An Advanced AIS Receiver using a Priori Information

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***Abstract*—Automatic Identification System (AIS) reception at flying platforms (satellites or airliners) has attracted an increasing level of attention over the last years. AIS allows vessels to communicate with each other and was originally designed as a vessel collision avoidance mechanism. Although AIS was not designed taking into account a satellite component, it is possible to receive AIS packets using satellites. However, satellite-aided AIS reception is challenging. Satellites receive AIS messages of all ships within a vast geographical area that usually tend to collide with each other. Consequently, the satellite receiver operates at lower SINR values compared to a conventional AIS receiver in a vessel or base station. In this paper we present an advanced receiver for AIS. This receiver exploits the a priori knowledge that the receiver has on some of the fields of the AIS position reports messages. In some cases this allows the receiver to double the number of training symbols that can be used for channel estimation. This receiver design is particularly suitable for receivers placed on flying platforms but it can also be used in other platforms such as vessels.**

I. Introduction

The Automatic Identification System [1], allows the exchange of navigational data between vessels and between vessels and shore stations. AIS uses Self Organized Time Division Multiple Access (SOTDMA). This means that time is divided into slots and that users in AIS (vessels or shore stations) coordinate with other users within their reception range in a decentralized manner in order to avoid interference. Most of the messages exchanged in AIS are position reports which contain the position and heading of vessels (among other message fields). The exchange of these messages allows ships to know if there are other vessels in their vicinity, where they are located and in which direction they are sailing. This information is very useful for collision avoidance, specially under low visibility conditions.

Originally, AIS did not consider a satellite or an airborne receiver platform. However, it was soon realized that satellite-aided reception of AIS messages was possible and of interest ([2], [3],[4], [5], [6] and [7]) because it allows the reception of AIS messages from a wide area without the need to deploy any infrastructure (except for the satellite or aircraft itself). This extended reception range is not only an advantage but also a challenge because the satellite usually illuminates several SOTDMA cells whose transmissions interfere with each other. In [8] and [9], the authors show how a satellite may receive a large number of collided AIS messages. This translates into an increase in the level of interference at the satellite receiver. Additionally, a LEO satellite needs to deal with a larger path loss than a conventional AIS receiver, due to the much larger distance between the transmitter (a vessel) and the receiver. In fact typical AIS Links between vessels or between vessels and base stations are at most 40 nautical miles long, whereas a typical LEO satellite orbits earth at an altitude ranging from 600 to 1200 km. Hence, due to collisions and due to the larger path loss, the AIS satellite receiver will operate at a low SINR. At these low SNIR values it is advantageous to use coherent receivers instead of non-coherent receivers [10].

In [11] it was reported that AIS packets are affected by phase noise which originates from imperfections in the transmitters oscillators. The effect of phase noise on differential (non-coherent) receivers is negligible. However, phase noise does degrade considerably the performance of coherent receivers. Conventional AIS receivers operate at a very high SNR values and use non-coherent detection. Therefore, they are not substantially affected by phase noise. However, the coherent detector which would be advantageous in a satellite receiver suffers a considerable performance degradation.

In this work, we present a technique that can be used to improve the performance of coherent AIS receivers in order to counteract the presence of phase noise. This technique is tailored to receive a special type of AIS messages, namely position reports. This however is not a limitation since satellite AIS receivers are usually interested in position report messages. This technique is based on the fact that some fields in the AIS position reports are not completely random, but can be predicted under the reasonable assumption that the receiver range is known in advance. Bits in those reports, whose value can be predicted, can be used as pilot symbols in order to improve the channel estimation, leveraging the performance of coherence detection. The proposed technique implies only a small increase in the complexity.

This paper is organized as follows. Section II details our analysis of the recorded AIS packets and shows the resulting SINR and phase noise measurements. In Section III we present the source model for AIS position report messages. The different receivers considered in this paper are described in Section IV, including the receiver which exploits the source model to estimate the channel. Section V shows simulation results comparing the different receivers in two different settings. Finally, we present the conclusions of our work in Section VI.

