SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549/ https://doi.org/10.14445/23488549/IJECE-V12I3P114

Volume 12 Issue 3, 143-150, March 2025

Original Article

Space Based Automatic Identification System (AIS) Receiver Architecture and its Performance in Collision Scenario

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Received: 09 January 2025 Revised: 10 February 2025 Accepted: 13 March 2025 Published: 29 March 2025

Abstract *- An effective and innovative Automatic Identification System (AIS) receiver design for maritime surveillance applications is presented in this study. The frequency of the receiving signal, the collision time, and the power level of the signals for VHF channels of AIS 87 B & 88 B have all been changed for the proposed receiver architecture, and simulations have been run to assess how well it performs in these different message collision cases. The Doppler shift resulting from the LEO satellite's orbital velocity at an altitude of 600–900 km, the signal transmission delay resulting from propagation time, as well as the signal power level based on the distance that the AIS transmission signals must travel have all been introduced to characterize the AIS receiver. Particularly in locations with a large density of ships, the suggested design in the present study is appropriate for creating an AIS receiver employing software-defined radio and on-board message processing capabilities that may be started on any Nanosatellite with better AIS signal decoding. Based on the simulation results, the sections below tabulate the efficiency of the suggested AIS receiver in the collision scenario when the AIS Transmit signals from two and three collided in various combinations due to varied signal characteristics.*

Keywords *- AIS, CRC, CPM, GMSK, LEO, Maritime, PER, PPR, SOTDMA.*

1. Introduction

The AIS is a terrestrial communication system installed on a vessel or ship that transmits various kinds of messages comprising position, identity, course, speed, and other travel-related information to base stations on the shoreline and other nearby ships or vessels. Being aware of the positioning details of other ships nearby through such AIS messages helps the ships prevent collisions. Additionally, AIS is useful for maritime monitoring in both military and civil applications.

In the huge oceans, ships and other boats are categorized into virtual cells that resemble GSM cells. Using Time Division Multiple Access (TDMA), the AIS messages from ships inside a given cell are automatically arranged into a frame of 2250 time intervals for each available frequency. The resulting TDMA frame is known as a SOTDMA message frame and has a one-minute frame transmission time. A ship or other vessel is assigned to each slot in this message frame, with a transmit period of about 26.67 milliseconds. Depending on the voyage velocity of each ship, fast sailing ships can be assigned more than one slot within the SOTDMA message and are delivered on two AIS frequencies at an RF power of 12.5 W. These frequencies are 162.025 MHz and 161.975 MHz. With the aforementioned arrangement, a single cell may receive approximately 4500 messages overall across the two AIS frequencies in a minute [1, 2].

The SOTDMA protocol ensures message collision avoidance within the 40-nautical mile SOTDMA cell coverage zone included in the present AIS system. Since the line-of-sight range of the terrestrial AIS communication system is limited, it is impossible to identify and monitor ships in the deep ocean using base station receivers along the coasts. These ships, unavailable to ground-based systems, might compromise national security and engage in illegal activity. A space-based AIS system offers a solution to finding and monitoring ships in regions inaccessible to the current terrestrial system. It also expands the ship detection service and offers worldwide coverage.

The number of SOTDMA cells that fall inside an LEO (Low Earth Orbit) satellite's region of coverage is determined by the FOV (Field of View) of the satellite's AIS receiver antenna, which causes messages received on the receiver end placed on the satellite to collide across the cells. With an energy/bit to noise spectral density (E_b/N_0) of 8.3 dB and a maximum slant range of 3600 km, for decoding the AIS signals from the Space platform under the specified interference settings for a typical altitude of 950 km LEO satellite with a 12.5 W isotropic radiated power transmitter classified as class B, the AIS Link Budget [1, 3] analyses are sufficient. Most of the work so far carried out by researchers in this field has not brought out the performance of AIS receivers in the collision scenario with variation in power level and frequency due to Doppler. Also, the study in terms of the AIS packet decoding pass percentage in high-density areas is more critical for space-based AIS receivers.

