

Research and Design of AIS Reception Signal Processing System Based on GNU Radio

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Abstract—The Automatic Identification System (AIS), as a standard communication and navigation device for ships, plays a significant role in ensuring the safety and efficiency of maritime traffic. The accuracy of the AIS receiver's signal processing directly affects the bit error rate (BER) and packet error rate (PER) of the AIS system, drawing considerable attention to AIS signal reception and processing technologies. Current research on AIS reception signals mainly focuses on custom implementations using hardware platforms like FPGAs; however, the high cost of hardware implementation has become a limiting factor in the development of AIS signal processing technologies. Therefore, this paper designs an AIS reception signal processing system based on GNU Radio, developing demodulation algorithm and NRZI decoding modules, and testing them with typical demodulation algorithms. Experimental results demonstrate the feasibility and effectiveness of the designed reception signal processing system.

Keywords— AIS reception signal processing, demodulation algorithm module, NRZI decoding module, GNU Radio, software-defined radio (SDR)

I. INTRODUCTION

With the growing number of ships, increasing cargo volumes, and the continuous development of the maritime industry, congested sea traffic and insufficiently advanced traffic management systems have led to numerous maritime accidents. These incidents pose severe risks to the lives of crew members and passengers, while also causing environmental pollution. Thus, efficiently managing maritime traffic has become a widely recognized and urgent issue that needs addressing [1-3]. In 1992, the International Maritime Organization (IMO) and other organizations introduced the AIS system [4], which has greatly improved the efficiency of real-time information exchange between ships and between ships and ports, effectively reducing maritime traffic accidents. Many manufacturers worldwide have developed AIS equipment, including prominent companies like the UK's SRT, Japan's Furuno [5], Norway's Navico [6], and South Korea's Samyung.

The accuracy of AIS receivers in processing received signals directly impacts the BER and PER of AIS systems. A well-designed signal processing scheme can enhance the robustness and anti-interference capabilities of AIS systems.

Currently, a group of scholars is focusing on theoretical research, dedicating themselves to studying various demodulation methods to improve the accuracy of signal processing [7-9]. However, whether these methods can be effectively applied in AIS systems still requires practical validation. Therefore, many signal processing solutions have been proposed, most of which are implemented using hardware platforms. For instance, a space-based AIS modem has been designed on a Virtex5-xc5vlx110t FPGA [10], and a new AIS satellite receiver has been developed using Fast Independent Component Analysis (FastICA) for blind source separation to resolve overlapping signals received by satellites, also implemented on a Virtex5-xc5vlx110t FPGA [11]. Another study proposed a method for implementing AIS transmission and reception functions on a development board [12]. Meanwhile, a compact, energy-efficient, reconfigurable, real-time onboard AIS receiver based on radiation-tolerant (RT) FPGAs has been introduced [13]. However, these hardware implementations are complex, costly, and have become a limiting factor for AIS signal processing technology development.

To address these challenges, this study proposes an AIS reception signal processing system based on GNU Radio, developing NRZI decoding and demodulation modules to implement hardware functions through software, significantly reducing development costs. Furthermore, AIS signal encoding and modulation modules were designed using MATLAB software to simulate transmission signals, which were then transmitted through a Universal Software Radio Peripheral (USRP) to the designed AIS reception signal processing system. Finally, a typical demodulation algorithm was selected to test the designed AIS reception signal processing system. Experimental results prove the feasibility and effectiveness of the system, providing robust technical support for testing and evaluating AIS signal demodulation algorithm performance.

The remainder of the paper is organized as follows. In Section II, the designed AIS reception signal processing system is described in detail. Besides, the transmission and reception process of AIS signals is simulated, focusing on the working process of the designed AIS receiving signal processing system, including downconversion, time

synchronization, and demodulation in Section III. Finally, conclusions are drawn in Section IV.

II. DESIGN OF AIS RECEPTION SIGNAL PROCESSING SYSTEM

A. Overall architecture

The AIS reception signal processing system considered in this paper is shown in Fig.1. The architecture is composed of GNU Radio, USRP, MATLAB, and Receiving Signal Processing Module (RSPM). The workflow of the AIS reception signal processing system is as follows: MATLAB generates the AIS transmission signal, which is then encoded and modulated before being transmitted to the USRP. The USRP processes the baseband signal through mixing, ADC, and downconversion, and transmits it to GNU Radio via an interface. GNU Radio decodes and demodulates the received signal using RSPM to obtain the original transmission signal, achieving the reception of the AIS signal.

