain can be lost completely, and for high E_b/N_J, the performance loss is not significant.

3.4 Jamming Near Relay in Source-Relay Link

3.4.1 BPSK Modulation without Normalization

Figure 14 shows BER performance of the S-R link jammed near the relay for BPSK modulation with normalization.

3.4.2 BPSK Modulation with Normalization

Figure 15 shows the corresponding BER with normalization.

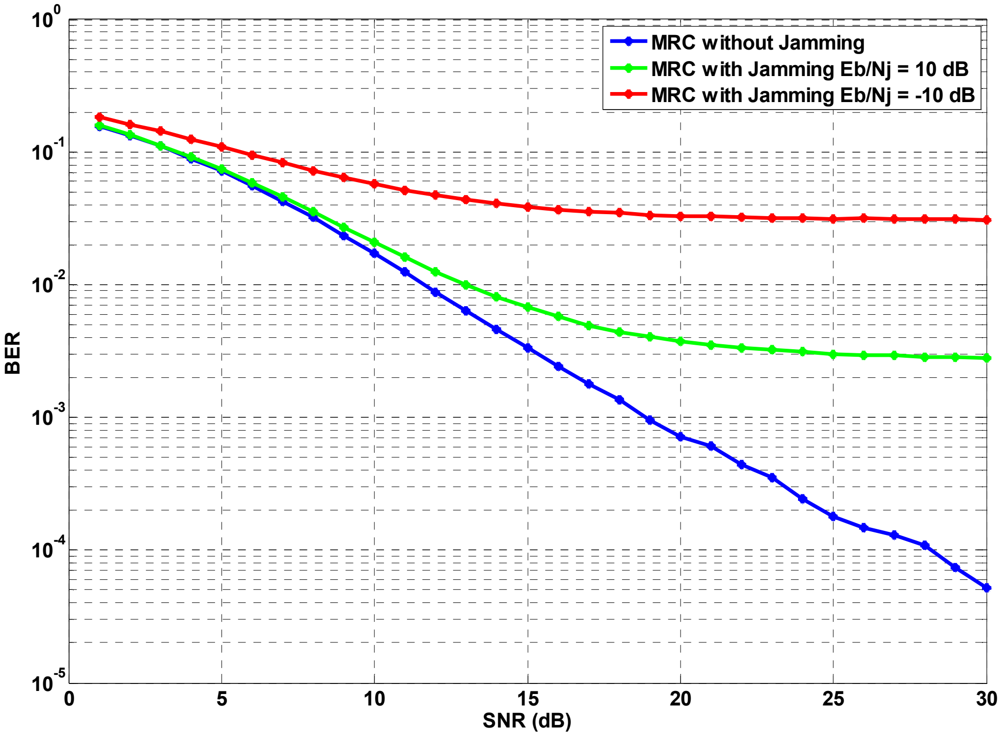

Figure 14. BER performance of R-D link jammed near relay with BPSK modulation without normalization.