1.1. Study of Challenges in the Implementation of Space-Based AIS

Satellite-based AIS faces additional technical challenges that were not considered in the original AIS standard. The new issues that arise due to the space-borne receiver are mentioned below

1.1.1. Message Collisions

The typical radius of a SOTDMA cell (where no message collisions occur) is around 40 Nm. The self-organized structure is lost when messages transmitted by more than one SOTDMA cell are received.

This is the case of a satellite-based receiver due to a large FoV covering a high number of SOTDMA cells. In these conditions, several messages can collide within the same time slot. The messages collide with a different received power level and are delayed due to the different channel propagation over the satellite antenna coverage.

1.1.2. Path Delay

The length of AIS messages was designed to face different propagation delays between messages from different ships up to 2ms. Path delays among vessels and spacecraft vary depending on the vessel's location and the maximum satellite antenna footprint.

1.1.3. Low SNR Values

Due to higher path losses and depending on the particular satellite antenna gains, SNR values between 20 to 0 dB are expected.

1.1.4. Faraday Rotation

A linearly polarized wave entering the ionosphere may have a different polarization angle when it leaves. This polarization rotation primarily depends on frequency, elevation angle, geomagnetic flux density and electron density in the ionosphere. When in the presence of a circularly polarized satellite receive antenna, a constant 3 dB loss is present when receiving the randomly rotated vertically polarized VHF wave as transmitted by the ship.

1.1.5. Doppler Effect

The Doppler frequency shift is a function of the relative velocity between the transmitter and receiver. In the case of the satellite-based AIS system, the ship velocity is small compared to the satellite, such that Doppler shift can be calculated as $\Delta f = vr/\lambda$ where $\lambda = c/f$ is the wavelength. For typical LEO altitudes and FoV used in AIS applications, the maximum Doppler shift is around 4 KHz. Due to the symmetry of the coverage area, the Doppler shift varies between -4 KHz to +4KHz with maximum relative Doppler between two messages of 8 KHz. In this research, an attempt has been made to address the above-mentioned areas and a novel AIS receiver architecture appropriate for the on-board decoding of AIS signals while taking the risk of collisions in SOTDMA cells is presented. Very few researchers have addressed the hardware requirement for the AIS message decoding in the collision scenario, but the FPGA resources used were large, limiting the power requirement for the onboard processing capability. The present work uses 40 decoders as compared to 126 in the literature [2]. Section II provides information on the AIS signal technical properties of the current terrestrial system that an LEO satellite will use to receive AIS signals from ships, and Section III presents a parallel demodulation receiver framework that would use less on-chip resources than the 126-demodulator design in [2] during implementation. Additionally, the suggested architecture may be ported to SDR equipment that requires less DC power. Section IV discusses the simulation structure of the AIS communication signals in two and three-user collision situations. The conclusion section discusses the overall performance and potential modifications of the proposed Space-based AIS (SB-AIS) receiver.

2. AIS Signal Characteristics and Message Structure

2.1. NMEA Standard and GPS Position Data

To enable interoperability between various electronic devices, an AIS transceiver placed on the vessel or ship is interfaced with the GPS receiver for location data contained in the National Maritime Electronics Association (NMEA) Interfacing Marine Electronic Devices. The output of a GPS receiver is a variety of NMEA sentences, among which the GPS Fixed Data (GGA) words are considered and included in the AIS system [6].

2.2. AIS Message Position Information Format (Type I)

As many as 27 distinct messages with various sorts of information may be uplinked by the Automatic Identification System (AIS) transmitter. The most crucial parameter to be gained with this method is position data. Because it provides the required scheduled position report for the vessel, Message 1 is considered in this study instead of Messages 2 and 3, which also provide position information. The technical features of AIS published by the ITU [4] specify the whole format of the message structure in detail.

