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**NAVAL  
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**MONTEREY, CALIFORNIA**

**THESIS**

**DIRECTION MODULATION AT THE MODULATOR  
FOR PHYSICAL LAYER SECURITY**

by

Jonathan D. Puckett

December 2019

Thesis Advisor:  
Second Reader:

Frank E. Kragh  
Ralph C. Robertson

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**DIRECTION MODULATION AT THE MODULATOR FOR PHYSICAL LAYER  
SECURITY**

Jonathan D. Puckett  
Lieutenant, United States Navy  
BSEE, The Citadel, 2013

Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL  
December 2019**

Approved by: Frank E. Kragh  
Advisor

Ralph C. Robertson  
Second Reader

Douglas J. Fouts  
Chair, Department of Electrical and Computer Engineering

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## **ABSTRACT**

Beam forming and directional modulation (DM) are known technologies at the antenna level. DM currently requires radio frequency (RF) phase shifting, etc., at the antenna with either multiple antennas or a phased array. We consider accomplishing DM in the modulator vice the antenna. The goal of DM is to transmit a signal in such a way as to have the signal be received undistorted at the intended receiver and hopelessly distorted at nearly any other location, thereby providing some physical layer security. In this thesis, we explore the notion of accomplishing this at baseband in the modulator instead of in the RF section, thereby achieving a simpler radio design. Currently, the complexity of directional modulation at the RF section brings a cost in either manufacturing or time. Herein, we discuss the theory and implementation of directional modulation and simulate its performance for noisy channels, both line-of-sight and non-line-of-sight.



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## LIST OF ACRONYMS AND ABBREVIATIONS

$5 \times 1$	five-transmitter, one-receiver
AWGN	additive white Gaussian noise
BER	bit error ratio
CSCGRV	circularly symmetric complex Gaussian random variable
DM	directional modulation
LOS	line-of-sight
MIMO	multiple-input, multiple-output
MISO	multiple-input, single-output
NLOS	non-line-of-sight
QPSK	quadrature phase-shift keying
RF	radio frequency
SNR	signal-to-noise ratio
SVD	singular value decomposition

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# I. INTRODUCTION

## A. MOTIVATION

The United States military uses wireless communications routinely, often in areas where secure communications is operationally necessary. The first layer of defense is to avoid interception. Once a wireless signal is intercepted, other security aspects must be relied upon, perhaps including encryption or code words. For example, when U.S. forces are in hostile territory and must use wireless communications, encryption is used for security; however, encrypted information may be able to be decrypted by an adversary, resulting in compromise [1]. Physical layer security includes methods designed to prevent adversaries from even receiving the encrypted information, thereby providing increased security beyond encryption alone.

Wireless communications can be via either line-of-sight (LOS) or non-line-of-sight (NLOS). There are factors that dictate whether a radio channel is LOS or NLOS. Such factors include the curvature of the earth, the radio frequency (RF) of the signal, the power output, atmospheric conditions, and physical obstructions such as mountains, trees, and buildings [2]. The transmission can also be sent via an unintended channel, leading to the interception of the signal by eavesdroppers; however, if the sender, a Navy ship or military unit, knew the direction to the intended receiver, another layer of protection can be added by using directional modulation.

## B. OVERVIEW

Directional modulation (DM) is defined as a transmitter-side technology that is capable of projecting digitally encoded information signals into a pre-specified spatial direction while simultaneously distorting the same signals in all other directions [3]. The intended effect of DM is that only the intended receiver can demodulate the information sent. A quadrature phase-shift keying (QPSK) DM transmitter and the resulting constellations of the QPSK signal received at three spatially separated receivers is shown in Figure 1. One receiver is considered the intended receiver and the others are considered eavesdroppers. The intended QPSK symbols were properly received at the legitimate



receiver, but the QPSK symbols were not received correctly by the two eavesdroppers. The symbols at the eavesdroppers were not received in the correct quadrants which results in very high bit error ratios (BER), effectively foiling the eavesdropper, as illustrated in this thesis. In this thesis, BER stands for a bit error ratio which is the ration of number of bits in error to total number of bits or equivalently the probability of bit error.

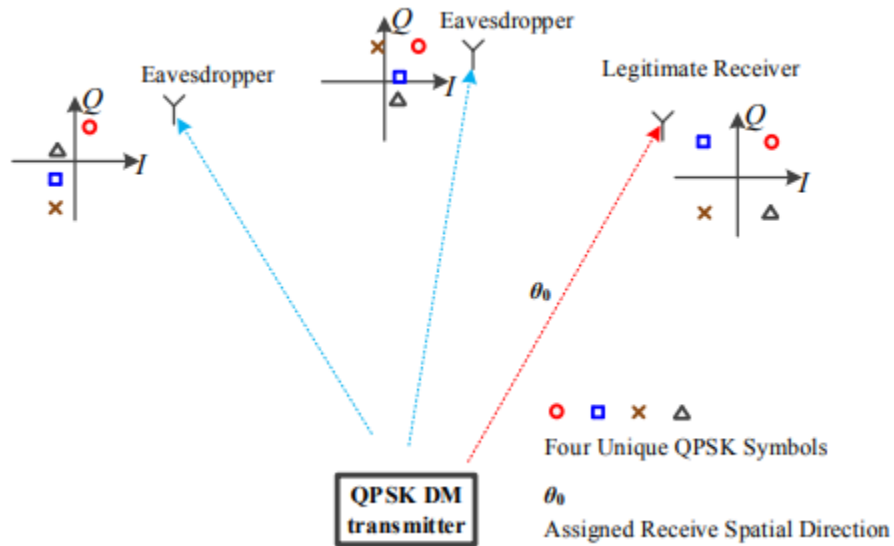


Figure 1. Illustration of the major properties of a QPSK DM transmitter.  
Source: [4].

Directional modulation can be accomplished with hardware phase shifters before the transmit antenna elements or with software modifications in the modulator. The former application of DM is referred to as analog directional modulation, and the software application is referred to as digital directional modulation [4]. The hardware approach is conceptually simpler but more expensive due to the cost of extra hardware for each antenna element and requires the antenna to be a phased-array antenna. Although digital directional modulation involves complex computation, current technology allows its implementation with acceptable computing latency and system costs for all but the simplest communications systems.

### **C. OBJECTIVES**

Wireless communication security has the same principles as network security, which provides layers of security. This layered security is a defense-in-depth approach using encryption in different layers [1]. The one layer that often has the least amount of security is the physical layer, or the actual transmission of the signal. The research contained in this thesis provides another layer of security. This layer of security is in the physical layer and attempts to prevent interception of the signal by unintended recipients [1]. In this thesis we study the application of DM in the modulator. There are two cases to consider regarding the communications channel. One is the non-line-of-sight (NLOS) case and the other is the line-of-sight (LOS) case. The NLOS case is in a multipath fading environment due to multiple paths the signal may take from the transmitter to the receiver [5]. The primary objective of this thesis is to further the application of DM in this case. DM in a line-of-sight (LOS) channel was explored herein using previous methods by [2]. The final objective is to examine the benefits, complexity, and applications of DM in the modulator.

### **D. THESIS ORGANIZATION**

This thesis is organized as follows. In Chapter II there is a thorough literature review. The literature review includes four main areas of research in directional modulation. A presentation of the theory and mathematical models used in this research is given in Chapter III, which includes the derivation for communication using directional modulation in both a multiple-input, single-output (MISO) line-of-sight channel and in a MISO non-line-of-sight channel. The experiments that confirm the models from Chapter III for both LOS and NLOS cases are discussed in Chapter IV. The results of these simulations are discussed in Chapter IV. Conclusions from this research and suggestions for future work are contained in Chapter V.

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## **II. LITERATURE REVIEW**

There has been much research into DM in recent years. The motivation for most of the research has been physical layer security. DM research began with an examination of side lobe transmission and beam forming techniques.

### **A. NEAR FIELD DIRECT ANTENNA MODULATION**

In 2006 through 2008, Babakhani and a team from the California Institute of Technology researched near-field DM for physical-layer security to protect radio transmissions from eavesdroppers. The technique researched in [6]-[8] was directly modulating the signal at the antenna, which focused on the result in the near field at the transmitter. A locked RF signal source was used to ensure the stability of the transmitted frequency [9]. Described in [7], the signal source and power amplifier were used to drive the antenna, changing the antenna characteristics and thereby altering the signal phase and amplitude. The authors stated that independent signals were transmitted in different directions, and switches were used with reflectors to transmit constellation points with random symbols to help with security. They discovered with these reflectors, the signal phase and amplitude were changed after the antenna, resulting in the signal modulated after transmission from the antenna. Only the desired constellation pattern was transmitted in the intended direction [7]. The constellation pattern in the unintended direction was scrambled and unable to be demodulated.

### **B. DIRECTIONAL MODULATION BY PHASED ARRAY**

Michael Daly of the University of Illinois at Urbana-Champaign wrote three articles [10]-[12] and his dissertation [13] about DM by using phased array and beam forming techniques for physical-layer security. Daly continued the research from the near-field direct antenna modulation and applied DM techniques before transmitting from the antenna. The proposed changes from a traditional beam forming transmitter and a DM transmitter are shown in Figure 2.

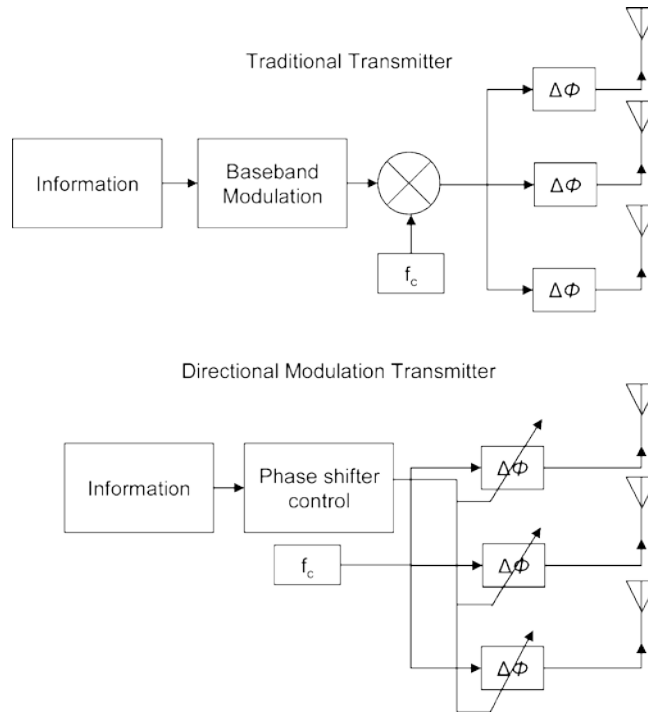


Figure 2. Top: Architecture of a traditional transmitter. Bottom: Architecture of a DM transmitter. Source: [10].

As seen in Figure 2 (top), a traditional transmitter has the modulation upconverted to the carrier frequency and then beamformed for each antenna element. As seen in Figure 2 (bottom), the signal from the phase shifter control, the carrier frequency, and a phase change for DM was combined before each antenna element. Daly’s journal papers explain the channel transfer function changes and how security of the transmitted signal was achieved. This phased array technique is called static DM. The parameter used to test the effectiveness of the DM was bit error ratio (BER).

### C. VECTOR APPROACH TO DIRECTIONAL MODULATION

Yaun Ding and Vincent Fusco of Queens University Belfast investigated DM from 2012–2017 and wrote [14]-[22]. Ding’s first article [14] expanded the near-field direct antenna modulation to far-field analysis using a Fourier Rotman lens and side-lobe levels. Ding and Fusco then explored a vector approach that constitutes a change from Daly’s phased-array approach. How the DM was implemented in the transmitter architecture for the phased-array approach is shown in Figure 3. The vector approach is shown in Figure 4.

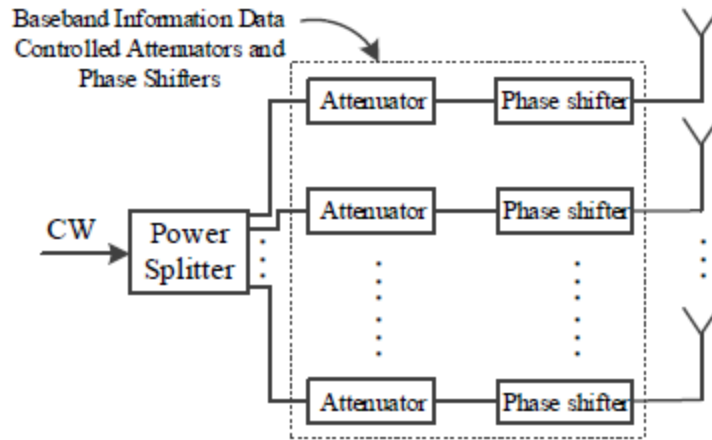


Figure 3. Generic analog DM transmitter architecture. Source: [15].

