# INTERFERENCE MITIGATION AND ERROR CORRECTION METHOD FOR AIS SIGNALS RECEIVED BY SATELLITE

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## ABSTRACT

This paper addresses the problem of error correction in a multi-user trellis coded system in the presence of bit stuffing. In particular, one considers the situation in which automatic identification system (AIS) signals are received by a satellite. The proposed receiver uses a cyclic redundancy check (CRC) for error correction. A Viterbi algorithm based on a so-called extended trellis is developed. This trellis is defined by extended states composed of a trellis-code state and a CRC state. Moreover, special conditional transitions are defined in order to take into account the possible presence of bit stuffing. The proposed algorithm was first developed in a single-user context. It is generalized in this paper to a multi-user scenario by designing an interference mitigation method. This method allows one to derive a demodulation algorithm whose complexity is almost identical to that obtained in the single-user context. Some performance results are presented in the context of AIS and compared with results provided by existing techniques.

***Index Terms***— AIS, Satellite, CRC, bit-stuffing, Viterbi decoding, interference mitigation.

## 1. INTRODUCTION

This paper addresses the problem of demodulating messages received by a satellite transmitted by the automatic identification system (AIS) [1]. AIS is a self-organized TDMA access system, whose objective is to avoid collision of large vessels. Basically, the AIS is not designed for a satellite reception. However, the demodulation of AIS signals received by a satellite would be useful for the global supervision of the maritime traffic. To that purpose, new correction methods have to be developed in order to obtain acceptable packet error rates at low $E_b/N_0$. An efficient demodulation algorithm has been recently proposed in [2] in the context of a single-user scenario. The proposed algorithm was based on the use of a cyclic redundancy check (CRC). CRCs were initially derived for error detection only in data transmissions. However, different techniques have been previously proposed to use CRCs for error correction (see [2–5] and references therein). Unfortunately, these techniques cannot be used in the presence of bit stuffing, which occurs in AIS signals. Stuffing bits are inserted after the CRC calculation in order to create additional transitions in the message, and/or to avoid confusion between information bits and the end flag byte.

This paper presents a CRC-assisted demodulation algorithm for multi-user AIS signals. Note however that the proposed approach is not restricted to AIS, and can be useful for any system involving CRC, trellis coding, and bit stuffing. In [2], a single-user demodulation scheme has been developed by designing an appropriate Viterbi algorithm. More precisely, the Viterbi algorithm proposed in [2] is based on an extended trellis defined by extended states. Extended states are composed of CRC states and trellis coded (TC) states. Appropriate conditional transitions have been defined in order to take into account the possible presence of stuffing bits. This strategy showed interesting results that have resulted in the submission of two patents [6, 7]. The present paper considers a multi-user scenario where the data of a given user of interest have to be recovered from the received multi-user signal. A generalization of the single-user algorithm to the multi-user scenario would lead to an exponential complexity, making the receiver unusable. Therefore, this paper proposes to use a preprocessing step based on multi-user interference reduction. The resulting preprocessed signal is then demodulated using the algorithm developed in [2]. This strategy results in a small complexity increase with respect to the single-user case.

The paper is organized as follows. Section 2 recalls some CRC properties and introduces the concept of bit stuffing. The single-user Viterbi algorithm based on extended states and conditional transitions is presented in Section 3. The interference mitigation scheme advocated in this study is presented in Section 4. Section 5 presents some simulation results obtained from a realistic AIS simulator (developed by the CNES of Toulouse, France). A comparison with the multi-

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The authors would like to thank the DGA and the CNES for funding.

user strategy investigated in [8] is also investigated. Conclusions are finally reported in Section 6.

## 2. TRANSMISSION SCHEME

The AIS transmission scheme is illustrated in Fig. 1: 168 information bits are transmitted. A CRC is then computed and concatenated to these bits. The bit stuffing procedure is applied on the resulting sequence. The final binary sequence is encoded in non-return-to-zero inverted (NRZI), and modulated using the GMSK modulation.