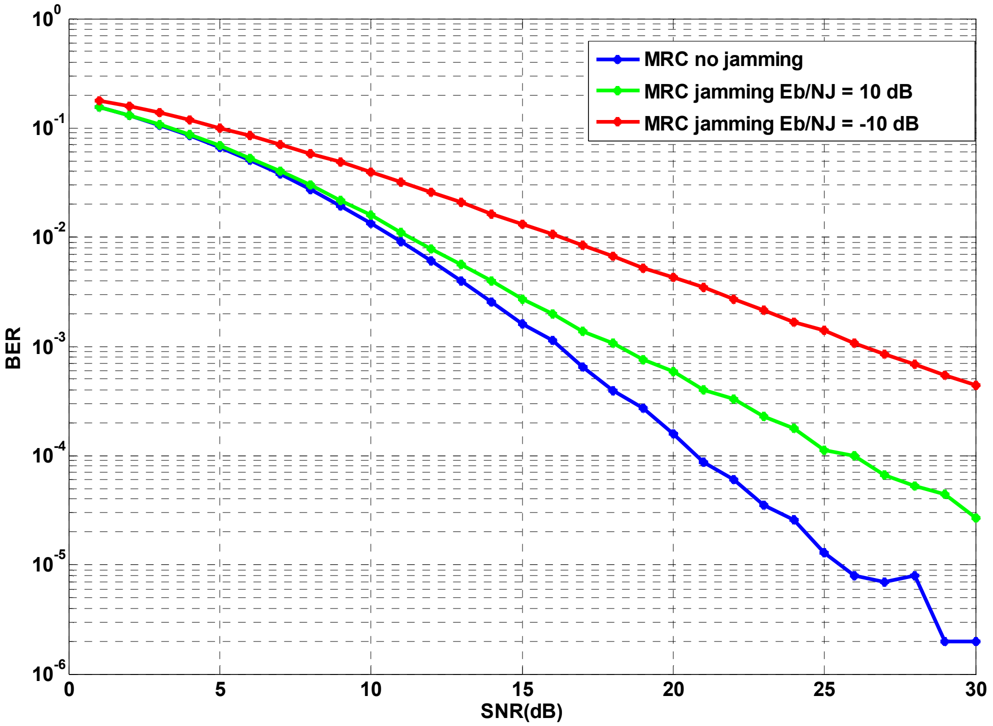

Figure 15. BER performance of S-R link jammed near relay with BPSK modulation with normalization.

It can be seen that at a BER of 10^{-4}, E_b/N_J = 10 dB, loss can be 4 dB even with normalization. Again, if E_b/N_J = -10 dB, then the diversity gain is completely lost.

3.4.3 QPSK Modulation without Normalization

Figure 16 shows BER performance of the S-R link jammed near the relay for QPSK modulation without normalization.