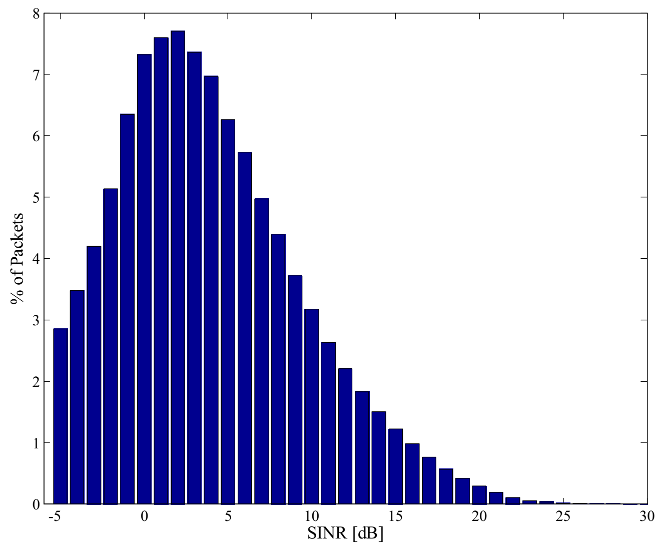


Fig. 1: Histogram of the SINR of Received AIS packets

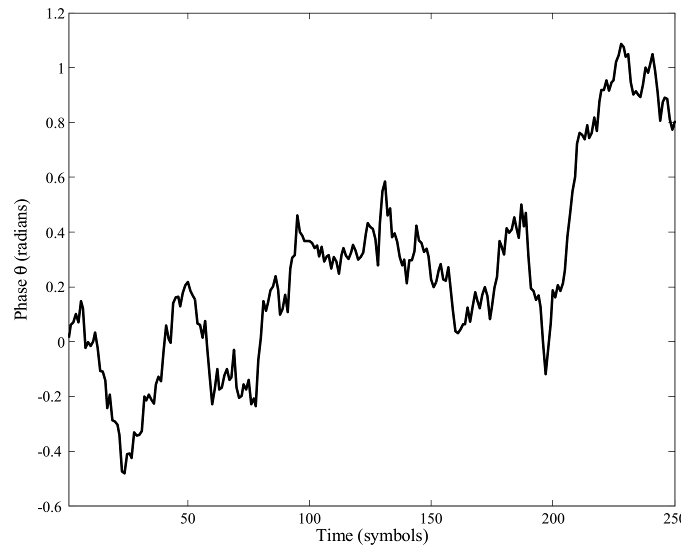


Fig. 2: phase noise θ with $\sigma = 4$

II. Measurements

In 2013 a campaign performed by DLR recorded AIS signals centered around 162 MHz above Germany and parts of the North Sea [6]. The data were recorded by an airplane that flew from Munich, above Hamburg port and to the North Sea and lasted for 46 minutes. The recorded signals were analyzed to determine the power level and the type of distortions that the channel adds.

A initial analysis was carried out in order to determine the SINR histogram of the AIS messages. For this purpose, the ML estimator developed in [6] was used to estimate the SINR of the received packets. Figure 1 shows the histogram of the received packets per SINR. It is clear that a substantial fraction of the received packets have an SINR lower than 5dB.

In a second stage, the phase noise affecting the AIS messages was characterized. Phase noise is fluctuation of the phase of a waveform due to an imperfect oscillator. Phase noise can be modeled by means of a random walk (Wiener model) as described in [12]. Using this model the additional phase variation due to phase noise can be described as:

$$\theta_i = \theta_{i-1} + \Delta_i \tag{1}$$

where Δ_i is a Gaussian random variable with zero mean and standard deviation σ. The phase increments Δ_i are independent and identically distributed (i.i.d). Hence, the channel phase at instant i, θ_i, is the summation of the previous phase increments. Figure 2 shows a realization of the phase noise that affects an AIS packet for $\sigma = 4^o$.