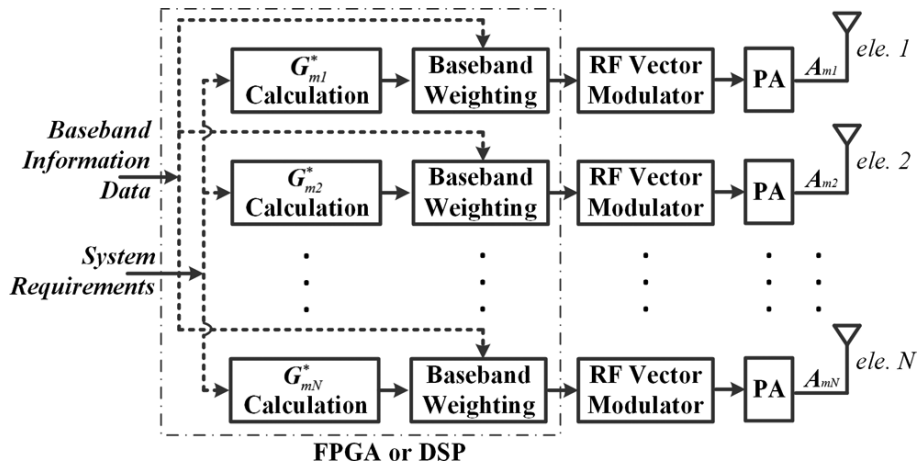


Figure 4. Generic digital DM transmitter architecture. Source: [15].

The vector approach for DM is also referred to as digital DM and dynamic DM. Ding analyzed a one-dimensional phased-array antenna with five elements. The research represented each symbol transmitted from an element of the antenna array as a vector. Since different vector addends may sum to the same constellation point, Ding used this mathematical model to excite the antenna and control the effectiveness of the signal received based on the angle from the transmitter. Two different vector paths reaching the same constellation point are shown in Figure 5.

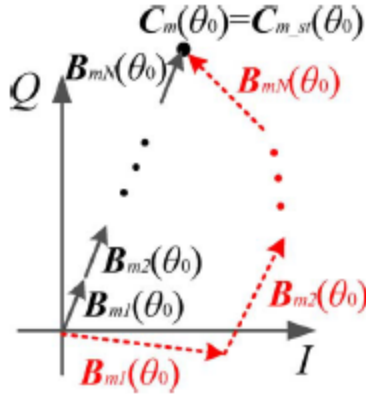


Figure 5. Different vector paths to same constellation point. Source: [3].

All of Ding’s research [3]-[4], [18]-[26] was for line-of-sight propagation. In [20], metrics for measuring success were established. The metrics were error vector magnitude (EVM), BER, and a secrecy rate metric. These metrics were adopted by other researchers in DM. In [17], an examination of two different DM techniques, static DM and dynamic DM, were examined including the complexity and effectiveness of each. Ding’s later articles included an examination of different DM techniques researched up to that point, research needed, and a tutorial explanation of DM.

#### D. MIMO AND IMPLEMENTATION

Building upon dynamic DM, the implementation of digital DM were examined in [26]-[36], including applications to different modulation schemes including QAM and the application to MIMO. Rayleigh fading is considered in [26]. The research was conducted between 2015–2019. The three articles about implementation [27]-[29] discussed implementing DM in a laboratory. Four articles [26], [30]-[32] considered different modulation and carrier schemes other than QPSK. MIMO and multipath fading are discussed in [28]-[32]. Ding was the first to switch to a matrix model for the channel. The articles that followed all did the same. Kalantari [27] was the only one that considered Rayleigh Fading. Application for physical-layer security is the focus of [33]-[37].

### III. THEORY APPLIED

In this thesis, directional modulation is analyzed for both the line-of-sight and non-line-of-sight cases. The modulation technique used is QPSK with Gray coding. The channel is multiple-input, single-output (MISO). The transmit antenna was arbitrarily chosen to have five elements with inter-element spacing equal to half a wavelength for illustration. The mathematical theory of both approaches is detailed in this chapter [38].

The path from a five-element antenna transmitting to one receiving antenna is shown in Figure 6. The channel gain from the transmit antenna element to the receiving antenna is  $H_n$ . The effect of all five channel gains is considered. The straight lines in Figure 6 represent the propagation paths for the line-of-sight case. These lines are also used to represent the NLOS case even though they only abstractly relate to the multipath propagation. The transmitter antenna elements are represented by  $x$  in the figure with a distance of  $\lambda/2$  between adjacent elements.

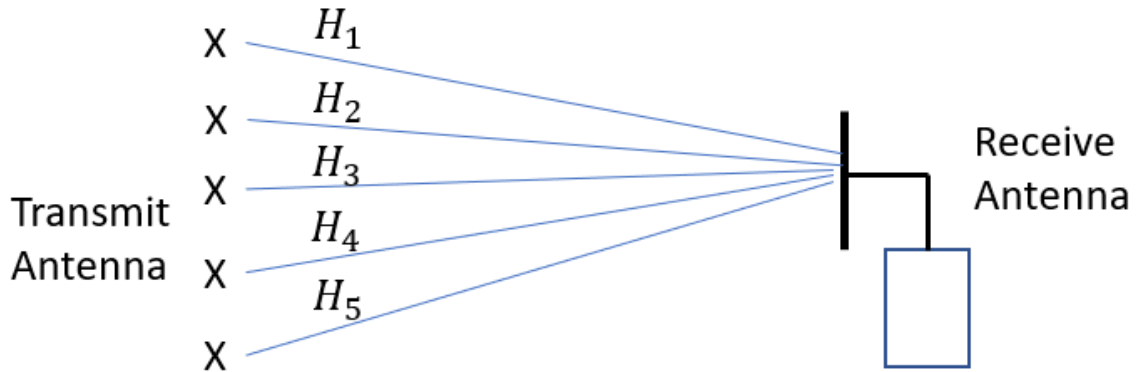


Figure 6. MISO LOS transmission path.

#### A. VECTOR APPROACH LINE-OF-SIGHT

The LOS approach is derived from reference [16]. In an  $n$ -element antenna, there are  $n$  complex numbers that need to be summed to achieve the constellation point desired.



With QPSK, there are four possible constellation points to receive. The  $m^{\text{th}}$  decision statistic in the receiver (which is at an angle  $\theta_0$  from the transmitter) is

$$C_m(\theta_0) = \sum_{n=1}^N A_{mn} H_n \quad (1)$$

where noise has been neglected,  $N$  is the number of transmit antenna elements,  $A_{mn}$  is the  $n^{\text{th}}$  transmit antenna element excitation at time  $m$ , and  $H_n$  is the complex-valued channel gain between the  $n^{\text{th}}$  element in the transmit antenna and the receive antenna [16]. This per-element channel gain is

$$H_n = e^{j2\pi d(n-1)\cos(\theta)} \quad (2)$$

where  $d$  is the distance in wavelengths between two adjacent antenna elements,  $\theta$  is the angle the signal is transmitted and is  $0^\circ$  to  $180^\circ$  from the antenna array perspective with  $0^\circ$  being to the right (straight down in Figure 6) and  $180^\circ$  to the left. Equation (2) is derived in [3] where the middle element of a five-element antenna array is used as the reference element. We used the first element as the reference element. The  $2\pi \cos(\theta)$  is derived from trigonometry involving the difference in transmit antenna element to receive antenna distance for the different transmit antenna elements. When  $\theta$  is the direction of the intended receiver,  $\theta = \theta_0$ . When  $\theta$  is the direction of the eavesdropper,  $\theta = \theta_e$ . When  $d = \lambda/2$ , these per-element channel gains can be expressed as

$$H = \left[ 1 \quad e^{j\pi(1)\cos(\theta)} \quad e^{j2\pi\cos(\theta)} \quad \dots \quad e^{j\pi(N-1)\cos(\theta)} \right] \quad (3)$$

for  $n = 1, 2, \dots, N$  from (2). For example, the channel gains for a MISO system with a five-element transmit antenna with inter-element spacing of  $d = \lambda/2$  is

$$H = \left[ 1 \quad e^{j\pi\cos(\theta)} \quad e^{j2\pi\cos(\theta)} \quad e^{j3\pi\cos(\theta)} \quad e^{j4\pi\cos(\theta)} \right]. \quad (4)$$

In (1),  $A_{mm}$  is a combination of the  $m^{\text{th}}$  symbol  $D_m$  to be transmitted and the DM gain  $G_n$  for the  $n^{\text{th}}$  element of the transmit antenna, i.e.,

$$A_{mm} = D_m G_n^* \quad (5)$$

where  $G_n$  needs to be calculated on the transmitter side. Substituting (5) into (1), we get

$$C_m(\theta) = \sum_{n=1}^N D_m G_n^* H_n. \quad (6)$$

The calculation of  $G_n$  for  $n = 1, 2, \dots, N$  is the key to LOS DM. To solve for every  $G_n$ , (6) may be expanded to yield  $N$  equations with  $N$  unknowns, where the  $G_n$ s are the  $N$  unknowns. For the intended receiver, it is desired to receive symbol  $D_m$  undistorted, i.e.,  $C_m(\theta_0) = D_m$ . As a result, for  $\theta = \theta_0$  (6) yields

$$1 = \sum_{n=1}^N G_n^* H_n. \quad (7)$$

Motivated by (7), we generate a system of  $N$  equations and  $N$  unknowns using  $N$  directions, i.e.,  $\theta_0, \theta_2, \dots, \theta_N$ . We allow  $C_m(\theta_i)$  to be represented with  $S_i = C_m(\theta_i)/D_m$ , with  $i$  representing the  $i^{\text{th}}$  received signal. The system of equations is

$$\begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_N \end{bmatrix}^T = \begin{bmatrix} G_1^* & G_2^* & \cdots & G_N^* \end{bmatrix} \begin{bmatrix} H_1(\theta_0) & H_2(\theta_0) & \cdots & H_N(\theta_0) \\ H_1(\theta_2) & H_2(\theta_2) & \cdots & H_N(\theta_2) \\ \vdots & \vdots & \ddots & \vdots \\ H_N(\theta_0) & H_N(\theta_2) & \cdots & H_N(\theta_N) \end{bmatrix}^T \quad (8)$$

In this thesis the system gain vector is represented by  $\mathbf{S}$ , the element gain vector by  $\mathbf{G}$ , and the channel matrix by  $\mathbf{H}$ . Then (8) can be expressed as

$$\mathbf{S} = \mathbf{G}^* \mathbf{H} \quad (9)$$

and  $\mathbf{G}$  solved for by

$$\mathbf{G} = [\mathbf{S}\mathbf{H}^{-1}]^*. \quad (10)$$

Equations (6) through (10) apply for the case of  $N$  antenna elements. For illustration, the number of elements in the antenna is set to  $N = 5$  and  $\theta_0 = \theta_1$ . The parameter  $S_i$  represents the net system gain in direction  $\theta_i$ ; i.e., for each direction  $\theta_i$ ,  $S_i$  represents the ratio between the receiver decision statistic and the transmitted symbol, neglecting noise. We desire this channel gain to be unity in the direction of the intended receiver and either zero or something that changes phase somewhat randomly at the symbol rate for the other  $N - 1$  directions; therefore, let  $S_1 = 1$  and  $S_2, S_3, S_4,$  and  $S_5$  represent the possibility for different eaves droppers. After  $S_1, S_2, S_3, S_4,$  and  $S_5$  have been set,  $\mathbf{G}$  can be solved for using (10) and MATLAB with five equations and five unknowns.

## B. NON-LINE OF SIGHT WITH RAYLEIGH FADING

The NLOS case for a MISO channel is derived in this section using a MIMO approach from [24]. For illustration, in this section we consider a MIMO channel with five transmit antenna elements and five receive antennas. A MIMO system with  $M$  transmit antenna elements,  $N$  receive antennas, and the channel gain between each transmit and receive antenna is illustrated in Figure 7. The channel gain is represented by  $H_{mn}$  with  $m$  being the specified transmit antenna element and  $n$  being the specified receive antenna. In this thesis, the intended receiver is the antenna  $n = 1$  and receive antennas 2 through 5 are the eavesdroppers; therefore, the channel gain from the transmitter elements to the intended receiver is  $H_{1m}$  and is treated as a MISO system from the transmitter to the intended receiver as seen in Figure 6.

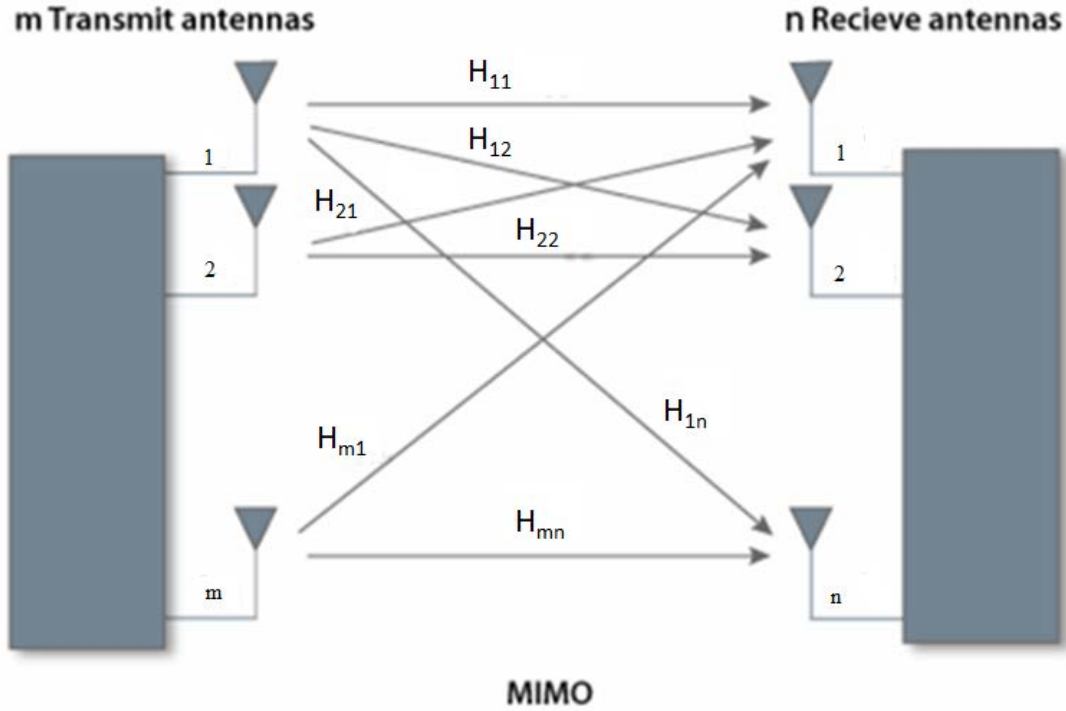


Figure 7. MIMO System. Source [39].