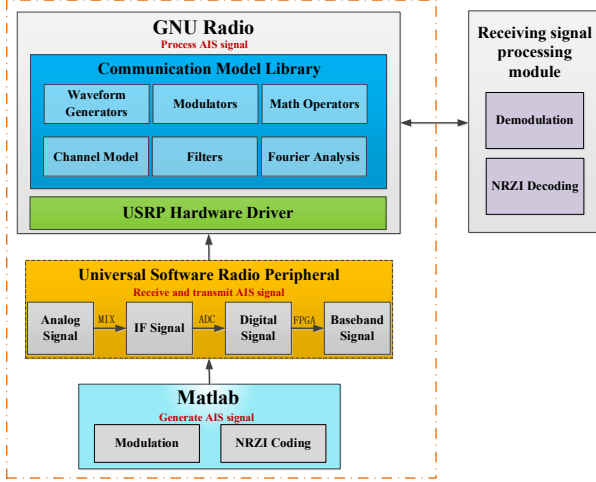


Figure 1. Architecture of AIS reception signal processing system

a. AIS Signal: AIS signals use Self-Organizing Time Division Multiple Access (SOTDMA) technology, dividing each minute into 2250 time slots numbered from 0 to 2249. Each slot lasts 26.67 ms and can transmit a 256-bit signal, with a data length of 168 bits. An AIS message frame consists of an 8-bit preamble, a 24-bit training sequence, an 8-bit start flag, 168 bits of data, a 16-bit frame check sequence (FCS), an 8-bit end flag, and a 24-bit buffer.



Figure 2. Frame structure of AIS signal

b. GNU Radio: GNU Radio is an open-source software with powerful signal processing capabilities. It includes a rich set of library functions and supports RF interfaces, such as the Universal Software Radio Peripheral (USRP). By combining GNU Radio with USRP, signal transmission and reception can be conducted through software-defined radio (SDR), forming a complete communication system that integrates both hardware and software.

c. AIS Signal Encoding Module: The 256-bit AIS data undergoes Non-Return-to-Zero Inverted (NRZI) encoding before modulation. The NRZI encoding rule is as follows: if the current signal is the same as the previous cycle's signal, the encoded signal is "1," indicating that the level remains unchanged. Conversely, if the current signal differs from the previous cycle's signal, the encoded signal is "-1," indicating a level transition.

d. AIS Signal Modulation Module: This module uses quadrature modulation. The signal first undergoes upsampling (with the upsampling factor determined by specific requirements) and then passes through a Gaussian filter to smooth the upsampled signal. Afterward, the signal is integrated and then processed through cosine and sine functions to form in-phase and quadrature components, respectively. Finally, these components are mixed with the carrier to produce a Gaussian Minimum Shift Keying (GMSK) modulated signal.

e. AIS Signal Decoding Module: To decode NRZI-encoded signals, first, the level state of the input signal is read. When a level change occurs (from high to low or low to high), a bit value of 1 is recorded; if there is no change in the signal level, a bit value of 0 is recorded.

f. AIS Signal Demodulation Module: A non-coherent 1-bit differential phase demodulation method is employed, which calculates the phase difference between consecutive symbols. This phase difference is used to recover the transmitted bit values, where each phase change represents only one bit of information.

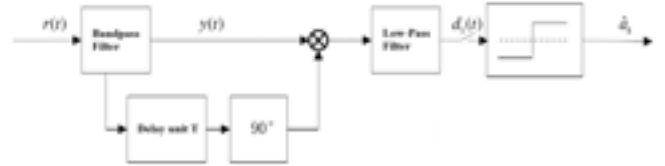


Figure 3. 1-bit differential demodulation algorithm flow

B. AIS Signal Transmission Generation Module

Due to the high cost of AIS signal generators and the focus of this paper on the AIS signal reception and processing phase, this study uses MATLAB software to simulate the transmitted signals. The precise simulation of AIS signals is achieved through NRZI encoding of the baseband signal and GMSK modulation. The specific implementation steps are as follows:

- Generation: First, generate a binary random sequence and perform NRZI encoding on the generated sequence. This involves applying a logical XOR operation between the current signal and the previous period's signal. If they are the same, the encoded signal is 1, and

the level remains unchanged; if they are different, the encoded signal is -1, and the level toggles.

