Improving the Efficiency of the AIS System Using Algorithms for Dealing Signal Collisions

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Abstract

The paper considers methods for receiving and processing automatic identification of ships (AIS) signals by a small satellite (CubeSat). A comparison of various methods for reducing the impact of collisions on the reliability of reception is given, such as the choice of orientation and type of the CubeSat receiving antenna, the use of various demodulation algorithms that take into account the presence of Doppler frequency shifts, as well as decollision processing algorithms. Using simulation modeling that takes into account the parameters of the space scenario (orbit altitude, antenna type, etc.), the efficiency of the considered methods in terms of reducing the packet error in the presence of first-order collisions is shown.

Keywords: *CubeSat, AIS, Doppler frequency shift, marine communication systems*

1. Introduction

The growth and development of the domestic segment of small spacecraft have made it possible to form a demand for the creation of a global system for monitoring the activity of marine vessels. To achieve this, it has been proposed to receive and process messages from ground stations on board small satellite (CubeSats).

However, such an application of automatic identification of ships (AIS) is characterized by a high level of signal collisions. In the space segment of AIS, the diameter of satellite coverage is ten times greater than the size of the self-organizing zone of ground stations. At any given time, the input of the receiver may receive messages from several areas that are not in agreement with each other. These messages are not differentiated by the receiver, resulting in a packet collision, which affects the quality of detected messages. This problem is especially significant when trying to receive messages from heavily congested areas and coastal regions. In this regard, studying, evaluating the applicability, and effectiveness of algorithms for de-cluttering AIS signals is a crucial task.

The main purpose of the work was to increase the reliability of receiving messages from the AIS space segment by using decollision processing algorithms. An increase in confidence means a decrease in the packet error rate. It was decided to conduct a comprehensive study of methods for minimizing signal collisions, including: the study of various antennas and their location, algorithms for demodulating AIS signals (according to the degree of complexity: a simple frequency detector, an average receiver based on the Laurent decomposition and the most computationally expensive based on the Viterbi algorithm), as well as the development of an additional decollision algorithm (Colavolpe et al. (2016), Eriksen et al. (2020) Clazzer et al. (2016)).

2. Space AIS Simulation model

To test the effectiveness of the algorithms, an imitation model was developed. The model generates an AIS message flow taking into account the real parameters of the transmitting stations, their location,

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and location relative to the spacecraft. Radiation timestamps are used to simulate packet collisions. Regarding the space scenario, the model supports loading file or manual adjustment of the spacecraft's orbital parameters. The location of the station relative to the spacecraft makes it possible to take into account the real Doppler displacement, the receiving angle, and the received signal power. The model evaluates the real signal-to-noise value in the AWGN channel, as well as estimates the magnitude of the signal-to-noise of conflicting signals.

The model (see the left top part of Figure 1) is universal, and any parameters can be entered into it. In the right part of Figure 1 is shown the field of view of a spacecraft located in an orbit of 500 km.

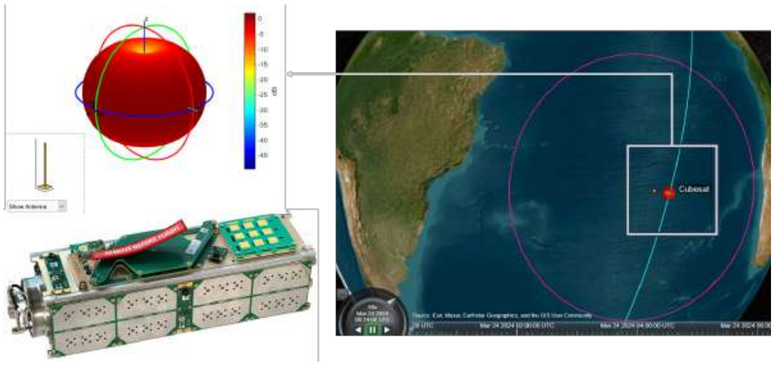

Figure 1. Field of View borders of a spacecraft Polytech Universe-3.

The real power distribution of the received signal in the field of view of the spacecraft for a monopole antenna in the nadir position is shown on the Figure 2. The power of the received signal is calculated using the formula, and depends on the power of the transmitter, the center frequency, the noise coefficient of the receiver, the angle of reception of the signal and propagation losses in free space:

$$(P_R)\text{dB} = (P_T)\text{dB} + (G_T)\text{dB} + (G_R)\text{dB} + (L_s)\text{dB} + (L_a)\text{dB}. \tag{1}$$

were P_R – received signal power in dB, P_T – transmitter power in dB, G_T, G_R– antenna gains, L_s – propagation in free space, L_a – additional loss factor. Propagation in free space could be writte as

$$L_s = \left(\frac{\lambda}{4\pi d}\right)^2. \tag{2}$$

Taken simulation parameters were: transmitter power $P_T = 12$ W, central frequency $f = 162$ MHz, bit rate $R_B = 9600$ bit/s, receiver noise figure 10 dB, receiver attitude: 500 km, antenna type = 'monopole'.

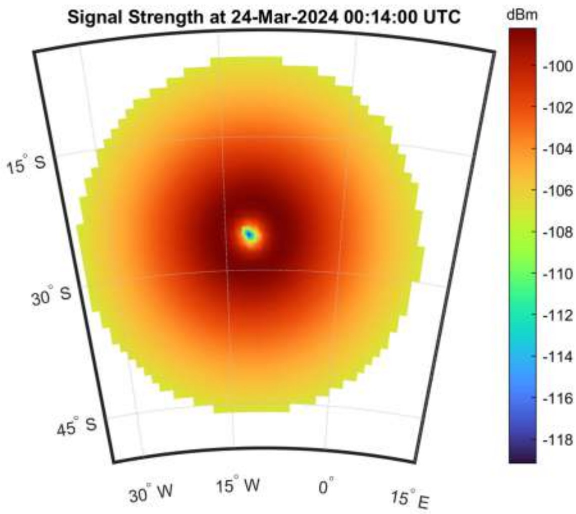

Figure 2. Power distribution of received signals in the spacecraft field of view.

