JOINT PHASE-RECOVERY AND DEMODULATION-DECODING OF AIS SIGNALS RECEIVED BY SATELLITE

Raoul Prévost[1,2], Martial Coulon[1], David Bonacci[2], Julia LeMaitre[3],
Jean-Pierre Millerioux[3] and Jean-Yves Tourneret[1]

[1] University of Toulouse, INP-ENSEEIHT/IRIT, 2 rue Charles Camichel, BP 7122, 31071 Toulouse cedex 7, France

[2] TéSA, 14-16 Port Saint-Étienne, 31000 Toulouse, France   [3] CNES, 18 Avenue Edouard Belin, 31400 Toulouse, France

{raoul.prevost, david.bonacci}@tesa.prd.fr, {martial.coulon, jean-yves.tourneret}@enseeiht.fr,
{julia.lemaitre, jean-pierre.millerioux}@cnes.fr

ABSTRACT

This paper presents a demodulation algorithm for automatic identification system (AIS) signals received by a satellite. The main contribution of this work is to consider the phase recovery problem for an unknown modulation index, coupled with a time-varying phase shift. The proposed method is based on a demodulator introduced in a previous paper based on a Viterbi-type algorithm applied to an extended trellis. The states of this extended trellis are composed of a trellis-code state and of a cyclic redundancy check state. The bit stuffing mechanism is taken into account by defining special conditional transitions in the extended trellis. This algorithm estimates and tracks the phase shift by modifying the Euclidean distance used in the trellis. Simulation results obtained with and without phase tracking are presented and compared in the context of the AIS system.

Index Terms— AIS, satellite, CRC, Viterbi decoding, phase tracking.

1. INTRODUCTION

The objective of this paper is to present a new phase-recovery scheme for demodulation of automatic identification system (AIS) signals received by satellite. The AIS system is a radio frequency-based communication system designed primarily as a collision avoidance system for large vessels. AIS messages consist of short bursts broadcasted in VHF with a self-organized TDMA (SO-TDMA) access [1]. The AIS system was not originally conceived for a satellite reception. However, it appears possible to demodulate AIS signals recorded by a satellite for maritime traffic surveillance. Even if operational systems are existing [2], new systems are under study in order to improve the detection rate of AIS signals [3–8]. One interesting way to improve this detection rate is to optimize the demodulation in order to work at low values of E_b/N_0. A powerful algorithm using the cyclic redundancy check of AIS signals to correct transmission errors (and considering bit-stuffing) was derived by the authors in [9], assuming a perfect phase recovery. In this paper, we propose a phase recovery scheme coupled with this algorithm leading to a very limited performance degradation. Phase recovery of AIS signals appears to be a challenging problem, especially because of possibly large fluctuations of the modulation index from an AIS equipment to another, due to the electronic of the transmitter. In this context, residual frequency offset and phase noise effects appear to be second

order problems. Note that the AIS system is an already operational system, in which link budgets between vessels allow the use of non coherent demodulators while keeping large margins. With non coherent demodulators and large margins, phase fluctuations and modulation index inaccuracy have limited consequences. However, when trying to optimize the value of E_b/N_0 with a coherent demodulator for satellite reception, specific approaches have to be considered. The algorithm proposed here is based on a per survivor processing (PSP) approach [10]. The main constraint for the algorithm design is to control its computational complexity (because of the large trellis [9]). This prevents us to use a decision directed algorithm [11, 12] and imposes to consider a very simple phase estimation upgrade of [9]. The proposed algorithm with joint phase recovery and demodulation/decoding is compared with an alternative approach using the Viterbi and Viterbi non data aided (NDA) phase recovery algorithm [13] followed by the demodulation/decoding presented in [9].

The principle of the approach proposed in [9] consists of designing an extended trellis for which a particular Viterbi algorithm is performed. This extended trellis is defined by extended states composed of a cyclic redundancy check (CRC) state and a trellis code (TC) state. On the other hand, the bit stuffing procedure is taken into account by introducing particular conditional transitions in the extended trellis. The principle of the extended trellis and its conditional transitions has been addressed in [9, 14, 15] assuming perfect phase recovery. The main contribution of this work is to consider the phase recovery problem by incorporating the unknown phase in the Euclidean distance used in the trellis of [9] and by minimizing this distance at each symbol period with respect to the phase.

