**Lab 4: MIMO Transmission System**

|  |  |
| --- | --- |
| **Author** | Name： 吉辰卿 Student ID: 11911303 |
| **Introduction**  In this experiment, 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 theory class. 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 to estimate the transmitted symbolic content from the received signal, and we also use these estimation algorithms for MATLAB programming exercises in our class. Finally, we focus on the space-time coding technology of MIMO --Alamouti, and realize the data transmission of QPSK through the Alamouti coding technology of 2x1 and 2x2 antennas. The results show that compared with SISO, MIMO of 2x1 antenna using Alamouti encoding has lower bit error rate under the same SNR. I will focus on these experimental results in the following section of experimental analysis. Now, I will focus on sorting out the important theories in this experiment.  **Theoretical analysis:**   1. **MIMO System**   In fact, MIMO is all around us. Take an common example, are there many antennas on the wireless router in our home? So what exactly do these antennas do? Could make the signal we receive more stable? Or make our Internet connections faster? All of these effects can be achieved with MIMO. MIMO, also known as multiple input multiple output technology, aims to improve data transmission efficiency and effectively reduce the bit error rate of data by using multiple antennas at the transmitter and receiver. When it comes to MIMO, we should firstly understand several other technologies: SISO, SIMO, and MISO. Obviously, we can divide our model into four types according to the different number of antennas at the transmitter and receiver: Single Input Single Output, Single Input Multiple Output, Multiple Input Single Output, Multiple Input Multiple Output, and the last one is our MIMO. So I'm going to briefly introduce these systems in very colloquial terms:   1. **SISO System:**   https://t11.baidu.com/it/u=650620138,76197517&fm=173&app=25&f=JPEG?w=640&h=315&s=1AAA70230B2B452018F5D4DA0000C0B1  SISO systems are vulnerable because there is only one antenna between the base station and the phone (transmitter and receiver), and the path between the transmitting and receiving antennas is their only channel for transmitting information. It is easy to see that only one path undoubtedly brings great uncertainty to the communication between the base station and the mobile phone. If there is interference anywhere, it will cause great interference to this channel. Therefore, the reception of SISO is very poor.   1. **SIMO system:**   https://t12.baidu.com/it/u=2775167480,589087380&fm=173&app=25&f=JPEG?w=639&h=306&s=1AAA7023135B5463587DD0CA000080B1  In SIMO, the above instability has been greatly improved. Since there are two antennas at the receiver, it doesn't matter if you lose some of the data sent on each road. It is enough for the mobile phone to receive one copy from any path. Although the maximum capacity remains the same for one road, the probability of successfully receiving data is increased doubled. This method is also called receive diversity.  So what about MISO? How is it different from SIMO?   1. **MIMO system:**   https://t10.baidu.com/it/u=1710618891,1663602171&fm=173&app=25&f=JPEG?w=640&h=307&s=1AAA7423171B50610EDDA1DA000080B1  We can try another way of thinking. The cell phone still has one antenna and the base station has two antennas. In this way, the base station can send two different data simultaneously. This works from the base station's point of view, but a phone has only one receiving antenna, and the two paths eventually have to be combined. So the base station still has to send the same thing, so it doesn't matter if you lose some of the data you're sending on each road, as long as you don't lose something on both roads. Therefore, the maximum capacity of communication in this way remains the same, but the success rate of communication is doubled. This approach is also called transmission diversity.   1. **MIMO system:**   https://t12.baidu.com/it/u=1795259123,3155301218&fm=173&app=25&f=JPEG?w=639&h=306&s=1AAA70231F5A50434C7DD0DA000080B1  As a couple, the base station and the mobile phone still have a tacit understanding. Everyone can use two antennas to send two channels of data independently, and the speed is doubled fluently, this method is the famous MIMO.  