**Project: Application Research on DOA Estimation Based on Software Defined Radio Receiver**

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| **Introduction**  In this project, we built an experimental platform using Kerberos SDR and Raspberry Pi to realize wireless direction finding and radar sensing system. The core of our experimental theory is MUSIC algorithm and ambiguity function. By using MUSIC algorithm, we can measure the angle of arrival between signal source and receiving antenna. By using ambiguity function, we can get doppler frequency deviation of moving object by cross correlation operation. As a lot of work was done in the theoretical analysis of the project in the early stage, we did not encounter too many difficulties in the algorithm design and the presentation of experimental results. However, in the part of building the experimental platform, we spent a lot of time on configuring the driver of Kerberos SDR. Meanwhile, how to design the relative position of antenna array elements and USRP is a problem we should think carefully. With the efforts of all team members, we overcame all these problems and realized the requirements of this project.  **Theoretical analysis**   1. **Introduction of DOA**   Estimation of direction of arrival is an active field in array signal processing. It has wide application value in communication [1-3,7], radar [4-7], detection [8], navigation [9-10] and other fields. There are four commonly used DOA estimation algorithms: Bartley algorithm, capon algorithm, maximum entropy algorithm and MUSIC algorithm. The MUSIC algorithm is used in this project.   1. **MUSIC Algorithm**   MUSIC algorithm is an important foundation of direction finding theory of spatial spectrum estimation. The prerequisite for the MUSIC algorithm is that the number of AOAs cannot be greater than the number of antennas. The specific algorithm principle is as follows:    Suppose there are element antenna array and incident sources. The incident signal can be represented as follows  The received signal inspired by is  and  The expression of overall received signal is as follows.  ***)***  The theoretically received signal autocorrelation matrix can be written as  The autocorrelation matrix of the actual received signal is  The eigenvalue decomposition is performed:  This formula is very similar to the previous one. Then arrange the eigenvalues in the diagonal matrix from large to small, all the values will be roughly divided into two groups. The one with the larger value has remainder and the one with the smaller value. The former represents the group signal received, while the latter is noise. The eigenvectors corresponding to the eigenvalues of noise are taken as the basis to form the noise space . If there is a signal at , then will be a very small value because they are orthogonal.  Define a function  Its peaks are the estimated AoAs.   1. **Doppler sensing**   The proactive sensing is that the BS has to generate the detection signal, and analyze the influence of the measured object on the detection signal to achieve the purpose of perception. So the BS has to both transmit and receive data Signals, which means it is full duplex mode. This mode is difficult to realize. So the other mode, named passive sensing, is chosen in this project.    In following system, the BS send data signal and the passive receiver is to receive the signal from surveillance channel and reference channel. The doppler frequency and velocity of moving object can be obtained by analyzing the signals from two channel.    Through the surveillance channel and reference channel 2 signals are obtained:  and  Define:  Ambiguity Function is used to do the estimation:  is the estimation of , is the estimation of .    : estimated via the phased array of the passive receiver, e.g., MUSIC algorithm  : estimated with and  : estimated with , and ,  : with the direction of car’s velocity and  can be calculated by where is carrier frequency and is the Doppler frequency offset.  **MATLAB Code**   1. **MUSIC Algorithm**     First of all, we need to initialize the parameters of our DOA estimation system.    Second, we need to do following steps respectively:   * Calculate the covariance matrix of the received signals * Do eigenvalue decomposition for * Arrange the eigenvalues of in descending order * Arrange corresponding eigenvectors in corresponding order * Calculate the sum of the eigenvalues * Create cumulative array of eigenvalues     Then, we need to extract the noise subspace, which is orthogonal to the AOAs (Angle of arrivals) matrices subspace:   * Set threshold value close to 1 to delimit the range of noise space * When , the iteration ends. All the eigenvalues between index we find and the last element of are taken as the corresponding eigenvalues of noise subspace.     Finally, calculate each AOAs matrix:  where .  And then define:  its peaks are the estimated DOAs.   1. **Ambiguity Function**   The formula to calculate the ambiguity function is:  And we need to get the estimation of the time delay of the received signal , i.e., , and the estimation of the doppler frequency , i.e., by using:  The first intuition to solve this problem is using two for loops to iterate all the values of and in time domain. But it takes time and has high calculation complexity.  Therefore, we choose to calculate it in frequency domain with multiple FFTs and one IFFT operations. There has already been high performance implementation of FFT and IFFT such as FFTW and OpenBLAS package, thus it is significantly faster to evaluate the ambiguity function in time domain, as the procedures shown below:  Firstly, the frequency domain expression of the two inputs is obtained by using FFT:  For one single delay, the doppler frequency shift is scanned through FFT.  Then use the vector to correlate with each column of the frequency scanning matrix :  The column-by-column correlation scans through all possible delay.  Finally, after rearranging the ambiguity function obtained by the butterfly rule of FFT and IFFT, the positive frequency part is taken by using the fftshift function.  