

Design and Implementation of a Software-Defined Radio AIS Transceiver using GNU Radio

Abdou-Halique A. A. Bouari, Luciano B. C. Silva, Walter A. dos Santos, Marcos V. T. Heckler

Abstract—This paper presents initial implementations and experimental validations of an Automatic Identification System transceiver based on Software-Defined Radio and GNU Radio Companion. The proposed platform enables the generation, transmission, reception, and decoding of AIS message type 1 in a controlled laboratory environment using two NI 2901 SDR devices and RF coaxial cable. The implemented system includes AIS frame generation, GMSK modulation and demodulation, NRZI processing, CRC verification, and AIVDM message reconstruction. Experimental results demonstrated the successful recovery of navigation parameters such as MMSI, position, speed, and course. The developed platform provides a framework for AIS experimentation, protocol analysis, and SDR-based maritime communication research.

Keywords—AIS, SDR, GNU Radio Companion, GMSK, Maritime Communications

I. INTRODUCTION

The Automatic Identification System (AIS) plays a critical role in navigation safety and traffic monitoring. According to the International Telecommunication Union (ITU) [1], AIS is a self-organised maritime communication system that automatically broadcasts a vessel's dynamic, static, and safety-related information. AIS supports several operational modes, including autonomous, assigned, and polled transmissions.

In this context, the BiomeSat satellite mission [2], under development at the National Institute for Space Research (INPE), prospects an AIS receiver as one of its payloads on board. In order to develop the Electrical Ground Support Equipment (EGSE) for testing this equipment, an AIS transmitter and a receiver were developed using the GNU Radio Companion (GRC) software framework. This approach enables controlled transmission, reception, and analysis of AIS signals under laboratory conditions, allowing for flexible experimentation with different system configurations.

This type of implementation has become increasingly viable due to the widespread adoption of Software-Defined Radios (SDRs), which have emerged as essential tools in modern telecommunications systems because of their flexibility, reconfigurability, and cost-effectiveness. By implementing radio functionalities in software rather than dedicated hardware, SDR platforms enable rapid prototyping, experimentation, and adaptation to different communication standards. As a result, SDRs are widely employed in instrumentation, signal analysis,

measurement systems, and the development of communication prototypes [3], [4].

Several AIS systems have been proposed and analysed in the literature, many of which rely on SDR platforms and software-based implementations using frameworks such as GRC or LabVIEW. In [5], an AIS transmitter implemented using SDR is presented. The system operates as a position reporter using a GPS module. The performance of this transmitter is validated using an SDR-based AIS receiver presented in [6].

The authors of [7] propose an AIS receiver based on GRC using an RTL-SDR device. The developed flowchart first detects the AIS package, then extracts the delimiter flags, and, subsequently, obtains the binary representation of the AIS message. The data bits are grouped into blocks of six, and each block is converted into a 6-bit American Standard Code for Information Interchange (ASCII) symbol representing the American Standard Code for Information Interchange (NMEA) AIS message.

In [8], a low-cost AIS transmitter based on SDR is presented. The developed system uses an ADALM-PLUTO device together with a NEO-7M GNSS module to transmit AIS information in a Time Division Multiple Access (TDMA) configuration. The resulting system is validated using an RTL-SDR dongle for signal reception and, additionally, through measurements performed with an oscilloscope. The experiments evaluate transmission power, transmission timing, and channel switching.

Although several SDR-based implementations of the AIS have been reported, dedicated experimental platforms remain essential for validating Satellite-based AIS (S-AIS) payloads in controlled testing environments. Moreover, many existing AIS SDR implementations rely on legacy GRC architectures and deprecated processing blocks, which severely limits their compatibility with recent GNU Radio releases and modern Universal Software Radio Peripheral (USRP) platforms running updated USRP Hardware Driver (UHD) frameworks. Consequently, updating these implementations is crucial to ensure experimental validation, reproducibility, and the advancement of future AIS research.