In order to estimate the phase noise present in the received AIS messages the following procedure was followed. Firstly, a differential (non-coherent) detector was used to decode AIS messages from the recorded signal. If the CRC check was successful and the estimated SINR was above 5 dB the packet was then re-modulated in order to carry out a phase noise estimation. Let $\hat{x}_k$ be the estimate of the k-th modulated symbol and y_k the signal received at instant k. Under the assumption that the channel is AWGN, an estimate of the phase of the channel at instant i can be obtained as [12]:

$$\phi_i = \sum_{k=i-w}^{i+w} \hat{x}_k^* y_k \tag{2}$$

This estimator is actually an ML estimator under the assumption that the phase of the channel stays constant over a window of $2w+1$ symbols. In reality the channel phase is not constant but varies due to phase noise and the estimator tends to underestimate the phase increments Δ due to averaging. After estimating the phase through the whole packet, the standard deviation σ of the phase increments is estimated. This method is actually biased and tends to underestimate σ but this bias can be corrected. In Figure 3 the phase noise was quantized and the estimation bias was corrected. These measurements indicate that AIS packets experience a large phase noise.

III. AIS Position Report Source Model

In AIS there are 27 possible messages types which can be exchanged. Each message type is assigned a different message ID. Messages of different types can have different length and contain different information. The main objective of satellite-aided AIS is monitoring and tracking vessels worldwide. This information is very important, for example, for authorities and shipping companies. Hence, the objective of a satellite AIS receiver is decoding the position reports that are sent periodically by ships. Position reports correspond to message ID 1, 2 or 3 and are actually by far the most frequently transmitted messages, as we will see shortly.

In this section we provide a source model for position reports messages. Our objective is to obtain a priori knowledge of the values of bits in these AIS messages based on statistical analysis. An AIS position report is 168 bits long and is divided into different fields as shown in Table I. In the following we

