Automatic Identification System modular receiver for academic purposes

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Abstract The Automatic Identification System (AIS) standard is encompassed within the Global Maritime Distress and Safety System (GMDSS), in force since 1999. The GMDSS is a set of procedures, equipment, and communication protocols designed with the aim of increasing the safety of sea crossings, facilitating navigation, and the rescue of vessels in danger. The use of this system not only is increasingly attractive to security issues but also potentially creates intelligence products throughout the added-value information that this network can transmit from ships on real time (identification, position, course, speed, dimensions, flag, among others). Within the marine electronics market, commercial receivers implement this standard and allow users to access vessel-broadcasted information if in the range of coverage. In addition to satellite services, users may request actionable information from private or public AIS terrestrial networks where real-time feed or historical data can be accessed from its nodes. This paper describes the configuration of an AIS receiver based on a modular design. This modular design facilitates the evaluation of specific modules and also a better understanding of the standard and the possibility of changing hardware modules to improve the performance of the prototype. Thus, the aim of this paper is to describe the system's specifications, its main hardware components, and to present educational didactics on the setup and use of a modular and terrestrial AIS receiver. The latter is for academic purposes and in undergraduate studies such as electrical engineering, telecommunications, and maritime studies.

1. Introduction

The Automatic Identification System (AIS) broadcasts high-speed, automatic, and granular information from the activity of vessels at sea. It is a very high frequency (VHF) radio broadcasting system that enables AIS-equipped vessels and shore-based stations to send and receive static (vessel-identifying details), dynamic (vessel position, speed, navigational status, among others), and voyage (destination port and the estimated time of arrival of the vessel) information.

An AIS transponder, as a shipboard device, automatically transmits vessel information allowing ships and shore stations to easily receive these details and track, identify, or exchange vessel traffic details. At the same time, vessels fitted with AIS transponders can be tracked by AIS receivers located along the coast lines or, when out of range of terrestrial networks, throughout a growing number of satellites (and lately nanosatellites) fitted with AIS receivers.

The communication standard of the AIS was conceived by the International Telecommunication Union and adopted by the International Maritime Organization. The latter through the Safety of Life at Sea Convention [*Safety of Life at Sea*, 1974] and its requirement for AIS transponders is to be fitted aboard international voyaging ships with gross tonnage (GT) of 300 or more and all passenger ships regardless of size. Communication devices that integrate the transmission and receiving capabilities of the AIS are commercially available [*Lanier*, 2012; MarineTraffic web, 2016, http://shop.marinetraffic.com/ais-receivers.html]. These enable the access to vessel information (speed, heading, course, vessel dimensions, and other particulars) when vessels are within coverage range. However, the acquisition of AIS-receiving devices or custom distribution channels from AIS-receiving networks commonly implies a substantial cost, and it is not always accessible for nonfunded and academic purposes. Based on the above described need and objective, the present paper has been structured as follows.

Section 2 discusses the description of the system in accordance with the Open Systems Interconnection (OSI) model (physical, link, and network layer) and the relevant specifications that all devices must have [*ITU-R Rec. M.1371-5*, 2014]. Section 3 presents our modular receiver design, implemented in compliance with the AIS

specifications. For this, general purpose and commercially available devices such as an FM demodulator RX1 of Radiometrix, a GMSK demodulator baseband, CMX589A CML Microcircuits integrated into a DV-MEGA plate, and an Arduino UNO R3 microcontroller (for the storage of information received) have been used. Also, a Front-End unit has been set up on a computer with open source software in order to decode the AIS frame. Section 4 presents device results of a preliminary performance test from the proposed modular receiver and an AIS commercially available receiver. This is to verify its correct operation. Finally, in section 5, the conclusions of this work are shown.

2. System Description

The AIS is an open system that allows nonencrypted and broadcasted information to be received by any device that meets the system specifications. This system operates in the VHF maritime band, and it is capable of handling well over 2250 reports per minute. Each AIS device (vessel transponder and coastal or satellite receiver) monitors the vessel speed and determines the interval when the messages are being sent out. As the speed of the transponder increases, the frequency of messages increases and vice versa when the velocity decreases. AIS static data are automatically transmitted every 2 to 10 s depending on the vessel's speed while underway and every 6 min while anchored. On the other hand, static- and voyage-related information is manually introduced by the vessel's crew and transmitted every 6 min regardless of the vessel's movement speed or status [*ITU-R Rec. M.1371-5*, 2014]. The principles of operation of the AIS are based on the Self Time Division Multiple Access (SOTDMA) protocol. This protocol is responsible for the organization of the packet and the information generated by the transponders and its order in time. These data packets contain two types of data: static-/voyage-related information (International Maritime Organization number, call sign, name, destination, and Estimated Time of Arrival) and dynamic details (Maritime Mobile Service Identity number (MMSI), rate of turn, position coordinates, course over ground, and heading), among others. This system can be described throughout the OSI model. The first three layers of this model are defined in the standard, leaving the other layers for the user to make its own implementation. It should be noted that the reception subsystem of transponders installed in vessels and receivers located in the coast comprise the same characteristics described in the OSI model.