The paper is organized as follows. Section 2 presents the transmitter characteristics and the received signal model. Section 3 describes the detection algorithm with a specific attention to the phase tracking technique, which constitutes the main novelty of this paper. Some simulation results are given in section 4, which illustrate the performances of the proposed approach on a realistic AIS simulator, developed by the CNES of Toulouse, France. Conclusions are reported in Section 5.

2. TRANSMITTER DESIGN AND CHANNEL MODEL

This paper considers single-user AIS transmissions. The information sequence is composed of 168 bits, on which is computed a 16-bit CRC. This CRC is concatenated to the 168 information bits. The bit stuffing procedure is then applied to the resulting sequence. The frame is encoded using the NRZI coding, and then modulated using a GMSK modulation. Some properties of the different parts of the

transmitter design are briefly recalled below.

2.1. Cyclic redundancy check properties

It is well known that the CRC is defined as the remainder of the division (modulo 2) of the polynomial derived from the data and a standardized generator polynomial, whose degree equals the length of the CRC plus one. Some zeros may be inserted before the remainder in order to obtain a fixed-length CRC. A comparison between the CRC computed from the received data and the CRC contained in the data frame allows the receiver to detect some errors. A key property of the CRC is that it can be computed iteratively by initializing the CRC to a standard value and by applying operations sequentially to each data bit [9]. This very important property enables an extended trellis to be defined, as explained in section 3.2. On the other hand, since the CRC is included in the information bits on which it is computed, one can define a joint CRC on the bit sequence composed of the data and the CRC. No error is detected at the receiver if this joint CRC is zero, i.e.,

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

2.2. Bit stuffing procedure

The bit stuffing procedure presents two main goals: i) by generating additional transitions in the transmitted signal, it allows the receiver to re-synchronize its clock; ii) it enables specific bit sequences to be avoided, such as begin or end flags. In the AIS system, a bit 0 is added after five consecutive bits 1, in order to avoid that a data sequence is considered as the end frame flag byte (composed of two bits 0 on each side of six consecutive bits 1). By definition of the stuffing bits, their presence and their location are random. The receiver must then detect and localize them before recovering the information bits.

2.3. GMSK modulation

The bit sequence obtained after the bit stuffing procedure is encoded using the non-return-to-zero inverted (NRZI) coding. The resulting sequence is modulated with the Gaussian minimum shift-keying (GMSK) modulation. Recall that, in the GMSK modulation, the transmitted signal $s(t)$ is a constant-modulus signal defined as

$$s(t) = e^{-j\theta(t;\mathbf{B})}$$

where the phase $\theta(t;\mathbf{B})$ contains the information symbols

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

In (2), T is the symbol period, $\mathbf{B} = \{b_k\}$ is the bit sequence, h is the modulation index, and $q(t)$ is the GMSK waveform [1]. In the AIS system, the modulation index is theoretically equal to $h = 0.5$. However, the actual modulation index can be significantly different ($\pm 15\%$ variations can be observed). At the receiver, non-data aided (NDA) estimation of the modulation index (e.g., see [16]) is very difficult because the bursts are very short with low E_b/N_0. A rough estimation is possible using the known preamble of AIS signals (32 bits). However this estimation is inaccurate. Consequently, it appears pragmatic for the receiver design to model the effect of an inaccurate modulation index as a simple random phase fluctuation.

2.4. Received signal model

Denote by $s(t)$ the signal generated by the GMSK modulator. In this paper, one considers a frequency-flat channel, whose transmission delay and Doppler shift are known by the receiver. These parameters could for instance be estimated by correlation-based techniques using the headers as pilot symbols. However, these estimation issues

are beyond the scope of this paper and will be addressed in future works. As mentioned above, variations of the modulation index can be interpreted as a random phase shift $\phi(t)$, so that the received signal can be expressed without loss of generality as

$$r(t) = e^{j\phi(t)}s(t) + n(t) \tag{3}$$

where $n(t)$ is a white additive Gaussian noise independent of the transmitted signals. The objective is to recover the information data contained in the signal $s(t)$ from the received signal $r(t)$. To that end, one proposes to generalize the CRC-based detection method proposed in [9] which jointly detects and removes the stuffing bits, and detects the information bits by incorporating a phase tracking procedure.