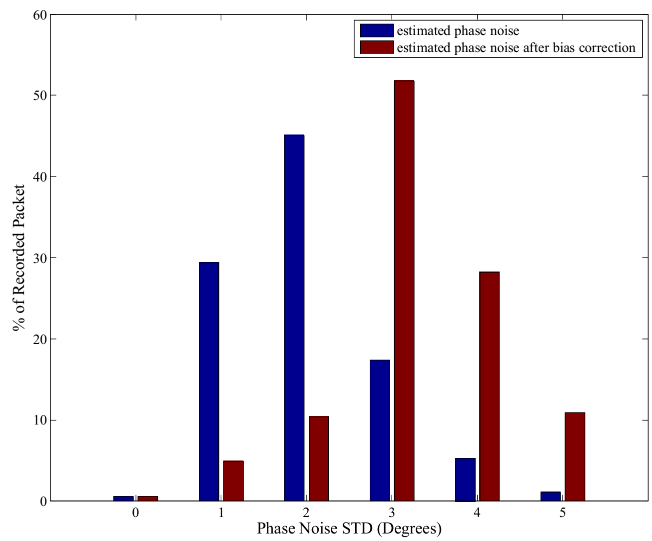


Fig. 3: Histogram of estimated (σ) before and after bias correction

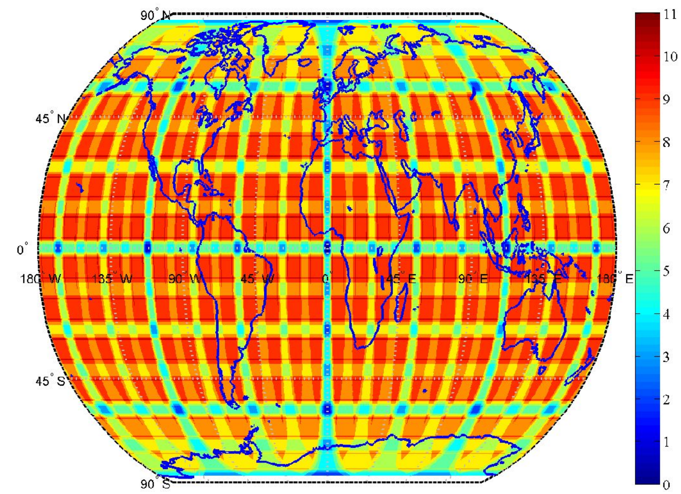


Fig. 4: Total number of known bits in the latitude and longitude fields for a circular receiver footprint of radius $r = 356$ km.

TABLE I: Message fields of AIS messages of type 1 and 2.

Field	Bits	Field	Bits
Message ID	6	Repeat Indicator	2
User ID	30	Navigational Status	4
Rate of Turn	8	Speed over Ground	10
Position Accuracy	1	Longitude	28
Latitude	27	Course over Ground	12
True Heading	7	Time Stamp	6
Maneuver Indicator	2	Spare	3
RAIM Flag	1	Communication State	19

provide a statistical analysis of the different fields of the AIS message:

- **Message ID**
  The Message ID field is 6 bits long, but only 27 values are defined. A quick review of the AIS Standard [1] will also reveal that many messages are (intuitively) rarely transmitted. Message 9 for example is sent by Search and Rescue airplanes and Message 21 is sent by Aid to Navigation stations. On the other hand one should expect a huge number of Messages $1-5$. These messages are scheduled position reports by ships and base stations and are periodically transmitted every few seconds depending on ship's speed. This is supported by the analysis performed on the AIS records, where almost 94% percent of the packets was found to be either message 1 or message 3 position reports. We conclude that the message ID field can be assumed to have a value of 1 or 3. In reality, our main purpose in this study is the detection of position reports, which happens to be messages $1-3$.
- **Latitude and Longitude Fields**
  The latitude and longitude fields are encoded using 2's complement and together amount for 55 bits of the total 168 bits which compose the position report messages. Under the assumption that the receiver range is known, it is possible to derive an a priori knowledge of the latitude and longitude fields. If a satellite is flying over the Mediterranean Sea, we expect that the position reports received at the satellite correspond to coordinates within the Mediterranean and not in the North Sea. We will consider a receiver on a flying platform whose antenna has a circular footprint of radius $r = 356$km, this corresponds approximately to the antenna footprint of the AISat from DLR [9], and also to the footprint of an omnidirectional antenna mounted on an airliner flying at 10km altitude [5]. With the knowledge of the altitude of the flying platform and the height of the vessel antenna, the range of the possible latitude and longitude values can be predicted. Under these assumptions, Figure 4 shows the number of bits within the latitude and longitude fields which are perfectly known depending on the flying platform position. It can be observed how, depending on the position, up to 11 bits can be perfectly predicted. Averaging over all possible platform coordinates, an average of 4.7 bits can be perfectly predicted. In Figure 4 a clear check pattern can be observed which is induced by the 2's complement encoding. The number of predictable bits is particularly low close to the equator and the Greenwich meridian. This corresponds to a sign change which inverts the value of all the bits. The fact that the squares become larger at the poles is due to the fact that in those coordinates points with different longitude are very close to each other.
- **Repeat Indicator**
  This field is only used by AIS base stations and is set to zero in all mobile AIS stations, which are the only stations that transmit messages 1 - 3.
- **Speed Over Ground**
  This field can encode speeds up to 102.2 knots. In reality,

TABLE II: Predictable AIS message fields

Field	Known Bits
Message ID	6
Longitude	0 - 5
Latitude	0 - 6
Repeat Indicator	2
Speed over Ground	2
Communication State	0 - 17
Rate of Turn	8
Spare	3
Total	**21 - 49**

the fraction of ships traveling at speeds above 25 knots is very low [9], so that the value of the 2 most significant bits of this field can be assumed to be known a priori. Moreover when ships are moored or very close to the coast, it is less likely that they travel at very high speeds [9].

