Advanced concepts for satellite reception of AIS messages

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Abstract — **This paper addresses the problem of demodulating messages received by a low-orbit satellite (altitude between 700 and 800 km) and transmitted by vessels using the Automatic Identification System (AIS). AIS is a Self-Organized Time Division Multiple Access (SO-TDMA) system, in which vessels periodically transmit information (mainly including MMSI – identification code of the ship– and its GPS position). The main application of the actual AIS system is collision avoidance between ships but a satellite reception would lead to a global supervision of maritime traffic, which could be of great interest for a lot of applications (military but also civil applications as fleet surveillance and monitoring).**

Keywords-AIS; demodulation; trellis; interference mitigation; beamforming

I. INTRODUCTION

Following AIS recommendation, vessels gradually insert themselves in the system after one minute listening the 2 frequency channels in order to determine the free time slots (each with 26.67 ms duration). The range of classical AIS equipments is approximately 20 to 25 Nautical Miles (NM), leading to a self-organized system in small areas, between ships which are in VHF range from each other. On a larger scale, there is no more organization. As the field of view from the satellite is much broader, time and frequency collisions of signals received by the satellite will occur.

TESA Laboratory has been working with the CNES (French Space Agency) for several years on the subject. This tight collaboration resulted in 4 research projects and one PhD (still in progress). Main addressed challenges for satellite reception of AIS messages were:

- Demodulation: New correction methods (taking advantage of the CRC in each AIS message) have been developed in order to obtain acceptable Packet Error Rates (PER) at the lower possible E_b/N_0. This strategy resulted in the publication of 2 conference papers ([1] and [2]) and two patents ([3] and [4]).
- Interference mitigation: Multi-user processings are based on a multi-sensor input. Thanks to the use of a realistic simulator developed by the CNES, several antenna processing methods could be evaluated (initial beamforming and inclusion of already demodulated and reconstructed signals as dummy sensors among the real sensors).

The paper gives details on the strategies developed to deal with those challenges and gives achieved results. For the second section (demodulation), comparison is done with classical Viterbi GMSK demodulators Bit Error Rate (BER) and Packet Error Rate (PER) versus E_b/N_0. In the third section (multi sensor interference mitigation), multi-user performance (in realistic conditions given by the CNES simulator) is compared to single-user performance in the same conditions.

II. DEMODULATION

A. Transmitter model

The information sequence is composed of 168 bits, on which is computed a 16-bit cyclic redundancy check (CRC). This CRC is concatenated to the 168 information bits. The bit stuffing procedure is then applied to this sequence. The resulting frame is encoded using the NRZI coding, and then modulated using a GMSK modulation.

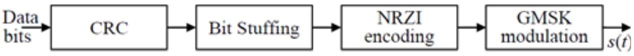

Figure 1. Illustration of the transmitter model.

The transmitted signal $s(t)$ with GMSK modulation is a constant modulus signal, which is expressed of the form

$$s(t) = e^{-j\theta(t;\boldsymbol{B})}, \tag{1}$$

where the phase $\theta(t;\boldsymbol{B})$ contains the information symbols, as follows (CPM Continuous Phase Modulated signal):

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$$\theta(t;\boldsymbol{B}) = 2\pi h \sum_{k=-\infty}^{n} b_k q(t-kT), nT \le t \le (n+1)T. \quad (2)$$

In (2), T is the symbol period, $\boldsymbol{B} = \{b_k\}$ is the bit sequence, h is the modulation index and $q(t)$ is the GMSK pulse waveform [5]. In the AIS system, the modulation index is theoretically equal to 0.5 but due to low-cost AIS equipments imperfections, the actual modulation index can be different (typically ±10% variation).