In the NLOS case, the signal propagation is not a straight line as in Figure 6 but is scattered due to multipath fading. Herein, we limit ourselves to the NLOS case where there is sufficient multipath to render each complex transmit-antenna-element-to-receive-antenna gain  $H_{mn}$  a circularly symmetric complex Gaussian random variable (CSCGRV). This case is referred to as the Rayleigh faded case in the literature. We choose this case for study because it is a common case. We also study the LOS case as presented in a previous section. Since most multipath channels can be effectively modeled as either of these two or as a mixture of both, we choose to study both [33].

Each complex gain  $H_{mn}$  is measured and used to create the DM gain. In the  $5 \times 5$  MIMO antenna case, the measured channel gain  $\mathbf{H}_{meas}$  is

$$\mathbf{H}_{meas} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} & H_{15} \\ H_{21} & H_{22} & H_{23} & H_{24} & H_{25} \\ H_{31} & H_{32} & H_{33} & H_{34} & H_{35} \\ H_{41} & H_{42} & H_{43} & H_{44} & H_{45} \\ H_{51} & H_{52} & H_{53} & H_{54} & H_{55} \end{bmatrix} \quad (11)$$

where  $H_{mn}$  represents the complex gain for transmit antenna element to receive antenna element which is a CSCGRV. We choose  $n=1$  as the receiving antenna for the MISO case, and  $n>1$  represent potential eavesdroppers.

The received signal  $Y$  at the intended receive antenna is

$$\mathbf{Y} = \mathbf{HT} \quad (12)$$

where  $\mathbf{H}$  is the channel gain  $5 \times 5$  matrix and  $\mathbf{T}$  is the  $5 \times 1$  vector representing the signal transmitted at each transmit antenna element. The matrix  $\mathbf{H}$  and vector  $\mathbf{T}$  are multiplied by matrix multiplication to model each signal from the specific antenna element traveling over the specified channel to the receiver. For example,  $Y_1 = H_{11}T_1 + H_{12}T_2 + H_{13}T_3 + H_{14}T_4 + H_{15}T_5$  where  $Y_1$  is the signal received at the intended receiver.

The desired signal received is

$$\mathbf{Y} = \mathbf{IX} \quad (13)$$

where  $\mathbf{I}$  is a  $5 \times 5$  identity matrix and  $\mathbf{X}$  is the  $5 \times 1$  input message bit stream with  $\mathbf{X} = [D_m \ 0 \ 0 \ 0 \ 0]^T$  and matrix multiplication is used; therefore, let

$$\mathbf{T} = \mathbf{WX} \quad (14)$$

where  $\mathbf{W}$  is the DM gain and  $\mathbf{HW} = \mathbf{I}$ .

The DM gain  $\mathbf{W}$  is calculated from  $\mathbf{H}_{meas}$ . To calculate  $\mathbf{W}$ , the singular value decomposition (SVD) of  $\mathbf{H}_{meas}$  is completed and is

$$[\mathbf{U} \ \mathbf{\Lambda} \ \mathbf{V}] = svd(\mathbf{H}_{meas}) \quad (15)$$

where  $\mathbf{H}_{meas}$  is the  $5 \times 5$  matrix made up of complex numbers in (11),  $\mathbf{U}$  and  $\mathbf{V}$  are  $5 \times 5$  unitary matrices, and the diagonal of  $\mathbf{\Lambda}$  contains the ordered singular values of the matrix. Additionally, to calculate  $\mathbf{H}_{meas}$  from the singular value decomposition terms,  $\mathbf{H}_{meas}$  is

$$\mathbf{H}_{meas} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^\dagger \quad (16)$$

where  $\dagger$  is the symbol for Hermitian transpose [34]. The matrix  $\mathbf{W}$  is calculated from  $\mathbf{U}$ ,  $\mathbf{\Lambda}$ , and  $\mathbf{V}$  by

$$\mathbf{W} = \mathbf{V}\mathbf{\Lambda}^{-1}\mathbf{U}^\dagger \quad (17)$$

where  $\mathbf{\Lambda}^{-1}$  is the inverse matrix of  $\mathbf{\Lambda}$  and  $\mathbf{U}^\dagger$  is the Hermitian transpose of  $\mathbf{U}$ . From (16) and (17),  $\mathbf{H}\mathbf{W} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^\dagger\mathbf{V}\mathbf{\Lambda}^{-1}\mathbf{U}^\dagger$  which results in the identity matrix and makes (13) true. This allows for the summation of the five transmitted signals from the five elements of the transmit antenna to be summed together at the intended receiving antenna. The signal can now be demodulated and the original message received.

The BER for the MISO LOS case for a QPSK is derived from [5] and is

$$P_b = Q(\sqrt{2\gamma_b}) \quad (18)$$

$$\gamma_b = \frac{E_b}{N_0} \sum_{n=1}^N |H_{mn}|^2 \quad (19)$$

where  $E_b$  is the average energy of the bit due to one transmit antenna element,  $N_0$  is the noise density,  $N$  is the number of transmit antenna elements.

The BER for a MISO channel with Rayleigh Fading from [38] is

$$P_b = \left( \frac{1 - \sqrt{\frac{\alpha SNR}{\alpha SNR + 1}}}{2} \right)^N \sum_{n=0}^{N-1} \binom{N-1+n}{n} \left( \frac{1 + \sqrt{\frac{\alpha SNR}{\alpha SNR + 1}}}{2} \right)^n \quad (20)$$

where  $\alpha SNR = \frac{E_s}{2NN_0}$ .

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## IV. SIMULATION AND RESULTS

### A. SIMULATION

The simulations for this thesis were accomplished in MATLAB. There were three simulations run. The first was for the QPSK MISO LOS DM case. The second was for the QPSK MISO NLOS DM with Rayleigh fading case. The third was for the QPSK MISO LOS DM case using the same DM method and modeling as the second case. The MATLAB scripts for these simulations are included in Appendix A.

#### 1. DM LOS

Directional modulation for a QPSK modulated signal transmitted through a MISO LOS channel was simulated by using the theory in part A of Chapter III. Constants were defined in accordance with (3). The number of antenna elements  $N = 5$ , the angle of the intended receiver  $\theta_0 = 45^\circ$ , and the distance between antenna elements  $d = 0.5\lambda$  were used.

After the constants were defined, the channel gain  $\mathbf{H}$  was generated using (4). Then, (10) was used to generate  $\mathbf{G}$  with  $\mathbf{S}$  being  $\mathbf{S} = [1 \ 0 \ 0 \ 0 \ 0]$ . The vector  $\mathbf{S}$  was chosen this way to ensure only the intended direction  $\theta_0$  could be demodulated. Two examples were investigated to compare how the values chosen for  $\theta_2$ ,  $\theta_3$ ,  $\theta_4$ , and  $\theta_5$  impacted the DM gain effectiveness. The first example had  $\theta_2$  through  $\theta_5$  chosen in increments of  $\pm 5^\circ$  from  $\theta_0$ ; therefore,  $\theta_2$  through  $\theta_5$  were assigned as  $\theta_2 = \theta_0 + 5^\circ$ ,  $\theta_3 = \theta_0 - 5^\circ$ ,  $\theta_4 = \theta_0 + 10^\circ$ , and  $\theta_5 = \theta_0 - 10^\circ$ . In the second example,  $\theta_2$  through  $\theta_5$  were chosen in increments of  $\pm 10^\circ$  from  $\theta_0$ ; therefore,  $\theta_2$  through  $\theta_5$  were assigned as  $\theta_2 = \theta_0 + 10^\circ$ ,  $\theta_3 = \theta_0 - 10^\circ$ ,  $\theta_4 = \theta_0 + 20^\circ$ , and  $\theta_5 = \theta_0 - 20^\circ$ .

Once  $\mathbf{H}$  and  $\mathbf{G}$  were calculated, a QPSK signal was generated from a vector of random integers between zero and three with a length previously defined for the number of symbols to be transmitted that were used as the information stream. The information



was then mapped to symbols using Gray coding. The symbol vector was sampled at one sample per symbol, resulting in the complex envelope of the modulated signal.

The complex envelope was simulated being passed through a processor and being multiplied by  $\mathbf{G} = [G_1 \ G_2 \ G_3 \ G_4 \ G_5]$ , the DM gain, and the result sent to the pre-specified antenna element. This output is  $\mathbf{A}_{mn} = [A_{m1} \ A_{m2} \ A_{m3} \ A_{m4} \ A_{m5}]$  from (5). Then (1) was used to determine the  $m^{\text{th}}$  decision statistic for each direction  $C_m = [C_m(\theta_0) \ C_m(\theta_2) \ C_m(\theta_3) \ C_m(\theta_4) \ C_m(\theta_5)]$ . Additive white Gaussian noise (AWGN) was created, scaled, and added to vary the signal-to-noise ratio (SNR). A SNR range of 0 to 25 dB was used to test the BER.

The decision statistics were demodulated and the symbols received assigned to the proper message bits. The received information stream was compared to the original information stream. The total number of incorrect comparisons was divided by the total number of bits received to yield the BER. The BER was calculated for each desired SNR. The theoretical BER was calculated using (17) and (18).

A received signal for each angle from 0 to 180 degrees was generated, demodulated, and a BER measured to be able to compare the effectiveness of the DM.

## 2. DM NLOS

The second simulation examined the NLOS case with multipath fading using Rayleigh fading to model multipath. The constants from the first simulation were used. The process of generating the complex envelope of the modulated signal remained the same. The differences between the LOS and NLOS cases are the channel gain and the DM gain.

The channel gain  $\mathbf{H}_{meas}$  was simulated in accordance with (11). The  $H_{mn}$ s are independent CSCGRVs generated by using a random number generator that has zero mean and a variance of one. Once  $\mathbf{H}_{meas}$  was obtained, the singular value decomposition of  $\mathbf{H}_{meas}$  was calculated in accordance with (15). From (17),  $\mathbf{W}$  was calculated. Given  $\mathbf{W}$ , we used (14) to calculate  $\mathbf{T}$ . We then used (12) to calculate the received signal at the antenna. For

each signal received, as in the previous simulation, AWGN was added to each signal stream received.

Once received, the five received signals were calculated with (12) and demodulated. After demodulating, the received information stream was compared to the sent information stream, and a BER for each SNR was calculated. The theoretical BER was calculated using (20).

There were two test cases for the NLOS case simulated. In one, the transmitter knew channel states of the four eavesdroppers. In the other, the channel states of four eavesdroppers were randomly generated. The latter is a more realistic scenario, as knowledge of the channel state of an eavesdropper requires the eavesdropper to transmit a known signal.

## **B. RESULTS**

### **1. LOS Case**

In this thesis for the LOS case, we examine different results. From our simulation, our results are plotted for BER versus the  $E_b/N_0$ , BER versus the spatial direction transmitted for a specific SNR, and the magnitude and phase with each versus the spatial direction.

In Figure 8, the BER of a QPSK system with DM for the LOS case is shown. There are six BERs shown on the plot. The red solid line is the theoretical BER according to (17). Two cases were simulated with the DM gain  $G$  calculated with  $\theta_2$  through  $\theta_5$  as discussed in the previous section and are almost identical. When the SNR is low, the BER is approximately the same as the theoretical being 0.27. As the SNR is increased the BER improves. The four dotted lines at  $\text{BER} = 0.5$  correspond to the four eavesdroppers. As described in the simulation section, 180 degrees were examined for eavesdroppers and the effect of the DM on the LOS transmission. The two angles of two eavesdroppers were chosen at  $+15^\circ$  and  $-15^\circ$  leading to an eavesdropper at  $30^\circ$  and one at  $60^\circ$ . These two eavesdropper BERs are shown to be 0.5 which equates to the theoretical BER of a QPSK that is unable to receive the sent message.