- **Communication State**
  This field is 19 bits long. Two bits encode the synchronization status and three other bits represent the slot time out, both values should be assumed to be random, since we cannot predict their values. However, the 14 remaining bits can be predicted since they carry a submessage that depends only on the slot timeout subfield. The communication state field is used every 8 slots to report the UTC time (the hour and the minute) encoded using 14 bits. The value of the field can easily be predicted since AIS terminals are synchronized to GPS time. Therefore 14 bits of the communication state can be predicted but only every 8 time slots.
- **Turn Indicator**
  This field represents the rate of turn of the vessel per minute and its 8 bits long. Statistical analysis of the recorded packets showed that this field is set to zero with a high probability (43 %), which means that the ships do not usually change their course during their voyage. Furthermore, most of the other vessels (54 %) report the default field value, indicating that no turn information is available. Therefore, our receiver can guess with a very high probability (97 %) that the rate of turn is either the default value -128 , or zero.
- **Spare Bits**
  The spare bits near the end of the position report is always set to zero.

As Table II shows, according to our source model a minimum of 21 bits and a maximum of 49 bits out of the total of 168 bits can be assumed to be perfectly known at the receiver. In Section IV-C we will show how this knowledge can be used to improve the performance of a coherent receiver.

IV. AIS Receiver Design

In the previous section we established a detailed source model for AIS position report messages. In this section we will review two different AIS receiver architectures then show how our knowledge of some of the bits can be used to build an enhanced coherent receiver.

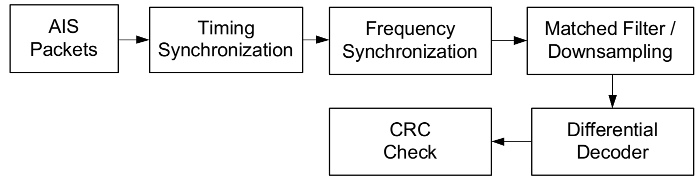


Fig. 5: Block diagram of the AIS receiver implemented in [6] along with the AIS simulator developed.

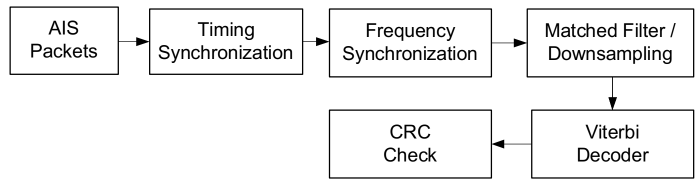


Fig. 6: Block diagram of the coherent AIS receiver. The synchronization stage is identical to the differential receiver but only the decoder is replaced with a ML Viterbi Decoder.

A. *Differential AIS Receiver*

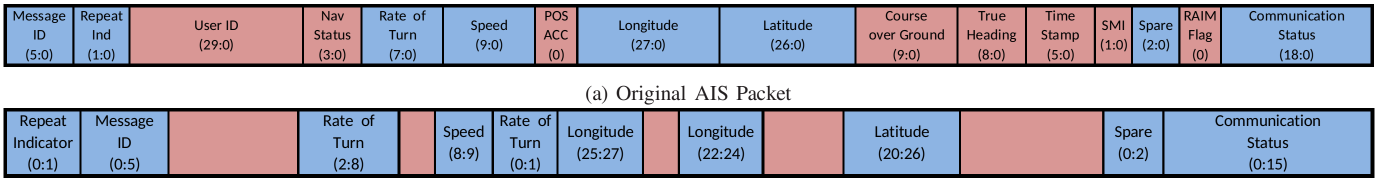
Figure 5 shows the block diagram of a conventional AIS receiver. Firstly, the received signal goes through a synchronization stage, where the time, frequency and phase offsets are corrected. Following [6], non-data aided synchronization algorithms were implemented. More concretely, the preamble of the AIS packet is used in a correlation based timing synchronization. Then the quadratic nonlinearity estimator developed in [13] is used to estimate the frequency offset. After that, the signal passes through the matched filter and then it is downsampled. Finally a simple differential demodulator is used to decode the signal.