- **Upsampling:** Upsample the encoded sequence. Set the upsampling factor to 20. Given the AIS symbol rate of 9600 baud, the sampling rate will be 192kHz.
- **Filtering:** Pass the upsampled signal through a Gaussian low-pass filter. Set the bandwidth of the Gaussian filter based on the AIS signal's BT product of 0.4. Perform phase integration on the output, and then apply quadrature modulation to shape the baseband signal.
- **GMSK Modulation:** Multiply the in-phase (I) component by the carrier $\cos(\omega_c t)$ and the quadrature (Q) component by the carrier $\sin(\omega_c t)$. Subtracting these components gives the real part of the modulated signal. The imaginary part can be obtained similarly, combining both to produce the complex GMSK signal.

Using a 40-symbol example, we can visualize the original AIS signal in Fig.4 and the final GMSK-modulated signal in Fig.8. The horizontal axis in Figures 4 to 8 represents time, and the vertical axis represents the amplitude of the AIS symbol.

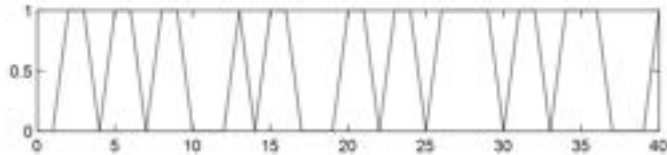


Figure 4. Original AIS symbol

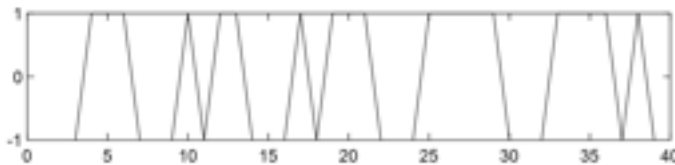


Figure 5. Encoded AIS symbol

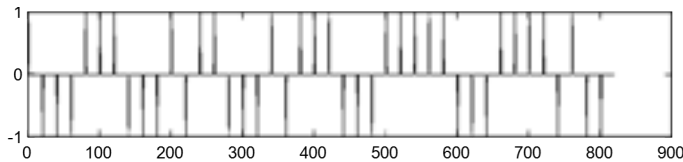


Figure 6. Upsampled AIS symbol

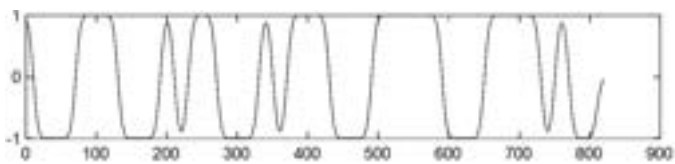
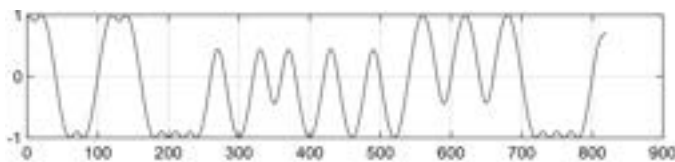
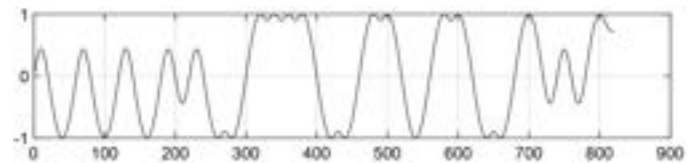


Figure 7. AIS symbol after Gaussian filtering



(a) The baseband I-channel signal of AIS symbol



(b) The baseband Q-channel signal of AIS symbol

Figure 8. The baseband signal of AIS symbol

C. AIS Signal Reception Module

According to system requirements, it is necessary to independently develop the demodulation algorithm module and the NRZI decoding module, while other functions can be directly called from the GNU Radio software platform. Using the gr_modtool, first create a new project, then navigate to the directory and name the module. After that, select the port type, modify the header files, and adjust the C++ files to complete the custom module development. The specific development process is shown in Fig.9.