A=ifftshift(ifft(F\_A(theta,f\_d)))  In addition, the Phased Array System Toolbox of MATLAB provides a built-in function ambgfun() to calculate the Ambiguity Function.    After analyzing the code, it is discovered that this toolbox function computes the Ambiguity Function by the frequency domain correlation method.  **Experiment**   1. **Basic experiments**   Then, we will introduce our physical experiment framework. The hardware for our physical experiment platform mainly includes USRP, Kerberos SDR, Raspberry Pi, and PC side. The design framework is shown in the following figure:    The design idea is to control the USRP to transmit the signal, which is received by the Kerberos SDR's antenna array through the wireless channel. Then, the Raspberry Pi reads the signal received by the antennas and converts it to a .csv file. The file is then transferred from the Raspberry Pi to the PC via SSH or VNC protocol transfer. Then, the .csv file is converted into a .mat file on the PC side, and the file is processed by MUSIC algorithm code and DOA and Doppler frequency deviation are calculated, and the result will be shown in the form of radiation map, motion map, bar graph, etc.  The field scene of this experiment is built as follows:    Part 1 is USRP, part 2 are the four antennas, part3 is the Kerberos SDR, part 4 is the Raspberry Pi.  Before we start the experiment, we need to configure the Kerberos SDR driver on the Raspberry Pi, when the result of the following figure appears, it means the driver configuration is successful.    In this test scenario, we obtained the following experimental results, where the Raspberry Pi captures the signals emitted by the USRP and generates waveforms corresponding to the four antennas.  图表  描述已自动生成  Then, we also added baffles in the path for reflecting signals and designed two optimization experiments as shown in the following figure:  人们在房间里  中度可信度描述已自动生成  Optimization experiment 1  图片包含 人, 女人, 室内, 桌子  描述已自动生成  Optimization experiment 2   1. **Extended Experiment**   In addition, we also did the extended experiment - Doppler radar perception experiment. The specific experimental build diagram is shown below:    The top right corner of the figure shows the antenna array element, and the three antennas on the left are surveillance channel antennas, the antenna on the right is reference channel antenna. USRP at the bottom of the figure for transmitting signals. We designed the experimenter to walk towards the surveillance channel antenna.  **Results & Analysis**   1. **Pre-recorded data recovery**   To verify the validation of our implementation of MUSIC algorithm, we first use the pre-recorded data provided by Prof. Wang in lecture to carry out the pre-recorded data recovery experiment.  The data is received from the base station which faces Runyang Gymnasium and is received by using four antennas with sample rate 25MHz, and center frequency 2.12GHz.      The estimated DOAs are shown as below:    From the figure shown above, we can find that there are three DOAs of the received signals.  And by using the satellite map to verify our result, we can find that there are one line-of-sight and two other paths (two main scatterers) for signal to transmit, and the DOAs for them are approximately -70°, -4°, and 23.5°, respectively.    Then, we try to use the Backward spatial smoothing (BSS) MUSIC algorithm to recover the pre-recorded data, which can get better resolution of multiple coherent signals. The corresponding MATLAB code is shown as below:    The estimated DOAs by using BSS MUSIC algorithm are shown as below:    From the figure shown above, we can find that the recovery result gets the better performance than before, which also means our received signals are coherent signals.   1. **Data processing**   First, use the Raspberry Pi to capture the antenna received signals transmitted by the USRP.  Then, save the data to the .csv file.    Second, use VNC to transfer the experimental data to the PC.      Third, merge the received .csv data.    Fourth, turn .csv data to .mat data in MATLAB.        Finally, load the .mat data in MATLAB and then we can analyze the data further.     1. **MATLAB simulation results - Original music algorithm**   As we have mentioned in Part 2, we have already designed the music algorithm in the MATLAB. So before we start our real experiment, we do the MATLAB simulation. We create the signal in the program and then use the algorithm to analysis.  We first process six coherent signals and six incoherent signals in the original ordinary music algorithm, and the results are shown in the figure below.    Incoherent signals    Coherent signals  We can see that the processing of incoherent signals in the original music algorithm is very good, but if our input signal is a coherent signal, it cannot be decomposed well, and the result is very chaotic. So we upgraded the algorithm to a certain extent, and we changed it to a forward (backward) space smoothing algorithm, and the result is shown in the figure below.    Forward spatial    Backward spatial  It can be seen that when the six incident signals are consistent and coherent, the MUSIC algorithm based on backward space smoothing can better estimate their DOA and have higher estimation accuracy.   1. **DOA Estimation**   In our first experiment, we laid out our equipment as shown in the figure below and made sure that the USRP and the receiving antenna array were almost aligned.  人们在房间里  中度可信度描述已自动生成  According to the theory of the MUSIC algorithm, we can estimate that the angle of arrival of DOA under ideal conditions is about 0 degrees. The experimental results are as follows (to make the results more accurate, we filter out angles greater or less than -90 degrees):  W_F){4}EVQ@ZI`P6`RDJ`RMpassiveFB_0  When we analyze the results obtained in the graph above, we can see that our DOA estimate is chaotic, and it produces peaks at multiple angles, producing 5 peaks in our experiment. We don't know why this happens, so we analyze and collect related data. After our discussion, we found that the main reason for the data error is because the signal transmitted by the USRP is oriented in all directions, and if we do not add a bezel around it, the device will receive the signal in all directions.  