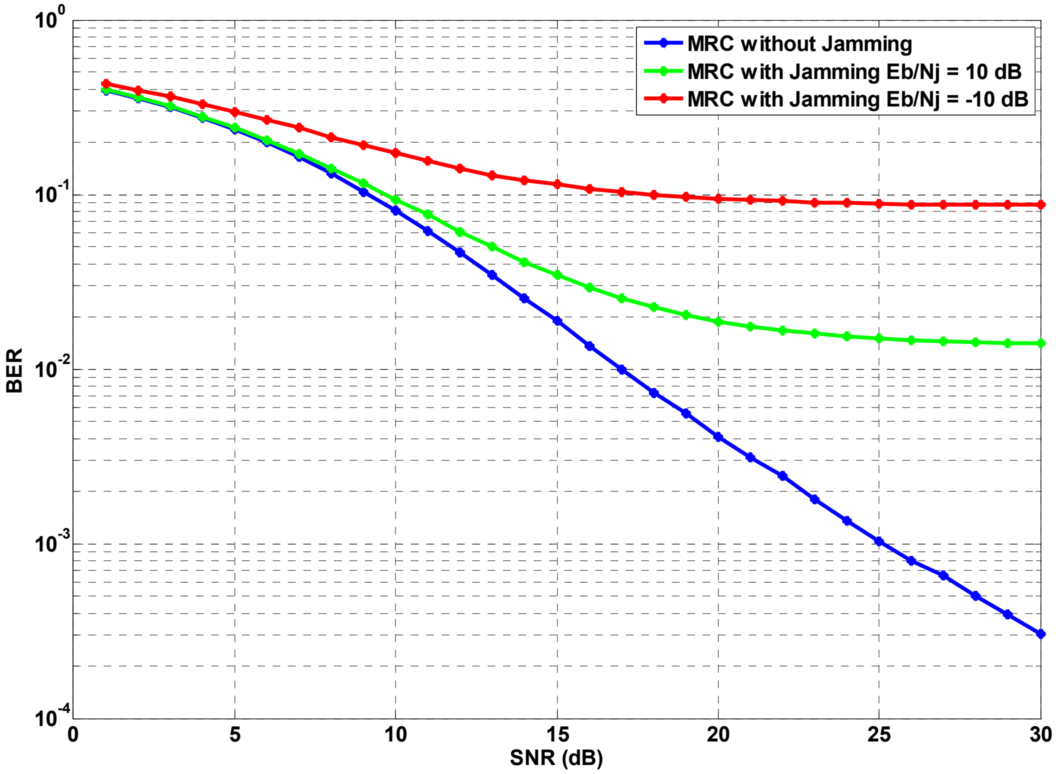

Figure 16. BER performance of S-R link jammed near relay with QPSK modulation without normalization.

3.4.4 QPSK Modulation with Normalization

Figure 17 shows the corresponding BER with normalization. Similar observations as in the BPSK case can be seen.

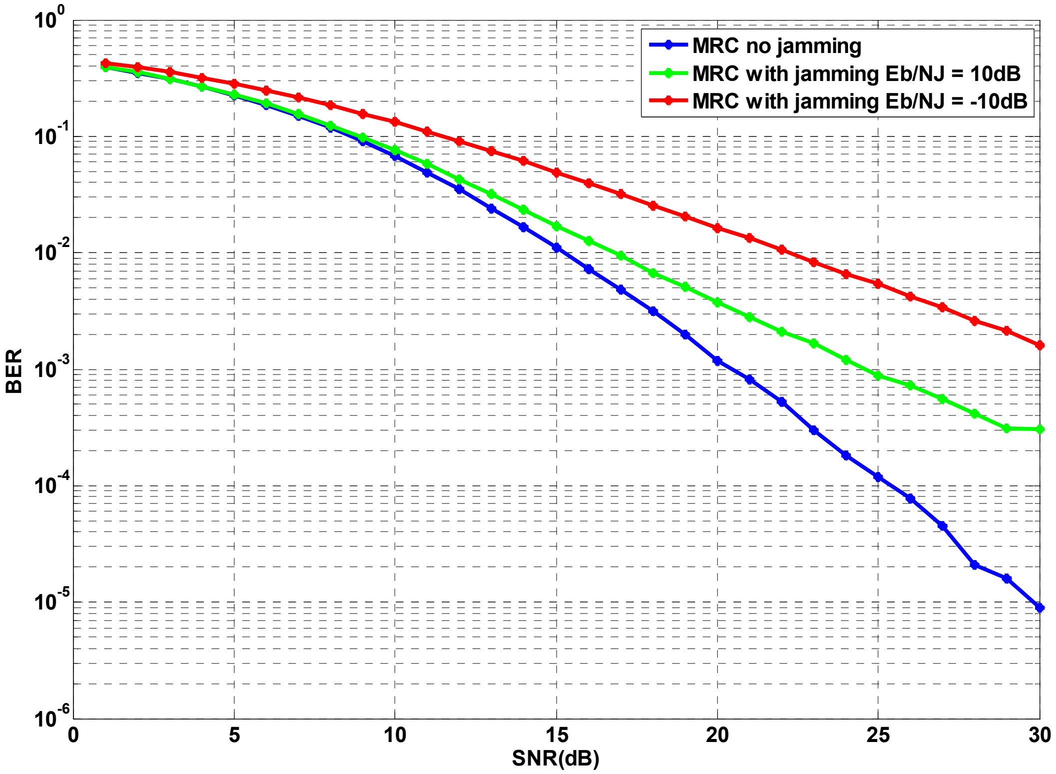

Figure 17. BER performance of S-R link jammed near relay with QPSK modulation with normalization.

CHAPTER 4

CONCLUSIONS

With the increasing power of jamming signals, BER performance degrades. However, in the case of jamming near a relay, not much degradation in BER performance can be seen for low jamming signal power. The different modulation techniques show the same effect of jamming on performance. Clearly from the system model. it can be seen that the MRC coefficients depend on the jamming signal power. The expression of the amplification coefficient changes as well under a jamming environment.