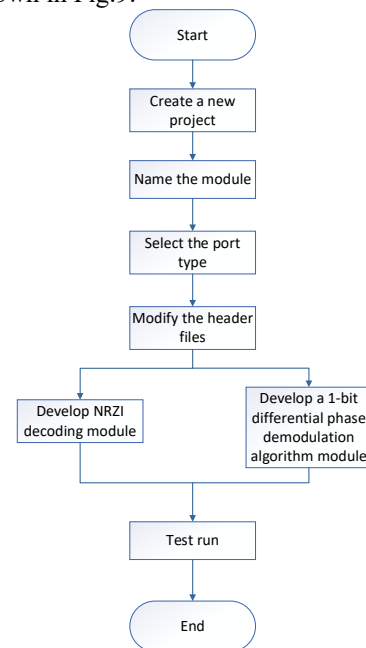


Figure 9. The specific development process

For the NRZI decoding module, the core code for functionality implementation is shown in Fig.10. Each output item $out[i]$ depends on the state of the current input item $in[i]$ and the previous input item $in[i-1]$. By using the XOR operation, the changes in the signal can be determined, and then through negation and the AND operation, the corresponding decoded result is ultimately output. After completing the coding, running GNU Radio, refreshing the module call area, and searching, it can be found that the module has been successfully loaded. A flowgraph can be created to verify the module, as shown in Fig.11. Running the flowgraph and observing the time-domain waveform, where the red signal represents the signal to be decoded and the blue signal represents the decoded signal, shows that the module successfully performs NRZI decoding, as illustrated in Fig.12.

```

if (d_coding == DIFF_NRZI) {
    for (int i = 0; i < noutput_items; i++) {
        out[i] = ~(in[i] ^ in[i - 1]) & 1;
    }
}

```

Figure 10. The core code of NRZI decoding

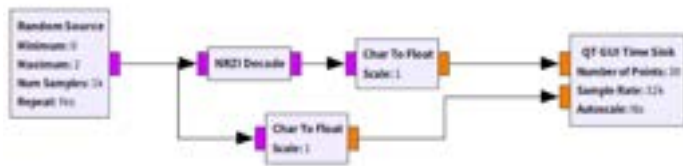


Figure 11. NRZI decoding module test flow chart

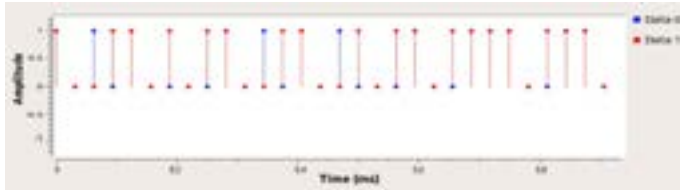


Figure 12. Time domain diagram of NRZI decoding

For the decoding algorithm module, this paper has chosen the classic 1-bit differential phase demodulation algorithm as the system testing algorithm. The core code for the functionality implementation is shown in Fig.13, which performs the conjugate multiplication of the current symbol with the previous symbol.

```

for (int i = 0; i < noutput_items; i++) {
    out[i] = in[i] * conj(in[i - 1]);
}

```

Figure 13. Core code of 1-bit differential phase demodulation module

III. EXPERIMENTS AND RESULTS

This experiment is based on the AIS signal reception processing system, where MATLAB generates the AIS transmission signal, which is sent to GNU Radio via USRP. GNU Radio uses RSPM to decode and demodulate the received signal to obtain the original transmission signal, achieving the reception of AIS signals. This experiment focuses on the reception processing part of the AIS signals, including digital downconversion, time synchronization, differential demodulation, and frame synchronization.

A. Experimental Scene Setup

First, connect the Ethernet cable and check the IP address, subnet mask, and gateway information of the signal generator. Using the Instrument Control Toolbox in Matlab, establish a connection between the computer and the Agilent signal generator via the wired network interface. Then, upload the modulation signal to the signal generator and connect it to the Deepwave hardware platform, using the USRP Source module for reception. Finally, GNU Radio, driven by USRP, receives the transmitted signal and completes the signal processing. This experiment uses version 3.7 of GNU Radio.

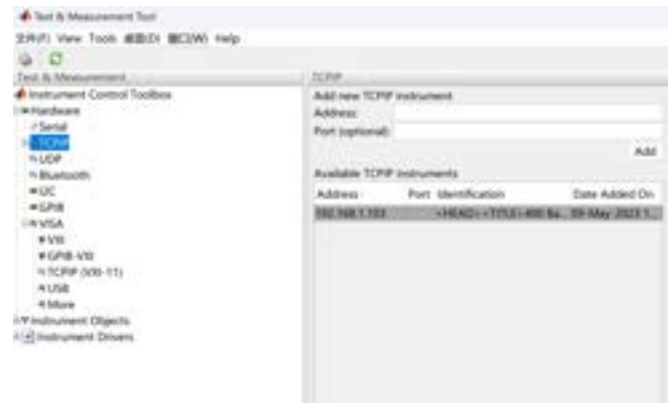


Figure 14. Matlab Instrument Control Toolbox Interface

B. Digital Downconversion

Digital downconversion is the process of shifting the intermediate frequency (IF) signal to baseband. The input signal is mixed with a local oscillator (LO) signal, followed by a low-pass filter. The signal after digital downconversion of the input signal is shown in Fig.15, where the signal-to-noise ratio (SNR) is 15 dB.