B. *Coherent ML AIS Receiver*

The Gaussian filter in GMSK modulation, used in AIS, results in an inherent intersymbol interference (ISI). The differential receiver ignores ISI and treats it as if it was noise. However ISI is not random and is completely determined by the signal which is transmitted. A very powerful technique to compensate ISI is Viterbi equalization, which is actually an ML algorithm. This algorithm outperforms differential decoding if the channel coefficient is perfectly known. However, it is based in coherent demodulation and when channel state information is not perfect it suffers a considerable performance degradation, as we will see later. The block diagram of the Viterbi ML decoder is shown in Figure 6. The synchronization part is identical to that of the differential decoder with the difference that in this case the channel phase needs to be estimated. In the standard Viterbi ML receiver this estimation is done using the preamble of the AIS packet.

C. *Enhanced AIS Receiver*

Figure 8 shows the block diagram of the proposed AIS receiver. A channel estimation stage was added, where bits that



(a) Original AIS Packet

(b) Transmitted AIS Packet

Fig. 7: Structure of AIS packets before and after bit reordering. The fields marked with blue represent the known sections of the AIS message and the fields marked in red represent bits whose value is not known.

are known thanks to the source model presented in Section III are used to estimate the channel phase. This stage is followed by a coherent ML Viterbi demodulator. It can be observed that there is a loop involving channel estimation and Viterbi decoding. This loop is used in order to resolve the ambiguity caused by differential modulation.

The source model presented is able to determine the value of some of the *logical* bits in an AIS message. However, in order to use the source model that was developed in Section III one needs to closely analyze how an AIS transmitter generates the waveform:

- The first step is byte mapping. The AIS packet is divided into bytes and the Least Significant Bit (LSB) of each byte is sent first which reverses the order with respect to the logical bits. Figure 7 shows the message fields before and after reordering. The fields marked with blue represent the known sections of the AIS message, whereas the fields marked in red represent the unknown bits.
- After byte mapping, the AIS transmitter applies bit-stuffing in order to avoid long sequences of 0's or 1's.
- Finally, the transmitter uses differential GMSK modulation to generate the transmit waveform.

In this work, for the sake of simplicity, we will assume that no bit-stuffing is performed. This should not have a noticeable effect on the performance of the proposed receiver, since only a maximum of 4 bits are possibly inserted [1]. Instead we will mainly focus on the effect of differential modulation which is more challenging.

Using the source model, we are able to determine the values of some contiguous bits in the AIS message as shown in Figure 7. However, due to the differential GMSK modulation whenever there is a chunk of unknown bits, the transmitted waveform cannot be determined uniquely. This is due to the fact that the phase of a certain symbol is affected by both the phases of all previous symbols and by inter symbol interference. Furthermore, in AIS the transmitted bits are NRZI encoded before GMSK modulation which adds another level of uncertainty. If all these uncertainties are summed up, the same bit sequence can have 8 possible GMSK representations.

In order to deal with this uncertainty, the GMSK linearization scheme presented in [14] was used to construct an approximation of the GMSK signal. Using this scheme, it is possible to reduce the possible GMSK reconstruction levels to two.