3. RECEIVER DESCRIPTION

3.1. General principle

The received signal (3) is first passed through a matched filter (MF) and sampled with one sample per symbol. Let r_k denotes the sample obtained for the kth symbol period. Denote as K the number of received symbols. One assumes that the phase variations are sufficiently slow to consider the phase shift $\phi(t)$ as constant during the kth symbol, i.e., $\phi(t) = \phi_k$. Hence, only one value of the phase has to be estimated. The objective of the Viterbi algorithm developed here is to determine the maximum likelihood symbol sequence which minimizes the square Euclidean distance defined by

$$\sum_{k=1}^{K} \left| e^{-j\phi_k} r_k - m_k \right|^2 \tag{4}$$

where m_k denotes the sample of the kth estimated symbol after MF. Due to the possible presence of stuffing bits and the use of the CRC, the minimization should satisfy the two following constraints

1. the joint CRC should verify (1).

2. the number of consecutive bits 1 is upper bounded by a value $\overline{P}$, specified by the application standard ($\overline{P} = 5$ for the AIS).

In the algorithm designed in this paper, these constraints are taken into account by defining a so-called extended trellis introduced initially in [9], whose states (referred to as extended states) are composed of a CRC state and a trellis code (TC) state. To ensure the first constraint, the trellis paths end with final states that give a message whose joint CRC is zero (hence, paths corresponding to a non zero CRC do not appear in the trellis). On the other hand, constraint 2 is obtained by defining specific transitions in the extended trellis. The extended trellis and the specific transitions are defined below, where the term CRC refers to as the joint CRC defined in section 2.1.

3.2. Extended trellis construction

Since the CRC can be computed iteratively, it can be initialized to a particular value given by the CRC standard, and then updated at each received bit. A CRC state is then defined as a particular intermediate CRC value. Two consecutive CRC states are connected if the second CRC state can be obtained from the first one by including a bit 0 or a bit 1.

To compose an extended state, a CRC state is associated with a state of the trellis code (a TC state) and both trellis behave in parallel with the same bits. This mechanism is depicted in (5), where the integer k corresponds to the kth received symbol.

$$
\begin{array}{ccccc}
\text{CRC state} & & \text{TC state} & & \text{Extended state} \\
{\scriptstyle k \quad\;\; k+1} & & {\scriptstyle k \quad\;\; k+1} & & {\scriptstyle k \qquad\quad k+1} \\
A \xrightarrow{0} B & \& & \alpha \xrightarrow{0} \beta & \Rightarrow & (A;\alpha) \xrightarrow{0} (B;\beta) \\
A \xrightarrow{1} C & & \alpha \xrightarrow{1} \gamma & & (A;\alpha) \xrightarrow{1} (C;\gamma)
\end{array} \tag{5}
$$

The number of states associated with the extended trellis equals the product between the number of states of the TC trellis (i.e., 4 for the AIS system) and the number of states of the CRC trellis (i.e., 2^{16}). The total number of states per symbol is therefore $2^{18} = 262\,144$. The decoding of an AIS message requires about 1 second per message for our simulator programmed in C with a 2.6-GHz processor. This is in agreement with the AIS application (even if the total number of states can seem to be large) which requires any message to be processed in less than 5 seconds. It is interesting to note here that the average computation time could be reduced by applying the proposed error correction method only when the CRC of the AIS message resulting from the conventional receiver is incorrect.

3.3. Phase tracking method

The important phase fluctuations induced by the modulation index inaccuracy make the use of an NDA algorithm difficult (as it needs a large integration window to limit noise effect). A full complexity PSP approach [11, 12] (i.e., considering all trellis paths) is not appropriate here because of the huge number of states and paths in the trellis considered in this paper. One might think of using reduced complexity PSP [17] or tentative decision (TD) algorithms. However, since these algorithms consider a limited number of paths, the selection of these paths (according to their probability) at each symbol period makes these algorithms intractable in our application. The method investigated in this paper overcomes this complexity issue by applying the Viterbi algorithm to the extended trellis designed previously, and by including a phase term in the Euclidean distances used in the algorithm. The procedure described below explains how the algorithm selects a path reaching a given state (denoted as $(B;\beta)$) at time $k + 1$ from different possible states at time k. Note that all the following variables should be indexed by $(B;\beta)$. However this notation has been omitted for clarity reasons.