So, in this way, there are 4 transmission paths between the base station and the mobile phone, which seems to be a lot more complicated. To be sure, because the base station and the mobile phone have two antennas, the hardware has the conditions for sending and receiving two channels of data at the same time. So how much can its maximum capacity increase compared to a path? From the previous analysis of SIMO and MISO, it seems that the maximum capacity depends on the number of antennas on both sides of the transmitter. The barrel principle tells us: how much water a bucket can hold depends on the shortest piece of wood. So, from this compare the number of antennas of the base station and the mobile phone, the maximum capacity is always restricted by the party with the fewer antennas, which is also the easiest way to judge the maximum capacity of MIMO.  MIMO system is generally written as AxB MIMO, where A represents the number of antennas of the base station and B represents the number of antennas of the mobile phone. Based  on the barrel principle we discuss it above: Which has more capacity, 4x4 MIMO or 4x2 MIMO? From the bucket principle, the 4x4 MIMO can send and receive channel data at the same time, and its maximum capacity can reach 4 times the SISO system in theory, while the 4x2 that can only receive 2 channels of data at the same time, because there are only two receiving antennas, its maximum capacity can only reach twice the SISO system. This method of using multiple antennas and different transmission paths to send multiple copies of different data in parallel in multiplexing space to increase capacity is called space division multiplexing.   1. **MIMO Transmission model**   We cam mark the data transmitted by the two antennas on the base station as X1 and X2, the data received on the two antennas of the mobile phone are marked as Y1 and Y2, and the four transmission paths in the middle are marked as h11, h12, h21 and h22. Then, we can get the MIMO transmission model as shown in the figure below.  **20220317221223**  The figure above adequately represents the mathematical model of a MIMO system: h is the channel matrix, and each h corresponds to the channel diagram on the left, s is the transmitted beam, and n corresponds to the noise of the channel. To simplify the discussion, let's go back to the 2\*2 MIMO system.  The two unknowns Y1 and Y2, there are two equations. But why sometimes the capacity of 2x2 MIMO can reach twice the capacity of SISO, sometimes a little several times, and sometimes it becomes the same as the capacity of SISO? This problem can be explained by the channel correlation just mentioned. The higher the correlation, the more difficult it is to distinguish each transmission path on the mobile phone side, which leads to a change in 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.  So, we can see that the secret of the MIMO channel lies in the judgment of the independence of the transmission path. In other words, the mystery is hidden in the four coefficients of h11, h12, h21 and h22 in the above two equations. These engineers are still dissatisfied with this qualitative explanation, and they think the equation is too long-winded, so they omit the plus sign in it and write it in the following form.  20220317231041  We can quickly see that the optimal transport matrix H should have the form:  20220317231139  When the transmission matrix has this "diagonal matrix" form, X1 and X2 are matrix multiplied by it, yielding X1 and X2 as if each had reached the receiver through a "transparent" sub-channel, with no interference between the two, it will be seen in the figure below:  20220317231634  Now, we still assume that the sender sends signals X1 and X2, and after multiplying by the whole matrix, we get two identical transmission equations, which is equivalent to just one equation. It is also impossible for us to solve two exact X1 and X2 from one equation, so although the maximum "degree of freedom" supported by 2x2 MIMO is 2, the channel provides us with only 1 degree of freedom in this case, as shown in the figure below:  20220317232240  Therefore, through the current analysis, we can clearly see that the channel matrix H seems to affect the correlation between channels. If the correlation between channels is too strong, the MIMO channel may degenerate into SIMO, MISO or even SISO. So how do we talk about the channel matrix H?  