A couple of conclusions can be made based on the simulation results. First, when jamming is applied near the relay in the relay-destination link, jamming with a low E_b/N_J can result in complete loss of diversity gain, whereas jamming with a high E_b/N_J does not degrade the BER performance much. Second, in most cases, the MRC scheme with normalization shows a significant gain over the MRC scheme without normalization.

Finally, both BPSK and QPSK modulations show similar performance under the jamming environment.

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REFERENCES

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APPENDIX

APPENDIX

AMPLIFICATION COEFFICIENT DERIVATION

The relay considered during this study was the AF protocol. In this protocol the relay amplifies the received signal, and that amplification factor is bounded by the relay power. Calculations of the amplification coefficients are shown below:

The received signals at the relay for the first time slot can be given as

$$Y_{s,d} = h_{sd}X + n_{sd}$$

$$Y_{s,r} = h_{sr}X + n_{sr}$$

For the second time slot, the received signal can be written as

$$Y_{rd} = bY_{sr}h_{rd} + n_{rd}$$

The amplification coefficient b can be calculated by assuming that the relay uses the same power as the source. Hence,

$$b^2E\left[\left(Y_{s,r}\right)\left(Y_{s,r}\right)^*\right] = P$$

In other words,

$$b^2E[(h_{sr}X + n_{sr})(h_{sr}X + n_{sr})^*] = P$$

Hence,

$$b^2[P\left|h_{s,r}\right|^2 + N_0] \leq P$$

where $E[XX^*] = P$

Therefore,

$$b^2 = \frac{P}{P\left|h_{s,r}\right|^2 + N_0}$$

or the amplification coefficient can be written as

$$b = \sqrt{\frac{P}{P\left|h_{s,r}\right|^2 + N_0}}$$

Amplification Coefficient Under Jamming

Consider the case of the S-R link jammed near the relay. The received signal for the AF protocol during both time slots can be given as

$$Y_{sd} = h_{sd}X + n_{sd}$$

$$Y_{s,r}^{J} = h_{sr}X + n_{sr} + J$$

where $J \sim N(0, N_J)$ is the jamming signal

At the second time slot, the received signal in the presence of the jamming signal can be written as

$$Y_{rd}^{J} = (b\, Y_{s,r}^{J})h_{rd} + n_{rd}$$

Hence,

$$b^2 E\left[(Y_{rd}^{J})(Y_{rd}^{J})^{*}\right] = P$$

In other words,

$$b^2 E[(h_{sr}X + n_{sr} + J)(h_{sr}X + n_{sr} + J)^{*}] = P$$

which is

$$b^2 E[(h_{sr}X)(h_{sr}X)^{*} + (n_{sr})(n_{sr})^{*} + (J)(J)^{*}] = P$$

Hence,

$$b^2 \left[P\left|h_{s,r}\right|^2 + N_0 + N_J\right] = P$$

Therefore,

$$b^2 = \frac{P}{[P\left|h_{s,r}\right|^2 + N_0 + N_J]}$$

or the amplification coefficient can be written as

$$b = \sqrt{\frac{P}{[P\left|h_{s,r}\right|^2 + N_0 + N_J]}}$$

SOURCE CODE

Case 1: Jamming at R-D link near Destination node.