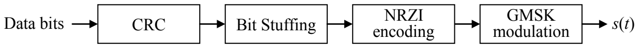


**Fig. 1**. Transmitter model for each user.

### 2.1. CRC Computation and Bit stuffing

It is well known that the CRC is defined as the remainder of the division (modulo 2) of the polynomial formed by the data and a standardized so-called generator polynomial, whose degree equals the length of the CRC plus one. Some zeros are generally added before the remainder to obtain a fixed-length CRC. At the receiver side, the CRC is computed from the received data, and compared with the CRC computed with the original data, which is added to the information bits before transmission. One or more errors are detected in the transmitted data if both CRCs are not identical. An important property of the CRC is that its computation can be performed iteratively by initializing the CRC to a standard value and by applying the operations to each data bit. This property is crucial for the strategy proposed in this paper, since the trellis is developed thanks to this iterative CRC computation.

Moreover, when the CRC is transmitted after the information bits, the receiver can compute a joint CRC on the sequence composed of the information bits and the CRC. Thus, instead of comparing two CRCs computed separately, there is no error when the joint CRC is zero such that

$$\text{CRC}([\text{Data}, \text{CRC}(\text{Data})]) = 0. \tag{1}$$

In addition to the CRC, some non-informative bits called stuffing bits can be inserted into the information message. The insertion of stuffing bits presents two main advantages: i) the generated additional transitions allows the receiver to resynchronize its clock; ii) it avoids some specific bit sequences, such as begin or end flags (composed of two bits 0 on each side of six consecutive bits 1 in the AIS system). Since only bits 0 are inserted in that case, this particular bit stuffing is called zero-bit insertion. In this paper, it is assumed for notation convenience, that the stuffing bit is always a bit 0, as specified for AIS.

### 2.2. GMSK modulation

The bit sequence obtained after the bit stuffing procedure is encoded using the NRZI coding. The resulting sequence is modulated with the Gaussian minimum shift-keying (GMSK) modulation. In the GMSK modulation, the transmitted signal $s(t)$ is a constant-modulus signal, which is expressed as

$$s(t) = \exp\left(-j2\pi h \sum_{k=-\infty}^{n} b_k q(t - kT)\right) \tag{2}$$

for $nT \leqslant t \leqslant (n+1)T$, where $T$ is the symbol period, $(b_k)_k$ is the bit sequence, $h$ is the modulation index, and $q(t)$ is the GMSK waveform [1].

## 3. SINGLE-USER SCENARIO

This section presents briefly the proposed detection algorithm in the single-user case (see [2] for the complete presentation), from which the interference mitigation-based algorithm is developed in the multi-user case.

### 3.1. General principle

Consider a frequency-flat transmission channel, whose transmission delay, Doppler and phase shifts are known by the receiver. The single-user received signal can be expressed without loss of generality as

$$r(t) = s(t) + n(t) \tag{3}$$

where $s(t)$ is the signal generated at the output of the encoding-plus-modulation block, as depicted in Fig. 1, and $n(t)$ is a white additive Gaussian noise, independent of the transmitted data. The received signal (3) is first passed through a matched filter and sampled with one sample per symbol. Let $r_k$ denotes the resulting sample obtained for the $k$th symbol period. The standard Viterbi algorithm minimizes the square Euclidean distance between the received samples and the estimated symbols defined as

$$d^2 = \sum_{k=1}^{K} |r_k - m_k|^2 \tag{4}$$

where $K$ is the number of received symbols, and $m_k$ is the sample of the $k$th estimated symbol after matched-filtering. The proposed algorithm is based on a constrained maximum likelihood estimator minimizing the square Euclidean distance defined in (4) subjected to two constraints: $C_1$) the number of consecutive ones is upper bounded by a maximum value $\overline{P}$ specified by the standard, $C_2$) the CRC satisfies (1). In order to satisfy these constraints, the proposed receiver is based on a trellis composed of extended states formed by a CRC state and a TC state.