A matrix with data on only one diagonal is called a diagonal matrix. The number of non-zero data on the diagonal is called the rank of the matrix. In 2x2 MIMO, it refers to the non-zero values of λ1 and λ2. The number is the maximum of the rank of 2x2 matrix.  If the rank is 1, it means that the transmission space of this 2x2 MIMO system is very correlated. It degenerates from MIMO to SISO or SIMO, and can only send and receive one data at the same time; if the rank 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.  So, if the rank is 2, is the capacity of the two transmission channels twice that of one? The answer is actually contained in the λ1 and λ2 in this diagonal matrix, which is the ratio of λ1 and λ2, also known as the condition number.  If the condition number is 1, it means that the values of λ1 and λ2 are the same, the quality of the two spatial channels is half a catastrophe, the independence is very high, and the capacity of the 2x2 MIMO system can reach the maximum.  If the condition number is greater than 1, it means that the values of λ1 and λ2 are one larger and the other smaller. Although there are two spatial channels, the quality is different. At this time, the system will put the main resources on the channel with good quality. The capacity of SISO is between 1 and 2 times that of the SISO system.  Of course, we don't have to worry about how the base station learns the channel information so that it knows which channel to place the information on. Because cell phones and base stations are a pair, they communicate with each other and there are no secrets. The phone sends its measured channel status, the rank of the transmission matrix, and pre-coded suggestions to the base station for reference. Here, I found a vivid picture to explain:  https://t11.baidu.com/it/u=1180017397,1091778205&fm=173&app=25&f=JPEG?w=640&h=375&s=1AAA7023058A55491ED491CE000080B1   1. **MIMO Pre-coding**   Although the diagonal matrix we saw in the previous section (the rank of the matrix is 2) seems nice because it completely separates the two channels. However, as we know, in the real transmission matrix, each element in it changes randomly according to a certain probability and statistics law, and there is no shadow of "diagonal matrix" at all. But the form of "diagonal matrix" is so good that even though we can't get it directly at the moment, we still wish there was a way to "transform" the real transport matrix into the form of diagonal matrix --SVD Decomposition (SingularValue Decomposition of matrices, SingularValue Decomposition) provides the perfect solution.  20220317233724  By SVD decomposition of the transport matrix H, we can obtain three matrices: left unitary matrix U, diagonal matrix S (S1 in diagonal matrix S, S2 is the singular value of H) and right unitary matrix V. Now, we have the diagonal matrix S, but we have two more unitary elements U and V on the left and right sides of it. What can we do? It doesn't matter. The unitary matrix has the nice property that it can simplify itself by multiplying itself by its conjugate transpose. If we first "preprocess" the signals before they pass through the channel, multiply them by the conjugate transpose of V, and then pass them through the channel, the right unitary matrix V is simplified, equivalent to sending the signal directly multiplied by the diagonal matrix S. Similarly on the receiving end, we cancel the received signal matrix by multiplying it by the conjugate transpose of the unitary matrix U. Then we were pleasantly surprised to find that the transport equation with the form of "diagonal matrix" came back, which was exactly what we expected. Therefore, the precoding process at the MIMO transmitter is shown as follows:  20220317234501  Finally, let's review how we recovered the transmission matrix in the form of "diagonal matrix". We firstly multiplied the signals by the conjugate transpose of the right unitary V before they were sent. Thus, we can extract the first benefit of having a channel matrix at the sender: If the sender has information about H, it can be SVD decomposed into a right unitary matrix V, which can be used to transform the transmission process into the desired "diagonal matrix" form.   1. **Alamouti: Transmit Diversity**   Alamouti scheme is the basis of the Space Time Coding technique. The mathematical explanation of the scheme with two transmitting and one receiving antenna is also explained here. In this example, a two-branch transmit diversity scheme is implemented. Using two transmit antennas and one receive antenna, the scheme provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit antenna and two receive antennas.  