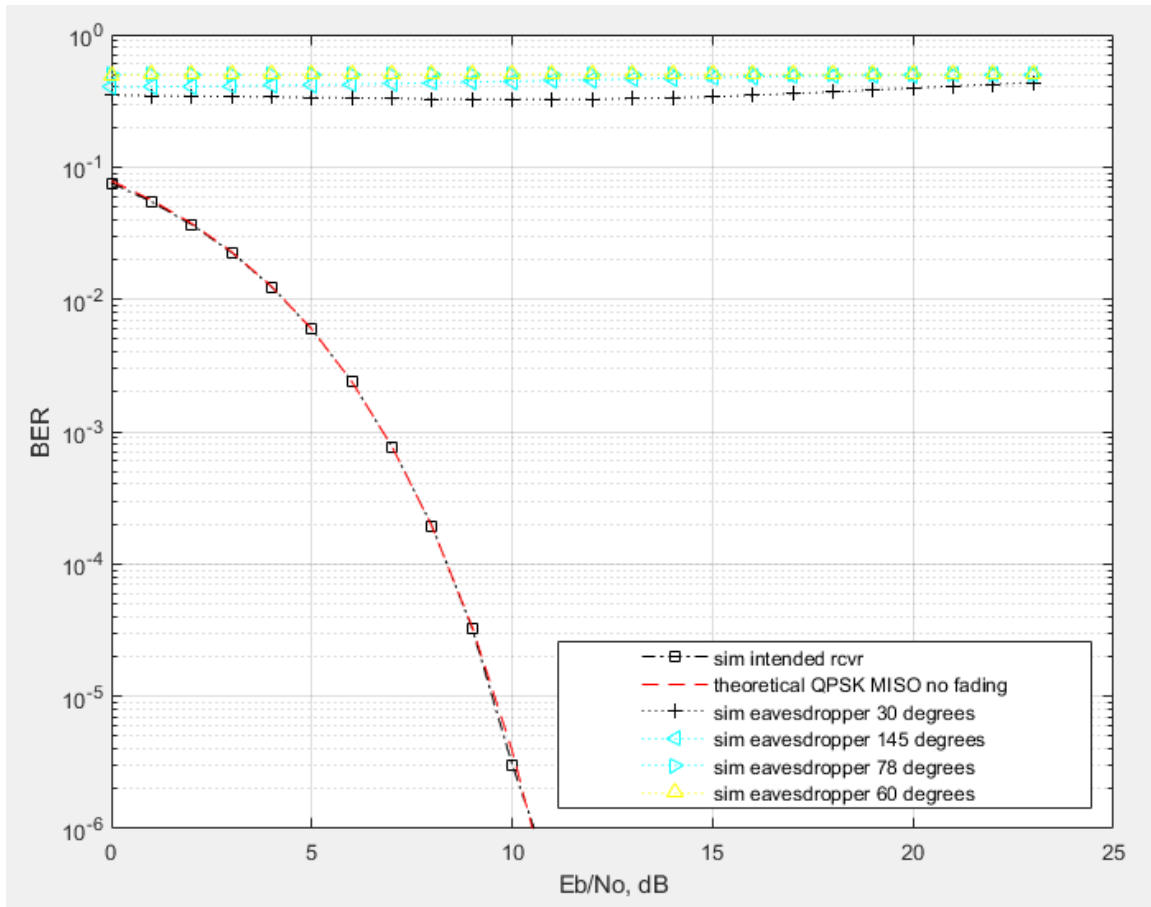


Figure 8. Line-of-sight QPSK signal with DM.

The results in Figure 8 show that a LOS DM process applied to a QPSK MISO system results in the signal transmitted to an intended receiver being demodulated with optimum probability of error. For example, in Figure 8, there are four eavesdroppers at  $30^\circ$ ,  $60^\circ$ ,  $78^\circ$ , and  $145^\circ$ , all of which experienced a high BER relative to the intended receiver. The eavesdropper at  $30^\circ$  had the lowest BER of 0.32. If the channel BER is 0.32, the transmitter can send about 0.1 information bits per channel bit resulting in a loss of 90% of the information or higher. The eavesdropper would receive very little of any of the sent message. In the same transmission, if there are eavesdroppers, the probability of error for them is high. This shows that DM for a LOS QPSK system yields good physical layer security.

In Figures 9, 10, and 11, the magnitude and phase of each receiver decision statistic for transmitter-receiver direction  $\theta = 0$  to 180 degrees is displayed in a plot for 100 symbols received. For Figure 9,  $\mathbf{G}$  was calculated with  $\theta_2$  through  $\theta_5 \pm 5^\circ$  and  $\pm 10^\circ$  from  $\theta_0$ . Likewise, Figure 10 is a plot where  $\mathbf{G}$  was calculated with  $\theta_2$  through  $\theta_5 \pm 10^\circ$  and  $\pm 20^\circ$  from  $\theta_0$ . The magnitude and phase in Figure 12 were calculated with  $\theta_2$  through  $\theta_5 \pm 45^\circ$  and  $\pm 90^\circ$  from  $\theta_0$ . In Figures 9, 10, and 11, the spatial angle of the intended receiver is marked on the magnitude and phase plots with a \*. In all three figures, the \* in the magnitude plot shows a magnitude at  $45^\circ$  of 0 dB, which is the desired result. In the phase plots, the \*s shows the four received phase angles at  $+45^\circ$ ,  $-45^\circ$ ,  $+135^\circ$ , and  $-135^\circ$ , as expected.

We see in Figure 9 that the phase between spatial directions 100 and 115 degrees has the same phase as the intended receiver of 45 degrees. This region produced zero-bit errors with 100 symbols received. This LOS case with the calculated  $\mathbf{G}$  appears to have a vulnerability area in the physical layer security. The research in [3] does not have a spatial direction that was vulnerable; however, the researchers did not shown how they derived  $\mathbf{G}$ . The differences in the effects of how  $\mathbf{G}$  is calculated is shown in Figures 10 and 11.

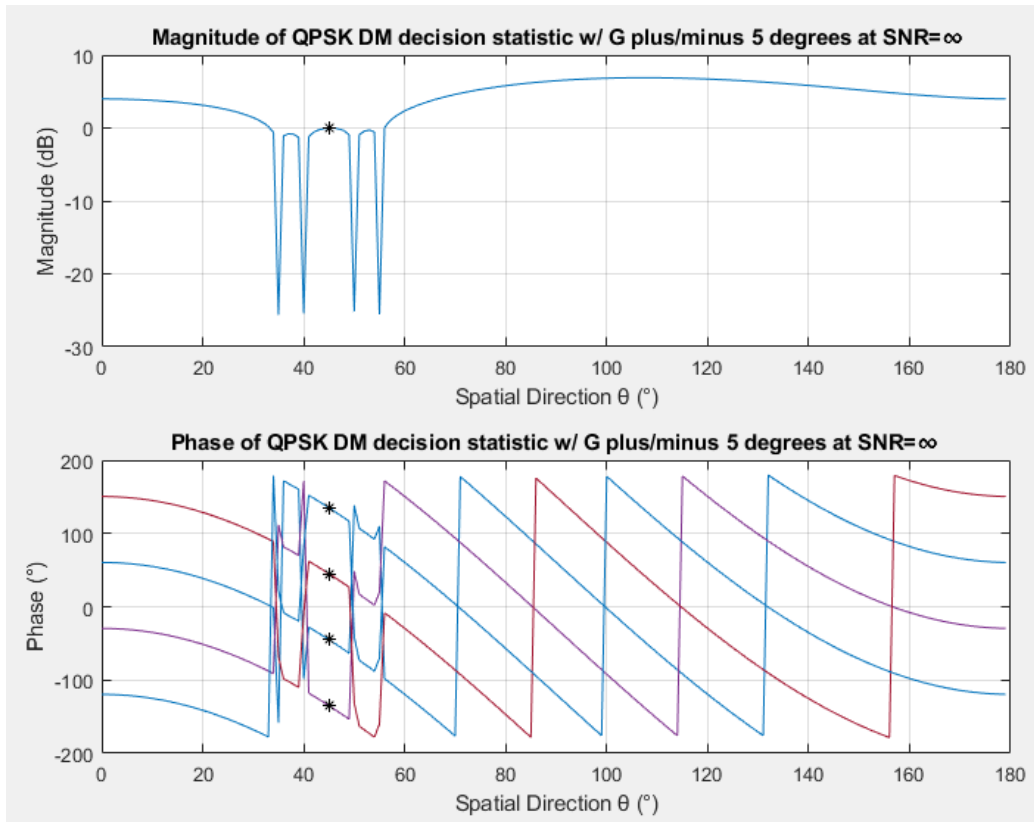


Figure 9. Magnitude and phase of a line-of-sight QPSK signal with DM.

In the magnitude plots of Figures 9, 10, and 11, where the nulls of  $G$  were placed is seen in the drastic dip at the angle chosen for that null. With an intended receiver at  $45^\circ$ , the nulls are seen in Figure 9 at  $35^\circ$ ,  $40^\circ$ ,  $50^\circ$ , and  $55^\circ$ . The nulls at  $25^\circ$ ,  $35^\circ$ ,  $55^\circ$ , and  $65^\circ$  are seen in Figure 10.

Also seen in Figure 10 is that the phase between 100 and 115 degrees has the same phase as the intended receiver of 45 degrees. This region produced zero bit errors with 100 symbols received. This LOS case with the calculated  $G$  of  $\theta_2$  through  $\theta_5 \pm 10^\circ$  from  $\theta_0$  appears to have a vulnerability area in the physical layer security as does the case with  $\pm 5^\circ$ .

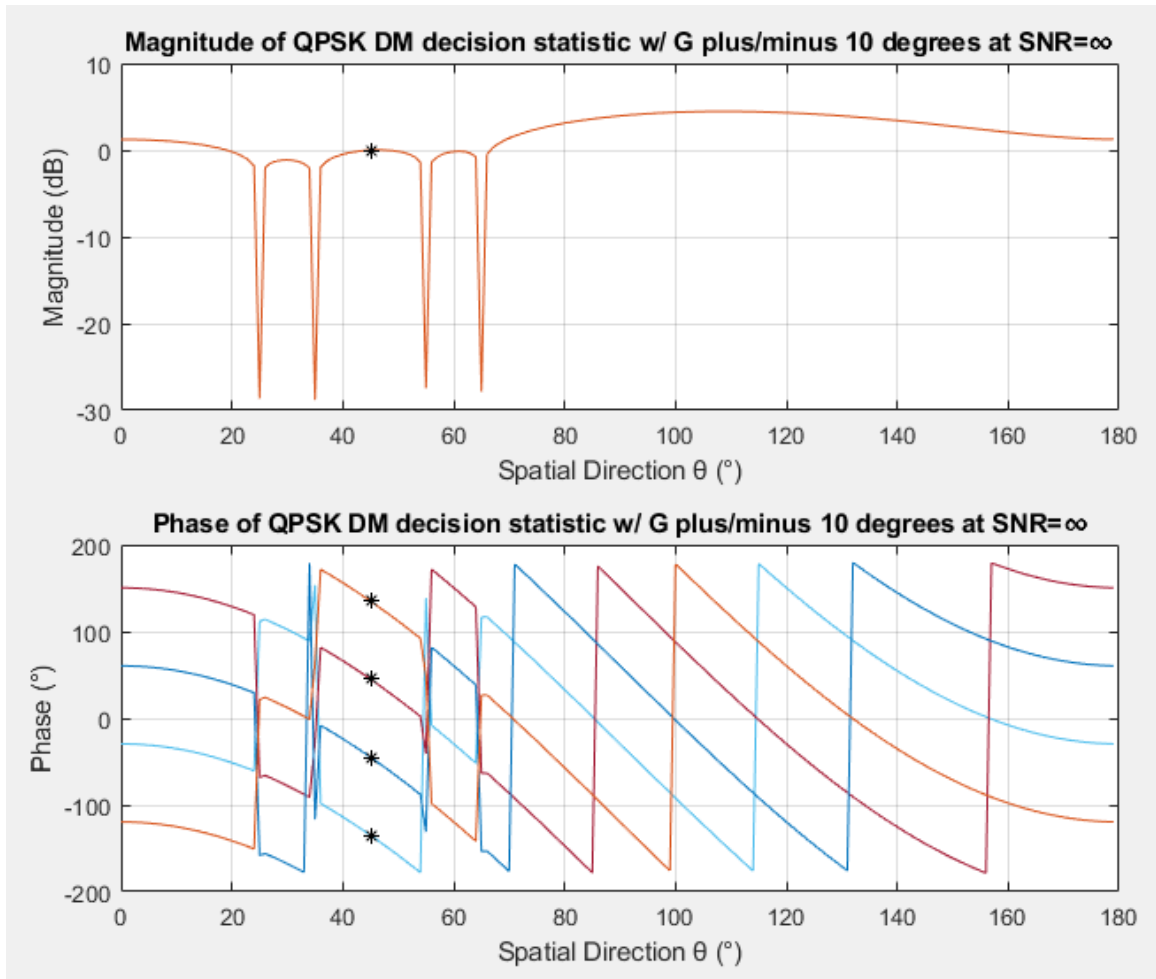


Figure 10. Magnitude and phase of a line-of-sight QPSK signal with DM.

Due to the plots in Figures 9 and 10, the angles used to generate  $\mathbf{G}$  were increased to  $\pm 45^\circ$ . From Figure 11 we see that the change produced a result with no spatial direction outside of the intended receiver that was able to reproduce a zero-bit error due to the phase alignment. In the Figure 11 phase plot, we see that at  $131^\circ$  the phase alignment is equal to that of  $45^\circ$ . Due to the null at  $135^\circ$ , the phase was changed, and the eavesdropper was unable to demodulate the signal. As a result, good physical layer security was achieved.