The trellis is designed so that all paths ending with a final state give a message whose joint CRC is zero, according to (1) (note that the paths corresponding to a non zero CRC do not appear in the trellis). Moreover, the stuffing bits are taken into account by considering specific transitions in the extended trellis.

### 3.2. Trellis design

Since the CRC can be computed iteratively, it can be initialized depending on the AIS standard, and updated for every received bit. The CRC states are then defined as the intermediate CRC values. Two consecutive CRC states are linked if the second CRC can be obtained from the first one by updating the first CRC with one bit 0 or 1.

The algorithm proposed in [2] is based on a so-called extended trellis, where each state is composed of a CRC state and a TC state. These extended states are denoted $(A;\alpha)$ where $A$ is the CRC state and $\alpha$ is the TC state.

In order to perform a Viterbi algorithm adapted to this extended trellis, the distance $\Gamma[k,(A;\alpha)]$ is defined as the distance between the received signal and the sequence of $k$ symbols coming to the extended state $(A;\alpha)$ at time $k$, i.e.,

$$\Gamma[k,(A;\alpha)] = \sum_{i=1}^{k} |r_i - m_i^{k,(A;\alpha)}|^2 \qquad (5)$$

where $m_1^{k,(A;\alpha)}, \ldots, m_k^{k,(A;\alpha)}$ denotes the symbol sequence reaching $(A;\alpha)$ at time $k$. Moreover, $\Gamma_{\textit{trans}}[k,(A;\alpha),b]$ is the transition variable defined as the sum of $\Gamma[k,(A;\alpha)]$ and the squared distance between the received symbol at time $k+1$ and the symbol coming from the extended state $(A;\alpha)$ containing the bit $b$, denoted by $m_k^{k+1,(A;\alpha),b}$. More explicitly, one has

$$\Gamma_{\textit{trans}}[k,(A;\alpha),b] = \Gamma[k,(A;\alpha)] + \Delta[k,(A;\alpha),b] \qquad (6)$$

with

$$\Delta[k,(A;\alpha),b] = |r_k - \boldsymbol{m}_k^{k+1,(A;\alpha),b}|^2. \qquad (7)$$

These transition variables of the form $\Gamma_{\textit{trans}}[k,(A;\alpha),b]$ are used to choose the transition which leads to a given state, among the different possible transitions leading to this state, as detailed in [2].

### 3.3. Bit stuffing

In order to take bit stuffing into account, specific transitions are defined in the extended trellis. These transitions noted *SB* (for Stuffing Bit) only occur when a stuffing bit is received, which requires the receiver to decide if a received bit is a stuffing bit or not. To that end, each extended state $(A;\alpha)$ is assigned a state variable $P[k,(A;\alpha)]$, which is defined as the number of consecutive bits 1 received before the state $(A;\alpha)$ at time $k$. The received bit at time $k$ is declared as a stuffing bit when $P[k,(A;\alpha)]$ reaches a fixed maximum value $\overline{P}$ ($\overline{P}=5$ for AIS): in that case, the only possible transition from $(A;\alpha)$ is the *SB* transition. After this transition, $P[k+1,(A;\beta)]$ takes the value 0 (recall that only stuffing bits equal to 0 are considered in this paper).

Finally, each extended state $(A;\alpha)$ is assigned a state variable $S[k,(A;\alpha)]$, defined as the number of stuffing bits received before reaching $(A;\alpha)$, which indicates the number of informative bits in the received frame. This variable, along with some other variables, allow one to determine the optimal path in the extended trellis, respecting the constraints $C_1$ and $C_2$, as detailed in [2].