Based on the previously discussed references and AIS implementations, this work extends prior SDR-based AIS developments by implementing and experimentally validating the complete AIS transmission and reception processing chain, including the generation of valid NMEA AIS-VHF Data-link Payload Message (AIVDM) messages. As an initial implementation, the proposed system enables the generation, transmission, reception, and analysis of AIS signals in a controlled laboratory environment, providing a flexible and

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reproducible framework for experimentation, validation, and future AIS-related research.

The remainder of this paper is organised as follows. Section II presents an overview of the AIS system, including its communication channels, operating frequencies, and protocol structure. Section III describes the implementation of the AIS transmitter and receiver using GRC and SDR hardware. Section IV presents the experimental setup and the obtained validation results. Finally, section V concludes the paper and discusses future work.

II. AIS OVERVIEW

AIS is a maritime communication system designed to improve navigation safety and maritime traffic monitoring through the automatic exchange of information between vessels, coastal stations, and satellite-based receivers using VHF radio channels [1]. The system continuously broadcasts dynamic, static, and voyage-related information, including vessel identity, geographical position, speed over ground, course over ground, and navigational status, thereby enhancing situational awareness and collision avoidance capabilities. AIS communications rely on TDMA-based channel access schemes, mainly Self-Organising TDMA (SOTDMA) and Carrier-Sense TDMA (CSTDMA), which enable multiple users to efficiently share the same communication channels through synchronised time-slot transmissions while reducing transmission collisions. Depending on the equipment type and operational configuration, AIS can operate in autonomous, assigned, or polled transmission modes.

A. Channels and Frequencies

AIS transmissions operate in the VHF maritime mobile band using two primary international channels: AIS 1 at 161.975 MHz (Channel 87B) and AIS 2 at 162.025 MHz (Channel 88B). Both channels employ Gaussian Minimum Shift Keying (GMSK) modulation with a bandwidth of 25 kHz and a data rate of 9.6 kbps. In standard operation, AIS stations alternate transmissions between these channels to reduce congestion and improve communication reliability. Additional channels, at 156.775 MHz namely (Channel 75) and 156.825 MHz (Channel 76), are reserved for Message Type 27, which is dedicated to long-range AIS applications.

B. AIS Message Structure

AIS messages are transmitted in structured frames composed of synchronisation sequences, payload data, and error detection fields. As illustrated in Fig. 1, each frame contains a preamble, a start flag, the encoded AIS payload, and a Cyclic Redundancy Check (CRC) field used for transmission error detection. The payload includes navigation and vessel-related information such as maritime mobile service identity (MMSI), position, speed, course, and navigation status.

For interoperability with maritime communication systems, AIS frames are commonly represented using the NMEA AIVDM sentence format. As shown in Fig. 2, an AIVDM sentence contains the sentence identifier, AIS channel information, encoded payload, and checksum field. The AIS payload is represented using a 6-bit ASCII encoding prior to transmission.

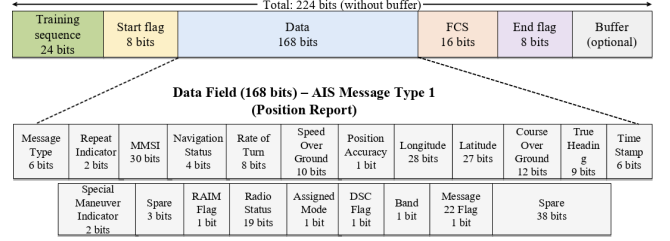


Fig. 1: AIS message structure.

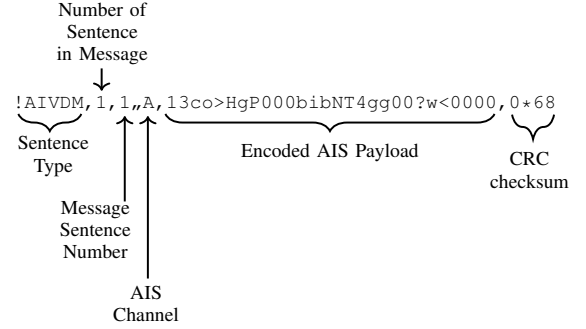


Fig. 2: Example of an AIS NMEA AIVDM sentence illustrating the main fields and the encoded AIS payload structure.

