**Lab 4: MIMO Transmission System**

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| **Introduction**  In this lab, we focus on Multiple Input Multiple Output (MIMO) system. The Multiple Input Multiple Output system is what we have initially encountered in the wireless communication lecture. In this experimental course, we first analyzed the transmission theory of MIMO, which involves the tradeoff between diversity and multiplexing. After that, we discuss three algorithms used to estimate the transmitted symbolic content from the received signal, and we also use these estimation algorithms for MATLAB programming exercises in our lab. Finally, we focus on the space-time coding technology of MIMO – Alamouti coding, and realize the data transmission of QPSK through the Alamouti coding technology of 2×2 antennas.  **Theoretical analysis**   1. **MIMO system application and deployment**   MIMO system is the system with multiple inputs and multiple outputs, which means using multiple antennas at the transmitter and receiver. MIMO is sometimes called spatially diverse because it uses multiple spatial channels to transmit and receive data. MIMO can be deployed only when a site (mobile device) or access point (AP) supports MIMO. It use multiple antennas to supress channel fading. According to the number of antennas at tansmitter and receiver, MIMO systems can also include SIMO(Single-Input Multiple-Outputs) system and MISO(Multiple-inputs Single-Outputs) system compared to SISO(Single-Input Single-Output) system.    MIMO system can increase the channel capacity and spectrum utilization of communication system doubly without increasing bandwidth. For SISO system, the channel capacity  is the the channel capacity in bits per second, is the bandwidth of the channel in hertz and is the signal-to-noise ratio.  For MIMO system, the channel capacity is  Both the transmitter and the receiver have antennas, and is orthogonal channel matrix.  According to the formula, the spectrum utilization of MIMO system is higher than that of SISO system.   1. **MIMO transmission model**   In this lab, we will meanly focus on the narrowband MIMO channel model as when the MIMO channel bandwidth is large relative to the channel’s multipath delay spread, the channel suffers from intersymbol interference, which means it is similar to the case of SISO channels.  We can mark the data transmitted from the two antennas on the base station or transmitter as X1 and X2, and mark the data received by the two antennas of the mobile phone or receiver as Y1 and Y2, and the four transmission paths between the transmitter and receiver are marked as h11, h12, h21 and h22. Then, we can get the MIMO transmission model as shown in the figure below:    The figure shown above adequately represents the mathematical model of a m×n MIMO system, where H is the channel matrix, and each h corresponds to the channel diagram on the left, s is the transmitted signal, and n corresponds to the noise of the channel. To simplify the discussion, we will go back to the 2×2 MIMO system.  There are two equations for the two unknowns Y1 and Y2. And the reason for why sometimes the capacity of 2×2 MIMO system can reach twice of the capacity of SISO, sometimes can reach several times of that, and sometimes it becomes the same as the capacity of SISO can be explained by the channel correlation. The higher the correlation, the more difficult it is to distinguish each transmission path on the receiver side, which will lead to a change in channel capacity. If the channels are exactly the same, it is equivalent to the two equations becoming one, and the two unknowns cannot be solved, so it can only use one path for transmission.  Therefore, we can see that the key idea of the MIMO channel lies in the judgment of the independence of the transmission paths. In other words, the key is hidden in the four coefficients which are h11, h12, h21 and h22 in the above two equations. Engineers are still dissatisfied with this qualitative explanation, and they think the equation is too fussy, so they omit the plus sign in it and write them in the following form with vectors and matrices:    From the equation and the transmission model shown above, we can easily find that the channel matrix H is important for the correlation between channels. If the rank of H is 1, it means that the transmission space of the 2×2 MIMO system is very correlated. The channel will degenerate from MIMO to SISO or SIMO, and can only send and receive one data at the same time; if the rank of H is 2, it means that the system has two relative data. Independent spatial channel, can send and receive two channels of data at the same time.   1. **Methods for implementing MIMO** 2. **Pre-coding**   In multi-user MIMO system, one of the main problem is to eliminate the interference between each user signal. In the downlink, the mobile stations can’t cooperate with each other because thay are geographically dispersed. Therefore, the receiving algorithm used in the uplink can’t be used to detect the transmitted signal jointly. At this time, the channel state information can be utilized at the transmitter, and the pre-coding technology of multi-user MIMO system can be adopted to preprocess the transmitted signal, so that each user can receive the pure signal that is not interfered by other users.  