2.3. AIS Transmission Frame Format

When a valid AIS transmission packet is used, the position information of the vessel or ship is inserted into it at the link layer [5]. The AIS message packet has a length of 256 bits and must be broadcast across the two AIS frequencies of 162.025 MHz and 161.975 MHz using a binary GMSK: Gaussian. Minimum Shift Keying modulation at a data rate of 9600 bps. The maximum range of a SOTDMA frame is 200 nautical miles, although the RF coverage is just 40 nautical miles. Every SOTDMA: Self-Organized Time Division Multiple Access frame is developed to handle route delays of roughly 12 bits. As a result, to prevent message collisions, all AIS ship broadcasts in this frequency band comply with the SOTDMA protocol.

Ramp Up (8-bits)	Training Sequence (24-bits)	Start Flag (8-bits)	Data (168-bits)	FCS (16-bits)	End Flag (8-bits)	Buffer (24-bits)

Fig. 1 Structure of 256-bit AIS message

2.4. AIS Encoding Process

The 256-bit AIS message frame from the ships in Figure 1 is formed as indicated below using 168-bits of real ship route data. For message synchronization, the start and finish flags, each with an 8-bit value encoded by '7E,' are employed. Bit stuffing is used in the data field to prevent the occurrence of data that looks like the start or end flag, as it does in the HDLC protocol. The GMSK modulator receives the bit-stuffed AIS packet data that has been NRZ line coded for transmission.

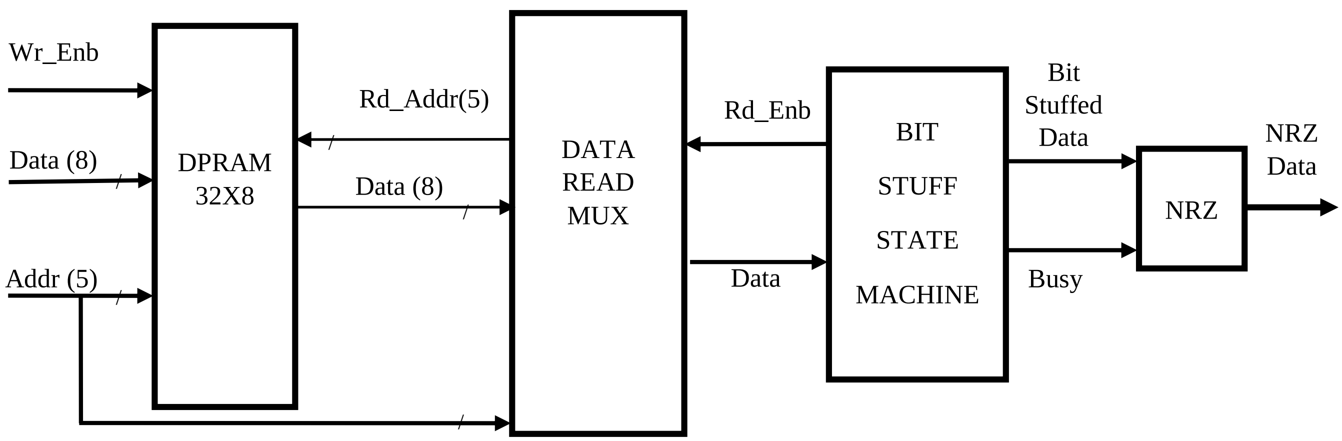

Fig. 2 AIS Packet design

Fig. 3 Conversion process for GMSK

2.5. Data Conversion and GMSK Modulation

The AIS system uses GMSK modulation for transmitting signal, which is mathematically described by

$$S(t) = \sqrt{(2\,E_b/T_b\,)}\cos(w_c t + \phi(t))$$

Where,
w_c = angular frequency
T_b = Bit duration
E_b = Energy/bit

The Minimum Shift Keying (GMSK) modulation of a baseband signal after it has been through a Gaussian low-pass filter. Thus, the Gaussian filter settings will decide how much adjacent symbols in the transmitted data will impact one another. According to AIS specifications, the GMSK modulator's maximum BT (Gaussian pre-modulation frequency pulse bandwidth and symbol time) product must be 0.4 while sending data and 0.5 when receiving data. The GMSK signal's main lobe spectrum will be wider, and the spectrum fall rate will be slower if the pulse bandwidth (BT) product is lower. The AIS packet encoded using NRZ is first transformed into bipolar data before being sent through the integrator and Gaussian filter sections to be converted to GMSK. An oscillator that generates sine and cosine signals in quadrature numerical control is used to I & Q modulate the data collected at the integrator part of Figure 3. Figure 4 depicts the multiplier and adder components.