1. **BPSK**

```
clc;
clear;
k = 1000000;
msg = randint(1,k);
s = pskmod(msg,2);
%Nj = 0.1;
for snr = 1:30
    p = (10^(snr/10))/2;
    Nj = 10*p;
    hsd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hsr = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hrd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    jam = (sqrt(Nj/2)*(randn(1,k)+sqrt(-1)*randn(1,k)));

    ysr = sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));
    b = sqrt(p)./sqrt(p.*(abs(hsr).^2)+1);
    dr = (b.*ysr);%+jam;

    ysd = sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));
    yrd = dr.*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)))+jam;

    a1 = sqrt(p).*conj(hsd);
    %x = (b.^2.*(abs(hrd).^2))+1+Nj;
    a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));%./x;
    %a2j = (b.*sqrt(p).*conj(hsr).*conj(hrd))./(x+((abs(hrd).^2).*100));
    y = (a1.*ysd)+(a2.*yrd);
    y1 = (a1.*ysd)+(a2.*yrd);
    m = pskdemod(y,2);
    er(snr) = nnz(msg-m);
    m1 = pskdemod(y1,2);
    er1(snr) = nnz(msg-m1);
    xax(snr) = 10*log10(p/(1.2589+(10^(Nj/10))));
    snr

end
ps = er/k;
semilogy(ps,'-r*');
hold on;
%semilogy(er1/k,'-k');
grid on
```

2. **QPSK**

```
clc;
clear;
k = 1000000;
%msg = randint(1,k);
```

```
msg = randint(1,k,[0,3]);
s = pskmod(msg,4);

for snr = 1:30
   p = 10^(snr/10)/2;
   Nj = 0.1*p;
   hsd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hsr = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hrd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));

    jam = sqrt(Nj/2).*(randn(1,k)+sqrt(-1).*randn(1,k));

   ysd =  sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));
   ysr =  sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));

   b = sqrt(p)./(sqrt((p.*(abs(hsr).^2)+1)));

   yrd = (b.*ysr).*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)))+jam;


   a1 = sqrt(p).*conj(hsd);
   %x = ((b.^2).*(abs(hrd).^2))+1+(Nj);
   a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));
   y = (a1.*ysd)+(a2.*yrd);
   y1 = ((conj(hsd).*ysd));%+((a2.*yrd)./(abs(a2.*yrd)));


   m = pskdemod(y,4);
   er(snr) = nnz(msg-m);

   m1 = pskdemod(y1,4);
   er1(snr) = nnz(msg-m1);
   snr

end
semilogy(er/(k),'-g*');
hold on
%semilogy(er1/(k),'-k*');
grid on
```

Case 2 : Jamming at R-D link near Relay

1. BPSK

```
clc;
clear;
k = 1000000;
msg = randint(1,k);
s = pskmod(msg,2);
%Nj = 0.1;
for snr = 1:30
    p = (10^(snr/10))/2;
```

```
    Nj = 10*p;
    hsd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hsr = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hrd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    jam = (sqrt(Nj/2)*(randn(1,k)+sqrt(-1)*randn(1,k)));

    ysr = sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));
    b = sqrt(p)./sqrt(p.*(abs(hsr).^2)+1);
    dr = (b.*ysr)+jam;

    ysd = sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));
    yrd = dr.*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));

    a1 = sqrt(p).*conj(hsd);
    %x = (b.^2.*(abs(hrd).^2))+1+(Nj.*(abs(hrd).^2));
    a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));
    %a2j = (b.*sqrt(p).*conj(hsr).*conj(hrd))./(x+((abs(hrd).^2).*100));
    y = (a1.*ysd)+(a2.*yrd);
    y1 = (a1.*ysd)+(a2.*yrd);
    m = pskdemod(y,2);
    er(snr) = nnz(msg-m);
    m1 = pskdemod(y1,2);
    er1(snr) = nnz(msg-m1);
    xax(snr) = 10*log10(p/(1.2589+(10^(Nj/10))));
    snr

end
ps = er/k;
semilogy(ps,'-r*');
hold on;
%semilogy(er1/k,'-k');
grid on
```