The system does not have the ability to spend resources on accurate frequency and time synchronization, so the implementation of multi-channel processing is necessary. Reception algorithms were analyzed to determine the channel pitch by frequency and character delay.

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For a receiver based on the *Viterbi* algorithm, it was found that for a fixed value of the bit error BER=10^{-3}, a 100 Hz Doppler shift gives a loss of 1 dB. A 1/6 T character synchronization shift gives a loss of 1 dB.

For a receiver based on the *Laurent* decomposition, with the same bit error of 10^{-3}, a frequency shift of 200 Hz gives a loss of $<$ 1 dB, and a character synchronization shift of 1/6 T gives a loss of 2 dB.

So, depending on the type of demodulator in the receiver circuit, it will be necessary to implement from 6 (for a frequency detector) to 456 (for a receiver based on the *Viterbi* algorithm) parallel processing channels. Each channel has its own frequency and time delay.

An iterative interference suppression method with repeated modulation was developed as a decollision algorithm (see Figure 3). The input record defines the signal with the maximum power. The signal is demodulated, and the CRC is calculated. If the CRC has converged, then the frequency and time synchronization values corresponding to this channel are saved. The signal is re-modulated and subtracted from the total recording. After that, the operation is repeated for the remaining packet in the record.

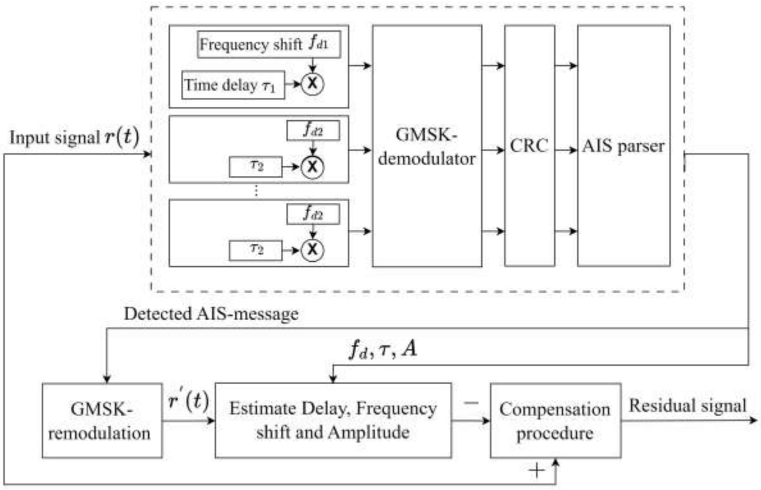

Figure 3. Structural diagram of the parallel demodulator block.

A numerical estimation of the packet error of two conflicting signals was performed depending on the signal-to-noise ratio for different demodulation algorithms with and without the proposed iterative decollision processing. As the signal-to-noise ratio increases, the packet error decreases. The smallest packet error is achieved by the receiver based on the *Viterbi* algorithm and is equal to 0.22 without decolonizing and 0.09 with decolonizing processing.

A study of the packet error in the case of a collision was conducted depending on the type and orientation of the antenna. The smallest packet error is achieved when the monopole is oriented perpendicular to the spacecraft motion with a pitch angle of 135 or 90 degrees.

The smallest packet error is achieved when the Uda-Yaga antenna is oriented in the nadir position and perpendicular to the motion of the spacecraft with a pitch of 45.

In summary, on average, iterative processing gives a gain of 45%. The transition from the currently implemented frequency detector to more complex receivers gives an increase in correct detection of more than 60%. The smallest packet error is achieved when using a demodulator based on the Viterbi algorithm, however, such an implementation requires the largest number of parallel tuning channels. The orientation of the antenna strongly affects the number of correctly detected messages. The choice in favor of the Uda-Yaga antenna gives an average increase of 15%.

3. Conclusion

The following methods were chosen to study the decollision signal processing in the space segment of AIS: different AIS-demodulators (frequency detector, noncoherent receiver based on Viterbi algorithm, serial receiver based on Laurent decomposition), different receiver antennas: Yagi-Uda and monopole (depending on orientation). An iterative interference cancellation algorithm with signal re-modulation is developed.

A simulation model has been developed that takes into account the orbital parameters of the spacecraft, the characteristics of ground and space antennas, the distribution of ground transmitting stations, and their

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radiation power. Using the model and orbital parameters of the Polytech Universe-3 satellite, numerical values of the parameters of the signals arriving at the spacecraft input from the receiver's field of view were obtained for two antennas of the monopole and Yagi-Uda.

The study of applicability of the algorithms showed the need for additional multichannel processing for frequency and time synchronization: for the frequency detector extra 6 channels of processing, for the receiver based on the Loran decomposition - 228, for the receiver based on the Viterbi algorithm - 456 channels.

The average gain from the decollision processing is 45%. For the monopole antenna, the gain for the first packet is 61%, for the second packet by a factor of 12; for the Uda-Yaga antenna, the gain for the first packet is 27%, for the second packet by a factor of 38. The smallest packet error is observed when the monopole is oriented perpendicular to the direction of motion with a pitch of 90 degree and nadir for the Uda-Yaga antenna. The benefit of using the Uda-Yaga antenna is 15%. The receiver based on the Viterbi algorithm has the best packet resolution, with signal-to-interference ratio C/I=12 dB detecting $<$ 90% of the first packets. For the Laurent decomposition based algorithm, $<$ 75% is detected at C/I=12 dB.

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