Take MIMO pre-coding as example. The steps for pre-coding are as below：  **Step1:** do SVD(Singular Value Decomposition of matrices) to .  The expression of the received signal is as below  is the channel matrix. The SVD of is  And  **Step2:**replace with the SVD of it  Define , which satisfy  Because , then  So  Multiply both sides of this equation by  Further expansion expression:  According to the expression, it is obvious that the received signal contains the pre-coded transimitted signal and the noise of the channel, which means interference from other users have been eliminated.     1. **Zero-forcing**   The essence of the zero forcing algorithm is to form the beam to separate the transmitted data stream by using the base station, so that the unit response is generated in the expected direction and the response in the non-expected direction is zero. Interference users form zero trap, completely eliminating interference between user data streams. The idea is to make use of the known channel state information, multiply the sender by the inverse (pseudo-inverse) matrix of the channel matrix, and implement linear zero forcing interference among independent signals based on the least square estimation, so as to obtain the required signals.  Assume that channels are held constant for the whole frame, the pre-coding matrix of zero forcing algorithm is  In order to ensure that the power of the transmitted signal remains unchanged after pre-coding, normalization processing is carried out. is used to represent the power normalization factor, and theexpression of final precoding matrix is:  The expression of is:  This precoding algorithm can completely eliminate the interference between users and the interference between data streams within users, that is  Therefore it is called zero forcing algorithm.  The advantage of zero forcing algorithm is low complexity, which can completely eliminate interference. The disadvantage is that it will affect the transmission power and make the additive noise amplified by weighting.     1. **Minimum Mean Squared Error (MMSE)**   The Minimum Mean Squared Error (MMSE) method is a widely used technique in Multiple-Input Multiple-Output (MIMO) communication systems for detecting transmitted signals in the presence of noise and interference. In a MIMO system, there are multiple antennas at both the transmitter and receiver. The transmitted signal passes through a channel that can cause the signal to be distorted and noisy. The goal of the receiver is to estimate the transmitted signal based on the received signal. MMSE method uses a linear filter at the receiver to estimate the transmitted signal. The filter coefficients are chosen to minimize the mean squared error between the estimated signal and the actual transmitted signal. The MMSE method takes into account the statistical properties of the noise and the channel. Overall, the MMSE method is an effective way to detect transmitted signals in MIMO systems and can significantly improve the reliability and performance of communication systems.  The main idea of the MMSE method is shown as following:    We now consider the flat fading channel model:    In the ideal case, assuming no noise, we have , if there is noise, we need to use a model that can reflect the effect of noise, and MMSE is just that. Besides, we need to notice that in MMSE, the matrix should be the matrix that minimizes the MSE by using the statistical properties of the received signal . If there is a correlation between and the error , the correlation should be able to be used to reduce the norm of . Thus, there must be a sweet spot where there is no correlation between and . So the formula for the matrix is based on the fact that is independent with , i.e., or , where .  Now we go back to the discussion of minimizing the MSE in MMSE, the derivation is shown as below:  To minimizes the MSE, i.e., the equation shown above, we first take the derivative of the MSE expression, and set it equal to 0, then we can get:  And we can finally get:  For , we have:    where is the transmission power, and is the noise power.  