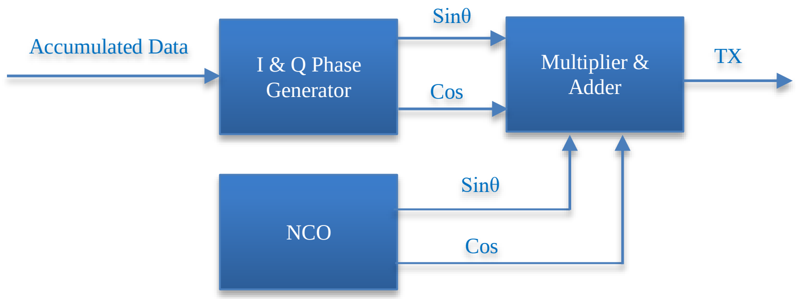

Fig. 4 Modulator

With a reporting period ranging between 2sec to 6min depending on the ship's velocity, AIS-equipped ships may broadcast the messages on two frequency channels, 162.025 MHz and 161.975 MHz, each needing a bandwidth of 25 KHz. The 2250 slots in the SOTDMA cell frame, as mentioned in the sections above, are used by the ships within that cell to broadcast their signals on the two frequency channels while switching between them continuously. The ships will transmit 256bps in each slot, which is allotted at a rate of 9600bps in around one minute using the complete SOTDMA frame length, which includes 2250 slots.

3. Proposed Parallel Decoder Design for Space-Based On-Board Processing ais a Receiver

The Continuous Phase Modulation (CPM) technique with excellent spectrum efficiency is called GMSK, and it is the modulation method utilized for AIS transmission. The PAM (Pulse Amplitude Modulation) pulses generated by the CPM signal provide the basis for the detection method applied for GMSK demodulation, which is based on Laurent's [6, 7] decomposition.

Table 1. Pulse shaping filter configuration

Index K	a_{n-1}	a_n	a_{n+1}	Pulse Shape
1	-1	-1	-1	$g_1(t)$
2	+1	-1	-1	$g_2(t)$
3	-1	+1	-1	$g_3(t)$
4	+1	+1	-1	$g_4(t)$
5	-1	-1	+1	$-g_4(t)$
6	+1	-1	+1	$-g_3(t)$
7	-1	+1	+1	$-g_2(t)$
8	+1	+1	+1	$-g_1(t)$

Laurent superpositioned many PAM signals to represent the CPM signal. Incoherent CPM detectors, the GMSK signal is linearized using Laurent decomposition, which also helps to minimize the size of the filter bank.

The highest intensity PAM pulse is sent through a matched filter in the suggested receiver, and the matching triplet of bits is indicated by the index K in the following table. It can be deduced from the information above that each decoder needs a maximum of 8 Matched filters. The fact that the four pulses are the inverse of the other four allows their reduction to 4. In this part, a novel parallel decoder-based AIS receiver with onboard processing capabilities for space applications is suggested.

Each VHF frequency channel needs 19 parallel decoders to cover the Doppler range of the anticipated frequency shift between -3800 Hz and +3800 Hz. The Doppler shift of around ±200 Hz from the center frequency may be accommodated by each parallel decoder.

Consequently, 38 parallel decoders are suggested to receive AIS signals on both channels (decoding the AIS messages requires 19 decoders for each VHF channel). Each AIS channel has a bandwidth of 25 KHz, and the channel bandwidth is decreased to around 125 KHz when a signal is received at the antenna and routed via a bandpass filter at the RF front end. Except for the IF frequency and the BPF dividing the two channels, the decoding logic for AIS channels 1 and 2 remains the same.