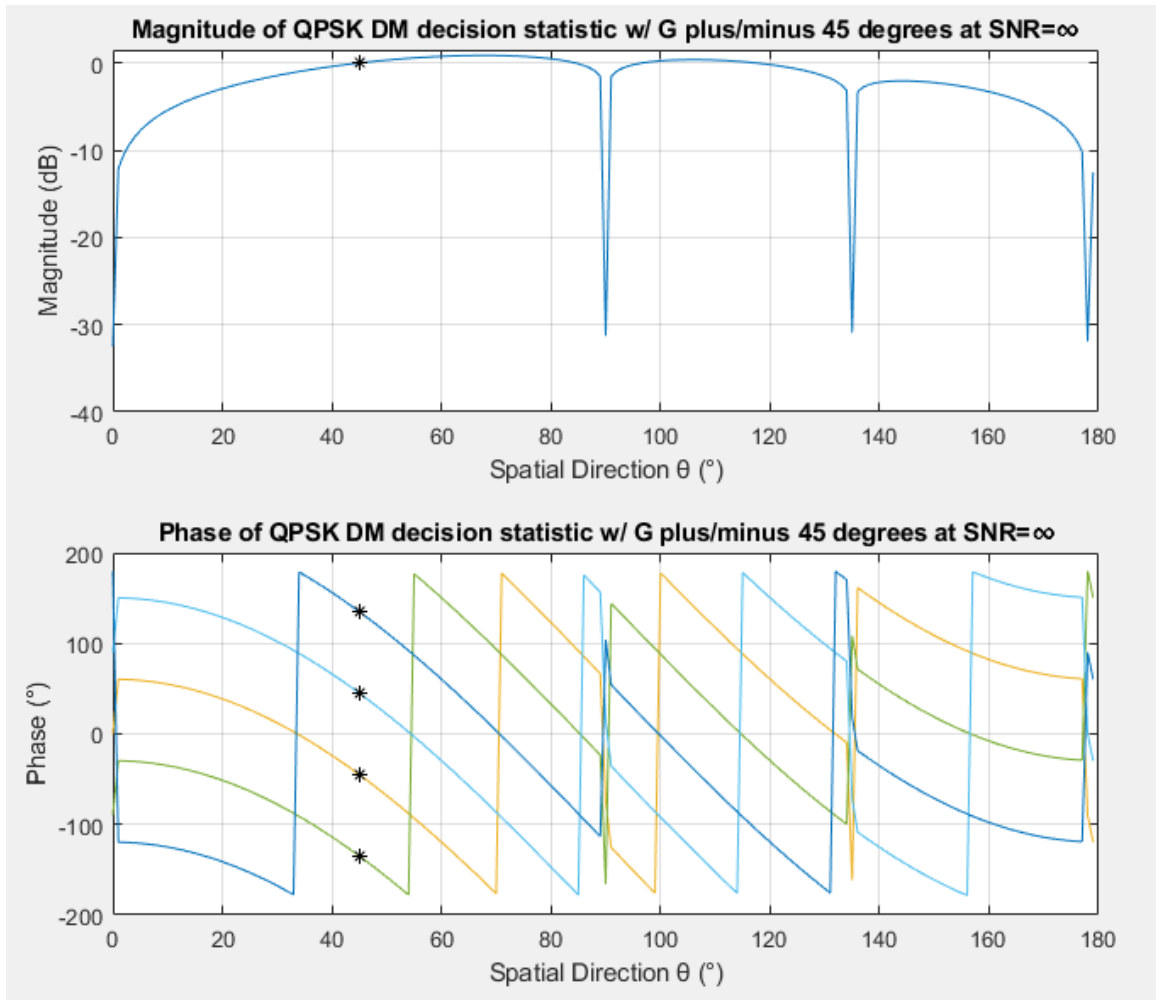


Figure 11. Magnitude and phase of a line-of-sight QPSK signal with DM.

The next plot generated is shown in Figure 12 and contains a BER at a specific SNR of 20 dB versus all 180 degrees transmitted from the antenna for the three simulations run with different angular spacing to generate the DM gain. For  $\mathbf{G}$  generated with  $\pm 5^\circ$  and  $\pm 10^\circ$ , most of the angles have a BER of 0.5 except for a dip at the angle of the intended receiver and a gap between 100 to 115 degrees. The gap correlates to the magnitude and phase discussed for Figures 9 and 10. For  $\mathbf{G}$  generated with  $\pm 45^\circ$ , there is no gap, and the signal at those spatial directions has the same BER as the surrounding angles.

For all three cases plotted, the dip at the angle of the intended receiver shows the BER at 20 dB. The width of the BER dip is the width around the intended receiver that can

receive the signal and reproduce the transmitted information as well as the intended receiver. The width is wider for the signals with greater angles to generate the DM gain.

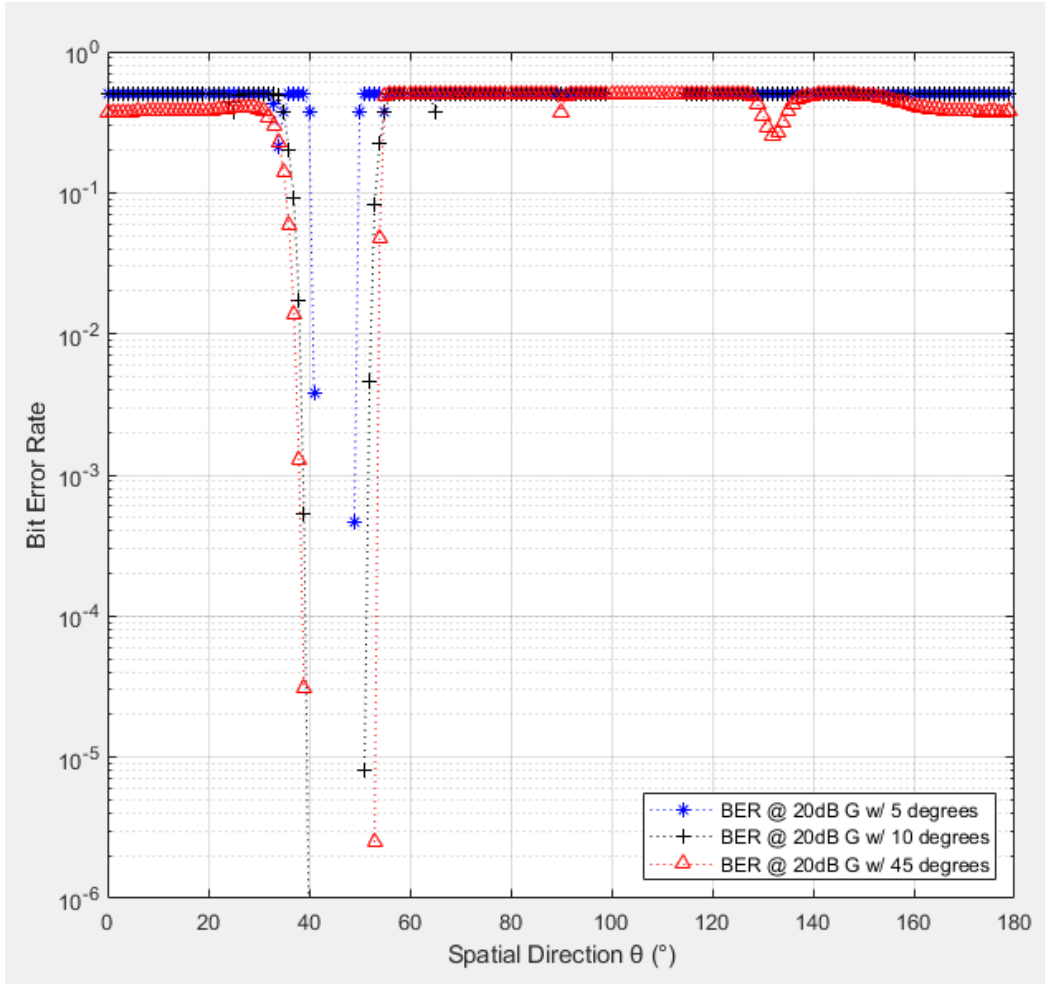


Figure 12. BER of a line-of-sight QPSK signal with DM at 20 dB.

## 2. NLOS Case

In the NLOS case, Figure 13 was produced for a BER plot versus SNR. The BER for the intended receiver, two different cases for an eavesdropper, and a theoretical curve to compare to the intended receiver is shown in Figure 13. The eavesdroppers plotted represent two different cases simulated. One case was with the eavesdropper channel gain known by the transmitter and the other case with the eavesdropper channel gain not known.



From Figure 12 we see that with either case good physical security is provided with both eavesdroppers having  $BER = 0.37$ .

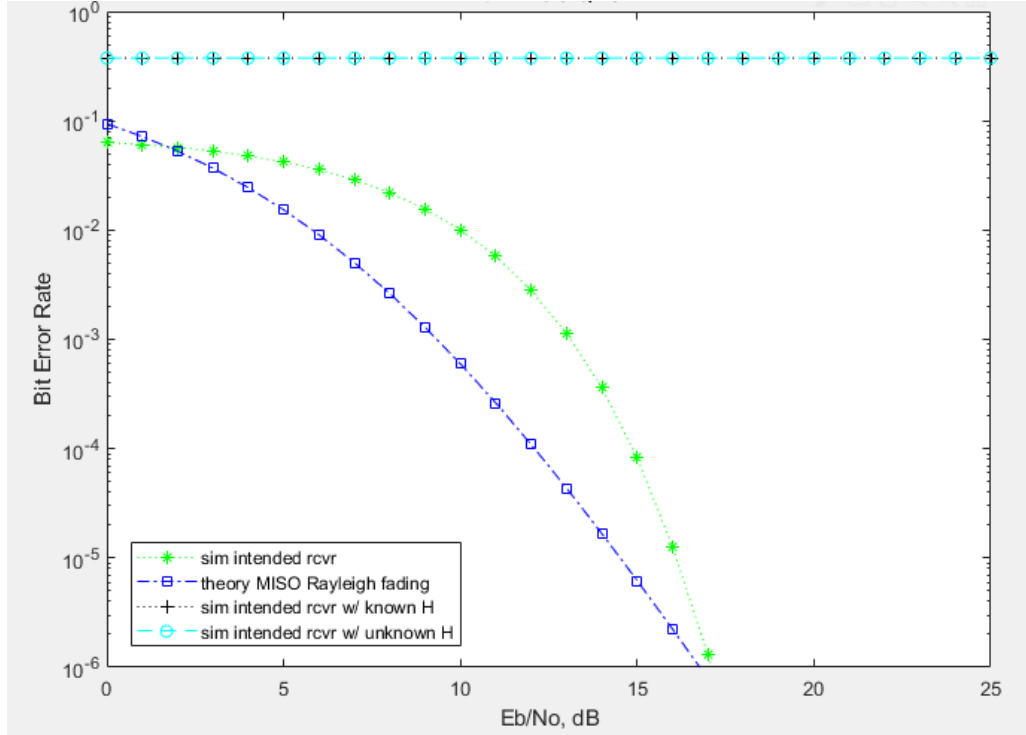


Figure 13. BER of a non-line-of-sight QPSK signal with DM.

The theoretical curve used for the BER was from [38] for a maximal ratio combining (MRC) receiver with Rayleigh fading. In [3], [4], and other literature used to research DM, there was no reference for BER with Rayleigh fading. The difference between this research and the theoretical MRC receiver is possibly due to how the receiver was simulated to combine the signals received. Even though the simulated BER results of the intended receiver does not closely follow the theoretical curve, it does show that as the SNR is improved the quality of the signal received is improved. At the same time, the eavesdropper quality of signal remains poor. The DM results show that this is a viable solution to provide physical layer security for a wireless signal, although perhaps the receiver design could be improved beyond that presented herein.

## V. CONCLUSIONS AND RECOMMENDATIONS

DM was studied during this research using analysis and computer simulations. The effectiveness and complexity of DM was illustrated when transmitting to intended receivers which were either LOS or NLOS. Security was also illustrated through examination of DM on would-be eavesdroppers.

### A. CONCLUSIONS

The primary contribution of this work is to extend the exploration of DM to the case of a NLOS channel between the transmitter and the intended receiver. The transmitter needs knowledge of the channel to the intended receiver for the DM gain to be calculated and implemented. Once the DM gain is applied, the transmitted signal, as simulated in Chapter IV.A.2, is seen to be securely received as shown in Chapter IV.B.2. The method results in zero information being received at the intended receiver due to having a  $BER = 0.5$ ; it is therefore deemed secure and effective according to information theory from Appendix B of [16]. If the transmitter is not able to receive the channel state from the receive antenna, the DM method derived in part B of Chapter III is not possible. The primary objective was met, and the research advances DM technology.

The second objective was to explore DM with a LOS channel using previous analytical methods. The analytical method for a LOS receiver that was reproduced in Chapters III and IV was the vector method. The vector approach was effective in most directions as shown in Chapter IV. A simulation for the LOS case applying the matrix SVD approach that was used in the NLOS case was completed and the results compared to the vector approach in Chapter V. Regardless of which DM method is used for the LOS case, the transmitter needs knowledge of the direction of the intended receiver or, equivalently, the channel state information. If the receiver moves or is moving, then the transmitter needs the ability to continually compute the DM gain to maintain the security DM provides. The second objective provided the knowledge and experience to lead to the primary objective.

In the LOS case, information theory using mutual information from appendix B of [16] is used to show that the eavesdroppers at best is receiving 10% of the information per

channel bit as discussed in Chapter IV.B.1. The reduction in channel capacity by 90% is strong validation of the security value of the DM methodology presented in this research.

