**Lab 1：16-QAM**

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| **Introduction**  **1.1 Basic principles of 16-QAM modulation and demodulation**  descript  16-QAM (Quadrature Amplitude Modulation) is a commonly used digital signal modulation method, which is a combination of phase modulation and amplitude modulation.  In 16-QAM, each symbol can carry 4-bit binary data, so that more information can be transmitted. The principle of 16-QAM modulation is to divide the digital signals into two separate parts, namely the I and Q signals. These two parts are then modulated into two orthogonal carriers using the relative magnitude of the modulation error to represent the digital data. The resulting signal has four possible phases, thus allowing the transmission of 4-bit binary information at the same time.  descript  In 16-QAM demodulation, the received signal must first be demodulated back to the baseband.  descript  QAM is to load signals on two orthogonal carriers (usually sine and cosine), adjust and stack the two carrier amplitude, and finally get a signal with both phase and amplitude modulated. These two carriers are often referred to as I signal and the other as Q signal, so this modulation mode is also known as IQ modulation.  In digital signal modulation, constellation maps are usually used to represent QAM modulation two-dimensional graphs. Each point on the constellation diagram, indicates a symbol. The components of the point I and Q axes represent amplitude adjustments on orthogonal carriers, respectively. The distance A from this point to the origin is the amplitude after modulation, and the Angle φ is the phase after modulation.  Although higher-order modulation rates are able to provide faster data rates and higher levels of spectral efficiency for radio communication systems, this comes at a cost. Higher-order modulation schemes are much less adaptable to noise and interference.  **1.2 Constellation diagram**  In communication engineering, a constellation diagram is a graph representing a mapping relationship of digital modulation. It can represent the difference between the actual signal and the ideal signal, intuitively judge the noise type in the signal, and find various modulation problems, which is conducive to the optimal design of the communication system.  descript  Conogram, that is, a coordinate, such as the high school unit circle, the abscissa is I, the ordinate is Q, corresponding to the projection to the I axis, called the same phase component, the same projection to the Q axis is called the orthogonal component. Because the signal amplitude varies, it is possible to fall within the unit circle. Specifically, for 64 QAM, there are 64 symbols, equal to 6 powers of 2, so each symbol needs 6 binary ones to represent them. These 64 symbols fall within the unit circle, and vary according to the amplitude and phase. Jump from one point to the other means that phase modulation and amplitude modulation are completed simultaneously  **1.3 Symbol mapping table**  In communication engineering, the symbol mapping table is a key concept, which is an important link in the digital modulation process. In this process, the input stream of bits is mapped to a specific symbol. The symbols represent the amplitude and phase of the carrier at a specific time and frequency.  For example, the modulation methods in LTE include QPSK, 16 QAM, and 64 QAM 1. In these modulation methods, each method has a corresponding symbol mapping table. For 16-QAM, 16 different waveforms can be obtained by QAM modulation, representing 0000,0001... which also means that there are 16 symbols, and one symbol can transfer 4 bit information.  This design allows digital signals to be transmitted at higher rates, while also improving spectral efficiency. However, this design also poses several challenges. For example, higher-order modulation schemes are much less adaptable to noise and interference. Because the carrier bandwidth used to send a symbol is fixed and the transmission time is certain, the higher order means that the difference between the two symbols is smaller. This not only requires high requirements on the devices of both parties, but also has high requirements on the environment  descript  **1.4 Maximum-likelihood estimation algorithm**  descript  Maximum likelihood estimation (Maximum Likelihood Estimation, MLE) is an algorithm for evaluating model parameters given observed data. It belongs to a statistical method used to find the parameters of the correlated probability density function for a sample set.  The basic idea of maximum likelihood estimation is that, using the known sample results, backward the most likely (i. e., the highest probability) parameter values will lead to this result.  descript descript  **1.5 The AWGN theoretical bit error rate**  descript  The AWGN (Additive White Gaussian Noise) channel is an ideal channel model, assuming that the noise in the channel is additive, white, and Gaussian distributed. In this channel, different digital modulation modes have different bit error rates (Bit Error Rate, or BER).  