## 4. MULTI-USER SCENARIO

### 4.1. Received signal model

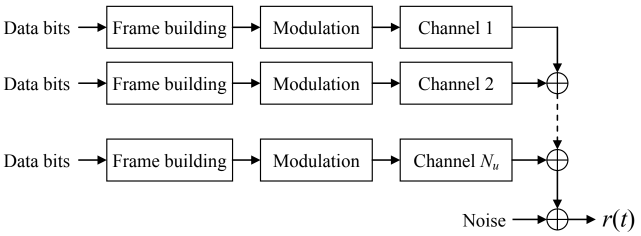


**Fig. 2**. Multi-user received signal model.

For each user, the transmission scheme is identical to that of Fig. 1. Denote $N_u$ as the number of users, and $s_j(t)$ the signal transmitted by the $j$th user, generated as in (2). In the case of frequency-flat channels, the multi-user received signal is the sum of multiple signals from each user defined as

$$r(t) = \sum_{j=1}^{N_u} a_j s_j(t-\tau_j) e^{-i(2\pi f_j t + \theta_j)} + n(t) \qquad (8)$$

where $\tau_j$, $f_j$, $\theta_j$ and $a_j$ are the delay, Doppler shift, phase shift, channel gain corresponding to the $j$th user, $N_u$ in the number of users and $n(t)$ is an additive white Gaussian noise. This paper assumes that, for a given user of interest, these parameters are known at the receiver side, along with the channel gains of all users. These parameters could for instance be estimated by correlating the pilot symbols (contained in the header) with the received AIS signal. This estimation procedure will be addressed in future works (see Section 6). The received signal can be processed to obtain the sum of the signal of interest and interferences as

$$r_u(t) = s_u(t) + \sum_{j \neq u} A_j s_j(t-T_j) e^{-i(2\pi F_j t + \Theta_j)} + n_u(t) \quad (9)$$

where $A_j = \frac{a_j}{a_u}$, $T_j = \tau_j - \tau_u$, $F_j = f_j - f_u$ and $\Theta_j = \theta_j - \theta_u$.

### 4.2. Multi-user interference reduction

A first possible demodulation strategy would consist of designing a multi-user extended trellis. However, this would assume that the system parameters of all users are available to the receiver, even for one single user of interest. Moreover, the computational complexity of the receiver would dramatically increase, since the trellis size is an exponential function of the number of users. Instead, one resorts to an interference mitigation technique, after which a single-user Viterbi algorithm based on an appropriate metric can be applied to demodulate the received signal. Hence, the computation increase due to the multi-user context is limited to that of interference mitigation, which is quite reduced. Consider first the case of one single interferer. The received signal (9) can be expressed as

$$r_u(t) = s_u(t) + A_I s_I(t - T_I) e^{-i(2\pi F_I t + \Theta_I)} + n_u(t) \quad (10)$$

where the subscript $I$ stands for the interferer. If the additive noise is negligible, and using the fact that $|s_I(t)| = 1$ (constant envelop signals), one has

$$\begin{aligned} |r_u(t) - s_u(t)| &\approx |A_I s_I(t - T_I) e^{-i(2\pi F_I t + \Theta_I)}| \\ &\approx A_I. \end{aligned} \quad (11)$$

Therefore, a least-squares (LS) approach can be investigated for signal demodulation. The LS approach consists of minimizing the energy of the difference $|r_u(t) - s_u(t)| - A_I$. The resulting cost function replacing (4) is

$$\sum_{k=1}^{K} ||r_{u,k} - m_{u,k}| - A_I|^2 \quad (12)$$

where $r_{u,k}$ and $m_{u,k}$ denote the sampled received signal $r_u(t)$ at the $k$th symbol period, and the sampled $k$th estimated symbol of the user of interest, respectively. With this new definition of the cost function, the detection algorithm presented in Section 3 can be used by transforming the transition variables (5) and (7) as

$$\Gamma[k, (A; \alpha)] = \sum_{i=1}^{k} \left| |r_i - m_i^{k,(A;\alpha)}| - A_I \right|^2 \quad (13)$$

and

$$\Delta[k, (A; \alpha), b] = \left| |r_k - m_k^{k+1,(A;\alpha),b}| - A_I \right|^2. \quad (14)$$