The final objective was to examine the benefits, complexity, and application of DM in a transmitter and, more specifically, in the modulator. Applying DM in the modulator is complicated and necessitates the ability to process calculations quickly. Applying the DM gain in the modulator requires fast execution of the software to quickly calculate the DM gain and apply it to the digitally encoded information stream. Overall, DM is feasible and is a beneficial source of added security at the physical layer.

## **B. CHALLENGES AND FURTHER RESEARCH OPPORTUNITIES**

There are several related areas relevant to the work documented in this thesis that warrant future research.

### **1. Performance Assessment**

In DM research there have been a few metrics used to assess the effectiveness and performance of DM. In [15] three performance metrics were suggested. In this thesis only BER metrics and the noiseless decision statistics were used to assess the effectiveness of the simulated DM. The additional metrics that should be analyzed and applied to the NLOS case are power efficiency and secrecy rate. These two metrics will help with the evolution of DM. The power efficiency mentioned in the literature is related to how many vectors and antenna elements are used to create the DM signal. The power efficiency is also said to be related to the secrecy rate. The secrecy rate and power efficiency help determine the effectiveness of the DM.

### **2. Modeling and Experimentation of NLOS DM**

The next step after the analysis and simulation herein is to research and model DM for both the LOS and NLOS cases in a software radio. A software radio toolkit that would be effective is the GNU software radio system. GNU radio would allow for thorough practical design and research that could be applied in actual experimentation with DM transmitters being built, providing further confirmation of the theoretical results contained herein.

### **3. Deeper Investigation of Eavesdropper Channel and Effect on DM**

In Chapter IV, it was shown that the transmitter-to-eavesdropper channels are included in the channel-state matrix. The full effects of the eavesdropper channel need to be investigated to ensure the effectiveness of the DM gain, particularly when these channels are unknown at the transmitter. Research comparing the efficiency of DM for known transmitted-to-eavesdropper channel states versus that for the unknown channel states would quantify the effectiveness of this physical layer security technique.

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## APPENDIX A. DM LOS MATLAB CODE

The following MATAB code was used in this thesis for the LOS case. A CD containing the following code is being stored by Donna Miller in the communications laboratory at the Naval Postgraduate School. The first function is the highest-level function that calls the other functions listed top-level function, the other functions are listed in alphabetical order.

### *DMQPSKLOS.m*

```
%%Directional Modulation
%Top level program to create a DM signal for intended rcvr and
eavesdropper
%for 180 degrees. G is created for plus/minus 5, 10, and 45 degrees
cases.
clear all
close all
clc
tic
%% constants
fs = 8;           % sample frequency
Tsym = 1;        % inter-symbol interval (symbol duration)
endtime = 1e3;   % signal runs from t=0 to end time
m = ceil(endtime/Tsym); % m symbols are transmitted
SAMP_PER_SYM = 1; % samples per symbol
impResponse = ones(1,SAMP_PER_SYM)*sqrt(1/Tsym);
                % impulse response of pulse shaping filter
fc = 5;          % carrier freq.
N = 5;           %number of elements for the antenna array
d = .5;          %d is fractional portion of wavelength (d*lambda)
Symbol = (1 + 1i)/sqrt(2);
AntiSymbol = 0;
theta0 = 45 * pi / 180;
EbNoDB = 0:23;
EbNo = 10.^(EbNoDB/10);
for gg = 1:length(EbNo)
tic
[BER,BER10,BER45,t,signal,Information,Information10,Information45] =
...
entiresignalprocessDM(impResponse,fc,fs,Tsym,endtime,EbNo(gg),N,Symbol,
AntiSymbol,theta0,d);
[SignalReceivedRF180,SignalReceivedRF180_10,SignalReceivedRF180NoNoise,
SignalReceivedRF180NoNoise_10,...
SignalReceivedRF180_45,SignalReceivedRF180NoNoise45,Information,Informa
tion10,Information45] = ...
entiresignalprocessDM180(impResponse,fc,fs,Tsym,endtime,EbNo(gg),N,Symb
ol,AntiSymbol,theta0,d);
SigRcvd180NoNoise(gg,,:) = SignalReceivedRF180NoNoise(:,1:100,:);
SigRcvd180NoNoise_10(gg,,:) =
SignalReceivedRF180NoNoise_10(:,1:100,:);
```

```

SigRcvd180NoNoise_45(gg, :, :) = SignalReceivedRF180NoNoise45(:, 1:100, :);
BERTtotal(gg) = BER;
BER10total(gg) = BER10;
BER45total(gg) = BER45;
clear SigRcvd180 SigRcvd180a SigRcvd180b SigRcvd180c
[BER180, BER180_10, BER180_45, Informationdemod180] = ...
entiresignalprocesseaves(SignalReceivedRF180NoNoise, SignalReceivedRF180
NoNoise_10, ...
SignalReceivedRF180NoNoise45, EbNo(gg), Information, Information10, Informa
tion45, impResponse);
BER180total(gg, :) = BER180;
BER180_10total(gg, :) = BER180_10;
BER180_45total(gg, :) = BER180_45;
InformDemodTotal(:, gg) = Informationdemod180(1:100);
clear SignalReceivedRF180 SignalReceivedRF180_10
SignalReceivedRF180NoNoise SignalReceivedRF180NoNoise_10
clear SignalReceivedRF180_45 SignalReceivedRF180NoNoise45 Information
Information10 Information45
toc
end
SigRcvd180_20 = SigRcvd180NoNoise(21, :, :);
SigRcvdSqueezed = squeeze(SigRcvd180_20);
SigRcvdSqueezedmag = 10*log10(abs(SigRcvdSqueezed));
SigRcvdSqueezedang = angle(SigRcvdSqueezed).*(180/pi);
SigRcvd180_10_20 = SigRcvd180NoNoise_10(21, :, :);
SigRcvdSqueezed_10 = squeeze(SigRcvd180_10_20);
SigRcvdSqueezedmag_10 = 10*log10(abs(SigRcvdSqueezed_10));
SigRcvdSqueezedang_10 = angle(SigRcvdSqueezed_10).*(180/pi);
SigRcvd180_45_20 = SigRcvd180NoNoise_45(21, :, :);
SigRcvdSqueezed_45 = squeeze(SigRcvd180_45_20);
SigRcvdSqueezedmag_45 = 10*log10(abs(SigRcvdSqueezed_45));
SigRcvdSqueezedang_45 = angle(SigRcvdSqueezed_45).*(180/pi);
spatialDirection = 0:179;
figure(2)
subplot(211)
for ii = 1:50
    plot(spatialDirection, SigRcvdSqueezedmag(ii, :)/N)
    hold on
    plot(spatialDirection(46), SigRcvdSqueezedmag(ii, 46), 'k*')
end
title('Magnitude of QPSK DM signal w/ G plus/minus 5 degrees at 20dB
SNR')
grid on
xlabel('Spatial Direction ?');
ylabel('Magnitude (dB)');
subplot(212)
for jj = 1:50
    plot(spatialDirection, SigRcvdSqueezedang(jj, :))
    hold on
    plot(spatialDirection(46), SigRcvdSqueezedang(jj, 46), 'k*')
end
title('Phase of QPSK DM signal w/ G plus/minus 5 degrees at 20dB SNR')
grid on
xlabel('Spatial Direction ?');
ylabel('Phase');

```

```

figure(3)
subplot(211)
for kk = 1:100
plot(spatialDirection,SigRcvdSqueezedmag_10(kk,:)/N)
hold on
plot(spatialDirection(46),SigRcvdSqueezedmag_10(kk,46),'k*')
end
title('Magnitude of QPSK DM signal w/ G plus/minus 10 degrees at 20dB
SNR')
grid on
xlabel('Spatial Direction ?');
ylabel('Magnitude (dB)');
subplot(212)
for ll = 1:100
plot(spatialDirection,SigRcvdSqueezedang_10(ll,:))
hold on
plot(spatialDirection(46),SigRcvdSqueezedang_10(ll,46),'k*')
end
title('Phase of QPSK DM signal w/ G plus/minus 10 degrees at 20dB SNR')
grid on
xlabel('Spatial Direction ?');
ylabel('Phase');
figure(4)
subplot(211)
for ii = 1:50
plot(spatialDirection,SigRcvdSqueezedmag_45(ii,:)/N)
hold on
plot(spatialDirection(46),SigRcvdSqueezedmag_45(ii,46),'k*')
end
title('Magnitude of QPSK DM signal w/ G plus/minus 45 degrees at 20dB
SNR')
grid on
ylim([-40 1.5])
xlabel('Spatial Direction ?');
ylabel('Magnitude (dB)');
subplot(212)
for jj = 1:50
plot(spatialDirection,SigRcvdSqueezedang_45(jj,:))
hold on
plot(spatialDirection(46),SigRcvdSqueezedang_45(jj,46),'k*')
end

title('Phase of QPSK DM signal w/ G plus/minus 45 degrees at 20dB
SNR')
grid on
xlabel('Spatial Direction ?');
ylabel('Phase');
M=4;
HofTheta = channelvector5array(theta0);
HforPb = mean(abs(HofTheta).^2);
gammac = EbNo * HforPb;
gammab = N * gammac;
mu = sqrt(gammac ./ (1 + gammac));
A = 0;
for kk = 0:(N-1)

```



```

    B = nchoosek(2*kk,kk) .* ((1-mu.^2)./(4-(2.*mu.^2))).^kk;
    A = A + B;
end
Pb1 = 0.5*(1-((mu./sqrt(2-mu.^2)).*A));
Pb = 0.5*(1-sqrt(EbNo./(EbNo+1)));
P4 = (M-1)./(M*log2(M))*sin(pi/M)^2.*gammab);
Ps = 3./(40*gammac);
P4a = P4/2;
Eb = 0.5;
N0 = Eb./EbNo;
Pbs = 2*qfunc(sqrt(2)./sqrt(N0));
Pbs1 = 0.5*qfunc(pi/4)./sqrt(N0/2));
Pbs2 = berawgn(EbNoDB, 'psk', 4, 'nondiff');
figure(7)
semilogy(EbNoDB, BER180_10total(:,45), 'ks-.')
hold on
semilogy(EbNoDB, BER180_10total(:,31), 'k:+')
hold on
semilogy(EbNoDB, BER180_10total(:,61), 'y:^')
hold on
semilogy(EbNoDB, BER180_45total(:,78), 'c:>')
hold on
semilogy(EbNoDB, BER180_10total(:,145), 'c:<')
hold on
semilogy(EbNoDB, Pbs2, 'r--')
ylim([10^-6 1])
grid on
legend('sim intended rcvr G w/ 45 degrees', 'sim eavesdropper 30
degrees', 'sim eavesdropper 60 degrees', ...
'sim eavesdropper 78 degrees', 'sim eavesdropper 145
degrees', 'theoretical QPSK MISO no fading');
xlabel('Eb/No, dB');
ylabel('BER');
title('BER for LOS QPSK DM');
figure(6)
semilogy(spatialDirection, BER180total(21,:), 'b:*')
hold on
semilogy(spatialDirection, BER180_10total(21,:), 'k:+')
hold on
semilogy(spatialDirection, BER180_45total(21,:), 'r:^')
ylim([10^-6 1])
grid on
legend('BER @ 20dB G w/ 5 degrees', 'BER @ 20dB G w/ 10 degrees', 'BER @
20dB G w/ 45 degrees', 'location', 'SouthEast');
xlabel('Spatial Direction');
ylabel('Bit Error Rate');
title('BER for LOS QPSK DM at 20dB')
toc

```

### ***channelvectordm.m***

```

function ChannelVector =
channelvectordm(ThetaVector, ChannelVectorOmniDirectional)
%Creates a NxN H matrix from Equation (8)
for ii = 1:length(ThetaVector)

```

```

    ChannelVector(ii,:) =
    ChannelVectorOmniDirectional(ThetaVector(ii)+1,:);
end
end

```

### ***channelvectornelementarray.m***

```

function HofTheta = channelvectornelementarray(theta,d,N)
%channelvectornelementarray Creates the channel vector for the N
element array just how it was presented in [3]
% theta is the angle of transmission. d is the
%distance of a wavelength that the antenna elements are spaced. N is
the number of antenna elements.
n = 1:N;
thetal = theta * pi / 180;
y = (d*2*pi) .* (n - 1);
HofTheta = exp((1i * cos(thetal.')).* y);
End

```

### ***channelvectoromnidirection.m***

```

function ChannelVectorOmniDirectional = channelvectoromnidirection(d,N)
%Calculates a channel vector H from 0 to 369 degrees
theta = 0:359;
HofTheta = channelvectornelementarray(theta,d,N);
ChannelVectorOmniDirectional = HofTheta;
end

```

### ***combinesignalsrcvd.m***

```

function SignalReceivedRFcombined = combinesignalsrcvd(rcvdsignal)
%Combines the N number of received signals into one signal
SignalReceivedRFcombined = sum(rcvdsignal);
end

```

### ***complexenvelopeMF.m***

```

function SignalInSymbols =
complexenvelopeMF(complexbdemod,impulseresponse, fs)
%complexenvelopeMF is the match filter with the same impulse response
as themodulator.
% Returns the signal in symbols.
T_samp = 1;
SignalInSymbols = T_samp * conv(complexbdemod,impulseresponse);
SignalInSymbols = SignalInSymbols(1:length(complexbdemod));
end