Let $(A;\alpha)$ denote one of the possible states at time k. The squared Euclidean distance between the received signal up to time time k and the sequence of k symbols coming to the extended state $(A;\alpha)$ at time k is defined by

$$\Gamma[k,(A;\alpha)] = \sum_{i=1}^{k} \left| e^{-j\phi_i^{k,(A;\alpha)}} r_i - m_i^{k,(A;\alpha)} \right|^2 \qquad (6)$$

where $\left(\phi_1^{k,(A;\alpha)}, \ldots, \phi_k^{k,(A;\alpha)}\right)$ and $\left(m_1^{k,(A;\alpha)}, \ldots, m_k^{k,(A;\alpha)}\right)$ denote the sequences of estimated phase shifts and symbols in the path reaching the state $(A;\alpha)$ at the kth symbol period, respectively.

Define as $\Delta[k,(A;\alpha),b,\phi]$ 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 $m_k^{k+1,(A;\alpha),b}$) for a given phase shift ϕ, i.e.,

$$\Delta[k,(A;\alpha),b,\phi] = \left| e^{-j\phi} r_{k+1} - m_k^{k+1,(A;\alpha),b} \right|^2. \qquad (7)$$

The transition variable $\Gamma_{\text{trans}}[k,(A;\alpha),b]$ from the state $(A;\alpha)$ at time k to the state $(B;\beta)$ at time $k + 1$ is obtained by minimizing $\Delta[k,(A;\alpha),b,\phi]$ with respect to the unknown phase shift ϕ, i.e., by solving the following optimization problem

$$\Delta_{\min}[k,(A;\alpha),b] = \min_{\phi \in \mathcal{I}_k^{(A;\alpha)}} \Delta[k,(A;\alpha),b,\phi] \qquad (8)$$

and then by defining

$$\Gamma_{\text{trans}}[k,(A;\alpha),b] = \Gamma[k,(A;\alpha)] + \Delta_{\min}[k,(A;\alpha),b]. \qquad (9)$$

Note that $\Delta_{\min}[k,(A;\alpha),b]$ represents the minimum increment to reach $(B;\beta)$ from $(A;\alpha)$ with respect to the unknown phase ϕ,

when b has been received. The minimization of (8) is achieved by varying ϕ in the set $\mathcal{I}_k^{(A;\alpha)}$ defined by

$$\mathcal{I}_k^{(A;\alpha)} = \left[\phi_k^{k,(A;\alpha)} - \Delta\phi; \phi_k^{k,(A;\alpha)} + \Delta\phi \right] \qquad (10)$$

where $\phi_k^{k,(A;\alpha)}$ is the current estimated phase shift in the path reaching the state $(A;\alpha)$ at time k, and $\Delta\phi$ is a positive real value. Eq. (10) means that one tracks the phase shift at time $k + 1$ from the phase shift at time k into a window of length $2\Delta\phi$. The problem (8) is an elementary minimization problem, whose analytic solution is omitted here for brevity. Let $\phi_{\text{trans}}^{k,(A;\alpha),b}$ denote the optimal phase shift in (8). Similarly to $\Gamma_{\text{trans}}[k,(A;\alpha),b]$, the transition phase $\phi_{\text{trans}}^{k,(A;\alpha),b}$ is used when the algorithm has to choose a transition toward the state $(B;\beta)$. Indeed, among the different states $(A;\alpha)$ which lead to $(B;\beta)$ at time $k + 1$, the selected phase $\phi_{\text{trans}}^{k,(A;\alpha),b}$ corresponds to the selected variable $\Gamma_{\text{trans}}[k,(A;\alpha),b]$. The value of the selected phase $\phi_{\text{trans}}^{k,(A;\alpha),b}$ becomes the new value of the phase $\phi_{k+1}^{k+1,(B;\beta)}$ at time $k + 1$ in the state $(B;\beta)$.

