New Receiver Algorithms for Satellite AIS

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Abstract—**Recently, satellite-aided automatic identification system (AIS) has opened new possibilities to the maritime world. Techniques able to capture the AIS traffic behavior at the satellite are of upmost importance for guiding the design of future maritime communication system integrating AIS and new services that can enhance the safety and awareness during navigation. In this context, our contribution focuses on the medium access (MAC) and system levels performance investigation of a common satellite AIS receiver, compared to an advanced one. We present a generic method, capable of evaluating any AIS receiver, making the use of a simplified yet tight model of the MAC layer and the multi-packet reception (MPR) matrix for physical layer (PHY) representation. Performance in terms of both throughput and first pass ship detection probability, show the benefits of such advanced receiver, especially when it is bundled with advanced signal processing capabilities as successive interference cancellation (SIC).**

I. Introduction

The possibility to detect automatic identification system (AIS) messages with low Earth orbit (LEO) satellites [1] has paved the road for worldwide vessel monitoring. Vessel routes and goods monitoring together with oceans supervision, in terms of fishing areas and water reserved areas as examples, are only some of the most relevant scenarios of interest. Lead by this, the maritime safety and security experts identified in satellite-aided AIS [2] one of the hot topics bridging researchers and standardization bodies [3] for enhancing the AIS system taking into account the satellite component.

Although the possibility to receive AIS messages at the satellite is viable and already demonstrated [4], [5], [6], AIS has been originally developed for inter-vessel radio communications. Specifically, self-organized TDMA (SOTDMA), the AIS medium access (MAC) protocol [2], is designed in a distributed manner trying to avoid most of packet collisions among the vessels that are in the reciprocal radio reception range.[1] While this approach has been proven to be robust for ship-to-ship and ship-to-shore communications, its effectiveness may degrade significantly when a satellite attempts to collect AIS traffic. In fact, the satellite field of view is orders of magnitude greater than the vessels radio reception range and thus prone to destructive collisions among packets of different ships. Especially in densely vessel populated regions this issue affects dramatically the tracking performance of a satellite-aided AIS system, all the more so considering the steadily increasing traffic generated by other maritime communication services being allocated to VHF band [8].

The design of more advanced receivers able to boost the probability of packet decoding has thus become a primary concern. In this perspective, the possibility of reliably predicting the performance of satellite-AIS and of identifying the key tradeoffs that impact the system is paramount. We will make the use of the general framework developed in [7], [9], [10] in order to derive the system level performance of such advanced AIS receiver. The work in [7], shows that the MAC protocol of AIS as perceived at a satellite can be well approximated resorting to random access such as slotted ALOHA (SA). This result is particularly interesting, as it allows to abstract the non-trivial details of SOTDMA and characterise the performance at the MAC layer through a single channel traffic coefficient. An analytical expression of such parameter was derived in [9] for any flying object capable of receiving AIS data, thus including satellites. The channel traffic is then expressed as a function of the vessels number in the satellite reception range as well as their speed. Nevertheless, these works rely on a simplified physical layer, the so-called *destructive collision channel model*, assuming that all packets involved in a collision are lost, while messages received over a collision-free slot are decoded with probability 1. Despite its mathematical tractability, this abstraction is not always realistic and might not be detailed enough. In this regard, an extension to a generic physical layer has been pursued in [10], where the use of the multi-packet reception (MPR) matrix, first introduced in [11], has been used. The MPR matrix characterizes the probability that one or more packets can be successfully decoded, conditioned to the collision size, i.e. the number of packets concurrently transmitted in a slot. Thanks to this approach compact and elegant expressions for the throughput and first pass vessel detection probability can be derived.

The objective of the paper is to investigate the MAC and system level performance for an advanced AIS receiver without and with successive interference cancellation (SIC) that can be used on board of LEO satellites.

II. System Model

A high level perspective of the tools used for modeling the satellite-aided AIS system developed in [7], [9], [10] is first presented. We focus on a satellite in a LEO orbit looking towards the Earth in the point of latitude and longitude

[1] SOTDMA is in fact the the most used out of four access schemes foreseen in AIS. A vessel implementing it, broadcasts its position, velocity and direction along with other data. In order to distribute up-to-date information to neighbouring vessels, messages are sent more often as the ship speed increases, resulting in 4 possible frequencies of packet transmission. For more details on SOTDMA, refer to [2], [7].