For BPSK (Binary Phase Shift Keying) and QPSK (Quadrature Phase Shift Keying) modulation, the bit error rate can be calculated by the following formula  descript  descript  descript  Where Pe is the bit error rate, Q () is the error function, Eb is the energy per bit, and N0 is the noise power spectral density.  **Lab results & Analysis**：   1. **The modulation/demodulation simulation of 16-QAM**   Firstly, the program block diagram of 16-QAM modulation is shown as follows:    This modulation module is to convert the input bits to the symbols as output. 16-QAM maps 4-bit binary bits into 16 symbols, and the corresponding mapping relationship between the constellation diagram and symbols is shown in the following figure:    Therefore, the first step of the program is to divide the input bit stream into some groups which represent a symbol, and each group contains 4 bits. Then it is weighted according to 8421 code to get the decimal index corresponding to each set of binary bits, and then use the index to get the corresponding symbol in the constellation point and symbol mapping relationship. These indexes are also called as bit words. The sequence of mapping symbols in 16QAM is generated by the following modules:    Next, we normalize the energy of each symbol so that the maximum energy is 1, which is convenient for the later SNR calculation.  Secondly, the program block diagram of 16-QAM demodulation is shown as follows:    The basic idea of the program is to first calculate the distance between the received symbol and the standard 16-QAM symbol, and find the point with the smallest distance, that is, the most likely standard symbol corresponding to the symbol, this process is also called the maximum likelihood receiver. In the program, its implementation is to first subtract the received symbol from the standard symbol generated by the module MT Generate System Parameters VI, find the point with the smallest amplitude after the subtraction, that is, the most likely bit word, and then map the bit word back to the corresponding bit number. The mapping method is to convert the decimal to binary, that is, to take the remainder of the reverse by dividing by two. This will allow us to recover the number of bits received.  The simulation results are shown as follows:    The constellation points after receiving and recovering are as follows, and we observe the effect of receiving and recovering by adjusting different noise powers:        From the figure above, we can see that with the increase of noise power, the effect of receiving and recovering gradually decreases, and the bit error rate gradually increases. Especially when the noise power is close to 0db, it can be found that it is difficult to distinguish different constellation points in the constellation diagram, and there is a large bit error rate at this time. Therefore, reducing the noise power and improving the signal-to-noise ratio (SNR) plays an important role in the normal reception of signals in our communication system.   1. **Bit error rate curve with SNR and anti-noise performance analysis**   In order to better analyze the anti-noise ability of different QAM modes, we can draw the change of bit error rate (BER) of different QAM modes with SNR through program simulation. The basic idea of programming is to package the whole simulation program of modulation and demodulation (as shown as follows) as a subVI: .    We set the terminal of the subVI to two inputs and one output, one of the inputs is modulation type (from BPSK, QPSK, 16QAM and 64QAM), the other input is noise power in db, and the output is Bit error rate (BER).  Then we can use the subVI obtained, write the following program to draw different curves:    The BER corresponding to different modulation modes varies with SNR as follows:    The figure above is the curve drawn when the number of iterations is selected as 1. In order to get a more accurate relationship curve, we can select the number of iterations as 1000 times to improve the accuracy of the data. The results are shown as follows:    It can be seen that the curve with 1000 iterations is more refined and the resulting curve is smoother. Then the analysis of the obtained graph shows that with the increase of SNR, the bit error rate of BPSK and QPSK decreases faster which means that BPSK has stronger anti-noise performance, better than QPSK, and followed by 16-QAM, and finally 64-QAM. This result is in line with theory and expectation, because for BPSK a symbol contains two bits, for QPSK a symbol contains four bits, for 16-QAM a symbol contains 16 bits, for 64-QAM a symbol contains 64 bits, and the more bits a symbol contains, the lower the anti-noise capability it has which is because that the probability of each bit making an error is almost equal, and as long as one bit makes an error, the whole symbol will make an error. Therefore, the more bits a symbol contains, the higher the error probability and the higher the BER.   1. **USRP implementation of 16-QAM modulation system**   The