As previously discussed, the central frequencies for a two-channel AIS system are 161.975MHz±12.5KHz and 162.025MHz±12.5KHz. With a LO of 161.875MHz, the signals from AIS channels 1 and 2 are combined. 100KHz +/- 12.5KHz is the mixer's output for Channel 1, and 150KHz +/- 12.5KHz is its output for AIS Channel 2. As a result, these channels are single down-converted to signals with zero or very zero IF that may be used with software radio receivers.

The cordic algorithm demodulates the AIS signal in each channel and decoder chain. Each decoder employs a non-coherent decoder within Doppler values of +/-200Hz and matching filters with 8 distinct levels to effectively demodulate the AIS signals even when two AIS signals of different strengths collide. In the previous work[8], a Frequency Locked Looped (FLL) was tried for the frequency estimation before the decoding is carried out.

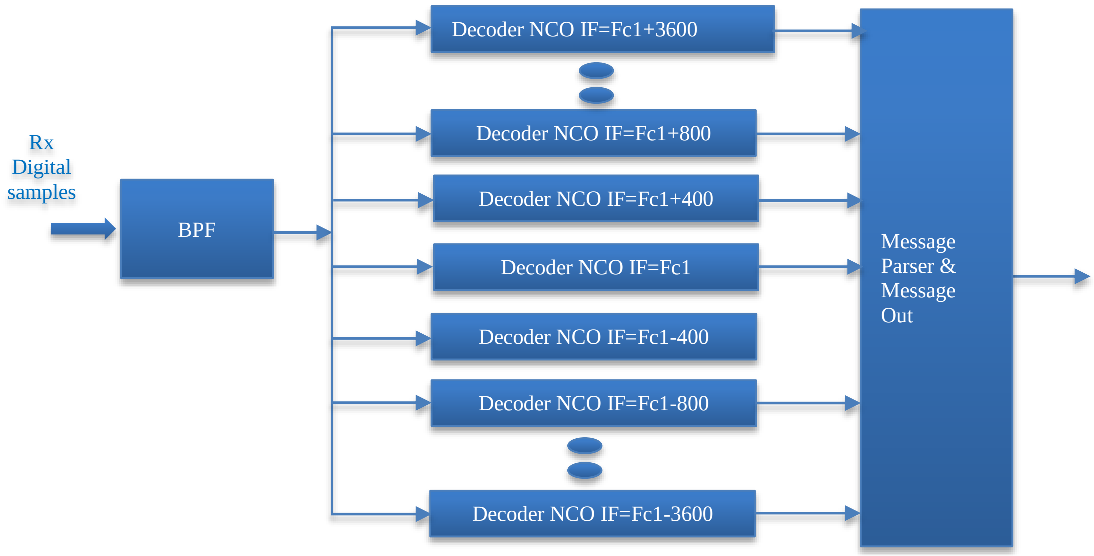

Fig. 5 Architecture for the proposed AIS receiver on a single-channel

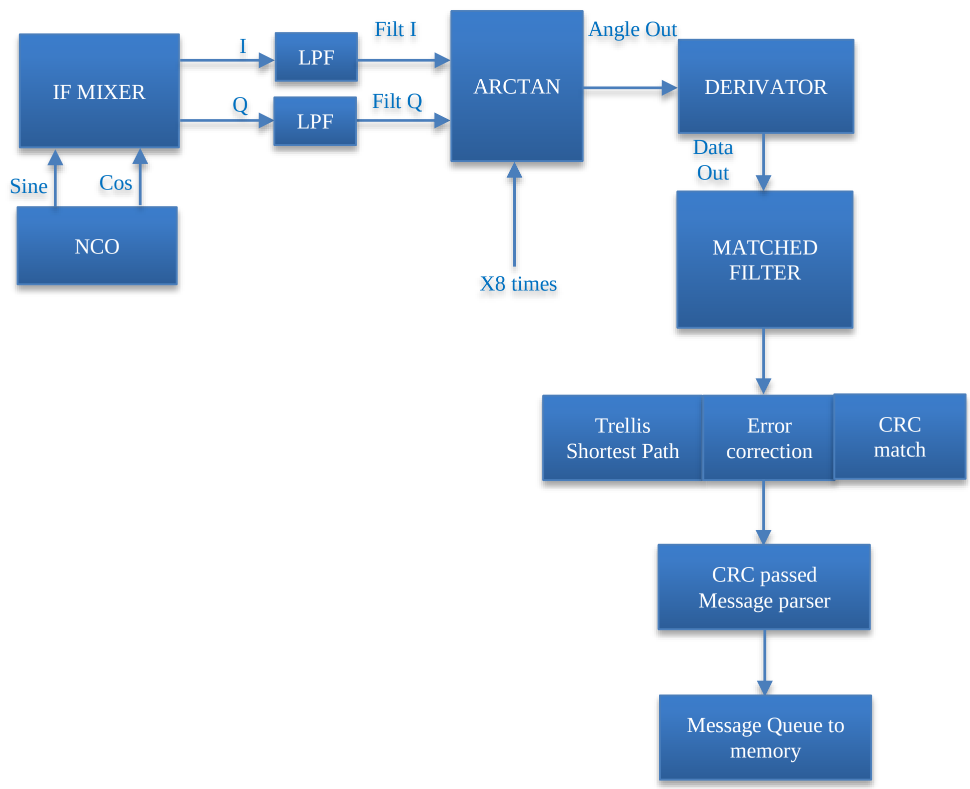

Fig. 6 Internal design of each decoder

However, the frequency estimation was inaccurate during the collisions, and hence the results were unsatisfactory. In the present work, the FLL block is removed, and a matched filter with multi-threshold values was introduced to arrive at better results even in the collision scenario. A Viterbi decoder is used for error correction in the data the matching filter outputs after demodulating. Following Viterbi decoding, the retrieved bits are CRC-checked for AIS message validation. Since the Cyclic Redundancy Check only utilizes 16 bits, the AIS receiver must calculate 2^{16} different permutations of CRC checks to verify the CRC of a single AIS message.

4. Simulation Studies & Performance Results