2.1. Physical Layer

The AIS transmission uses non-return-to-zero (NRZ) digital data encoded with a rate of 9.6 kbit/s using a GMSK modulation baseband and band pass subsequently modulated by FM. The frequency bands used are two (AIS-1: 161.975 MHz and AIS-2: 162.025 MHz) using a 25 kHz channel [*ITU-R Rep. M.2123*, 2007].

2.2. Link Layer

The link-level details support the management of bit patterns, as well as the error detection and correction that are carried out before sending packets over the network. Therefore, it is the layer that assures the reliability of bitstream. This layer is divided into three sublayers: the Medium Access Control (MAC), the Data Link Service (DLS) sublayer, and the Link Management Entity (LME).

2.2.1. MAC Sublayer

The MAC sublayer ensures a correct data transfer. For this reason, it is necessary to include references to common time between AIS receiving stations within the network. Thus, all AIS stations should be synchronized under a common time reference called universal time coordinated (UTC) which is given by the Global Position System (GPS) of the transmitting network of vessels.

2.2.2. DLS Sublayer

The DLS sublayer is responsible for providing a format in AIS frames. Each AIS frame consists of 32 bytes following the High-level Data Link Control standard, and this is organized as follows. First, the Preamble (3 bytes: 0x55 0x55 0x55) is transmitted, next the Start Flag (1 byte: 0x7E) and subsequently the data field (21 bytes), the cyclic redundancy check (CRC) (2 bytes) field to control errors in AIS frames, and finally, Stop Flag (1 byte: 0x7E). In addition, a 24 bit temporary buffer supplementing the frame and used for tasks bit stuffing, distance delay, repeater delay, and jitter effects is included.

2.2.3. LME Sublayer

The LME sublayer implements the scheme of TDMA. Thus, each AIS receiving station has an assigned time interval (slot) to share the channel with other stations and the transfer of data. This implies that the receiving
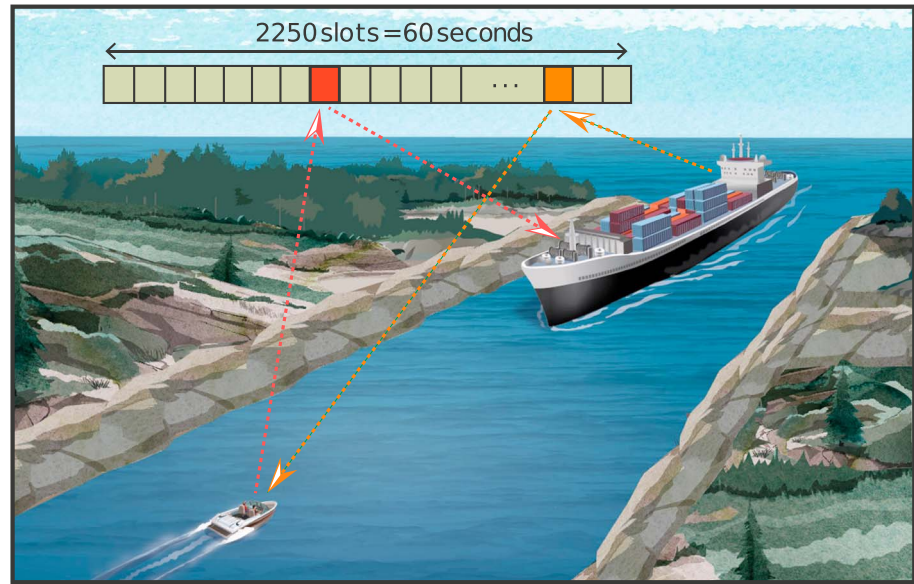
Figure 1. AIS TDMA scheme.

stations are synchronized. This timing is determined by the reference time UTC (obtained in the MAC), common to all AIS receiving stations integrated into a region of coverage.

Within the AIS standard, each slot has a duration of 26.67 ms. If each frame has a time duration of AIS of 60 s, the total number of slots in a frame AIS is

$$N = 60 \cdot \Delta t_{slot} = 60 \cdot 26.67 \approx 2250 \text{ slots} \tag{1}$$

In Figure 1, a TDMA scheme for both AIS channels available is observed, verifying the duration for each slot of 26.67 ms. The AIS standard incorporates different media TDMA access schemes, but the main one is the SOTDMA scheme [*Eriksen et al.*, 2006].