(φ_s, λ_s) and covering region $\mathcal{A}$ of the Earth surface. Vessels navigating in this region are transmitting AIS traffic following the SOTDMA protocol and we assume that the slot synchronicity at the LEO receiver is guaranteed. The description of the traffic profile at the satellite is in general cumbersome because it does depend on ship and speed distributions as well as on the AIS frame composition which is dynamically adapted by the SOTDMA. On the other hand, due to the very large footprint of typical very-high frequency (VHF) receivers on board of LEOs, the aggregate traffic behavior of such clusters resembles very closely to random access (RA) schemes, and in particular to SA. Based on this observation in [7] a MAC approximation resembling SA has been introduced and has been shown to hold tight in many practical scenarios. The key benefit of such approximation is in its simplicity, since all the system level metrics depends only on a single parameter G, the average aggregated channel traffic injected by the vessels. As example, the probability that U packets are sent by the ships in region $\mathcal{A}$ assuming a Poisson model (typical for RA) follows [10]

$$\Pr\{U = u\} = \frac{e^{-G}\, G^u}{u!}. \tag{1}$$

The channel load G is the parameter that embeds all the dependencies on ship and speed distributions and can be explicitly written as [9]

$$G = \sum_i \frac{\omega_i}{N_s} \left(n \int_{V_{i-1}}^{V_i} f_v(v)\, \mathrm{d}v \right) \quad \text{[pk/slot]}. \tag{2}$$

In equation (2), ω_i represents the number of messages a ship is required to send in an AIS frame while sailing at speed $v \in [V_{i-1}, V_i]$. We define f_v as the probability density function (PDF) of vessel speed, while n is the number of vessels transmitting in region $\mathcal{A}$ and can be computed as $n = \int_{\mathcal{A}} f_s(\varphi, \lambda)\, \mathrm{d}\varphi \mathrm{d}\lambda$. Here f_s is the ship distribution PDF. In this way, the channel load can be estimated once the PDFs of the vessel position f_s and the vessel speed f_v are known. These PDFs can be derived in several ways, e.g. via dedicated models, via simulations or via real-world collected data as is done in the present contribution.

The vessel speed distribution f_s is derived from data collected by the operating satellite-AIS system of exactEarth®. In particular, we base our results on the density map reported in Fig. 1, which shows the PDF of the vessels positions coming from data collected in January 2013. Similarly, the vessel speed distribution f_v, is derived from data collected in January 2013 by the satellite system of exactEarth®. Specifically, in Fig. 2, the average vessel speed in knots [kn] for each Earth location has been reported. This speed is then associated to all the vessels that are located in the specific latitude and longitude point.

In order to take into account different AIS receiver characteristics, in our model we will make use of a flexible tool introduced in [11], which is the MPR matrix. If we consider u colliding packets at the receiver in a given slot, we define $\alpha_{u,c}$ as the probability of successfully decoding c packets out

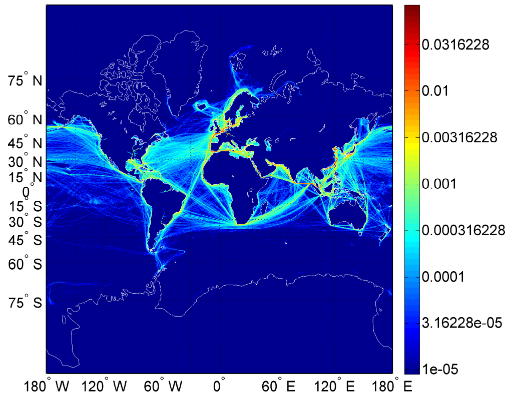


Fig. 1. PDF of vessel positions [%] derived from exactEarth® data collected in January 2013. The PDF has been computed based on the received AIS messages from the satellite system of exactEarth®.