above experiments are based on simulation. Next, we can use USRP to realize the modulation and demodulation of 16-QAM for verficcation. The basic principle and processing diagram are as follows:    It can be seen that the basic principle is similar to the simulation experiment. We need to design the modulation and demodulation module of 16-QAM. The block diagrams are as follows:  The modulation module:    The demodulation module:    The design and simulation process of the block diagram is the same. The basic principle is to divide the input binary bit stream into several groups that each has four bits in the modulation stage, and use the binary to convert into decimal to find the codeword. The codeword is used as an index to find the corresponding symbol in the mapping diagram and output it. In the demodulation stage, the maximum likelihood estimation method is used to obtain the most likely codeword received, and the decimal to binary is used to convert the codeword into the corresponding binary bit and output it.  The running results are shown as follows:  TX: transmitted signal constellation:    TX: transmitted signal eye diagram:    RX: received signal constellation:    From the results figures, we can find that the constellation and eye diagram don’t have huge problem which means that the design process of the TX is correct. In RX, as can be seen from the figures, the overall positions of the symbol constellation points after demodulation in receiver are almost accurate, but there are many noise points around each constellation point, which is due to the influence of the real noise in the environment at the time of usrp realization, but it can be seen that the overall influence is little to some extent, and the signals can still be received relatively accurately. There are a number of parameters that will have a greater impact on the modulation and demodulation effect, the first parameter is the filter parameter, if the pulse shaping filter is selected as a root-raised cosine function, the parameter refers to the filter's roll-off factor, the maximum value of which is 1, the larger the value the better the effect, and if the parameter is set to 0.5, the effect of transmission and reception will be reduced. If the parameter is set to 0.5, both transmission and reception will be degraded, as can be seen in the figure below, if the parameter is set to 0.5, the transmitted constellation will be missing a point.  TX:  descript  RX:  descript  Another parameter is the packet length, which determines how many bits to process, the larger the value, the probability of error will be reduced and the modulation and demodulation will be improved, for example, even if the filter parameter is set to 0.5, and we set the packet length to 6,000, we can solve the problem of missing a constellation point that occurs above. The results of packet length is equal to 6000 are shown as follows:  descript  descript | |
| **Experience**  **Screenshots of the class:**          **Problems we meet:**   1. When we were working on the 16-QAM usrp implementation, we found that the constellation diagram transmitted from the TX side was missing a constellation point, and then we improved the filter parameters and packet length to solve the problem, so it can be seen that these two parameters have a greater impact on the performance of the modulation and demodulation signals, and improving these two parameters will help to improve the performance of the communication, and to prevent the above errors from occurring.   descript   1. When we plotted the BER versus SNR curves for different modulation modes, the first time we plotted the images had large fluctuations and the curves were not smooth enough, then we realized that it was because the number of iterations was low, so we increased the number of iterations to make the curves smoother, reduce the impact of individual singular data on the performance, and reduce the chance.   Number of iterations=1：    Number of iterations=1000：    **Harvested experience:**  We learn and master the modulation and demodulation technology of 2/4/16/64QAM, understand the principle of QAM modulation, adopt two quadrature carrier modulation, and modulate the amplitude and phase at the same time, so that the bit stream in the digital signal, in the form of symbols, is mapped on the constellation diagram. Through the analysis of amplitude and phase, the received signal uses the maximum likelihood estimation algorithm to infer the closest QAM coordinate point of the signal mapping on the constellation diagram, so as to classify the signal as the QAM coordinate point and realize the demodulation of the signa1.  **Contribution**  We two finish the whole labview program together. Zhang Haodong complete procedure design including 16-QAM simulation, usrp realization and performance analysis. The introduction of basic principle in QAM modulation system were completed, and the conception of constellation chart and maximum likelihood estimation algorithm was elaborated by Song Yihang. | |
| **Score** | 98 |