2.2.4. Network Sublayer

In this layer the sending and receiving of data packets is performed. The network layer performs the task of sending frames, commonly through a Transmission Control Protocol (TCP)/Internet Protocol network through of TCP or User Datagram Protocol (UDP) ports. The AIS allows users to implement the upper layers with the only requirement of being compatible with the network level.

3. Modular Receiver Description

Once the AIS characteristics and components have been discussed in the previous section, the modular design of a receiver will be described (DV-MEGA web, 2016, http://www.dvmega.auria.nl/GMSK_shield.html). The modular design of the receiver presented in this section is of interest in academic environments that allow to evaluate each device independently. The elements that characterize this receiver are as follows: a maritime VHF antenna, a FM receiver RX1 Radiometrix, a GMSK modem DV-MEGA, and a microcontroller Arduino UNO R3. In Figure 2, the connections between each module can be observed. Furthermore, the last block reflects a personal computer with a Front-End Program to process the data and send the data over the network. A compact receiver design is achieved by choosing the sizes of all modules equal to the size of the Arduino UNO. For this reason, both the DV-MEGA board and the breakout board Radiometrix RX1 meet these requirements. The connections between the modules are made via USB and Mini DIN-6 connectors. A GPS is only required in AIS transponders. In this case a GPS is not required due to the exclusive frame-receiving purposes of its use.

3.1. Radiometrix Demodulator

The Radiometrix RX1-161.975-10 chip is a FM demodulator device that enables the connection to the VHF frequency 161.975 MHz and delivers the demodulated output (baseband) with a sensitivity of −119 dBm.
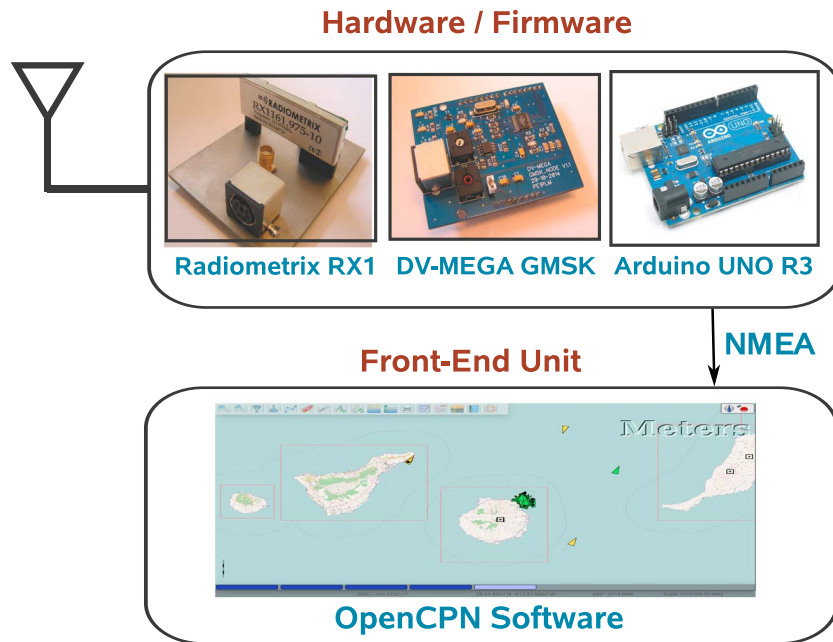
Figure 2. AIS receiver prototype block diagram.

The input impedance of Radiometrix RX1 is of 50 Ω connected to a VHF antenna with Voltage Standing Wave Ratio less than 1.3. This device has nine-pin input and output of encapsulation, which are the RF In, RXD, GND, Vcc, RSSI, and Enable pin. The RX1 Radiometrix chip is designed with a dual conversion superheterodyne topology FI (Radiometrix web, 2016, http://www.radiometrix.com/files/additional/tx1rx1.pdf) (Figure 3). Signals from the device input pass through the RF stage where a preamp followed by a band-pass filtering is performed. Once filtering is performed in RF, the signal passes through a mixer through another input connected to a crystal oscillator frequency to 161.975 MHz, allowing the RF signal conversion to perform the first IF stage (FI1). Then, this signal passes through a band-pass fitter and is amplified. Finally, the intermediate frequency FI2 is obtained through a second mixer thereby improving the selectivity.