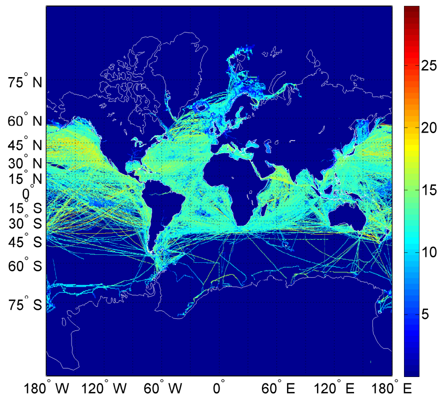


Fig. 2. Average of vessel speed [kn] derived from exactEarth® data collected in January 2013. The vessel speed has been computed based on the received AIS messages from the satellite system of exactEarth®.

of the u concurrently received. In this way, the MPR matrix $\boldsymbol{A}_m$ is defined as [10]

$$\boldsymbol{A}_m = \begin{pmatrix} \alpha_{1,0} & \alpha_{1,1} & 0 & 0 \\ \alpha_{2,0} & \alpha_{2,1} & \alpha_{2,2} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{m,0} & \alpha_{m,1} & \cdots & \alpha_{m,m} \\ \alpha_{m+1,0} & \alpha_{m+1,1} & \cdots & \alpha_{m+1,m} \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix} \tag{3}$$

We are here assuming that a maximum of m data units can be recovered by the receiver in a given time slot. Letting m go to infinity gives the most general expression of the MPR matrix.

Defining the throughput S as the average number of packets that can be successfully received per time slot, we can write

$$S = \boldsymbol{\pi} \boldsymbol{A}_m \boldsymbol{v}_m. \tag{4}$$

Where $\boldsymbol{\pi}$ is a row vector expressing the probability that 1, 2, etc. users select exactly the same time slot for transmission. Under the Poisson traffic model it follows (1), i.e. $\boldsymbol{\pi} = [e^{-G}G, \frac{e^{-G}G^2}{2}, ...]$. The form of equation (4) is particularly useful as it helps isolating the effects of physical layer (PHY) and MAC layer. The latter is captured by $\boldsymbol{\pi}$, while the former is handled by the MPR matrix $\boldsymbol{A}_m$. Even more interestingly, the general form of the throughput in this equation can embed any MAC and PHY model, once the vector $\boldsymbol{\pi}$ and the matrix $\boldsymbol{A}_m$ are given.

An additional metric that gives more hints on the system performance for the satellite-aided AIS is the first pass ship detection probability ζ [10], i.e. the probability that a given vessel is detected by a satellite which is flying over it. In order to detect a vessel is sufficient that a least one of its AIS messages is correctly received during the satellite pass. The expression of ζ follows

$$\zeta(\varphi, \lambda, r) = 1 - \prod_{i=1}^{I(r)} \left(\sum_{u=1}^{\infty} \frac{e^{-G_i} G_i^u}{u!} \alpha_{u,0} \right)^{k_i}. \quad (5)$$

ζ is a function of the satellite position (φ, λ) and of its coverage radius r. Here, k_i is the average number of AIS messages sent by a ship in the i-th frame, $I(r)$ is the number of frames during which the receiver illuminates the location with coordinates (φ, λ). We would like to highlight that the channel load $G_i(\varphi, \lambda, r)$ depends on the specific location illuminated by the satellite as well as by the receiver coverage radius.

In the following Section we will describe a novel advanced receiver for AIS and integrate it with the present system level model. In particular, the advanced receiver performance will be reflected in the MPR matrix (3) which will assume a specific form as we will show in Section IV.

III. Advanced AIS Receiver

Conventional AIS reception at vessels or base stations does not require complex receiver processing. First because SOTDMA makes sure that there is no multi-user interference and second because the distance between AIS users is small (at most 40 nautical miles) and, hence, the signal-to-noise ratio (SNR) is sufficiently high. However, the situation is quite different for satellite-aided AIS reception. In this case the receiver needs to cope with multi-user interference coming from several SOTDMA cells and also with a lower SNR because of a high free space loss. Therefore, a satellite AIS receiver will in general operate at a low signal-to-interference and noise ratio (SINR) and will have to make use of more complex processing.

In [12] for example a receiver architecture is proposed for a satellite AIS receiver. Improved algorithms for estimation, detection and error correction are proposed that allow to considerably improve the receiver performance. However, in this work, like in the majority of works on satellite AIS reception, the initial step consists of a differential detection. In this paper, following [13] we will make use of a scheme that allows detect AIS messages using a coherent receiver that can provide gains of several dBs with respect to a differential detector.