Block-level features of the AIS data packet processing, GMSK modulation, and data conversion were described in Sections II, D and E. The simulation configuration for the AIS single channel transmitter is shown in the figure below, along with the ability to manage power and change the Doppler shift over the anticipated whole spectrum of -3800Hz to +3800Hz.

In the above AIS transmitter implementation, a fixed AIS packet is transmitted so that it is easy to check the PER (Packet Error Rate). The packet pass rate is calculated by comparing the no of successfully decoded AIS receiver output messages with the no of transmitted AIS messages having a fixed AIS data packet at a data rate of 9600bps. This simulation has been performed in each condition by sending at least 10,000 packets.

The two situations, a) Collision, and b) Non-collision, are provided individually in Tables 2 and 4 for the performance outcomes of the AIS receiver shown. In the case of non-collision, the AIS receiver operates as a typical GMSK demodulator with a sensitivity of -110dBm. Since channel 1 and channel 2 in the design are identical, the PER for channel 1 (161.975MHz) was less than 4 percent, and the same findings are also true for channel 2 (162.025MHz).

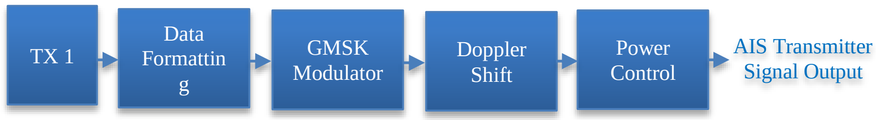

Fig. 7 Configuration of an AIS transmitter for a single user

4.1. Case 1: Non-Collision Case

The 168 bits total transmitted from TX 1 that constitute the 256-bit AIS packet's data bits are received error-free, according to the PPR (Packet Pass Rate) shown in Table 2; PER (Packet Error Rate), which is expressed as a percentage, is summarized in Table 4. The Packet Pass Rate was calculated at different doppler conditions where the doppler range can be between -3800 Hz to + 3800 Hz.