```

### ***constellationvector.m***

```

function CmVector = constellationvector(Symbol,AntiSymbol,N)
%Generates the S vector for equation (8)
C_mOfTheta = [];
for ii = 1:N
    if ii == 1
        C_mOfTheta = [C_mOfTheta;Symbol];
    else
        C_mOfTheta = [C_mOfTheta;AntiSymbol]; %AntiSymbol(ii-1)
    end
end
CmVector = C_mOfTheta;

```

end

### ***directionalmodulation.m***

```
function [Gain_n,CVTheta0,ChannelVectorOmniDirectional] = ...
    directionalmodulation(Symbol,AntiSymbol,theta0,d,N)
%Calculates the DM gain, G, from equation (10). A G was claculated with
% +/- 5 degree increments. Two other functions were run for +/- 10 and
45
%degree increments. They are on the CD.
CmVector = constellationvector(Symbol,AntiSymbol,N);
ChannelVectorOmniDirectional = channelvectoromnidirection(d,N);
ThetaVector = thetavectorelement(theta0,N);%Contains the thetas in
degrees to retrieve the associatedchannel vector
ChannelVector =
channelvectordm(ThetaVector,ChannelVectorOmniDirectional); %the
Channel vector to be used in solving A_mn
A_mn = CmVector.' * (ChannelVector.').^-1;
Gain_n = conj(A_mn./Symbol);
CVTheta0 = ChannelVector(1,:);
end
```

### ***entiresignalprocessDM.m***

```
function
[BER,BER10,BER45,t,signal,Information,Information10,Information45] =
...

entiresignalprocessDM(impResponse,fc,fs,Tsym,endtime,EbNo,N,Symbol,Anti
Symbol,theta0,d)
%Simulates and calculates the DM process from signal creation,
%transmission, reception, demodulation, and BER for the intended
receiver.
[Gain_n,CVTheta0,ChannelVectorOmniDirectional] = ...
directionalmodulation(Symbol,AntiSymbol,theta0,d,N);
[signal,t,Information,ComplexEnv,CEwDM] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n);
[Gain_n10,CVTheta0_10,ChannelVectorOmniDirectional10] = ...
directionalmodulation10(Symbol,AntiSymbol,theta0,d,N);
[Gain_n45,CVTheta045,ChannelVectorOmniDirectional45] = ...
directionalmodulation45(Symbol,AntiSymbol,theta0,d,N);
[signal45,t45,Information45,ComplexEnv45,CEwDM45] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n45);
[signal10,t10,Information10,ComplexEnv10,CEwDM10] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n10);
clear signal10 t10 ComplexEnv10 Gain_n Gain_n10 signal45 t45
ComplexEnv45
[SignalLeavingAntennaDM] = signalleavingantennaDM(CEwDM,CVTheta0);
[SignalLeavingAntennaDM45] =
signalleavingantennaDM(CEwDM45,CVTheta045);
clear CVTheta0 CVTheta045
[SignalLeavingAntennaDM10] =
signalleavingantennaDM(CEwDM10,CVTheta0_10);
clear CVTheta0_10
for kk = 1:length(EbNo)
SignalReceivedRF =
signalreceivedRFDM(SignalLeavingAntennaDM,EbNo(kk));
```

```

SignalReceivedRF45 =
signalreceivedRFDm(SignalLeavingAntennaDM45,EbNo(kk));
SignalReceivedRF10 =
signalreceivedRFDm(SignalLeavingAntennaDM10,EbNo(kk));
[desampledSig,Informationdemod] =
QPSKdemodRF(SignalReceivedRF,impResponse,EbNo(kk));
[desampledSig10,Informationdemod10] =
QPSKdemodRF(SignalReceivedRF10,impResponse,EbNo(kk));
[desampledSig45,Informationdemod45] =
QPSKdemodRF(SignalReceivedRF45,impResponse,EbNo(kk));
clear desampledSig desampledSig10 desampledSig45
[BER(kk)] = signalBER(Information,Informationdemod);
[BER10(kk)] = signalBER(Information10,Informationdemod10);
[BER45(kk)] = signalBER(Information45,Informationdemod45);
end
end

```

### ***entiresignalprocessDM180.m***

```

function
[SignalReceivedRF180,SignalReceivedRF180_10,SignalReceivedRF360NoNoise,
...

SignalReceivedRF360NoNoise_10,SignalReceivedRF180_45,SignalReceivedRF36
0NoNoise45,...
Information,Information10,Information45] = ...

entiresignalprocessDM180(impResponse,fc,fs,Tsym,endtime,EbNo,N,Symbol,A
ntiSymbol,theta0,d)
%Generates the received DM signal for all 180 degrees simulated to
examine
%the eavesdroppers and the intended target.
[Gain_n,CVTheta0,ChannelVectorOmniDirectional] = ...
directionalmodulation(Symbol,AntiSymbol,theta0,d,N);
[signal,t,Information,ComplexEnv,CEwDM] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n);
[Gain_n10,CVTheta0_10,ChannelVectorOmniDirectional10] = ...
directionalmodulation10(Symbol,AntiSymbol,theta0,d,N);
[Gain_n45,CVTheta045,ChannelVectorOmniDirectional45] = ...
directionalmodulation45(Symbol,AntiSymbol,theta0,d,N);
[signal45,t45,Information45,ComplexEnv45,CEwDM45] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n45);
[signal10,t10,Information10,ComplexEnv10,CEwDM10] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,Gain_n10);
clear signal10 t10 ComplexEnv10 Gain_n Gain_n10 signal45 t45
ComplexEnv45
clear CVTheta0 CVTheta045 signal45 ComplexEnv
[SignalLeavingAntennaDM180] =
signalleavingantennaDM360(CEwDM,ChannelVectorOmniDirectional);
clear ChannelVectorOmniDirectional
[SignalLeavingAntennaDM180_45] =
signalleavingantennaDM360(CEwDM45,ChannelVectorOmniDirectional45);
clear CVTheta0_10 t
[SignalLeavingAntennaDM180_10] =
signalleavingantennaDM360(CEwDM10,ChannelVectorOmniDirectional10);

```

```

clear ChannelVectorOmniDirectional10 ChannelVectorOmniDirectional45
signal
[SignalReceivedRF180,SignalReceivedRF360NoNoise] = ...
signalreceivedRFDM360(SignalLeavingAntennaDM180,EbNo,N);
[SignalReceivedRF180_45,SignalReceivedRF360NoNoise45] = ...
signalreceivedRFDM360(SignalLeavingAntennaDM180_45,EbNo,N);
[SignalReceivedRF180_10,SignalReceivedRF360NoNoise_10] = ...
signalreceivedRFDM360(SignalLeavingAntennaDM180_10,EbNo,N);
end

```

### *entiresignalprocesseaves.m*

```

function [BER180,BER180_10,BER180_45,Informationdemod180] = ...

entiresignalprocesseaves(SignalReceivedRF180,SignalReceivedRF180_10,...
SignalReceivedRF180_45,EbNo,Information,Information10,Information45,impulseresponse)
%demodulates the signal received at all 180 degrees. Calculates the BER
%for each direction. Eaves dropper LOS
for mm = 1:180
    [desamplesig360(mm,:),Informationdemod180(mm,:)] =
    QPSKdemodRF(SignalReceivedRF180(:, :, mm),impulseresponse,EbNo);
    [desamplesig360_10(mm,:),Informationdemod180_10(mm,:)] =
    QPSKdemodRF(SignalReceivedRF180_10(:, :, mm),impulseresponse,EbNo);
    [desamplesig360_45(mm,:),Informationdemod180_45(mm,:)] =
    QPSKdemodRF(SignalReceivedRF180_45(:, :, mm),impulseresponse,EbNo);
end
clear desamplesig360 desamplesig360_10
for nnn = 1:180
    Information180(nnn,:) = Information;
    Information180_10(nnn,:) = Information10;
    Information180_45(nnn,:) = Information45;
end
BER180 = signalBER360(Information180,Informationdemod180);
BER180_10 = signalBER360(Information180_10,Informationdemod180_10);
BER180_45 = signalBER360(Information180_45,Informationdemod180_45);
end

```

### *info2symbol.m*

```

function symbols = info2symbol(In)
%info2symbol assigns QPSK symbols to information
% Symbol is one bit per symbol. In is the random generated
information
% vector.
Symbols = QPSKsymbols;
zerosymbol = Symbols(1); %00
onesymbol = Symbols(2); %01
twosymbol = Symbols(3); %10
threesymbol = Symbols(4); %11
symbols = zerosymbol*(In == 0) ... % using logical indexing. It's a
good trick to know.
+ onesymbol*(In == 1) ...
+ twosymbol*(In == 2) ...
+ threesymbol*(In == 3);
end

```

### ***QPSKdemodRF.m***

```
function [MF_out,Informationdemod] =
QPSKdemodRF(complexenv,impulseresponse,EbNo)
%QPSKdemod demodulates the received signal using a match filter.
% Returns the signal in the form of the complex envelope, symbols, one
bit
% per sample, and the information.
SAMP_PER_SYM = 1;
N = length(complexenv);
noise = (1/sqrt(2)*randn(1,N))+ ((1/sqrt(2))*1i*randn(1,N));
complexenvnoise = ((2*sqrt(EbNo)/sqrt(2)).*complexenv) + noise;
MF_out = (5)*complexenvelopeMF(complexenvnoise,impulseresponse);
Informationdemod = symboltoinformation(MF_out);
end
```

### ***QPSKsignalDM.m***

```
function [signal,t,Information,ComplexEnv,CEwDM] =
QPSKsignalDM(impResponse,fc,fs,Tsym,endtime,GainDM)
%QPSK signal is the tope function to create a QPSK signal.
% impResponse is the impulse response for the filter.
TimeSamp = 1;
m = ceil(endtime/Tsym); % total number of symbols
numbOfSampPerSymb = Tsym/TimeSamp;
numbOfSampTotal = numbOfSampPerSymb*m; % total # of samples
Information = randInform(m);
symbols = info2symbol(Information);
SymbolsWithZeros = samplespersym(numbOfSampPerSymb,symbols);
ComplexEnv = symbolfilter(impResponse,SymbolsWithZeros);
t = (0:numbOfSampTotal-1)*TimeSamp;
signal = real( ComplexEnv .* exp(1i*2*pi*fc*t) );
CEwDM = GainDM' * ComplexEnv;
end
```

### ***QPSKsymbols.m***

```
function symbolsvector = QPSKsymbols
%QPSKsymbols assigns symbols for a QPSK signal
% a0 is for 00; a1 is for 01, a2, is for 10, and a3 is for 11
a0 = (1 + 1i)/sqrt(2);
a1 = (-1 + 1i)/sqrt(2);
a2 = (1 - 1i)/sqrt(2);
a3 = (-1 - 1i)/sqrt(2);
symbolsvector = [a0,a1,a2,a3];
end
```

### ***randInform.m***

```
function [Information] = randInform(length)
%randInform returns random information string for QPSK
% length is how many n information bits desired.
Information = randi(4,1,length) - 1;
end
```

### ***samplespersym.m***

```
function SymbolswithZeros = samplespersym(numbOfSampPerSymb,Symbols)
```

```

%samplespersym takes the symbol vector and stuffs it zeros.
% This is the matrix that goes into the filter and is convoluted with
the
% impulse response.
SymbolswithZeros = upsample(Symbols, numoSampPerSymb);
end

```

### ***signalBER.m***

```

function [BER] = signalBER(Information, InformDemod)
%Calculates BER for DM signal
correct = Information == InformDemod;
BER = sum(not(correct))/(2*length(Information));
end

```

### ***signalBER360.m***

```

function [BER] = signalBER360(Information180, InformDemod180)
%SIGNALBE360 calculates BER for 180 to evaluate DM signal
for ii = 1:180
correct = Information180(ii,:) == InformDemod180(ii,:);
BER(ii) = sum(not(correct))/(2*length(Information180(ii,:)));
end
end

```

### ***signalleavingantennaDM.m***

```

function [SignalLeavingAntennaDM] =
signalleavingantennaDM(signal, CVTheta0)
%signalleavingantenna creates the RF signal at each antenna element
% multiplies the signal wanting to transmit for each phase shift for
that
% particular antenna element.
%signal is the complex envelope ready to be transmitted at each
antenna
%element. theta is the angle of transmission in radians.
SignalLeavingAntennaDM = signal .* CVTheta0.';
end

```

### ***signalleavingantennaDM360.m***

```

function [SignalLeavingAntennaDM180] =
signalleavingantennaDM360(CEwDM, ChannelVectorOmniDirectional)
%Calculates the signal leaving the transmit antenna for 360 degrees
for ii = 1:180
SignalLeavingAntennaDM = CEwDM .*
ChannelVectorOmniDirectional(ii,:).';
SignalLeavingAntennaDM180(:, :, ii) = SignalLeavingAntennaDM;
end
end

```

### ***signalreceivedRFDM.m***

```

function [SignalReceivedRF] =
signalreceivedRFDM(SignalLeavingAntenna, EbNo)
%signalreceivedRFelement creates the received signal by adding the N
received
%signals from each channel vector
N = length(SignalLeavingAntenna);