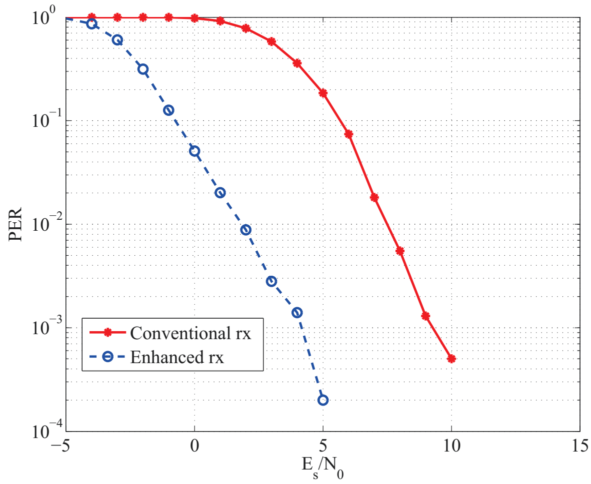


Fig. 3. PER vs E_s/N_0 for a conventional receiver and an enhanced receiver. The presence of phase noise is assumed, following a Wiener model leading to phase increments between consecutive symbols of 3° of standard deviation.

The key idea behind the enhanced AIS receiver proposed in [13] is that many of the fields of the an AIS message can be predicted. Although AIS can be used to transmit different types of messages, according to [13], about 94% of the messages are position reports. These messages contain, among other fields, the GPS position, the direction in which the vessel is traveling and its speed. Some of these fields are known a priory. Take, for example, the GPS position. The GPS position reported by vessels must correspond to a point within the coverage area of the satellite. That is, if the satellite under consideration is overflying the Mediterranean, the position reports cannot lead to coordinates corresponding to the Pacific ocean. For example, for a circular coverage area of 356 km of radius, out the total of 168 bits between 21 and 49 bits can be predicted depending on the position of the satellite. These known bits can be used to perform channel estimation, that is needed to enable coherent detection.

In Fig.3 the packet error rate (PER) vs. E_s/N_0 is represented for a conventional (differential) receiver and an enhanced receiver following [13]. The results are obtained through simulations assuming the presence of phase noise following a Wiener model leading to phase increments between consecutive symbols of 3° of standard deviation. As it can be observed, the enhanced receiver provides in this case a gain of approximately 4 dB compared to a conventional receiver.

IV. Numerical Results

The MPR matrix for the presented AIS advanced received will depend also on the SINR distribution, which is the result of several effects. In particular, it is affected by the vessel distribution f_s and by the relative link budget. Although it is required to evaluate the vessel distribution for each position of a given satellite, we make the assumption of uniform vessel distribution for deriving the MPR matrix, as suggested in

TABLE I
PARAMETERS OF THE VHF LINK BUDGET OF SATELLITE-AIS

Parameter	Value	Description
P_{tx}	12.5 W	Transmitting power
P_{rx}	computed	Receiving power
G_{tx}	0 dB	Transmitting antenna gain
G_{rx}	0 dB	Receiving antenna gain
ϕ	162 MHz	Link frequency
d	computed	Vessel-satellite distance
c	$3 \quad 10^8$ m/s	Speed of light constant
L	$\left(\frac{4\pi d\phi}{c}\right)^2$	Free space loss
T_a	50 K	Antenna noise temperature
B	25 kHz	Carrier bandwidth
k	$1.379 \quad 10^{-23}$ J/K	Boltzmann constant

[10]. There, it has been observed that for LEO satellites and their very broad coverage, the differences between uniform vessel distribution and exact vessel distribution is anyhow very limited in absolute terms.

We assume that the received power is exponentially distributed (Rayleigh fading), due to the presence of reflecting elements on board the ships, with mean ν that follows

$$\nu = \frac{P_{tx} G_{tx} G_{rx}}{L},$$

where P_{tx} is the transmitting power, G_{tx} and G_{rx} are the transmitter and receiver antenna gain respectively and L is the free space loss. In order to compute the free space loss L, the vessel-satellite distance d is calculated and the AIS VHF frequency is considered for the communication link. The values selected are recalled in Table I. The received SNR γ follows

$$\gamma = \frac{P_{rx}}{T_a k B},$$

being P_{rx} the received power, exponentially distributed with mean value ν. T_a is the antenna noise temperature and B is the carrier bandwidth.