While a simple analytic solution exists for problem (8), the algorithm can be speed up by discretizing the phase estimation problem. It means that one estimates the phase shift in the finite set $\{0, \delta_\phi, 2\delta_\phi, \ldots, 2\pi - \delta_\phi\}$ instead of estimating it in the continuous set $[0; 2\pi]$. The quantizing step is defined by $\delta_\phi = 2\pi/N_\phi$, where N_ϕ is the number of possible phase values, which tunes the estimation accuracy. In this case, the research set $\mathcal{I}_k^{(A;\alpha)}$ in (10) has to be replaced by the finite set $\widetilde{\mathcal{I}}_k^{(A;\alpha)}$ defined by

$$\widetilde{\mathcal{I}}_k^{(A;\alpha)} = \left\{ \phi_k^{k,(A;\alpha)} - n_\phi\delta_\phi, \ldots, \phi_k^{k,(A;\alpha)} + n_\phi\delta_\phi \right\} \qquad (11)$$

where the integer n_ϕ is the integer part of $\Delta\phi/\delta_\phi$. Note that $\phi_k^{k,(A;\alpha)}$ appearing in (11) (obtained at the previous iteration) is also a multiple of δ_ϕ. Similarly, $\Delta_{\min}[k,(A;\alpha),b]$ is defined by

$$\Delta_{\min}[k,(A;\alpha),b] = \min_{\phi \in \widetilde{\mathcal{I}}_k^{(A;\alpha)}} \Delta[k,(A;\alpha),b,\phi] \qquad (12)$$

and $\phi_{\text{trans}}^{k,(A;\alpha),b}$ is the value of the phase which minimizes (12). The discrete minimization simply reduces to find the minimum value among the $2n_\phi + 1$ values of $\Delta[k,(A;\alpha),b,\phi]$, which greatly speeds up the computation of $\Delta_{\min}[k,(A;\alpha),b]$ (n_ϕ is generally small, e.g., $n_\phi \leq 10$ in the simulations presented below). Moreover, since the number of states is significant, the minimization (12) does not need to be computed for each state at a given time k. Indeed, there is only a small number of possible symbols $m_k^{k+1,(A;\alpha),b}$ denoted as N_{symb}. It means that there are $N_{\text{symb}}N_\phi$ possible values of $\Delta[k,(A;\alpha),b,\phi]$ for all states b and ϕ. Thus, for a given time instant k, these $N_{\text{symb}}N_\phi$ values, their minima in the N_ϕ possible sets $\widetilde{\mathcal{I}}_k^{(A;\alpha)}$ and the arguments of these minima can be precomputed and saved into tables. Hence, for a given state $(A;\alpha)$ and a given b, $\Delta_{\min}[k,(A;\alpha),b]$ and $\phi_{\text{trans}}^{k,(A;\alpha),b}$ are simply obtained by selecting appropriate values in these tables.

After the phase tracking, the variables $\Gamma_{\text{trans}}[k,(A;\alpha),b]$ are used to choose the transition which leads to a given state minimizing $\Gamma_{\text{trans}}[k,(A;\alpha),b]$.

3.4. Bit stuffing consideration

The extended trellis presented above allows the CRC to be used as an error correction tool. However, it cannot take into account the possible presence of stuffing bits. Thus, one proposes to complete the extended trellis by introducing specific transitions, which are only used when a stuffing bit is received. The principle of these transitions consists of generating a change in the TC state when a stuffing bit is detected while keeping unchanged the CRC state. Indeed, since
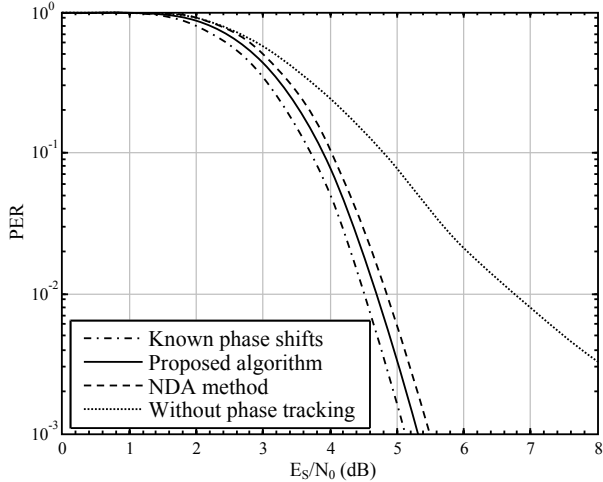
Fig. 1. PER for a fluctuating phase. The proposed receiver is compared with the NDA algorithm and the algorithm presented in [9] that assumes a known phase shift.

the CRC is computed (at the transmitter side) before the bit stuffing procedure, the stuffing bits must not modify the CRC state. These specific transitions have been introduced in [9].

3.5. Final state decision

Once the extended trellis has been designed, one has to determine the optimal path in this trellis. The proposed procedure is identical to the one described in [9] and is not recalled here for brevity.