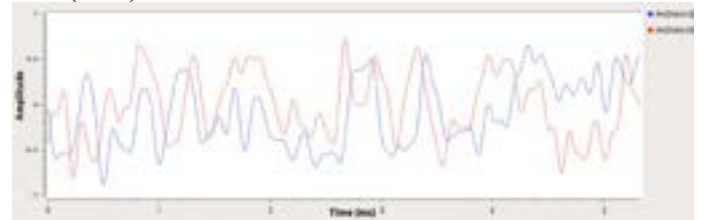


Figure 15. Demodulated baseband signal (SNR=15dB)

C. Timing Synchronization

For timing synchronization of the downconverted signal, the Symbol Sync module provided by GNU Radio can be used, which contains several timing synchronization algorithms. The parameter settings for this module are shown in Fig.16, where samples per symbol is set to 20, loop bandwidth is 0.045, and maximum deviation is 1.5. Fig.17 shows the signal after timing synchronization.

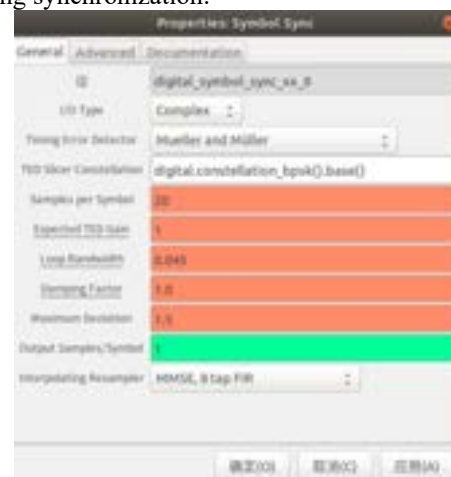


Figure 16. Parameter settings for timed synchronization module

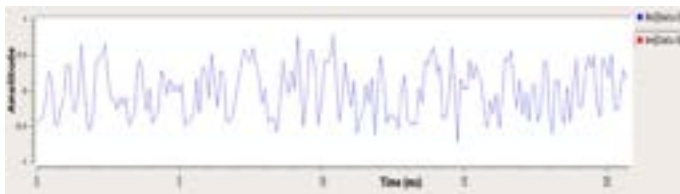


Figure 17. The timing-synchronized signal

D. Differential Demodulation and Frame Synchronization

The signal after timing synchronization is passed through 1-bit differential phase demodulation to obtain the undecided signal, as shown in Fig.18. Based on the 1-bit differential decision rule, if the signal is greater than 0, it is decided as 1, and if it is less than 0, it is decided as 0. The decided demodulated signal is shown in Fig.19.

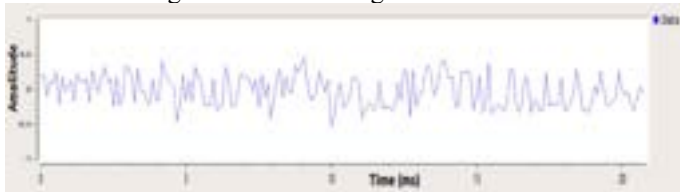


Figure 18. 1-bit differential demodulated signal



Figure 19. Symbol after 1-bit differential demodulation decision

Due to the requirement of the 1-bit differential algorithm for AIS signals, after demodulation, NRZI decoding is performed, followed by frame synchronization of the decoded symbols. Frame synchronization is achieved using the Correlate Access Code module in GNU Radio, which can recognize a specified sequence. The start sequence for the AIS signal is "01111110". The parameter settings for the module are shown in Fig.20. Fig.21 demonstrates the successful identification of the frame header of the signal.

After finding the frame header, the signal is compared with the original binary sequence to calculate the bit error rate (BER). Fig.22 shows the waveform of the signal demodulated using 1-bit differential phase modulation, compared with the original signal. It is evident that, except for a few symbols with errors, most of the symbols were demodulated correctly. Finally, the Error Rate module in GNU Radio is used to calculate the signal's BER. At a signal-to-noise ratio (SNR) of 15 dB, the bit error rate for the 1-bit differential demodulation is found to be 0.0173.