By means of Monte Carlo simulations, vessels are placed uniformly in a circle of radius $r = 1500$ km equal to the receiver's reception range, under all possible collisions sizes. The radius has been selected considering the fact that the LEO satellite is equipped with a dedicated antenna which is not an omni directional antenna (specific antenna design has been developed for example for the DLR's AISat-1 [9]). The LEO is assumed to fly at 524 km over the Earth surface. The link budget result provides the SINR distribution that can be fed into any AIS received including the advanced AIS receiver presented in Section III.[2] In this way, the PER corresponding to any SINR can be derived and the MPR can then be computed.

In Fig. 4 the MPR matrices for both the common AIS receiver and the advanced one are presented. Additionally the case of an advanced receiver employing SIC is also added, see Fig. 4(c). In this case, the receiver once the decoding is successful, removes the interference contribution of the decoded packet and makes a second decoding attempt. The procedure is then iterated until the decoder is successful, possibly retrieving more than one packet in a given slot. In our case for a collision of two packets there is almost 50% probability that both packets can be decoded, which is then reduced to 31% in case of a collision of three packets. Anyhow, the advanced receiver coupled with SIC shows a very promising performance, since even in the presence of multiple packets in a slot, there is a non negligible probability to decode all, or a part, of them. Comparing the common AIS receiver, in Fig. 4(a), and the advanced one, of Fig. 4(b), we observe that the probability of correctly decoding one packet also in presence of collisions is strongly enhanced in the latter. As an example, for a collision involving 7 packets the probability that one is correctly received is still above 10%, while for the common receiver it has already dropped below 1%. The reason lies in the great improvement of the advanced receiver compared to the common one, for the SINR range around 0 dB.

[2]We are here implicitly approximating the interference as a Gaussian r.v. with zero mean and variance related to the interference power. This is valid especially when multiple packets are colliding in a given slot.

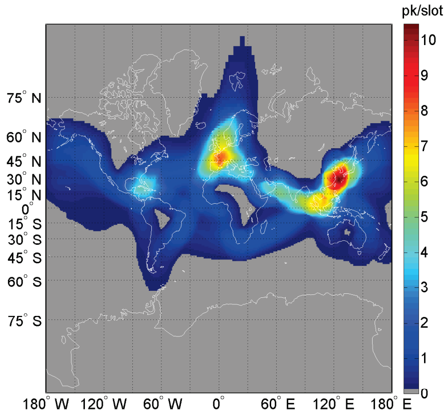
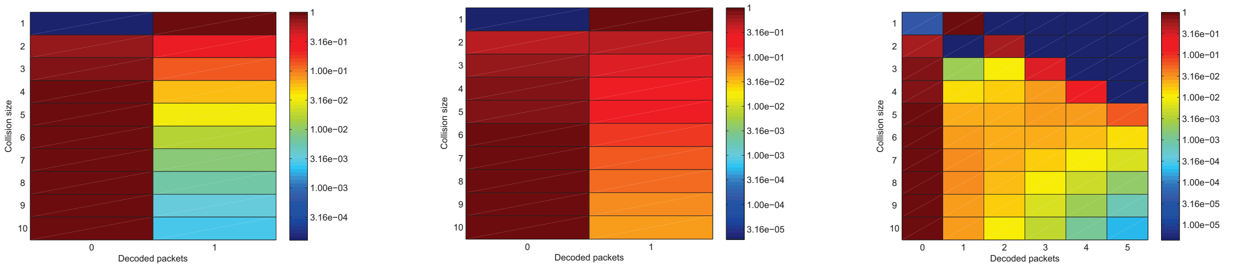


Fig. 5. Global average channel load G measured in pk/slot, observed by a LEO satellite with a coverage radius of 1500 km.

Before analysing the results of the different receivers in terms of throughput and first pass ship detection probability, we show the channel load results computed based on equation (2) for the LEO with 1500 km receiver radius, in Fig. 5. There are three main areas where the average AIS traffic generated by the vessels exceeds 4 packets per slot, in the Gulf of Mexico, in Europe around the Mediterranean Sea and in the North Sea, and finally south from India, in the area of Thailand, Chinese Sea and Japan. This last geographical area is the one showing the highest average channel load G, exceeding 10 pk/slot. On the opposite value of the scale, we high lightened with grey color the areas where the AIS traffic is negligible.