C. AIS Message Types

AIS defines several message types dedicated to the transmission of position reports, voyage-related information, safety messages, and base-station communications, enabling continuous maritime traffic monitoring and navigation awareness. AIS equipments are mainly divided into Class A and Class B devices, where Class A equipment is intended for large commercial vessels with higher reporting rates and full SOTDMA support, whilst Class B are designed for smaller vessels with reduced transmission complexity and lower reporting rates. The main differences between both classes are summarised in Table I.

TABLE I: Comparison between AIS Class A and Class B devices.

Parameter	Class A	Class B
Typical Vessel Type	Commercial Ships	Small/Recreational Vessels
Access Scheme	SOTDMA	CSTDMA/SOTDMA
Transmission Power	12.5 W	2 W / 5 W
Reporting Rate	Higher	Lower
Mandatory Usage	Yes	No

The most commonly used message types are:

- Message Types 1, 2, and 3: Position reports for Class A vessels.
- Message Type 4: Base station report.
- Message Type 5: Static and voyage-related data.
- Message Type 6: Addressed binary message.
- Message Type 8: Broadcast binary message.
- Message Type 9: Standard SAR aircraft position report.
- Message Type 12: Addressed safety-related message.
- Message Type 14: Broadcast safety-related message.
- Message Type 18: Standard position report for Class B vessels.

- Message Type 21: Aid-to-navigation report.
- Message Type 24: Static data report for Class B vessels.
- Message Type 27: Long-range AIS broadcast message.

Together, these message types enable continuous maritime traffic monitoring by vessels, coastal authorities, and satellite-based AIS systems. In this work, only AIS message type 1 is considered for transmission and experimental validation purposes.

D. Implementation Layers

From an implementation perspective, AIS can be organised into physical, data link, and application layers, as illustrated in Fig. 3. These layers respectively handle radio signal processing, channel access and frame management, and AIS message generation and interpretation. In SDR-based implementations using platforms such as GRC, this layered architecture enables flexible development of AIS transmitters and receivers for experimentation, signal analysis, and rapid prototyping.

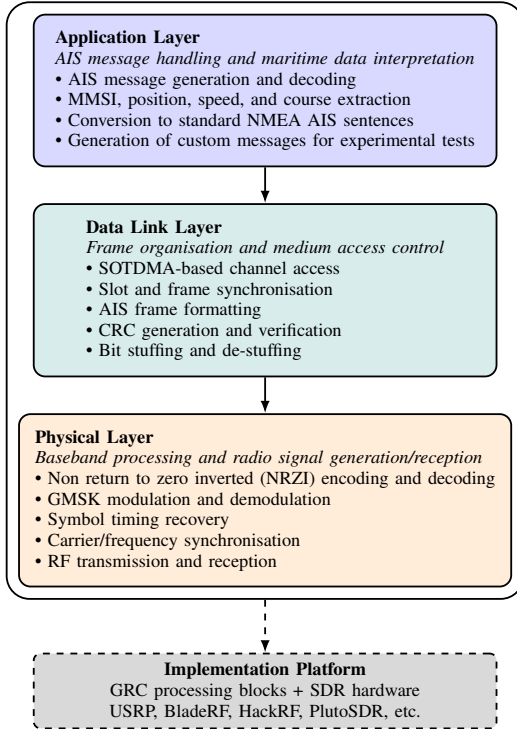


Fig. 3: Simplified layered organisation of an SDR-based AIS transceiver implementation.