Once the double-conversion FI is performed, the signal passes through a frequency discriminator which converts frequency variations into amplitude variations linearly so that the FM modulated signal performs
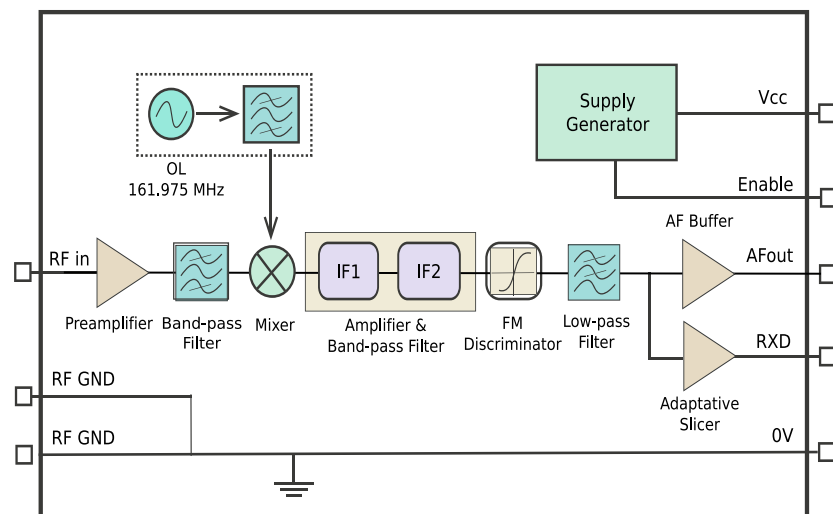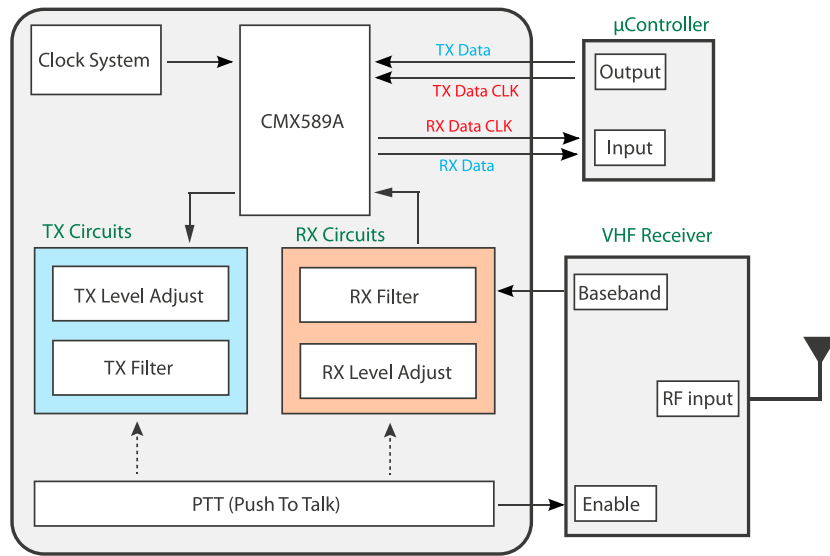

Figure 3. Radiometrix RX1.

Figure 4. DV-MEGA GMSK shield.

a conversion to AM modulated signal. Since the information is located in the envelope of the AM signal, an envelope detector enables demodulation of the modulated signal. The last stage uses a low-pass cutoff frequency of 7 kHz and is used to improve the selectivity of the demodulator filter. Finally, a receiver buffer to store data received during a certain period of time in order to adapt transmission rates to different types of protocols is added. The output data are obtained via the RXD pin at a speed which depends on the filing of the buffer.

3.2. Baseband GMSK Demodulation

The DV-MEGA board is a shield for Arduino, designed to perform GMSK modulation and demodulation tasks baseband to speed 9.6 kbit/s. This board (Figure 4) consists of a CMX589A GMSK modem with external sync stages, also with filtered transmit and receive gain and PTT controller.

3.2.1. Modem GMSK CMX589A

The CMX589A chip is encapsulated 24-pin designed by the company CML Microcircuits described as a GMSK baseband modem. This chip supports full-duplex and half-duplex communication modes and allows transmission rates between 4 kbit/s and 200 kbit/s. BT (Bandwidth per symbol period) has a configurable pin factor to select the values 0.3 and 0.5. This chip transmits and receives bit serial data with corresponding sync pin to be connected to the microcontroller for data transfer. Rx input levels can be set with external components around an on-chip Rx Input Amplifier.

3.2.2. Clock System

CMX589A GMSK modem employs a synchronization circuit based on a crystal 9.8304 MHz. This crystal fixed clock signal 9.8304 MHz to set a bit rate of 9.6 kbit/s. For this, the value $N = 1024$ is set through ClkDivA and ClkDivB lines so that the value of the bit rate is

$$R_B = f_{XTAL}/N = 9.6 \ \text{kbit/s} \tag{2}$$

However, since the DV-MEGA board has a crystal oscillator of 4.9608 MHz, the desoldering and soldering of this crystal oscillator was necessary. A more detailed explanation of the process and the new oscillator is found in IDeTIC-AIS Github Repository (2016, https://www.github.com/IDeTIC-AIS/RX-AIS).