Table 2. PPR with Doppler fluctuation in a non-collision case

S.No	Frequency (MHz)	Power Level (dBm)	Doppler (Hz)	Threshold	PPR (%)
1	161.975	-90	3800	1700	97.97
2	161.975	-109	3800	1700	98.80
3	161.975	-90	0	1700	99.61
4	161.975	-109	0	1700	96.80

Table 3. PER with doppler fluctuation in a non-collision case

Proposed Receiver Sensitivity	-110dBm
Ch1: 161.975MHz Doppler is changed between -3800 and 3800Hz in steps of +/-400KHz.	PER <4%

4.2. Case 2: Collision Case-Two Users

The simulation setup of the AIS transmitter for two users is shown in the figure below, along with options for power variation and changing the Doppler shift over the anticipated whole spectrum of -3800Hz to +3800Hz. When two ships send AIS messages simultaneously and collide, the two users create two different signal combinations called TX #1 and TX #2 by changing the power and Doppler levels across them. These simulation outcomes are summarized in Tables 4 and 5, demonstrating how the packet pass rate will increase as the power difference between the collision signals increases.

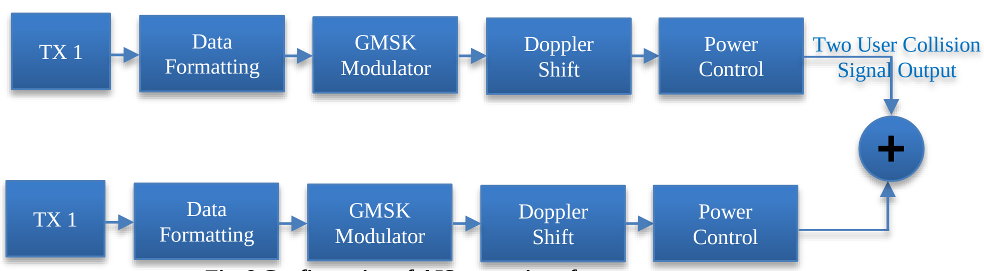

Fig. 8 Configuration of AIS transmitter for two users

Table 4. PPR with Doppler fluctuation in a non-collision case in steps of 400Hz

S. No	Frequency (MHz)	TX 1 Power Level	TX 2 Power Level	TX 1 Doppler	TX 2 Doppler	Detection Threshold	PPR%
1	161.975	-105	-110	0	400	1700	43.07
2	161.975	-105	-110	0	-400	1700	51.42
3	161.975	-105	-110	0	800	1700	12.21
4	161.975	-105	-110	0	-800	1700	10.81
5	161.975	-105	-112	0	400	1700	71.00
6	161.975	-105	-112	0	-400	1700	87.80
7	161.975	-105	-112	0	800	1700	20.35
8	161.975	-105	-112	0	-800	1700	29.38
9	161.975	-105	-112	0	1600	1700	12.96

10	161.975	-105	-112	0	-1600	1700	11.82
11	161.975	-105	-114	0	1600	1700	30.68
12	161.975	-105	-114	0	-1600	1700	28.76
13	161.975	-105	-115	0	2400	1700	26.67
14	161.975	-105	-115	0	-2400	1700	39.29
15	161.975	-105	-117	0	2400	1700	53.53
16	161.975	-105	-117	0	-2400	1700	53.59
17	161.975	-105	-117	0	3800	1700	25.22
18	161.975	-105	-117	0	-3800	1700	16.40
19	161.975	-105	-118	0	3800	1700	30.95
20	161.975	-105	-118	0	-3800	1700	55.56

Table 5. PER with Doppler deviation in a collision case

AIS Receiver Sensitivity in two user collision case (The effective decoding of AIS Receiver data during a collision is expected)		**-105dBm (Max S/I will maintain at 5dB)**	
S. No	Doppler variation between user #1 and #2 (Hz)	S/I ratio (dB) (The other AIS signal will function as the interfering signal for each one)	PER (%)
1	±400	i) 5 ii) 6 iii) 7	70 60 30
2	±800	i) 6 ii) 7 iii) 8	60 50 30
3	±1600	i) 8 ii) 9 iii)10	70 40 30
4	±2400	i) 10 ii) 11 iii)12	75 40 20
5	±3800	i) 12 ii) 13	60 20

4.3. Case 3: Collision Scenario-Three Users

The figure below illustrates the simulation setup of the AIS transmitter for three users, with the possibility of adjusting the Doppler variation for the anticipated whole spectrum of -3800Hz to +3800Hz and power control. All possible combinations of variations can be introduced to match the real-time scenario for satellite-based AIS reception.