III. TRANSCEIVER IMPLEMENTATION ON GNU RADIO COMPANION

The implemented system starts with the generation of the AIS message Type 1 based on vessel parameters, as depicted in Fig. 4. Initially, the AIS message fields, including the MMSI, navigation status, position, speed over ground, course over ground, heading, and timestamp, are organised according to the AIS message Type 1 structure defined by the standard. The generated information is then encoded into the AIVDM sentence format, from which the encoded AIS payload is extracted.

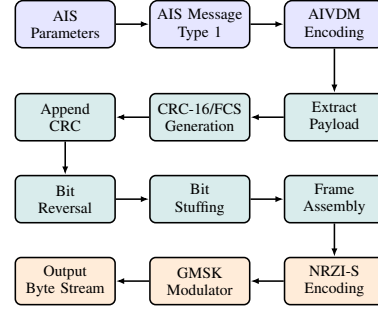


Fig. 4: Processing flow of the AIS frame builder implemented in GRC.

After payload extraction, a CRC-16 Frame Check Sequence (FCS) is generated and appended to the message in order to provide error detection capability during reception. The resulting binary sequence then undergoes bit reversal and bit stuffing operations before being assembled into the complete AIS frame with the corresponding synchronisation sequences and frame delimiters. Subsequently, the assembled frame is processed using Non-Return-to-Zero Inverted Space (NRZI-S) encoding prior to GMSK modulation and SDR transmission.

Based on the previously described AIS processing chain, the practical transmitter was implemented in GRC, as illustrated in Fig. 5. In this implementation, the generated AIS frame is forwarded to the GMSK modulator, which performs the baseband modulation of the AIS bitstream. The modulator operates with four samples per symbol and a Gaussian filter with a bandwidth-time product (BT) of 0.4, according to the modulation characteristics defined for AIS transmissions. After modulation, the generated baseband samples are processed by a rational resampler block, in order to increase the sampling rate and match the requirements of the SDR transmission stage. This interpolation stage ensures compatibility between the GRC processing chain and the sampling rate configured in the SDR hardware.

Finally, the resampled complex baseband signal is transmitted through the UHD USRP Sink block, which is responsible for configuring the SDR transmission parameters, including the operating frequency, RF bandwidth, transmitter gain, RF SDR channel, and sampling rate. In the experimental setup, the transmitter operates at the AIS carrier frequency using the NI 2901 SDR platform.

As presented in Fig. 6, the corresponding constellation diagram, shown in the lower part of the figure, presents the nearly circular trajectory expected from continuous-phase frequency modulation schemes such as GMSK. This behaviour confirms the correct operation of the implemented modulator and validates the generation of the complex baseband AIS waveform prior to SDR transmission. The lower plot shows the in-phase and quadrature components of the complex baseband signal, demonstrating smooth phase transitions without abrupt discontinuities due to the Gaussian pulse shaping filter. A more rigorous spectral analysis of the transmitted AIS signal was performed using a Keysight N9915A spectrum analyser, as illustrated in Fig. 7. The measurement was carried out at the AIS operating frequency of 161.975 MHz, corresponding to AIS channel 1. The observed spectrum confirms the correct

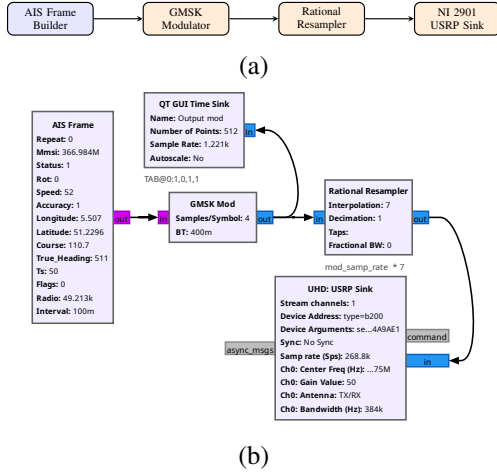


Fig. 5: AIS transmitter. a) Simplified AIS transmitter flowgraph; b) GRC implementation of the AIS transmitter using a USRP SDR.