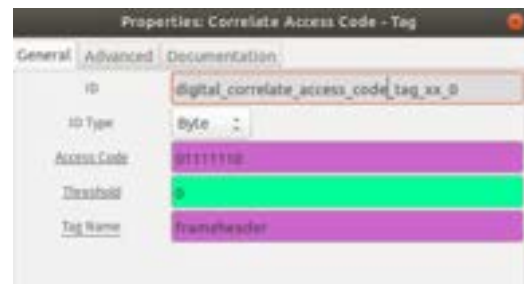


Figure 20. Frame synchronization module parameters

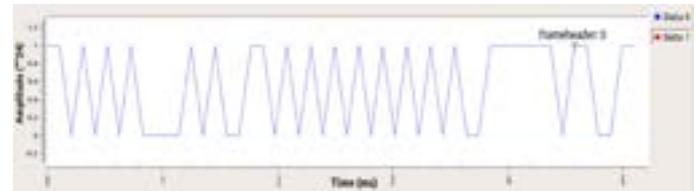


Figure 21. The frame header of the signal



Figure 22. Comparison between demodulated signal and original signal

IV. CONCLUSIONS

To address the high hardware implementation cost of AIS signal reception research, this paper designs an AIS signal processing system based on GNU Radio. It develops demodulation algorithm modules and NRZI decoding modules, using software to implement hardware functionality, significantly reducing development costs. At the same time, typical demodulation algorithms were used for testing, demonstrating the operability and effectiveness of the designed AIS signal processing system. This provides strong technical support for the performance testing and evaluation of AIS signal demodulation algorithms.

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REFERENCES

- [1] F. Maggio, T. Rossi, E. Cianca, M. Ruggieri. Digital beamforming techniques applied to satellite-based AIS receiver[J]. IEEE Aerospace and Electronic Systems Magazine, 2014, Vol.29(6): 4-12.
- [2] A. Bodenmüller, Bayesian Target Identification and Classification: Application of AIS, GMTI and BFT in Command and Control Systems(Conference Paper)[J]. Communications in Computer and Information Science, 2019, Vol.1074: 135-150.
- [3] I. Berbić, V. Stupalo, N. Kavran, M. Bukljaš, Overview of machine learning methods in maritime traffic monitoring based on Automatic Identification System[J]. Transportation Research Procedia, 2023, Vol.73: 220-226.

- [4] Organization I M. Guidelines for The Installation of A Shipborne Automatic Identification System (AIS)[J]. <http://www.imo.org/OurWork/Safety/Navigation/Documents/227.pdf>, 2003.
- [5] H. Yuichi, Introduction of Autonomous Navigation Technology Development Department, Furuno Electric CO., LTD.[J]. NAVIGATION, 2023, Vol.223: 33-37.
- [6] Navico Launches C-Map Embark, the Latest in Nautical Navigation Technology.[J].ThomasNet News,2018,: 44.
- [7] Z. Yi, Y. Liu, W. Wang and X. Zheng, "AIS Signal Demodulation Algorithm Based on Joint One and Two Bit Differential Viterbi," 2023 3rd International Conference on Electronic Information Engineering and Computer Communication (EIECC), Wuhan, China, 2023, pp. 699-703.
- [8] An Improved AIS Incoherent Demodulation Algorithm Based on 2-bit Decision Feedback. [J]. Telecommunication Engineering, 2024, Vol.64(9): 1494-1501.
- [9] Tang, R.;Zhao, Y.;Wu, H..Automatic Identification System Signal Detection Algorithm Based on Improved Feedback Decision(Article)[J]. Shanghai Jiaotong Daxue Xuebao/Journal of Shanghai Jiaotong University,2019,Vol.53(5): 610-615.
- [10] M. A. Adarsh, K. Adithya and A. Nimbal, FPGA Implementation of Space-Based AIS, 2018 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, India, 2018, pp. 1-5.
- [11] A. Krishna, A. Nimbal, A. A. Makam, V. R. Sambasiva, Implementation of fast independent component analysis on field - programmable gate array for resolving the slot collision issue in the space - based automatic identification system[J]. International Journal of Satellite Communications and Networking,2020,Vol.38(6): 480-498.
- [12] J. A. Lorenzo and G. P. Mappatao, Implementation of the Basic Transmit and Receive Functions of Automatic Identification Systems for Marine Vessels, 2023 International Conference on Advanced Technologies for Communications (ATC), Da Nang, Vietnam, 2023, pp. 456-461.
- [13] G. Sahay, S. Naskar, H. K. Reddy N and V. D, A Novel Architecture and Design of FPGA based Space-borne AIS Receiver, 2021 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT), Bangalore, India, 2021, pp. 1-6.



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