B. Received signal model

Considering a frequency-flat channel, the model of the signal received by one antenna of the satellite during a given time-slot in the presence of collisions (presence of signals corresponding to several vessels during the same time-slot) can be expressed as

$$r(t) = \sum_{k=0}^{K-1} a_k x_k(t) + b(t), \quad (3)$$

where:

- $b(t)$ is a white additive Gaussian noise.
- K is the number of vessels present in the mixture.
- a_k is the magnitude associated with the k^{th} vessel.
- $x_k(t) = s_k(t-\tau_k)e^{j(2\pi f_k t + \Phi_k(t))}$ and $s_k(t)$ is the message transmitted by the k^{th} vessel that is to be isolated and then decoded (1).
- τ_k is the time delay of the k^{th} vessel (related to the distance between the boat and the satellite).
- f_k and $\Phi_k(t)$ are respectively the associated Doppler shift and phase shift (time dependence of $\Phi_k(t)$ stands for inaccurate modulation index modelling and oscillator phase noise).

C. Parameters estimation

In this section, the received signal is assumed to be collision-free (K=1). An estimation of the parameters τ_0, f_0 and modulation index h in DA (Data Aided) is done using the known preamble of AIS signals (32 bits). These parameters are estimated by a correlation-based technique using the preamble.

In the AIS system specifications, the initialization bit of the NRZI encoding is not specified. As a consequence, 2 (complex-conjugate) 32-bits length preambles are possible, leading to 2 possible results for the correlation with the received signal. Note that the developed procedure is able to derive the result of the 2nd correlation from the intermediate results of the 1st one without further calculation.

D. Advanced receiver description

The objective of a Viterbi algorithm is to determine the symbol sequence which minimizes the square Euclidean distance between estimated and received symbols. Due to the presence of the stuffing bits and the use of the CRC, this minimization must satisfy the two following constraints:

1) the joint CRC (CRC of the message concatenated with its CRC) must be 0.
2) the number of consecutive bits 1 is upper bounded by a value M (M=5 for AIS where the stuffing bits are bits 0).

In the new demodulator algorithm designed for the CNES, these constraints are taken into account by defining a so-called extended trellis, whose each state (named extended state) is composed of a CRC state and a trellis code (TC) state. To ensure constraint 1), the trellis paths ending with a final state give a message whose joint CRC is zero (hence, paths corresponding to a non-zero CRC do not appear in the trellis) [3]. On the other hand, constraint 2 is obtained by defining special transitions in the extended trellis [4].

E. Simulation results

In the simulations, the messages are generated according to the AIS recommendation: they are composed of 168 information bits concatenated with a 16-bit CRC. The stuffing bits are then inserted. The frame is encoded with NRZI, and modulated in GMSK with a bandwidth-bit-time product parameter BT=0.4. The generator polynomial for CRC computation is $G(x) = x^{16} + x^{12} + x^5 + 1$ (recommendation). An additive white Gaussian noise (AWGN) channel is considered, which is usual in satellite communications.

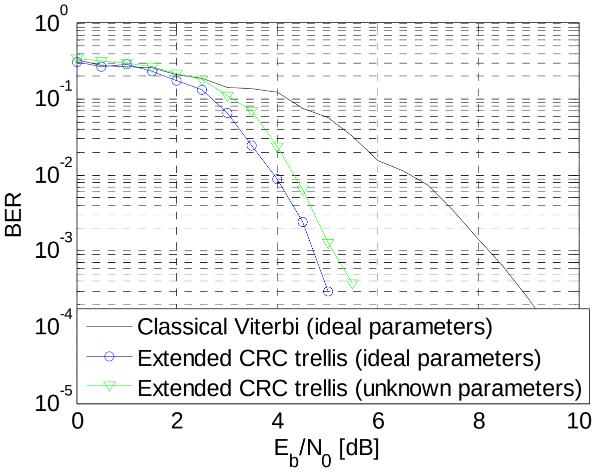

Figure 2. Demodulators BER performances.