3.2.3. Rx Level Adjust System

Two filters are placed on pin RxOut of CMX589A chip. The first of these filters is responsible for setting the bit rate output of the device, while the second low-pass filtering performs on the data and includes, via a potentiometer, the gain control to the modem output.

In a first step, the passive RC filter low-pass first-order consists of the resistance $R = 47 \text{ k}\Omega$ and capacitor $C = 470 \text{ pF}$ determines the BT factor equal to 0.5, according to the selected bit rate, and eliminates
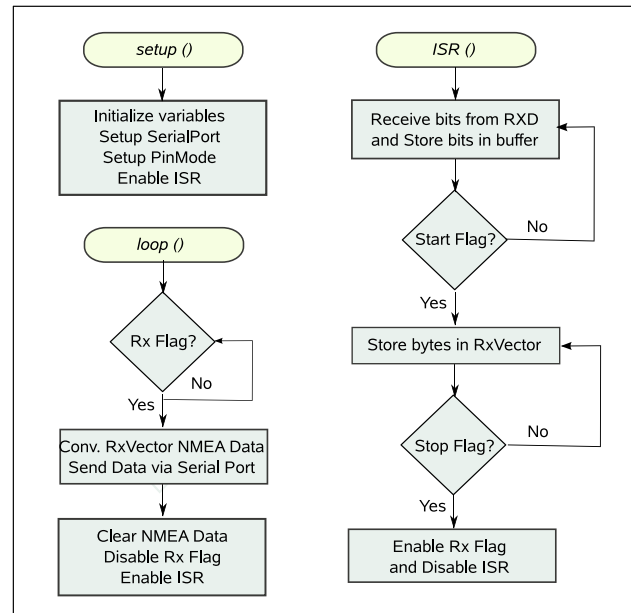
Figure 5. Simplified *setup()*, *loop()*, and *ISR()*.

high-frequency noise. The second filter is an active low-pass filter based on an operational amplifier in inverting configuration. The gain of this filter is given by the ratio between the resistive values and thus depending on the output of the GMSK modem can adjust the signal level. The solution adopted is to put a fixed and a variable resistance so that we have a gain value between 7 dB and 10 dB.

3.2.4. Push to Talk

The circuits Push to Talk (PTT) are integrated into systems for activating and deactivating RF subsystems transmitting and receiving in half-duplex mode. In this design, the activation signal is generated by the Arduino microcontroller.

3.3. Arduino Microcontroller

Arduino is an open programmable hardware platform. It is based on a microcontroller and a development environment, including specific programming language Processing based, with a syntax similar to C ++. Arduino UNO R3 model integrates an ATmega328P microcontroller 32 KB of Flash memory, 2 KB of SRAM, and 1 KB of EEPROM. It has 14-pin digital input and output and 6 analog input pins that connect to other devices (shield) as the DV-MEGA board. It also has a serial port where programs are loaded and performs serial communications.

After creating a *setup()* function, which initializes and sets the initial values, the interrupt service routine *ISR()* is responsible to decode AIS frames. This interrupt is enabled via clock lines DV-MEGA board. This routine reads the bits via pin RXD and identifies the start and stop flags to the store data in the frame, as shown in Figure 5. Once stored, data are converted to NMEA format and through the routine *loop()* data are sent to the Front-End Unit via the serial port.

3.4. Front-End Unit

The Front-End Unit has been implemented through the use of free and open software available that meets the requirements of our hardware. OpenCPN (OpenCPN web, 2016, http://www.opencpn.org) is a free software with GNU license that displays maps of any area through the use of OpenSeaMap (OpenSeaMaps web, 2016, http://www.openseamap.org) and allows an easy integration with our AIS-receiving system by using serial port connection. OpenCPN decodes the data using NMEA [*ISO/IEC 13239*, 2002], visualizing it on the map and allowing the decode of 22 different types of messages. It also allows the implementation of the network layer allowing to send the NMEA sentences by using a TCP or UDP port.

4. Results

As mentioned within the structure description of the paper, this section describes results of a preliminary performance test from the proposed modular receiver and an AIS commercially available receiver. This is to verify its correct operation.

First, each module has been revised independently to ensure proper operation. Second, a test set has been performed in the laboratory to check the system operation. Finally, a proper operation has been verified with a live stream of AIS signals.