When several interferers are present in the received signal, the property (11) does not hold anymore. However, this property allows us to define an empirical approach, similar to the one proposed in [9]. More precisely, inspired by [9], we propose to define a cost function based on the LS criterion (12), given by

$$\sum_{k=1}^{K} \left| |r_{u,k} - m_{u,k}| - \sqrt{\bar{e}_u^2} \right|^2 \quad (15)$$

where $\bar{e}_u^2$ is the average power of interfering signals

$$\bar{e}_u^2 = \sum_{j \neq u} A_j^2 = \frac{1}{a_u^2} \sum_{j \neq u} a_j^2. \quad (16)$$

It can be observed that the cost function (15) actually reduces to (12) for a single interferer, and to (4) in the single-user scenario, where the gains $A_j$ are all zero. Note that the cost function of [9] would not be consistent with (4) and (12). With these definitions, the multi-user detection algorithm can be obtained from the single-user algorithm developed in Section 3, by replacing $A_I$ by $\sqrt{\bar{e}_u^2}$ in (13) and (14).

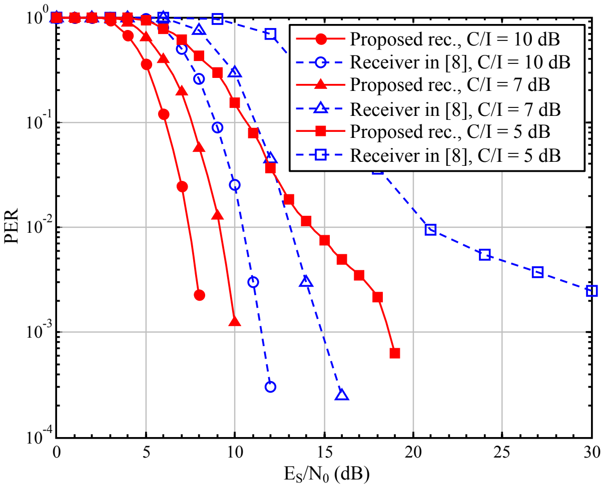
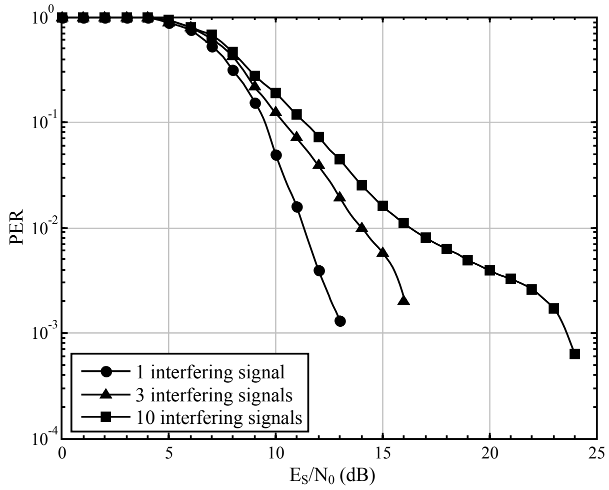


**Fig. 3**. Comparison in PER between the proposed receiver with 4 interfering signals and the strategy introduced in [8] for different career-to-interference power ratios (C/I).