The global throughput performance for the common receiver can be seen in Fig. 6. In this case, the throughput does not exceed 0.45 pk/slot, which is a limited performance improvement w.r.t. the performance of SA under the collision channel, where the maximum throughput is 0.36 pk/slot. Good



(a) MPR matrix for a common AIS receiver under Rayleigh fading.

(b) MPR matrix for the advanced AIS receiver under Rayleigh fading.

(c) MPR matrix for the advanced AIS receiver under Rayleigh fading employing SIC.

Fig. 4. MPR matrices for various type of receivers, under Rayleigh fading for a reception range of 1500 km and for a receiver altitude of 524 km.

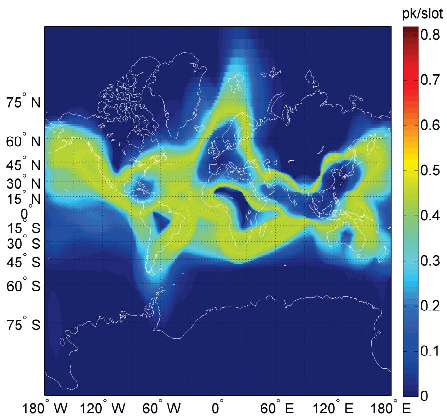


Fig. 6. Global average throughput S measured in pk/slot, observed by a LEO satellite with a coverage radius of 1500 km and employing a common AIS receiver.

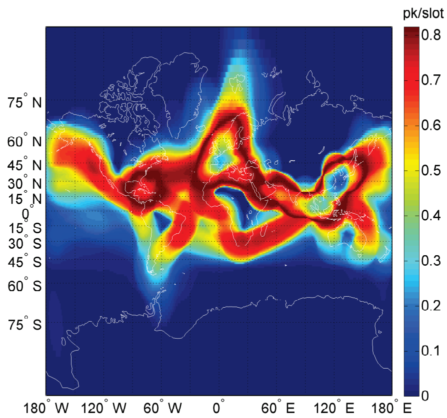


Fig. 8. Global average throughput S measured in pk/slot, observed by a LEO satellite with a coverage radius of 1500 km and employing the advanced AIS receiver with SIC.

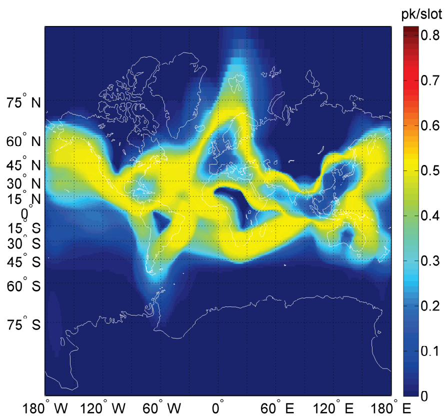


Fig. 7. Global average throughput S measured in pk/slot, observed by a LEO satellite with a coverage radius of 1500 km and employing the advanced AIS receiver.

performance of the satellite AIS receiver can be identified in all areas except for the very high loaded spots aforementioned (cf. also with Fig. 5), where the throughput is very limited due to the very high channel traffic causing unresolvable collisions.

Moving to the performance of the advanced receiver without and with SIC, presented respectively in Fig. 7 and Fig. 8, we can observe preeminent improvements in the throughput, especially in the latter. While the advanced AIS receiver employed in the LEO is able to reach a maximum throughput of 0.51 pk/slot, with a gain of 14% w.r.t. to the common receiver, enabling SIC allows to reach up to 0.82 pk/slots, with a 82% gain in maximum throughput compared with the common receiver. For example, already without SIC, the advanced receiver is able to reach non negligible throughput in the Gulf of Mexico area. Instead, when also SIC is enabled on the advanced receiver, in that geographical area throughput exceeding 0.6 pk/slot can be found. Moreover, also in the Mediterranean sea and North Sea area, the throughput has a great improvement reaching at least 0.25 pk/slot. Finally, in the last high load area in the Middle East and Chinese Sea, the region where the throughput is lower than 0.25 pk/slot is reduced significantly compared to the case with a common receiver.

In Fig. 9, the throughput gain of the advanced AIS receiver with SIC and the common receiver is depicted in dB domain.[3]

[3] The throughput gain definition follows [10] as $\xi = (S_{SIC}/S_C) \quad 1$.