The RX1 Radiometrix was verified through a comparison of a baseband signal generated by a function generator with the demodulated signal RX1 device. The GMSK demodulator was verified by mounting two DV-MEGA. The first generates a random GMSK signal and demodulates the second one. In Figure 6, the

D0 = Transmission Clock Signal (TXCLK)
D1 = Transmitted Signal from Arduino (TXD)
D2 = Received Signal from Arduino (RXD)
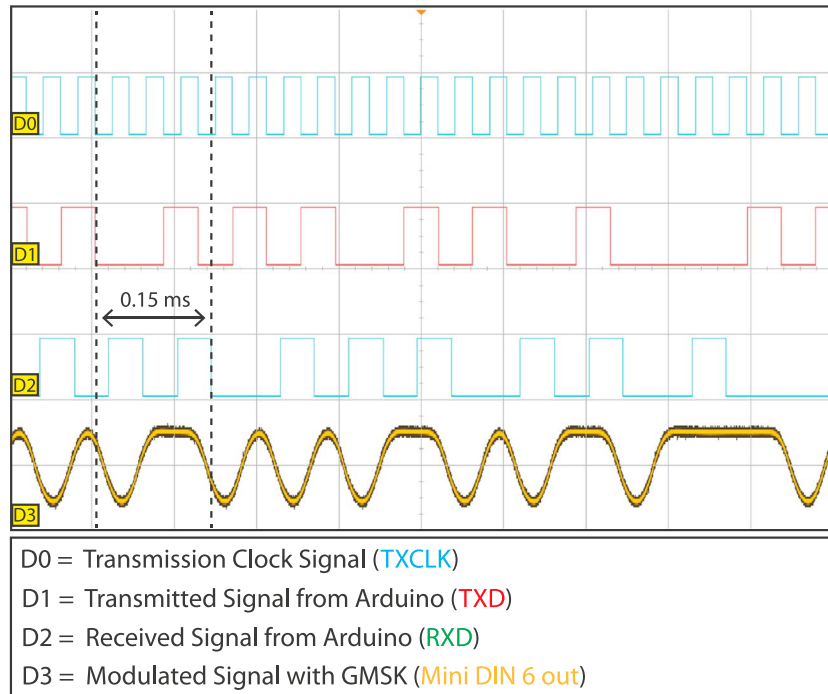D3 = Modulated Signal with GMSK (Mini DIN 6 out)

Figure 6. Random binary sequence in the DV-MEGA modem.

different signals are shown. First, D0 clock signal is generated by the module. The D1 random sequence is transmitted from Arduino. D3 and D2 are the GMSK modulated and demodulated. It is noted that a match exists between the two signals having a propagation delay of 0.15 ms between D1 and D2.
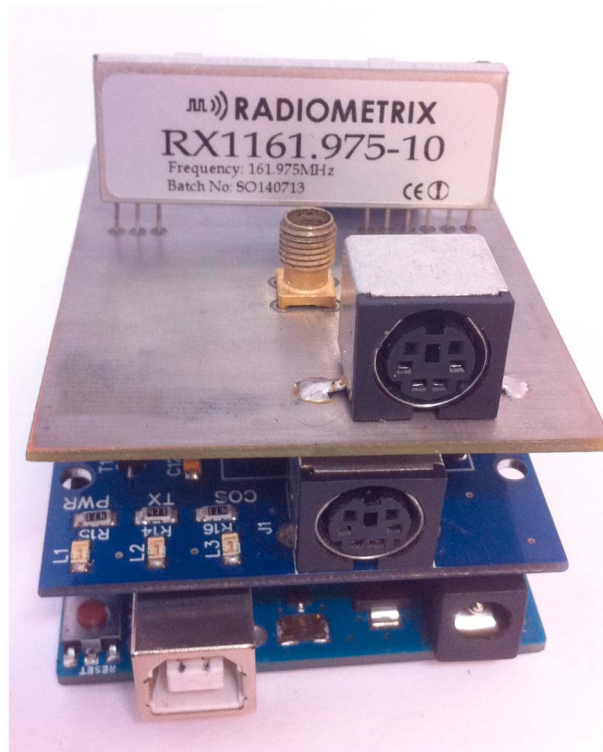

Figure 7. A developed hardware receiver prototype.

Figure 7 shows the prototype receiver finally implemented. This receiver has been tested using an AIS test system organized by a modular receiver equipment and other similar transmitter, where both devices are separated by a distance of 1 m. AIS frames sent in this test have been compared with the received frames. The 2250 time slots were used to verify that all had been correctly received.