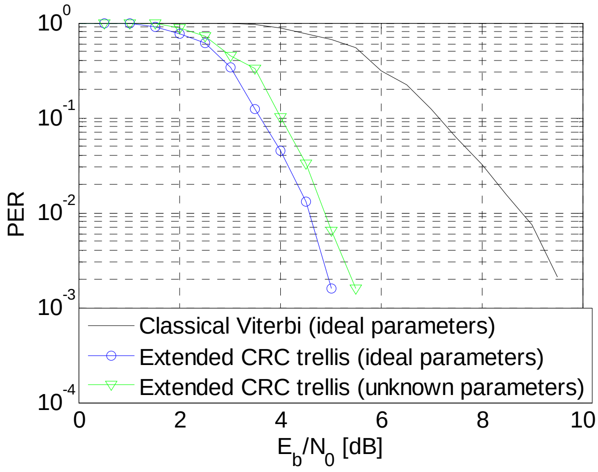

Figure 3. Demodulators PER performances.

The performances of the proposed receiver (using CRC as Error Correcting Code) illustrated in Fig. 2 and 3 (respectively showing Bit Error Rate and Packet Error Rate versus noise power) largely outperform those of the classical Viterbi algorithm with a gain of 4.5 dB.

III. MULTI SENSOR INTERFERENCE MITIGATION

In this section the general case of a satellite reception with collisions is considered. Considered satellite solutions will include multiple antennas, consequently antenna processing methods were implemented and tested based on digital beamforming. Note that other multi-user and interference mitigation techniques (using only one sensor) has also been addressed by the authors in [6].

A. *Scenario*

As real satellite signals are difficult to obtain, the CNES developed a realistic simulator taking as parameter the satellite trajectory, the number, geometry, phase and gain diagrams of antennae and the density of vessels and AIS traffic in given parts of seas and oceans. As a result, the simulator returns AIS signal mixtures received at each antenna versus time and directional vectors. An example of the simulator output in time-frequency plane is given Fig. 4.

More precisely, the received signal in presence of *K* AIS signals on *P* sensors is the vector

$$\underline{y}(t) = \sum_{k=0}^{K-1} \underline{h}_k x_k(t) + \underline{b}(t) \qquad (3)$$

where the complex directional vectors $\underline{h}_k = (h_{0,k}, h_{1,k}, \ldots, h_{P-1,k})^T$ depend on the direction of arrival (including antenna phase and gain) and also include relative powers between signals and noise (all received signals $x_k(t)$ can then be supposed to have unitary power).

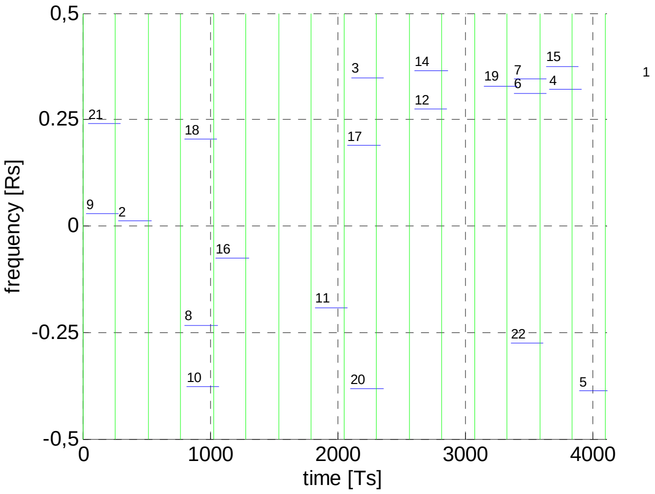

Figure 4. time/frequency repartition of the received signals with collisions (satellite above Mediterranean).

B. *Dummy sensor method description*

Let us define

$$R = E\left[\underline{y}(t)\underline{y}(t)^H\right] \qquad (4)$$

and

$$\underline{r} = E\left[\underline{y}(t)s^*(t)\right] \qquad (5)$$

where *E[]* is the mathematical expectation, ^{H} is the Hermitian operator (transpose complex conjugate), * is the complex conjugate and *s(t)* is the learning sequence shifted in time and frequency (composed of the 32 bits pilot symbols). Then the classical method consists in finding maxima of the criterion

$$c(\tau, f) = \underline{r}^H R^{-1} \underline{r}\,. \qquad (6)$$

For a given maximum (τ_k, f_k) of the criterion, the beamforming weights are then derived as

$$\underline{\omega}_k = R^{-1}\underline{r}\,. \qquad (7)$$

It is then possible to use those weights to remove interferences and recover signal *k* from the k^{th} vessel as follows:

$$\hat{s}_k(t) = \underline{\omega}_k^H \underline{y}(t)\,. \qquad (8)$$

Monouser demodulators described in section II (or any other demodulator) can then be used to demodulate the signal.