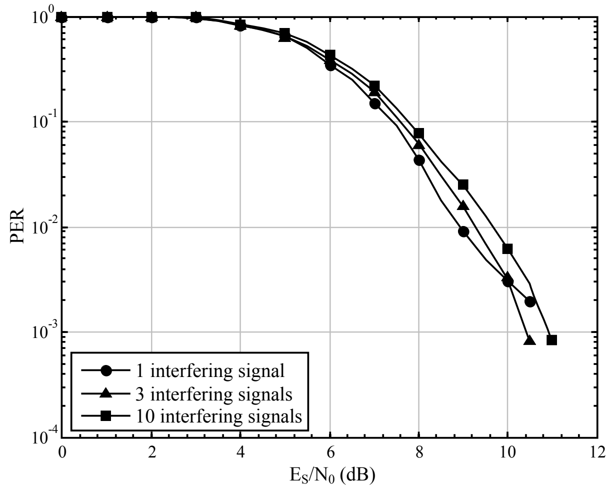
The different steps of the multi-user detection algorithm are then identical to those of the single-user scenario. Note that the computational cost in the multi-user scenario is very similar to that of the single-user algorithm, since it just increases by the introduction of the average power $\bar{e}_u^2$ (which is computed once at the initialization of the algorithm) into the squared distances (13) and (14). In particular, this increase does not depend on the number of users, which is a key advantage of this approach.

## 5. SIMULATIONS

This section presents some simulation results obtained for the AIS in the multi-user scenario. Each user sends fixed length data messages composed of 168 bits concatenated with a 16-bit CRC. The stuffing bits are then inserted according to the AIS recommendation. The frame is encoded with NRZI, and modulated in GMSK with a bandwidth-bit-time product parameter $BT = 0.4$. In this system model, NRZI coding and GMSK modulation constitute the TC. The generator polynomial for CRC computation is $G(x) = x^{16} + x^{12} + x^5 + 1$ (specified by the AIS recommendation). The multi-user channel corresponds to (8). In this paper, one assumes perfect carrier and timing recoveries for the user of interest. A simple transformation is applied to the received signal to obtain the desired signal model (9). The proposed receiver is compared with the method presented in [8], which uses a non-coherent GMSK demodulator and an error correction mechanism based on the presence of the CRC. Fig. 3 compares the performances in terms of packet error rates (PER) of the proposed receiver with 4 interfering signals, with those given



(a) C/I $= 5$ dB



(b) C/I $= 7$ dB

**Fig. 4**. Influence of the number of interfering signals on the performance in PER with C/I $= 5$ dB (a) and C/I $= 7$ dB (b).

in [8] (PER is the main performance criterion in AIS). Note that the PER curves associated with the technique developed in [8] have been obtained without introducing bit stuffing, contrary to the PER curves for the proposed receiver.

The proposed method provides a gain of at least 3 dB when the interference level is low and more than 6 dB when the interference level is high. These results show that the proposed receiver is more resistant to interferences than the receiver of [8] (in addition, the receiver allows bit stuffing to be considered, contrary to the algorithm of [8]). This is due jointly to the interference mitigation and to the efficiency of the proposed error correction strategy.

Fig. 4(a) shows the evolution of performance with respect to the number of interfering signals, for a carrier-to-interference ratio (C/I) fixed to 5 dB. One can see that, the more concentrated the interference power into one single signal, the better the performance. This can be explained as follows: the interference is better reduced when the interference is concentrated into one single interfering user. Indeed, in this case, the mean power $\bar{e}_u^2$ is close to the instantaneous interference power resulting in good interference reduction. The performance difference decreases when C/I increases, as shown in Fig. 4(b) (corresponding to C/I $= 7$ dB). Indeed, with higher C/I, the interference power is negligible, and interference mitigation techniques are less relevant.

## 6. CONCLUSION

This paper studied a multi-user version of a CRC-based receiver algorithm for the demodulation of AIS signals. The proposed algorithm resulted in a small increase of computational complexity with respect to the single-user case. The error correction method allowed all the redundancies present in the messages to be considered. The bit stuffing included between CRC computation and trellis coding was also compensated. Simulation results illustrated the algorithm performance in terms of packet error rates. A gain of at least 3 dB was obtained when compared to another demodulation technique developed in the same context. Future investigations include the study of the phase recovery problem in the case of an unknown phase shift and/or a variation of the actual modulation index. An interesting solution was proposed in [10] for the single-user scenario. The generalization of this method to the multi-user case is currently under investigation.

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