And for , we have:    Then we plug the two results above into the expression for :  Finally, we can get the expression of :   1. **Alamouti coding**     Alamouti’s scheme is designed for a digital communication system with two-antenna transmit diversity. The scheme works over two symbol periods and it is assumed that the channel gain is constant over this time. Over the first symbol period, two different symbols and (each with energy ) are transmitted simultaneously from antennas 1 and 2, respectively. Over the next symbol period, symbol is transmitted from antenna 1, and symbol is transmitted from antenna 2, each again with symbol energy . Assume complex channel gains between the i-th transmit antenna and the receive antenna. The received symbol over the first symbol period is , and the received symbol over the second symbol period is , where is the AWGN sample at the receiver associated with the i-th symbol transmission. We assume that the noise sample has mean 0 and power N.  The receiver uses these sequentially received symbols to form the vector given by  where , , and  Let us define the new vector . The structure of implies that  is diagonal and thus  where is a complex Gaussian noise vector with mean 0 and covariance matrix . The diagonal nature of effectively decouples the two symbol transmissions, so that each component of corresponds to one of the transmitted symbols:  The equations shown above show that the Alamouti scheme achieves a diversity order of 2 – the maximum possible for a two-antenna transmit system – despite the fact that channel knowledge is not available at the transmitter.  The Alamouti scheme can be generalized for M > 2; this generalization falls into the category of orthogonal space-time block code design.    Because a MIMO channel has input–output relationship , the symbol transmitted over the channel each symbol time is a vector rather than a scalar, as in traditional modulation for the SISO channel. Moreover, when the signal design extends over both space (via the multiple antennas) and time (via multiple symbol times), it is typically referred to as a space-time code.  Most space-time codes are designed for quasi-static channels, where the channel is constant over a block of T symbol times and the channel is assumed unknown at the transmitter. Under this model, the channel input and output become matrices with dimensions corresponding to space (antennas) and time.  The rank and determinant criteria have been primarily applied to the design of space-time trellis codes (STTCs), which are an extension of conventional trellis codes to MIMO systems. They are described using a trellis and are decoded using ML sequence estimation via the Viterbi algorithm. STTCs can extract excellent diversity and coding gain, but the complexity of decoding increases exponentially with the diversity level and transmission rate. Space-time block codes (STBCs) are an alternative space-time code that can also extract excellent diversity gain with linear receiver complexity.   1. **comm.OSTBCEncoder**   The OSTBCEncoder object encodes an input symbol sequence using orthogonal space-time block code (OSTBC). The block maps the input symbols block-wise and concatenates the output codeword matrices in the time domain. To encode an input symbol sequence using an orthogonal space-time block code we first need to define and set up an OSTBC encoder object, then call **step** to encode an input symbol sequence according to the properties of comm.OSTBCEncoder.  This object contains the following properties:   |  | | --- | | NumTransmitAntennas | | SymbolRate |   And it also has a fixed-point property:   |  | | --- | | OverflowAction |   In addition, this object contains the following methods:   |  |  | | --- | --- | | clone | getNumInputs | | getNumOutputs | isLocked | | release | step |   When we use this object to process variable-size signals we need to notice that:   * If the input signal is a column vector, the first dimension can change, but the second dimension must remain fixed at 1. * If the input signal is a matrix, both dimensions can change.  1. **comm.OSTBCCombiner**   The OSTBCCombiner object combines the input signal (from all of the receive antennas) and the channel estimate signal to extract the soft information of the symbols encoded by an OSTBC. The input channel estimate does not need to be constant and can vary at each call to the **step** method. The combining algorithm uses only the estimate for the first symbol period per codeword block. A symbol demodulator or decoder would follow the Combiner object in a MIMO communications system. To combine input signals and extract the soft information of the symbols encoded by an OSTBC we first need to define and set up an OSTBC combiner object, then call **step** to Combine inputs using an orthogonal space-time block code according to the properties of comm.OSTBCCombiner.  