4. SIMULATIONS

This section presents some simulation results obtained in different scenarios. The proposed algorithm and the algorithm presented in [9] (assuming the modulation index h and the phase shift are known) are illustrated and compared for all these scenarios. Moreover, the performance of the NDA algorithm [13] is also given for comparison. 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 $G(x) = x^{16} + x^{12} + x^5 + 1$. An additive white Gaussian noise (AWGN) channel is considered. In this paper, one assumes perfect carrier and timing recovery. The first scenario involves a fluctuating phase, while an inaccurate modulation index h is considered in the second scenario.

4.1. Phase fluctuations

The first scenario considered in this paper consists of a phase fluctuation of the AIS transmitter which can be due to a temperature variation of the modulator components. In order to simulate this fluctuating phase, a phase shift is applied to the signal at the generator output. This phase rotates randomly between symbols with a standard deviation of $\sigma = 1°$ and remains constant during the symbols. For this simulation, $\Delta\phi$ used in $(10) - (11)$ is set to $4°$ and the integration time of the NDA estimator corresponds to 30 symbols.

Fig. 1 shows the packet error rate (PER) curves for the different methods. The proposed receiver slightly outperforms the NDA method. Its performance is also close to that obtained with a known phase shift (which can be considered as the optimal performance). The gain with respect to the receiver without phase tracking is larger than 1 dB for an E_S/N_0 higher than 4 dB.
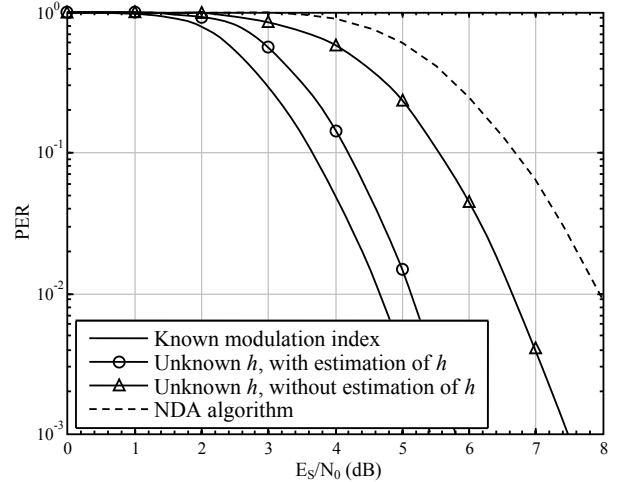

Fig. 2. PER for an inaccurate modulation index h. The proposed receiver is compared with the NDA algorithm and the algorithm presented in [9] that assumes a known h.

4.2. Inaccurate modulation index

To simulate an incorrect modulation index in the transmitter, the modulations have been generated using $h = 0.45$ (instead of 0.5 specified by the AIS recommendation). Two cases are investigated in this paper: i) h is estimated using the AIS preamble and a cross-correlation method, and the parameter $\Delta\phi$ is set to $4°$; ii) h is not estimated, and the value given by the AIS recommendation ($h = 0.5$) is used in the algorithm. In that case, one sets $\Delta\phi = 10°$. Due to the fast phase rotation induced by the modulation index inaccuracy, the integration time of the NDA estimator should be short. It has been set to 8 symbols in all experiments.

The performance of the proposed receiver for an inaccurate modulation index h is shown in Fig. 2. A significant improvement is obtained with respect to the NDA algorithm especially when the modulation index is estimated using the AIS preamble. The performance with and without estimation of h are 2.5 dB and 1 dB better than those of the NDA algorithm. Moreover, they are about 0.5 dB and 2 dB above those obtained with known modulation index. This figure illustrates the fact that the proposed method outperforms the usual NDA approach in the situation (encountered in the AIS system) where the actual modulation index deviates from its nominal value.

5. CONCLUSION

This paper presented a demodulation algorithm coupled with a phase tracking procedure for AIS signals received by a satellite (with unknown phase shift and modulation index). This algorithm based on an extended trellis jointly estimates the phase shift, detects and removes the stuffing bits, and demodulates the information bits. Simulations showed that the proposed method performs better than the NDA phase recovery algorithm. Future works will concentrate on the time-delay estimation and multi-user transmissions.