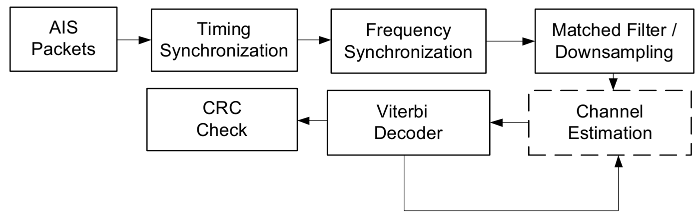


Fig. 8: Block diagram of the proposed AIS receiver

That is, one is left with two possible waveform that may have been transmitted. In order to discriminate between these two hypothesis a channel estimation is performed for each. If we assume that the phase was known perfectly before the chunk of unknown bits, one can then simply choose the hypothesis which leads to a smaller distance to the previous known phase. Obviously, if a packet is impaired with a large phase noise, then the channel estimation may incorrectly choose the wrong signal representation and the channel estimation will diverge from the actual channel value. In cases in which the two hypothesis cannot be clearly distinguished the enhanced receiver tries both of the hypothesis. This corresponds to the feedback loop in the receiver block diagram in Figure 8.

V. Numerical Results

An AIS simulator was developed to assess the performance of the three receiver architectures described in Section IV. In Section V-A we present physical layer simulation results for the three receivers assuming an AWGN channel, with and without phase noise. In Section V-B, we present some system level simulation results which build on the results of the physical layer simulation.

A. AWGN Simulator

We assume an AWGN channel with a uniformly distributed time and phase delay and a frequency deviation within $+/-$ 700Hz. This frequency deviation correspond to the maximum possible Doppler shift for an airplane traveling at a speed of 840 km/h which is the speed of the airplane that recorded the AIS signals in [6].

The AIS simulator generates data packets according to the source model introduced in Section III. The latitude and longitude values are generated assuming a receiver located on a flying platform with a circular range of 356km centered on the coordinates 79° degrees west and 8° north. This corresponds

TABLE III: Packets correctly decoded by the different AIS receivers for different phase noise standard deviation values.

Phase Noise STD (σ) (Degrees)	Differential Receiver (% of Packets)	Coherent Receiver (% of Packets)	Enhanced Receiver (% of Packets)
0	48.8%	90.9%	91.8%
1	48.3%	90.2%	91.5%
2	48.1%	88.4%	90.5%
3	47.7%	83.0%	88.2%
4	46.6%	70.8%	82.4%
5	45.3%	52.2%	70.2%

to a point near the Panama Canal. In this coordinates 4 bits from the latitude field and 6 bits from the longitude field can be assumed to be perfectly known.

Two different scenarios were simulated. In the first scenario no phase noise is assumed, while the second scenario considers the case of phase noise with a standard deviation of $\sigma = 3°$. The three AIS receiver architectures described in Section IV were assessed. Figure 9 shows the PER of the three decoders for the two scenarios. In Figure 9a, the packets are not impaired with any phase noise. Here the coherent AIS receiver is atleast 8 dB better than the conventional receiver. On the other hand, Figure 9b shows how the packet error rate (PER) of the coherent receiver is degraded drastically when the effect of phase noise is considered. However, this effect is mitigated by the enhanced receiver, which estimates the channel using the developed source model. Nevertheless, for a phase noise standard deviation $\sigma = 3°$ a coherent receiver still outperforms a differential receiver for SNR values below 7 dB.