Once the modular receiver has been verified with real AIS frames, the developed prototype had been connected to a VHF maritime mobile band antenna located on the rooftop of the *ULPGC Science and Technology Park* (28.08°N/15.46°W). In Figure 8, the assembly is shown in the laboratory, by using the digital oscilloscope to display the received frames. Once stored, frames and changing the time base on the oscilloscope are shown in Figure 9 as the bitrate is 9.6 kbit/s. This signal passed through the Arduino microcontroller that performed the tasks of NRZ inverted decoding and data

Figure 8. Assembly of an AIS real test system.

extraction RxVector later to make the CRC checksum. The last step has been the conversion to the NMEA 0183 format and its transmission to the computer's serial port. Table 1 shows an example of this message format and the most relevant parameters of the manual decoding (using *ITU-R Rec. M.1371-5* [2014]) where the message ID (1) indicates the Position Report.

Figure 10 shows the graphical representation of OpenCPN through a map of the Canary Islands where the number of vessels collected in real time is observed. Vessel information can be obtained by clicking on the icon of each. By clicking on the coordinates that have previously been manually decoded, it is found that there is a vessel in the same coordinates and time sharing the same MMSI number. This verifies that manual decoding has been performed satisfactorily. Furthermore, these results were revised again through the MarineTraffic network and data sent by the BMT-IDeTIC AIS terrestrial node.

By using the OpenCPN software, AIS messages have been received from a coverage distance of up to 100 NM and a frequency of up to 300 messages per minute. The latter is below the maximum standard (2250). To use this software simultaneously by multiple users, OpenCPN has been configured as a server program using UDP
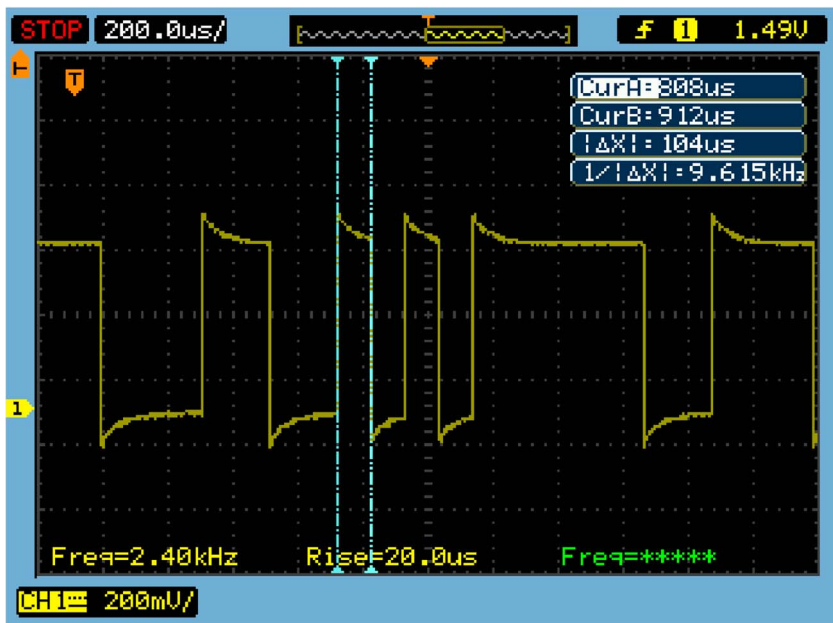

Figure 9. Demodulated AIS received signal.

Table 1. NMEA 0183 Frame and the Most Relevant Parameters Using a Manual Decoding

NMEA 0183 frame	
!AIVDM,1,1,,A,13aN2dPOilNtC1L@@lf0g@`l0H=o,0*78	
Parameter	Value
Message ID	1
MMSI	244810418
Speed over ground (SOG)	11.6 knots
Longitude	−14.789895°
Latitude	28.421427°
Course over ground (COG)	18.9°
True heading	20°

port 3245 in a laboratory of 10 computers. Each computer can collect server information, allowing to perform measurements such as distance and routes.

Finally, a comparative table with other receivers is shown in Table 2. This table reflects the prototype developed with the Comar SLR300N receiver (Comar System web, 2016, http://www.comar-systems.com/slr_300n.html) located in the same place and used as a node called BMT-IDeTIC in the MarineTraffic Network [*Tichavska et al.*, 2015], Daisy-AIS receiver (Tindie web, 2016, https://www.tindie.com/products/astuder/daisy-ais-receiver/), and RTL-SDR receiver (RTL-SDR web, 2016, http://www.rtl-sdr.com/rtl-sdr-tutorial-cheap-ais-ship-tracking/). It should be noted that all receivers get NMEA0183 messages at a rate of 38.4 kbit/s. Test results reflect that the receiver sensitivity developed has better features than others but has nevertheless been implemented in a single channel. The prototype as the Daisy-AIS and the RTL-SDR has not implemented the network layer, thus allowing an external program performing it. Finally, the cost of the developed prototype has been 125 € where the major cost has been covered by the DV-MEGA GMSK device. This price may be of course reduced if many units are purchased. The Front-End Unit has not been included since a unit dedicated to the AIS is not necessary. In a comparison with the other receivers it is noticeable that the prototype is cheaper than the SLR300N but more expensive than the Daisy-AIS and RTL-SDR.