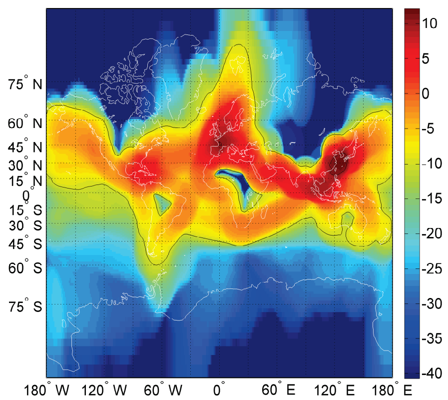


Fig. 9. Global average throughput gain of the advanced AIS receiver with SIC compared to the common receiver. The gain follows $\xi = (S_{SIC}/S_C) \quad 1$, and $\xi_{dB} = 10log10(\xi)$, being S_{SIC} the throughput of the former receiver and S_C the throughput of the latter.

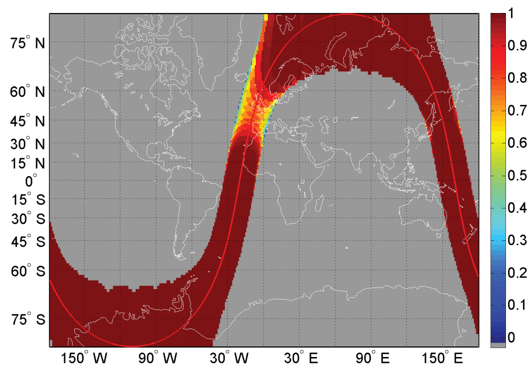


Fig. 10. First pass ship detection probability ζ computed as in equation 5 for a LEO satellite track flying at 524 km with a reception range of 1500 km in radius equipped with the advanced receiver and employing SIC.

The black line represents the boundary for throughput equal to 0.25 pk/slot. Throughput gains of -6 dB or above are found for the vast majority of the area with throughput exceeding 0.25 pk/slot, which means that a generalized throughput gain of at least 25% can be found in the areas of interest (where we have a non negligible throughput). Interestingly there are also many areas where the throughput gain exceeds 0 dB, meaning that a throughput gain of 100% compared to the common receiver can be found. This is particularly true for the three densely populated vessel regions identified in the previous discussion. Finally, gains of even more than 10 times can be found in Europe and in the Chinese sea as well as around Japan, showing that the advanced AIS receiver with SIC can reach outstanding performance.

In Fig. 10 the first pass ship detection probability for a possible LEO ground track is depicted. The ground track is selected in a way that two out of the three regions heavily

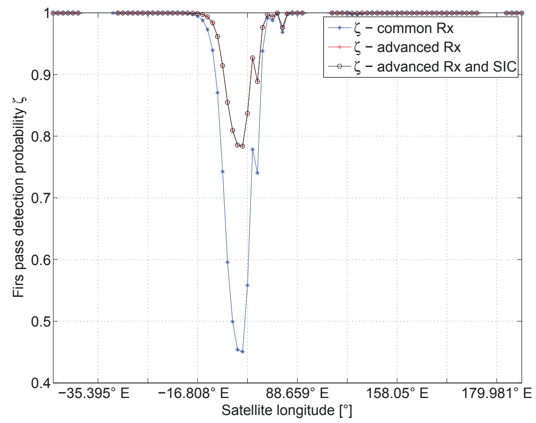


Fig. 11. First pass ship detection probability ζ at a LEO satellite with reception radius of 1500 km. ζ is computed over the ground track of Fig. 10 and compared for the receivers.

populated with vessels are covered. Interestingly, if we are analysing the probability that a vessel is tracked by a LEO satellite employing the advanced receiver with SIC we see that there is a very high probability that this can be achieved in the first pass, regardless from the area covered. This is also true for the Mediterranean Sea as well as close to the Japanese coasts, where the population of vessel generates AIS traffic exceeding 10 pk/slot.