This object contains the following properties:   |  | | --- | | NumTransmitAntennas | | SymbolRate | | NumReceiveAntennas |   And it also has the following fixed-point properties:   |  |  | | --- | --- | | RoundingMethod | OverflowAction | | ProductDataType | CustomProductDataType | | AccumulatorDataType | CustomAccumulatorDataType | | EnergyProductDataType | CustomEnergyProductDataType | | EnergyAccumulatorDataType | CustomEnergyAccumulatorDataType | | DivisionDataType | CustomDivisionDataType |   In addition, this object contains the following methods:   |  |  | | --- | --- | | clone | getNumInputs | | getNumOutputs | isLocked | | release | step |   **Lab results & Analysis**   1. **Methods for implementing MIMO** 2. **Programming procedure of Pre-coding**   The function of pre-coding is as below:         1. **Programming procedure of Zero-forcing**   The function of zero forcing algorithm is as below:       1. **Programming procedure of Minimum Mean Squared Error (MMSE)**   The programming procedure of realizing the MMSE method in MATLAB is shown as following:    In the program, we model a 2×2 MIMO link with 3 flat fading MIMO channels. And in this part, we will focus on the realization of MMSE.  In our theoretical analysis, we have known that:  According to the formula shown above, we can create the matrix .  And follow the equation below:  Then we can get the estimated signal .   1. **BER comparison**     From the above picture, what can be known is that when SNR is less than 8dB, the BER using zero forcing is less than those using pre-coding and MMSE. When SNR is greater than 8dB, the BER using MMSE is less than those using pre-coding and zero-forcing. That means the performance of zero-forcing algorithm is better under the condition when SNR is low and the performance of MMSE algorithm is better under the condition when SNR is high. In practice, we should choose the corresponding method of MIMO system according to the actual signal-to-noise ratio.   1. **Apply Alamouti 2×2 to the QPSK transceiver** 2. **Programming procedure**   In order to explore the relationship between the SNR and BER of 2×2 Alamouti encoding MIMO system, we need to modify the original SISO QPSK system program into MIMO transmission system which uses Alamouti encoding scheme. The important steps of the programming procedure are shown as following:   * **Transmitter**      * **Receiver**      * **Channel**      1. **Text recovery and BER results**  * **EbNo = 0 dB**     The figure shown above is the text recovery and BER results when EbNo = 0 dB.   * **EbNo = 5 dB**     The figure shown above is the text recovery and BER results when EbNo = 5 dB.   * **EbNo = 10 dB**     The figure shown above is the text recovery and BER results when EbNo = 10 dB.  From the figures shown above, we can easily find that the performance of the recovery of the transmitted text message at the receiver becomes better if we increase the SNR, i.e., the value of EbNo. At the same time, the bit error rate of the received text message will decrease if we increase the SNR, i.e., the value of EbNo. | |
| **Experience**  **Experience**  孙逸涵:   1. In this lab, we have learned how to use MATLAB to implement MIMO system. Before this lab, we have learned some basic knowledge of MIMO in the Wireless Communication lecture in last semester, but there are still many questions about that we don’t understand, which also includes how to implement a simple MIMO system. And after this lab, we get a deeper understanding about that, and also learned three equalizer schemes in this system with the flat fading channel. 2. When I wrote the part about the principle of the MMSE method, I have looked us many materials online, and I finally found that there are some conflicts between my derivation solution and Dr. Wu’s solution, the correct expression should be:   But the final expression from my derivation is:  And I have changed the code of implementing the equalizer matrix to:    Then I tried to run the program and found that the final expression from my derivation is wrong. And I will continue to trying to derive the correct result.  张旭东:   1. I have a deep understanding the application and deployment of MIMO system and the advantages of it. 2. I have a deep understanding of the pre-coding algorithm and be preliminarily familiar with the process of algorithm derivation and the process of code programming. 3. I have a deep understanding of the zero forcing algorithm and be preliminarily familiar with the process of algorithm derivation and the process of code programming.   **In-class lab screenshot**  孙逸涵:    张旭东: | |
| **Score** | 100 |