5. Conclusions

Within this paper, we propose and describe the implementation of an AIS terrestrial modular receiver, to be used for academic purposes. Also, we compare its performance with AIS general purpose receiving devices. The proposed modular design proves its use for education and student learning in areas such as electronic engineering, telecommunications, and maritime studies. The performance of the prototype also proves to be useful for the live reception of AIS frames at a not too expensive cost.
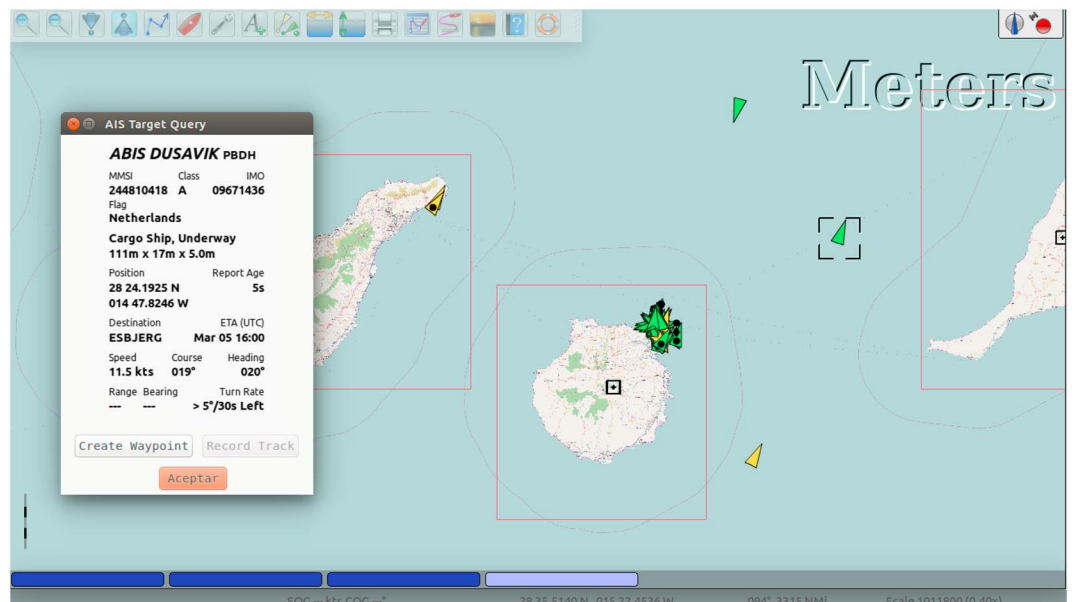

Figure 10. Data decoded and displayed on a map of the Canary Islands in the software OpenCPN.

Table 2. Comparative of Receiver Developed and Commercial Receivers (Comrad SMR300N, Daisy-AIS, and RTL-SDR)[a]

	Receiver Prototype	SLR300N	Daisy-AIS	RTL-SDR
Sensitivity	−119 dBm	−112 dBm	−105 dBm	−116.5 dBm
No. of channels	1	2	2	1
Output format	NMEA0183	NMEA0183	NMEA0183	NMEA0183
BaudRate	38.4 kbit/s	38.4 kbit/s	38.4 kbit/s	38.4 kbit/s
Ethernet port	No	Yes	No	No
Cost	125 €	304 €	76 €	20 €

[a]RTL-SDR sensitivity is an estimated value (IDeTIC-AIS Github Repository, 2016, https://www.github.com/IDeTIC-AIS/RX-AIS).

Moreover and within this work, the process and firmware code to be used with a single hardware receiver has also been described and included as an open source, the latter to simultaneously visualize and map decoded AIS vessel traffic details within a network of computers and thus facilitate AIS-based research and the dissemination of regional vessel traffic-based knowledge.

At last, results of this work motivate and support the implementation of a more accessible AIS-receiving node toward the potential advance of applied and theoretical research within the areas of innovative system architectures for the future internet of things, transport intelligent systems, Geographical Information Systems, hardware sensors, low-power computing, vessel and route efficiency, port optimization, among others. Indeed, AIS-data access, related research, and the advance of knowledge and science may allow unprecedented opportunities to a better understanding and the improvement of the blue territory and shipping, among others, throughout descriptive and predictive analytics applied to a more efficient, transparent, and green operations at sea and in ports. Also, it may facilitate the design, development, and implementation of computing systems and actionable intelligence services that further support maritime policy and management [*Shelmerdine*, 2016; *Tichavska and Tovar,* 2015a, 2015b].

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