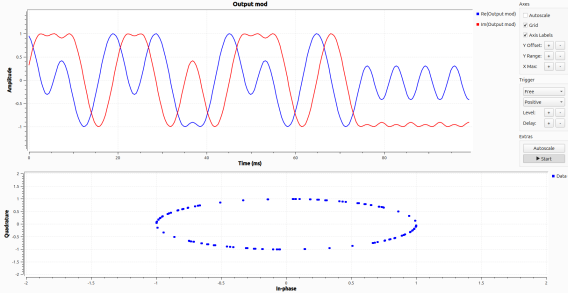


Fig. 6: Output modulator waveforms analysis.

spectral behaviour of the implemented GMSK-modulated signal generated by the SDR transmitter. The measured occupied

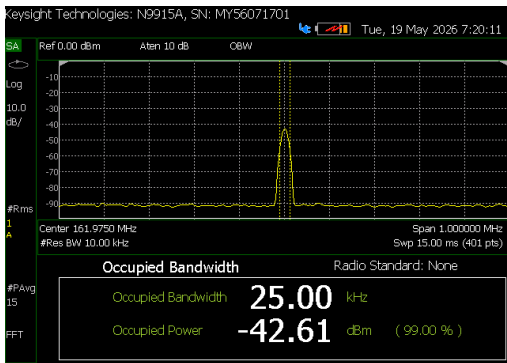


Fig. 7: Spectrum analyser measurement.

bandwidth was approximately 25 kHz, which is consistent with the nominal bandwidth specified for AIS transmissions using GMSK modulation. The smooth spectral shape and the reduced sidelobe levels observed in the measurement are direct consequences of the Gaussian filtering applied prior to modulation, which limits the out-of-band spectral components and improves spectral efficiency.

Considering the receiver side, as illustrated in Fig. 8, the received AIS signal is initially acquired by the UHD USRP Source block, which performs the digitisation of the RF signal

using the configured AIS carrier frequency, receiver gain, RF bandwidth, and sampling rate parameters. The received complex baseband samples are then forwarded to the GRC processing chain for demodulation and frame recovery. A

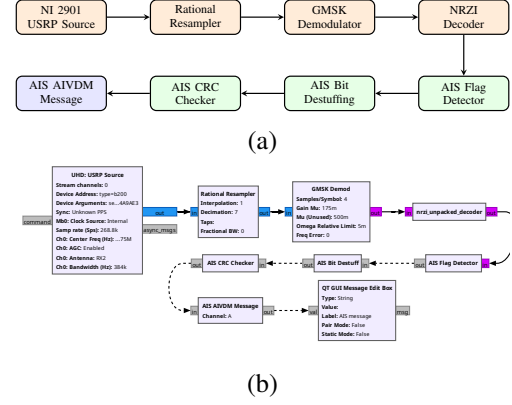


Fig. 8: AIS receiver. a) Simplified AIS receiver flowgraph; b) GRC implementation of the AIS receiver using a USRP SDR.

rational resampler block is first employed to adapt the sampling rate of the received signal to the processing requirements of the demodulation stage. More specifically, the received samples are decimated using the same resampling ratio adopted in the transmission chain in order to recover the original baseband sampling configuration. Subsequently, the resampled signal is processed by the GMSK demodulator, which recovers the transmitted binary sequence from the received AIS waveform.

After demodulation, the recovered bitstream undergoes NRZI decoding, AIS flag detection, and bit de-stuffing operations in order to reconstruct the original AIS frame structure. A CRC verification stage is then applied to validate the integrity of the received message and detect possible transmission errors.

Finally, the validated AIS payload is decoded into the corresponding AIVDM sentence and converted into human-readable AIS information, including the MMSI, vessel position, speed over ground, course over ground, heading, and navigation status.