The question of whether this is thanks to the advanced receiver or if it can be achieved also with a normal receiver is answered looking at Fig. 11. In this figure, the first pass ship detection probability for the three receivers, i.e. common receiver, advanced receiver and advanced receiver with SIC, is depicted. We can observe that, while the advanced receiver without or with SIC ha exactly the same performance, the common receiver performs worse. In the Mediterranean sea region for example, the common receiver has less than 50% probability of detecting a vessel, while the advance receiver reaches almost 80% probability. On the other hand, SIC in this case does not bring any advantage due to the fact that the metric depends only on the probability of error for the decoder, which is in the two cases equal, as can be expected.

V. Conclusions

In this paper we analyzed the MAC and system level performance of an advanced AIS receiver that can be potentially employed on board of a LEO satellite for satellite-aided AIS systems. The advanced receiver smartly makes the use of side information that can be retrieved thanks to satellite position information and a priori known fields into the AIS packets payload. This information is then used for enhancing the channel estimation and brings undoubtable performance advantages. The general framework developed in [10] was used for analyzing both the advanced AIS receiver and the common AIS receiver. Throughput and first pass ship detection probability investigations show through numerical simulations the benefit of such receiver especially when used in conjunction with signal processing techniques as SIC. Gains more than 80% are reached in terms of maximum throughput by the advanced receiver with SIC. Depending on the geographical areas up to 100 times the throughput of a common receiver can be reached by the advanced one. Finally, first pass ship detection probability gains of almost 100% in region heavily populated by vessel can be also expected employing such advanced receiver.

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References

[1] T. Eriksen, G. Hoye, B. Narheim, and J. Meland, "Maritime traffic monitoring using a space-based AIS receiver," *Acta Astronautica*, vol. 58, pp. 537–549, 2006.

[2] Recommendation ITU-R M.1371-4, "Technical characteristics for an automatic identification ssystem using time-division multiple access in the VHF maritime mobile band," ITU, Tech. Rep., 2010.

[3] Recommendation ITU-R M.2169, "Improved satellite detection of AIS," ITU, Tech. Rep., 2009.

[4] T. Eriksen, A. N. Skauen, B. Narheim, O. Helleren, O. Olsen, and R. B. Olsen, "Tracking Ship Traffic with Space-Based AIS: Experience Gained in First Months of Operations," in *Waterside Security Conference (WSS), 2010 International*, Carrara, Italy, 3-5 November 2010, pp. 1–8.

[5] J. A. Larsen, H. P. Mortensen, and J. D. Nielsen, "An SDR based AIS Receiver for Satellites," in *Recent Advances in Space Technologies (RAST), 2011 5th International Conference on*, Istanbul, Turkey, 9-11 June 2011, pp. 526–531.

[6] J. A. Larsen and H. P. Mortensen, "In Orbit Validation of the AAUSAT3 SDR based AIS receiver," in *Recent Advance in Space Technologies (RAST), 2013 6th International Conference on*, Istanbul, Turkey, 12-14 June 2013, pp. 487–491.

[7] F. Clazzer, A. Munari, M. Berioli, and F. Lazaro Blasco, "On the Characterization of AIS Traffic at the Satellite," in *IEEE/MTS Oceans14*, Taipei, Taiwan, April 2014.

[8] Electronic Communications Committee, "Information Paper on VHF Data Exchange System (VDES), CPG PTC(13) INFO 16," CEPT, Tech. Rep., 2013.

[9] F. Clazzer, A. Munari, S. Plass, and B. Suhr, "On the Impact of Coverage Range on AIS Message Reception at Flying Platforms," in *7th Advanced Satellite Multimedia Systems Conference (ASMS)*, Livorno, Italy, September 2014, pp. 128–135.

[10] F. Clazzer and A. Munari, "Analysis of Capture and Multi-Packet Reception on the AIS Satellite System," in *IEEE/MTS Oceans15*, Genova, Italy, May 2015.

[11] S. Ghez, S. Verdú, and S. C. Schwartz, "Stability Properties of Slotted Aloha with Multipacket Reception Capability," *IEEE Transactions on Automatic Control*, vol. 33, no. 7, pp. 640–649, July 1988.

[12] G. Colavolpe, T. Foggi, A. Ugolini, J. Lizarraga, S. Cioni, and A. Ginesi, "A highly efficient receiver for satellite-based automatic identification system signal detection," in *Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, Sep. 2014, pp. 120–127.

[13] A. Hassanin, F. Lázaro, and S. Plass, "An advanced AIS receiver using a priory information," in *IEEE/MTS Oceans15*, Genova, Italy, May 2015.