In a situation when 2 AIS signals are mixed on the same time slot, the proposed method improvement consists in demodulating the most powerful signal (or more precisely the one for which (6) is maximal) then reconstruct this signal in GMSK (without noise) and use it as a dummy sensor to re-derive the weights (7) with P+1 sensors. This procedure is then generalized to the case of a mixture of K AIS signals by demodulating and reconstructing iteratively the signals.

C. Simulation results

In this simulation, signals 9 and 21 of the first slot are considered (Fig. 4). Signal 9 is the most powerful and it is then demodulated first with classical beamforming then reconstructed. Figs. 5 and 6 show obtained performances with the classical Viterbi demodulator when using classical beamforming and the proposed interference mitigation technique (with demodulated and reconstructed signal 9 as dummy sensor).

On these figures, the abscissa $\Delta E_b / N_0$ corresponds to the difference between a nominal SNR (Signal to Noise Ratio) stated by the simulator for a given scenario and the scenario simulated E_b / N_0 directly linked to the noise power on the sensors.

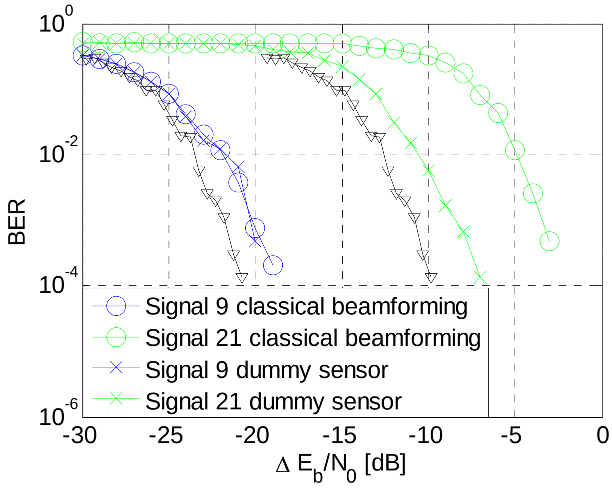

Figure 5. Initial beamforming and improved proposed method BER performances.

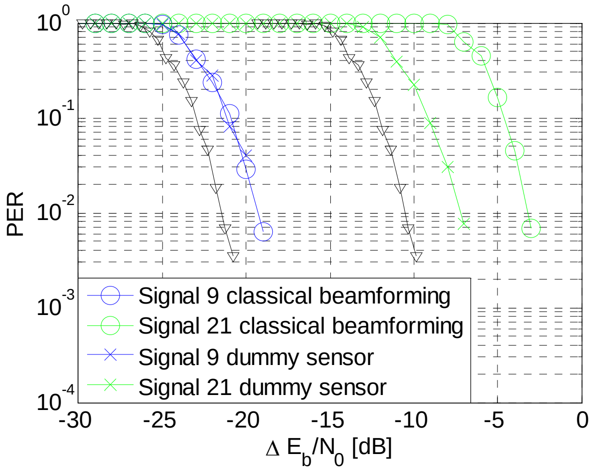

Figure 6. Initial beamforming and improved proposed method PER performances.

On those figures, monouser reference performances (representing best achievable results) are plotted with triangles. A 4 dB improvement on PER performances is observable for the weakest signal 21.

IV. CONCLUSION

This paper presented improved demodulation algorithm and interference mitigation technique for AIS signals received by a satellite. The demodulation algorithm, based on an extended trellis, detects and removes the stuffing bits, and demodulates the information bits taking into account the CRC. The dummy sensor beamforming technique allow to iteratively decode weak AIS signals present in the mixture. Simulations showed that proposed methods perform very well, showing large gains when compared to classical methods. Future works will address real signals (terrestrial) performance evaluation and reconstruction..

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