IV. RESULT AND DISCUSSION

The experimental validation was conducted using two NI 2901 SDR devices connected to a Dell Pro Slim Plus workstation, as illustrated in Fig. 9. The AIS signal generated by the transmitter SDR was directly routed to the receiver SDR through a coaxial cable, providing a controlled environment for transceiver validation while minimising external interference and channel impairments. In addition, Fig. 10 presents the GRC graphical interface developed for real-time monitoring and configuration of the AIS transceiver parameters, allowing dynamic adjustment of transmission settings while displaying the generated GMSK waveform. The interface also presents the successfully decoded AIS message in JSON format together with the reconstructed AIVDM sentence, confirming the correct operation and experimental validation of the implemented SDR-based AIS transmission and reception chains. As illustrated in Fig. 11, the receiver was capable of correctly

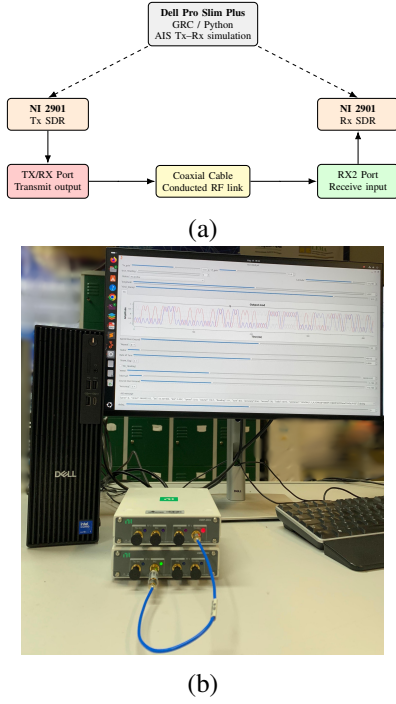


Fig. 9: Experimental test setup. (a) - Flowgraph.; (b) - Setup in laboratory environment.

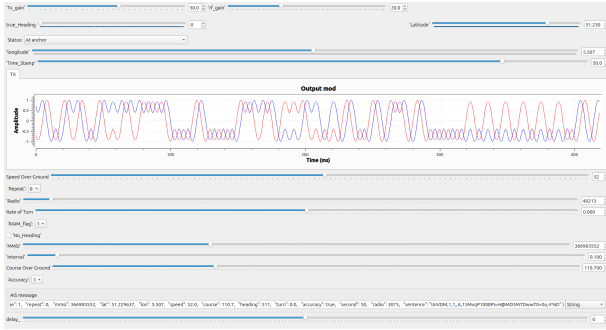


Fig. 10: AIS Transmission and Decoding Interface.

reconstructing the transmitted AIS message and recovering relevant navigation parameters, including the MMSI, vessel coordinates, speed over ground, course over ground, and heading information contained in the AIS payload. The successful reconstruction of the corresponding AIVDM sentence further confirms the correct operation of the implemented transmission and reception chains. In addition, the CRC verification has validated the integrity of the reconstructed messages under the adopted laboratory conditions.

V. CONCLUSIONS

Experimental results confirmed that AIS messages were successfully transmitted and received using the proposed SDR-based architecture. The entire processing chain of both transmitter and receiver was validated and tested, enabling the recovery of realistic AIS data.

Despite this successful experimental validation, some challenges remain for future developments. Accurate carrier and timing synchronisation under realistic propagation conditions,

```
msg_type : 1
mmsi     : 366983552
lat      : 51.229637
lon      : 5.507
speed    : 52.0 kn
course   : 110.7 deg
heading  : 511

AIVDM:
!AIVDM,1,1,,A,
15MvqP1088PI=H@MD5MTDwwT0<0u,
4*6D
```

Fig. 11: Example of a successfully decoded AIS message obtained from the receiver log.

channel impairments, Doppler effects, and low signal-to-noise ratio scenarios may significantly affect AIS reception performance, particularly in satellite-based AIS applications. In addition, the implementation of the complete SOTDMA mechanism, defined by the AIS standard, remains an important step toward a fully compliant AIS transceiver platform.

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