At the transmitter side, a block of two symbols is taken from the source data and will be sent to the modulator. After that, Alamouti space-time encoder takes the two modulated symbols, in this case called and creates encoding matrix where the symbols and are mapped to two transmit antennas in two transmit time slots. The encoding matrix is given by:  In receive antenna, we can get:  We can convert above equations to a matrix operation:  We defined:  We can get:  Then, we use multiplex above equation:  Then, we can get:  So, from our analysis above, we can easily know that: Even if we don’t know the CSIT of transmitter, we can also use the Alamouti scheme to achieve the diversity gain of 2.  **Lab results & Analysis：**  **Task1: Implementing QPSK include the Alamouti encoding scheme**  **Result:**  20220318003852 20220318100523  **EbNo = 0dB**  **EbNo = 5dB**  **20220318004352 20220318004436**  **EbNo = 10dB EbNo = 20dB**  **Figure 1.1 Output results of Alamouti 2x2 in command line at different SNR**  **20220318100317**  **Figure1.2 The bit error rate of 2x2Alamouti encoding scheme under different SNR**  **Analysis:**  In order to explore the relationship between SNR and BER of 2x2 Alamouti encoding, we need to modify Teacher Wu's source program to make the original SISO QPSK system into MIMO transmission system of Alamouti encoding scheme. The important contents to be modified are as follows:  **20220318005513**  **The transmitter performs Alamouti encoding**  20220318005550  **The receiver performs Alamouti decoding**  20220318005818  **Create channel responses based on Rayleigh distribution**  By running the program, we can get the above results. The Figure 1.1 correspond to the results received by Alamouti 2x2 MIMO system and the statistics of bit error rate(BER) when the SNR(EbNo) is 0, 5, 10 and 20dB respectively. Through the comparison of these four figures, we can easily see that with the increase of SNR(EbNo), the receiver's recovery of the transmitted text information becomes better and better. At the same time, the bit error rate of received text message decreases with the increase of SNR(EbNo). When the SNR is 20dB, the bit error rate is even reduced to 0. In order to further verify the correctness of our conclusion, we changed the selection range of SNR to -20 to 20dB to draw the image of the relationship between the bit error rate(BER) and SNR of the receiver using Alamouti coding scheme within this SNR range.Results is in the result display above.  From this figure above(Figure 1.2), I can see from this picture that the bit error rate of the receiver is decreasing with the increase of the SNR. When SNR is around 0dB, the slope of bit error rate decline begins to increase sharply and when the bit error rate is less than -5 or greater than 5dB, the bit error rate gradually flattens out. For this phenomenon, I think it can be explained as follows: when SNR is small, the noise and interference in the channel are very large, and the bit error rate of the received information is generally very high. When the SNR of the channel increases to a certain threshold, the bit error rate of the received message begins to decline significantly, and the slope of the decline will increase significantly. As the SNR continues to increase, the quality of the channel is already very good, and the bit error rate stabilizes to a very low level again, which does not change significantly with the increase of SNR.  **Task2：Compare the performance of Alamouti 2x2 and SISO under different SNR conditions**  **Result：**  **20220318131426** 20220318131517  **EbNo = 0dB**  **EbNo = 5dB**  20220318131546 20220318131618  **EbNo = 10dB EbNo = 20dB**  **Figure 2.1 Output results of SISO in command line at different SNR**  20220318100659  **Figure 2.2 Bit error rate of SISO under different SNR**  20220318100737  **Figure 2.3 Bit error rate of Alamouti 2x2 and SISO under different SNR**  **Analysis:**  In this task, we mainly plotted the change of BIT error rate of SISO with the increase of SNR, and compared the transmission performance of SISO. Firstly, let me explain how the picture above was drawn. We run SISO and Alamouti 2x2 programs separately in a loop with different SNRs and store the BER obtained in each loop in a matrix. Later, when the loop is complete, we export the BER matrix to