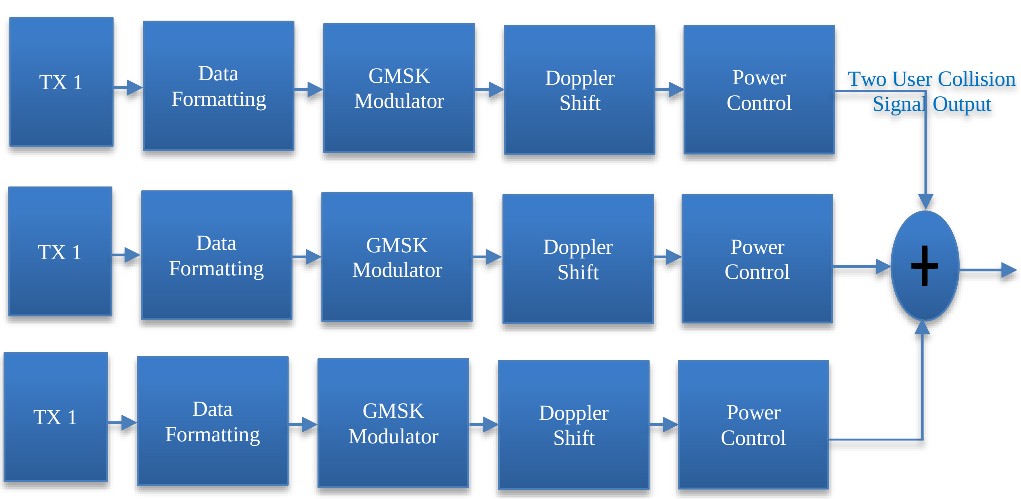

Fig. 9 Configuration of AIS transmitter for three users

Table 6. PPR with doppler variation in a collision case

S.No	Frequency (MHz)	TX 1 Pwr Level	TX 2 Pwr Level	TX 3 Pwr Level	TX 1 Doppler	TX 2 Doppler	TX 3 Doppler	Threshold	PPR
1	162.025	-105	-112	-112	0	100	-100	1800	8.65
2	162.025	-105	-113	-113	0	100	-100	1800	40.35

Several combinations of the transmission signals, i.e., TX - #1, #2, and #3 with variations in their power and Doppler values between them, are modelled for the three-user collision case, and the findings are summarized in Table 6.

4.4. Summary of the Results

Most of the research papers on the AIS receiver do not deal with the performance metric in terms of the packet pass rate statistics. Compared with the available few, the results obtained are better in the collision scenario. In the non-collision scenarios, the AIS receiver is just a GMSK demodulator and, hence, does not require any comparison.

Better results are possible due to the matched filter configuration, which eliminates the frequency-locked loop. The results can be improved using successive interference cancellation algorithms in case of more than two collisions. However, for onboard implementation, the proposed configuration is suited for a Nano Satellite with less power requirement, typically less than 6W.

5. Conclusion

The simulation data have been reported for collision and non-collision situations (for two and three-signal collisions) using a new space-based onboard processing capable AIS receiver structure. The hardware resources needed to create an AIS receiver capable of retrieving AIS signals in real-time have been preliminary estimated using SDR devices.

The size, weight, and power consumption of a space-based AIS receiver are the primary factors to be considered. Each decoder's Doppler frequency coverage may be further decreased (by around <100Hz) for improved performance, but this comes at a cost regarding the resources needed to implement it.

Nomenclature

w_c : Angular frequency
T_b : Bit duration
E_b : Energy/bit

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