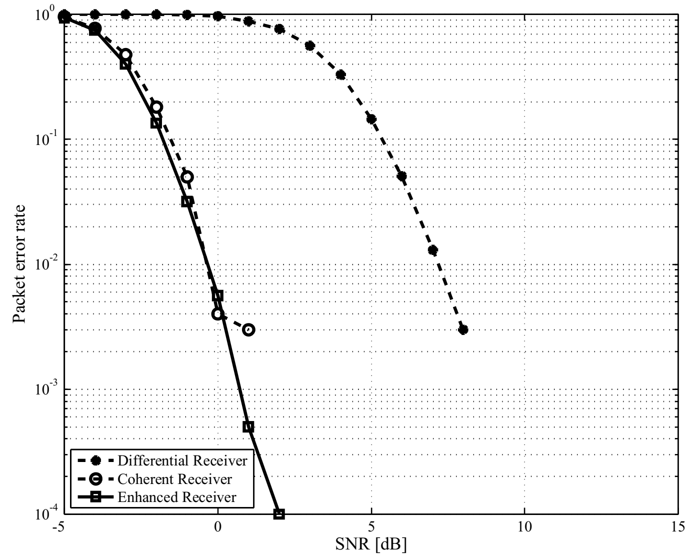
B. System Level Simulator

A system simulator was developed in order to asses the performance of the three receivers considered in a realistic scenario. The same receiver range was assumed as in Section V-A. However, in this case the SINR was assumed to be distributed according to the histogram in Figure 1 and the phase noise variance σ was assumed to be distributed according to Figure 3.

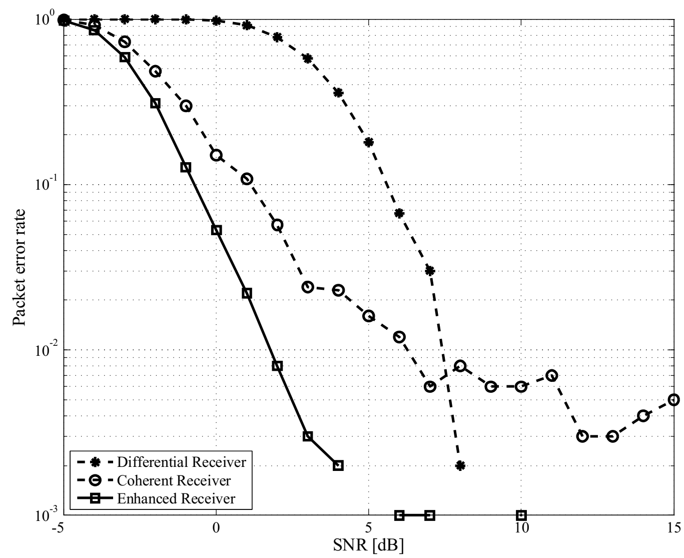
In an initial preprocessing stage, the packet error rate for the three receivers were obtained for phase noise with standard deviations (σ) between $0°$ and $5°$.

Table III shows the percentage of correctly decoded AIS messages for different values of phase noise assuming the SINR distribution shown in Figure 1. It can be observed how the enhanced AIS receiver always outperforms the conventional and coherent receivers and decodes noticeably more packets.

Finally, in Table IV we show the percentage of packets correctly decoded for the three different receivers assuming a phase noise standard deviation with histogram as in Figure 3. It can be observed how the enhanced receiver proposed in this paper can increase the percentage of correctly decoded packets from 82.8% to 91.3%, an almost 10% increase. In addition, the enhanced receiver decoded 80% more packets than the conventioanl AIS receiver.



(a) Packet error rate for the three receiver architectures when the packets are not impaired with phase noise ($\sigma = 0°$)



(b) Packet error rate for the three receiver architectures assuming a phase noise with a STD $\sigma = 3°$

Fig. 9

VI. Conclusions

This paper detailed the development of an AIS protocol source model. Thanks to this source model the value of some of the bits in AIS position report messages can be known a priory if the receiver range is known. An enhanced receiver was proposed which exploits these known bits in order to perform channel estimation and counteract the effect of phase noise. This receiver is able to increase the number of correctly received AIS messages by 10% when compared to coherent AIS receiver, and 80% more packets than conventional receivers. This increase in the number of correctly detected packets could boost the performance of a receiver based on successive interference cancellation.

TABLE IV: Packets correctly decoded by the different AIS receivers

	Differential Receiver (% of Packets)	Coherent Receiver (% of Packets)	Enhanced Receiver (% of Packets)
Correctly received packets	50.4%	82.8%	91.3%

In this work the source model was exclusively used for channel estimation purposes. However it is possible to use it for synchronization and it can also deliver soft a priory information which could be exploited in a SISO decoder.

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