```

```
SignalReceivedRF = combinesignalsrcvd(SignalLeavingAntenna);
end
```

### ***signalreceivedRFDM360.m***

```
function [SignalReceivedRF360,SignalReceivedRF360NoNoise] = ...
    signalreceivedRFDM360(SignalLeavingAntennaDM360,EbNo,N)
%Calculate the received signal for all 180 degrees with noise and
without.
M = length(SignalLeavingAntennaDM360);
for ii = 1:180
    noise = (1/sqrt(2)*randn(5,M))+ ((1/sqrt(2))*1i*randn(5,M));
    temp = SignalLeavingAntennaDM360(:, :, ii);
    complexenvnoise = ((sqrt(EbNo)/sqrt(2)).* temp) + noise;
    SignalReceivedRF = combinesignalsrcvd(complexenvnoise);
    noisel = 0;
    complexenvnoisel = ((sqrt(EbNo)/sqrt(2)).* temp) + noisel;
    temp1 = SignalLeavingAntennaDM360(:, :, ii);
    SignalReceivedRFno = combinesignalsrcvd(temp1);
    SignalReceivedRF360(:, :, ii) = [0,0;0,0];
    SignalReceivedRF360NoNoise(:, :, ii) = SignalReceivedRFno;
end
end
```

### ***symbolfilter.m***

```
function ComplexEnvSig = symbolfilter(ImpulseResponse,symbolswithZeros)
%symbolfilter convolutes the impulse response and the signal matrix of
%symbols with zero padded.
ComplexEnvSig = conv(symbolswithZeros,ImpulseResponse);
ComplexEnvSig = ComplexEnvSig(1:length(symbolswithZeros));
end
```

### ***symboltoinformation.m***

```
function Informationdemod = symboltoinformation(desampledsg)
%symboltoinformation assigns the input symbols to the information
%stream
% a0 is for 00; a1 is for 01, a2, is for 10, and a3 is for 11
% a0 = (1 + 1i)/sqrt(2);   quadrant 1
% a1 = (-1 + 1i)/sqrt(2);  quadrant 2
% a2 = (1 - 1i)/sqrt(2);   quadrant 4
% a3 = (-1 - 1i)/sqrt(2);  quadrant 3
Inform = [];
for ii = 1:length(desampledsg)
    A = desampledsg(1,ii);
    if real(A) >= 0 && imag(A) >= 0
        Inform = [Inform, 0];
    end
    if real(A) < 0 && imag(A) >= 0
        Inform = [Inform, 1];
    end
    if real(A) >= 0 && imag(A) < 0
        Inform = [Inform, 2];
    end
    if real(A) < 0 && imag(A) < 0
        Inform = [Inform, 3];
    end
end
```



```

    end
end
Informationdemod =Inform;
end

```

### ***thetavectornelement.m***

```

function ThetaVector = thetavectornelement(theta0,N)
%Calculates a vector based on theta0 that includes the other
directional
%degrees to calculate G. There are tow other functions on the CD for
+/-
%10 and 45 degree increment.
theta0degrees = theta0*180/pi;
thetavector = zeros(1,N);
thetavector(1) = theta0degrees;
if theta0degrees < 355
    nUp = theta0degrees;
else
    nUp = theta0degrees - 360;
end
if theta0degrees > 4
    nDown = theta0degrees;
else
    nDown = theta0degrees + 360;
end
tempnUp = theta0degrees;
tempnDown = theta0degrees;
for ii = 2:N
    if mod(ii,2) == 0
        thetavector(ii) = nUp + 5;
        tempnUp = nUp + 5;
    if tempnUp < 355
        nUp = nUp + 5;
    else
        nUp = nUp + 5 - 360;
    end
    else
        thetavector(ii) = nDown - 5;
        tempnDown = nDown - 5;
    if tempnDown > 4
        nDown = nDown - 5;
    else
        nDown = nDown - 5 + 360;
    end
    end
end
ThetaVector = thetavector;
end

```

## APPENDIX B. DM NLOS MATLAB CODE

The following MATAB code was used in this thesis for the NLOS case. A CD containing the code is being stored with the code in Appendix A. The first function is the highest-level function that calls the other functions listed below. After the top-level function, the other functions are listed in alphabetical order. Any functions used that were duplicates from Appendix A are not listed.

### *DMMISONLOS.m*

```
%%DM MISO NLOS
%Top level function that generates the simulation for DM QPSK NLOS MISO
%signal.
clear all
format long
tic
%% constants
fs = 8;           % sample frequency
Ts = 1/fs;
Tsym = 1;        % inter-symbol interval (symbol duration)
endtime = 1e4;   % signal runs from t=0 to endtime
K = 1;
m = ceil(endtime/Tsym); % m symbols are transmitted
SAMP_PER_SYM = 1; % samples per symbol
impResponse = ones(1,SAMP_PER_SYM)*sqrt(1/Tsym);
                % impulse response of pulse shaping filter
fc = 2;          % carrier freq.
N = 5;           %number of elements for the antenna array
EbNoDB = 0:25;
EbNo = 10.^(EbNoDB/10);
M = 4;
for mm = 1:K
    [BER,t,signal,Hactual,SignalLeavingAntenna,Information,Eb] = ...
    entiresignalprocessDM(impResponse,fc,fs,Tsym,endtime,EbNo,N);
    [BERofeaveswoP,BERofeavesLOS,BERofeaveswoPnoteqR] = ...

entiresignalprocesseaves(SignalLeavingAntenna,Hactual,N,fs,Tsym,Informa
tion,EbNo);
    if mm == 1
        BERTtotal = BER/5;
        BERTotaleaveswoP = BERofeaveswoP;
        BERTotaleavesLOS = BERofeavesLOS;
    end
    if mm > 1
        BERTtotal = BERTtotal + BER;
        BERTotaleaveswoP = BERTotaleaveswoP + BERofeaveswoP;
        BERTotaleavesLOS = BERTotaleavesLOS + BERofeavesLOS;
    end
    EbNo = 10.^(EbNoDB/10);
    No = 1./(2*EbNo);
```

```

HforPb = mean(mean(abs(Hactual(:,1,:)).^2));
gammac = 1./(10*No);
gammab = N * gammac;
mu = sqrt(gammac ./ (1 + gammac));
A = 0;
for kk = 0:(N-1)
    B = nchoosek(N-1+kk,kk) .* ((1+mu)./2).^kk;
    A = A + B;
end
Pb1 = ((1-mu)/2).^N.*A;
Pb = 0.5.*(1-sqrt(EbNo./(EbNo+2)));
P4 = (M-1)./((M*log2(M))*sin(pi/M)^2.*gammab);
end
BERTtotal = BERTtotal/mm;
toc
ber = berfading(EbNoDB, 'psk', 4, 5);
figure(2)
semilogy(EbNoDB,BERTtotal, 'g*:')
hold on
semilogy(EbNoDB,Pb1, 'b-.s')
hold on
semilogy(EbNoDB,BERofeaveswoP(1,:), 'k:+')
hold on
semilogy(EbNoDB,BERofeaveswoPnoteqR(1,:), 'c--o')
ylim([10^-6 1])
legend('sim intended rcvr', 'theory MISO Rayleigh fading',...
'sim intended rcvr w/ known H', 'sim intended rcvr w/ unknown H');
xlabel('Eb/No, dB');
ylabel('Bit Error Rate');
title('BER for NLOS QPSK DM');

```

### ***entiresignalprocessdm.m***

```

function [BER,t,signal,Hactual,SignalLeavingAntenna,Information,Eb] =
...
entiresignalprocessDM(impResponse,fc,fs,Tsym,endtime,EbNo,N)
%Calculates the signal from transmitter to receiver with the BER for
the
%intended receiver.
[signal,t,Information,ComplexEnv] =
QPSKsignal(impResponse,fc,fs,Tsym,endtime);
[SignalLeavingAntenna,Hactual,Eb] = signalforantenna(ComplexEnv,N);
EbF = mean(abs(Hactual(:,1)).^2) * Eb;
for kk = 1:length(EbNo)
[SignalReceivedRF] =
signalreceivedRFDm(SignalLeavingAntenna,Hactual,N,EbNo(kk));
[MF_out,Informationdemod] =
QPSKdemodRF(SignalReceivedRF,Tsym,EbNo(kk),EbF);
BERoftheta0Demod(kk) = signalBER(Information,Informationdemod);
end
BER = BERoftheta0Demod;
end

```

### ***entiresignalprocesseaves.m***

```

function [BERofeaveswoP,BERofeavesLOS,BERofeaveswoPnotR] = ...

```

```

entiresignalprocesseaves(SignalLeavingAntenna,Hactual,N,fs,Tsym,Information,EbNo)
%Calculates the DM signal for the eavesdroppers in the NLOS case
%%Eaves dropper NLOS
M = length(SignalLeavingAntenna);
for ii = 2:N
for nn = 1:length(EbNo)
SignalReceivedRFwoP =
signalreceivedRFDMeaves(SignalLeavingAntenna,Hactual,N,ii,EbNo(nn));
InformationdemodeaveswoP = ...
QPSKdemodRF(SignalReceivedRFwoP,Tsym,EbNo(nn),1);
BERofeaveswoP(ii-1,nn) =
signalBER(Information,InformationdemodeaveswoP);
end
BERofeaveswoP(ii) = signalBER(Information,InformationdemodeaveswoP);
end
%%Eaves dropper NLOS w/ Hm not = Hr
M = length(SignalLeavingAntenna);
for kk = 1:M
HforDMeaves(:, :,kk) = rayleighchannel(N);
end
for ii = 2:N
for nn = 1:length(EbNo)
SignalReceivedRFwoP =
signalreceivedRFDMeaves(SignalLeavingAntenna,HforDMeaves,N,ii,EbNo(nn))
;
InformationdemodeaveswoP =
QPSKdemodRF(SignalReceivedRFwoP,Tsym,EbNo(nn),1);
BERofeaveswoPnotR(ii-1,nn) =
signalBER(Information,InformationdemodeaveswoP);
end
end
BERofeavesLOS =1;
end

```

### ***QPSKdemodRF.m***

```

function [desampled sig,Informationdemod] =
QPSKdemodRF(complexenv,Tsym,EbNo,EbF)
%QPSKdemod demodulates the received signal.
N = length(complexenv);
SAMP_PER_SYM = 1;
desampled sig = [];
aa = 1;
for jj = 1:(N/SAMP_PER_SYM)
temp = sum(complexenv(aa:(SAMP_PER_SYM*jj)))/SAMP_PER_SYM;
aa = aa + SAMP_PER_SYM;
desampled sig(jj) = temp;
end
Informationdemod = symboltoinformation(desampled sig);
end

```

### ***rayleighchannel.m***

```

function [H] = rayleighchannel(N)
%Calculates the rayleigh channel for the NLOS channel

```

```
H = 1/sqrt(2)*(randn(N,N) + 1i*randn(N,N));
end
```

### ***rayleighchanneldesired.m***

```
function [Pdesired] = rayleighchanneldesired(H)
%Calculate W from equation (17)
Hdesired = H;
[Udesired,Sdesired,Vdesired] = svd(Hdesired);
Pdesired = Vdesired * Sdesired^-1 * Udesired';
end
```

### ***signalforantenna.m***

```
function [SignalForAntenna,Hactual,Eb] = signalforantenna(signal,N)
%Calculates the signal for the antenna, T from equation (14)
M = length(signal);
for kk = 1:M
Hactual(:, :,kk) = rayleighchannel(N);
Pdesired(:, :,kk) = rayleighchanneldesired(Hactual(:, :,kk));
end
L = length(signal);
signaltemp = zeros(N,L);
for ii = 1:L
signaltemp(:,ii) = signal(ii);
end
Eb = mean(abs(signaltemp(:,1).^2))/2;
SFA1 = [];
for jj = 1:L
temp = zeros(5,1);
temp(1) = signaltemp(1,jj);
SFA0 = (Pdesired(:, :,jj) .' * temp);
SFA1 = [SFA1,SFA0];
end
SignalForAntenna = SFA1;
end
```

### ***signalreceivedRFDM.m***

```
function [SignalReceivedRF] =
signalreceivedRFDM(SignalLeavingAntenna,Hactual,M,EbNo)
%signalreceivedRFelement creates the received signal for intended
signal
N = length(SignalLeavingAntenna);
No = 1/(EbNo);
B=1;
alpha = sqrt(2*B*No);
SignalArrivingAtAntenna = zeros(M,N);
noise = ((alpha/sqrt(2))*randn(1,N)) + ((alpha/sqrt(2))*1i*randn(1,N));
complexenvnoise = ((sqrt(EbNo))*SignalLeavingAntenna) + (noise);
for ii = 1:N
temp = (complexenvnoise(:,ii) .* Hactual(:,1,ii));
SignalArrivingAtAntenna(:,ii) = temp(:,1);
end
SignalReceivedRF = combinesignalsrcvd(SignalArrivingAtAntenna,N);
end
```

### ***signalreceivedRFDMeaves.m***

```

function [SignalReceivedRFwoP] = ...
    signalreceivedRFDMeaves(SignalLeavingAntenna,Hactual,M,column,EbNo)
%calculates the received signal for the eavesdroppers
N = length(SignalLeavingAntenna);
No = 1/(EbNo);
B=1;
alpha = sqrt(2*B*No);
noise = ((alpha/sqrt(2))*randn(5,N)) + ((alpha/sqrt(2))*1i*randn(5,N));
complexenvnoise = ((sqrt(EbNo))* SignalLeavingAntenna) + (noise);
SignalArrivingAtAntennawoP = zeros(M,N);
for ii = 1:N
    temp = (complexenvnoise(:,ii) .* Hactual(:,column,ii));
    SignalArrivingAtAntennawoP(:,ii) = temp(:,1);
end
SignalReceivedRFwoP = combinesignalsrcvd(SignalArrivingAtAntennawoP,N);
end

```

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