6. RELATION TO PRIOR WORK

The reception of AIS signals by satellite is a very active subject [3–8] which led us to propose new transmission error correction methods [9, 18]. This paper is considering a more realistic model for AIS signals including an unknown (possibly time-varying) phase. The performance of the resulting joint phase-recovery and demodulation decoding algorithm is shown to be very promising.

7. REFERENCES

[1] Recommendation ITU-R M.1371, "Technical characteristics for a universal automatic identification system using time division multiple access in the VHF maritime mobile band." ITU, 2001.

[2] "exactEarth," *http://www.exactearth.com*, 2010.

[3] A. Scorzolini, V. D. Perini, E. Razzano, G. Colavolpe, S. Mendes, P. Fiori, and A. Sorbo, "European enhanced space-based AIS system study," in *Proc. Adv. Sat. Mul. Sys. Conf.*, no. 5, Cagliari, Italy, Sept. 2010, pp. 9–16.

[4] M. J. Gallardo and U. Sorger, "Coherent receiver for AIS satellite detection," in *Int. Symp. Commun. Control Signal Process.*, vol. 4, March 2010, pp. 1–4.

[5] J. Larsen, H. Mortensen, and J. Nielsen, "An SDR based AIS receiver for satellites," in *Proc. Int. Conf. Recent Advances in Space Technologies*, vol. 5, June 2011, pp. 526–531.

[6] M. Zhou, A. van der Veen, and R. van Leuken, "Multi-user LEO-satellite receiver for robust space detection of AIS messages," in *Proc. IEEE Int. Conf. Acoust., Speech, and Signal Processing*, vol. 37, March 2012, pp. 2529–2532.

[7] N. Bouny, J. LeMaitre, and J.-P. Millerioux, "Results of measurement campaign for characterisation of AIS transmitters," in *Proc. Adv. Sat. Mul. Sys. Conf.*, vol. 12, Sept. 2012, pp. 258–265.

[8] M. Picard, M. R. Oularbi, G. Flandin, and S. Houcke, "An adaptive multi-user multi-antenna receiver for satellite-based AIS detection," in *Proc. Adv. Sat. Mul. Sys. Conf.*, vol. 12, Sept. 2012, pp. 273–280.

[9] R. Prévost, M. Coulon, D. Bonacci, J. LeMaitre, J.-P. Millerioux, and J.-Y. Tourneret, "CRC-assisted error correction in a trellis coded system with bit stuffing," in *Proc. IEEE Workshop on Stat. Signal Process.*, Nice, France, June 2011, pp. 381–385.

[10] R. Raheli, A. Polydoros, and C. Tzou, "Per-survivor processing: a general approach to MLSE in uncertain environments," *IEEE Trans. Commun.*, vol. 43, no. 234, pp. 354–364, 1995.

[11] M. Morelli, U. Mengali, and G. M. Vitetta, "Joint phase and timing recovery with CPM signals," *IEEE Trans. Commun.*, vol. 45, no. 7, pp. 867–876, 1997.

[12] Q. Zhao and G. L. Stüber, "Joint time and phase recovery for CPM and its asymptotic behavior," in *Proc. IEEE Global Commun. Conf.*, vol. 4, Dec. 2005, pp. 2302–2306.

[13] A. J. Viterbi and A. M. Viterbi, "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," *IEEE Trans. Inf. Theory*, vol. 29, no. 4, pp. 543–551, 1983.

[14] R. Prévost, D. Bonacci, M. Coulon, J. LeMaitre, J.-P. Millerioux, and J.-Y. Tourneret, "Multi-encodage error correction with extended trellis," Patent Pending.

[15] ——, "A Viterbi algorithm with conditional transitions," Patent Pending.

[16] P. Bianchi, P. Loubaton, and F. Sirven, "Non data-aided estimation of the modulation index of continuous phase modulations," *IEEE Trans. Signal Process*, vol. 52, no. 10, pp. 2847–2861, 2004.

[17] R. Raheli, G. Marino, and P. Castoldi, "Per-survivor processing and tentative decisions: What is in between?" *IEEE Trans. Commun.*, vol. 44, no. 2, pp. 127–129, 1996.

[18] R. Prévost, D. Bonacci, M. Coulon, J. LeMaitre, J.-P. Millerioux, and J.-Y. Tourneret, "Extended constrained Viterbi algorithm for AIS signals received by satellite," in *Proc. IEEE-AESS Conf. Telecom. Satellite*, Rome, Italy, Oct. 2012.