the .mat file and import the .mat file into our drawing program. Finally, according to the imported Alamouti 2x2 and SISO BER .mat files, we can draw the figure above. The drawing code as follows:  20220318103519  **The MATLAB code of Drawing SISO and Alamouti 2X2 image**  After drawing, we began to analyze the performance of the two schemes. Firstly, let's take a look at SISO's performance separately, as shown in Figure 2.1 and Figure 2.2. As can be seen from Figure 2.1 and Figure 2.2, the performance of SISO is similar to the figure of Alamouti performance we analyzed earlier in Figure 1.1 and Figure 1.2. With the increase of SNR, the bit error rate of SISO also decreases, and when SNR is around 0dB, the slope of bit error rate decline begins to increase sharply. When the bit error rate is less than -5 or greater than 5dB, the bit error rate gradually flattens out. These conclusions are similar to Alamouti 2x2, so next I will put the BER of SISO and Alamouti 2x2 as SNR changes into one graph to better compare the performance of the two schemes, as shown in Figure 2.3.  As we can see from Figure 2.3, some subtle differences emerge when we put the two figure (Figure 1.2 and Figure 2.2) together. Firstly, when the SNR is below -3dB, the bit error rate of SISO is higher than that of Alamouti 2x2 at the same SNR. However, when the SNR is higher than -3dB, the situation is reversed and the bit error rate of SISO is lower than that of Alamouti 2x2 at the same SNR. What explains this phenomenon? Through the analysis of relevant theories, I can draw the following conclusions:When the SNR is very small, the noise and interference of the channel is very large. Because Almaouti 2x2 is equivalent to 2x2 MIMO, it takes the diversity gain into account when transmitting data, so the transmission is more reliable than that of SISO, and its bit error rate is also lower than that of SISO at the same SNR. When the SNR is higher, it is important to know that the Almaouti 2x2 takes into account diversity gain to minimize the bit error rate at the receiving end, but it can be equivalent to transmitting two different data at a time. As a result, Almaouti 2x2 will inevitably sacrifice some bit error rate while increasing the transmission rate compared to SISO, which transmits only one data at a time. Therefore, when the SNR is high, the bit error rate of Almaouti 2x2 transmission scheme in the same SNR is higher than that of SISO. | |
| **Experience**  Through this experiment practice, I further deepened the understanding of the relevant knowledge of MIMO that I learned in the wireless communication theory class last semester, and also made me more proficient in the application of MTLAB communication programming system. At the same time of programming, I also deepened my understanding of coding functions such as Alamouti encountered in programming by consulting MATLAB help documents. At the same time, in the Tsak2 part of this experiment, since the SNR interval I set at the beginning was 0~20dB, my simulation results show that the BER of Alamouti coding is higher than that of SISO in this interval, which seems to be inconsistent with the content of Teacher Wu's class. By asking Teacher Wu, I further confirmed my initial assumption of this phenomenon. However, in the writing of the experimental report, I found that I still could not explain this phenomenon well, and always felt that there was something missing. Here I would like to thank Ye Haoteng for timely pointing out my problem. In fact, I should set a wider range of SNR to explain the problem. Therefore, I later set the SNR to -20dB~20dB, and sure enough the problem came out. Alamouti did not have a bit error rate higher than SISO in this SNR range, but had a critical SNR value. Therefore, I was able to basically understand the experimental result through further reference to theoretical knowledge. This was the most important experience I had in this experiment.  通过这次实验的练习，我进一步加深了对上学期无线通信理论课所学的MIMO的相关知识的理解，同时也让我对MTLAB通信编程体系的运用更加熟练。 在进行编程的同时，我也通过查阅MATLAB帮助文档的方式加深了对编程中遇到的诸如Alamouti编码函数的理解。 同时，在完成这次实验的Tsak2部分时，由于一开始我设置的信噪比区间是0~20dB的，我的仿真结果表明在这个区间内Alamouti编码的误码率是高于SISO的，这个结果貌似与吴老师课上讲的内容是不太一致的。通过询问吴老师，进一步证实了我对这个现象的初步设想。然而，在实验报告的撰写中，我发现我还是不能很好地解释这个现象，总感觉还少点什么东西。在这里感谢叶浩腾同学为我及时指出问题，其实我应该设置的信噪比范围更广一些才能更好地说明这个问题。因此，后来我把信噪比设置为-20dB~20dB，结果果然问题就出来了，Alamouti并不是在这个SNR的范围内误码率都是高于SISO的，而是有一个临界的SNR值。因此，通过进一步查阅理论知识，我能够基本理解这个实验结果。这是我在本次实验中最重要的一次经历。 | |
| **Score** | 自评分数：98 |