2. QPSK

```
clc;
clear;
k = 1000000;
%msg = randint(1,k);
msg = randint(1,k,[0,3]);
s = pskmod(msg,4);

for snr = 1:30
   p = 10^(snr/10)/2;
   Nj = 10*p;
   hsd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hsr = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hrd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));

    jam = sqrt(Nj/2).*(randn(1,k)+sqrt(-1).*randn(1,k));

   ysd =  sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));
   ysr =  sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));
```

```
   b = sqrt(p)./(sqrt((p.*(abs(hsr).^2)+1)));

   yrd = (b.*ysr+jam).*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));


   a1 = sqrt(p).*conj(hsd);
   %x = ((b.^2).*(abs(hrd).^2))+1+(Nj.*(abs(hrd).^2));
   a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));
   y = (a1.*ysd)+(a2.*yrd);
   y1 = ((conj(hsd).*ysd));%+((a2.*yrd)./(abs(a2.*yrd)));


   m = pskdemod(y,4);
   er(snr) = nnz(msg-m);

   m1 = pskdemod(y1,4);
   er1(snr) = nnz(msg-m1);
   snr

end
semilogy(er/(k),'-r*');
hold on
%semilogy(er1/(k),'-k*');
grid on
```

Case 3 : Jamming at S-R link near Relay

1. BPSK

```
clc;
clear;
k = 1000000;
msg = randint(1,k);
s = pskmod(msg,2);
%Nj = 0.1;
for snr = 1:30
    p = (10^(snr/10))/2;
    Nj = 10*p;
    hsd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hsr = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    hrd = (sqrt(0.5)*(randn(1,k)+sqrt(-1)*randn(1,k)));
    jam = (sqrt(Nj/2)*(randn(1,k)+sqrt(-1)*randn(1,k)));

    ysr = sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)))+jam;
    b = sqrt(p)./sqrt((p.*(abs(hsr).^2))+1+Nj);
    dr = (b.*ysr);

    ysd = sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));
    yrd = dr.*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1)*randn(1,k)));

    a1 = sqrt(p).*conj(hsd);
    %x = (b.^2.*(abs(hrd).^2))+1+(b.^2.*Nj.*(abs(hrd).^2));
```

```
    a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));
    %a2j = (b.*sqrt(p).*conj(hsr).*conj(hrd))./(x+((abs(hrd).^2).*100));
    y = (a1.*ysd)+(a2.*yrd);
    y1 = (a1.*ysd)+(a2.*yrd);
    m = pskdemod(y,2);
    er(snr) = nnz(msg-m);
    m1 = pskdemod(y1,2);
    er1(snr) = nnz(msg-m1);
    xax(snr) = 10*log10(p/(1.2589+(10^(Nj/10))));
    snr

end
ps = er/k;
semilogy(ps,'-r*');
hold on;
%semilogy(er1/k,'-k');
grid on
```

2. QPSK

```
clc;
clear;
k = 1000000;
%msg = randint(1,k);
msg = randint(1,k,[0,3]);
s = pskmod(msg,4);

for snr = 1:30
   p = 10^(snr/10)/2;
   Nj = 10*p;
   hsd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hsr = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));
   hrd = sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k));

    jam = sqrt(Nj/2).*(randn(1,k)+sqrt(-1).*randn(1,k));

   ysd =  sqrt(p).*s.*hsd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));
   ysr =  sqrt(p).*s.*hsr+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)))+jam;

   b = sqrt(p)./(sqrt((p.*(abs(hsr).^2))+1+Nj));

   yrd = (b.*ysr).*hrd+(sqrt(0.5).*(randn(1,k)+sqrt(-1).*randn(1,k)));


   a1 = sqrt(p).*conj(hsd);
   %x = ((b.^2).*(abs(hrd).^2))+1+((b.^2).*Nj.*(abs(hrd).^2));
   a2 = (b.*sqrt(p).*conj(hsr).*conj(hrd));
   y = (a1.*ysd)+(a2.*yrd);
   y1 = ((conj(hsd).*ysd));%+((a2.*yrd)./(abs(a2.*yrd)));


   m = pskdemod(y,4);
   er(snr) = nnz(msg-m);
```

```
   m1 = pskdemod(y1,4);
   er1(snr) = nnz(msg-m1);
   snr

end
semilogy(er/(k),'-r*');
hold on
%semilogy(er1/(k),'-k*');
grid on
```