Then we added reflective surfaces on both sides to block part of the scattered signal. The experimental scene is shown in the figure below(The block is approximately 30 degree with the USRP):  图片包含 人, 女人, 室内, 桌子  描述已自动生成  Then we get the following result:  ]GI%GQ1V6)R4LFVOK04XNYN  Looking at the DOA estimation results of the experiment after this improvement, we can find that the number of peaks detected is less than the first experiment, this time only 4 peaks are detected, and there is a strong peak near plus or minus 30 degrees, which shows that we can reflect the angle 30 degrees within a certain range and be received by the receiver at the same time. In addition, the range of peak angles we detected this time is also larger than in the first experiment, because our baffle acts as a reflection and blocking signal, which will increase the signal strength reaching the receiver.  Since our experimental scene is in the laboratory, there are not only a lot of equipment in the laboratory, but also a lot of students back and forth, which will affect the transmission and reception of our signals. We tried many different solutions, but none of them picked up the signal well. So we chose to find a set of data from the Internet to recover, and we can get the following results.    This result is perfect and verifies the rationality and correctness of our code.   1. **Doppler frequency bias**   After our reproduction of the literature and the discussion of the research, we searched for relevant materials and thought about what else we could do with the device for other relevant positioning and signal analysis. Finally, we chose an analysis of the Doppler shift.  For the Doppler bias test, two channels are required, one for reference and one for monitoring. However, we cannot specify which of the receiving antennas is responsible for receiving the reference signal of the USRP and which is responsible for receiving the monitoring signal reflected by the human body. So we had to physically separate them, so we designed the following experimental environment.    Then we had a group member walk back and forth between the two to create a Doppler shift. The result is as following:    According to the picture results, we can clearly see that the Doppler frequency shift has occurred, but because of the simplicity of our scene, the results cannot be reproduced well, and there is a certain gap with the theoretical value.  **Conclusions**  In this project, we have mainly completed the following two parts of the project research, the first part is our three basic tasks: Understand DOA algorithms and hardware capabilities, Simulation implementation of the music algorithm and Use SDR to receive measurement position information. Then are our two exploration tasks: Pre-recorded data recovery and analysis and Exploration of the Doppler shift.  Through this project, we learned DOA angle estimation and music algorithm very well, and we also tested it through our own building entities. We learned a lot in the process, and the specific problems we encountered will be explained in detail in the experience section. | |
| **Experience**   1. Because the core of this experiment is our hardware experiment, we hardly encountered problems in the code editing part, but encountered a lot of problems in the physical test, here we will select some experience for analysis. 2. The first problem we encountered was installing the corresponding package on the Raspberry Pi, we first looked for the SDR package that needed to be installed. At first, we chose the wrong mirror site, the download speed was particularly slow, and during the download process, due to our Raspberry Pi version conflicts and other problems for a long time, finally we chose to change the network while uninstalling the initial version and installing the latest package to deal with the problem. And we also need to understand the hardware specifications first. Each device has different requirements. For example, the maximum frequency of the signal that Kerberos SDR can receive is only 1.75GHz. The center frequency we set at the beginning is higher than this value, so the signal cannot be received. 3. Then, when we testing the connections of the antennas, we just tested one antenna at the first time, and there is an error which took us a lot of time to debug. However, when testing all four antennas together, we found that when we started testing the third antenna, the connection was aborted. Therefore, we finally found the problem for that is the power supply of SDR is insufficient so that we cannot drive all four antennas simultaneously. So we add additional power cord to power supply. 4. Additionally, in our future physical experiments, we will need to check the reference manual first, and then test each device. In the course of our experiment, after the system was completely built, we found that there were problems in each part, which caused us to spend a lot of time debugging and wasting a lot of time. If we detect in advance, we can save a lot of time and effort. 5. Finally, when using MUSIC algorithm to estimate DOA, it should be noticed that the number of receiving antennas must be more than the number of received signals. So we can conclude that MUSIC algorithm cannot be used in situations where there are large number of received signals (large number of scatters). 6. In all, this is the first time that we have completely used physical objects to build communication scenarios, and we have mostly done code simulations in previous learning. The gap between simulation and physical objects is still very large, and we should cherish the opportunity of such physical experiments and learn more experience from them. Finally, thank you Mr. Wu Guang, we have gained a lot in this course.   **Basic task**   * Understand DOA algorithms and hardware capabilities * Simulation implementation of the music algorithm * Use SDR to receive measurement position information   **Exploration**   * Pre-recorded data recovery and analysis * Exploration of the Doppler shift | |
| **Score** | 100 |