Space-Based AIS Performance

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Abstract—**The performance of a space-based Automatic Identification System (AIS) receiver, can be estimated in terms of the probability of detection of an uncorrupted ship's AIS message. Signal collisions arising from other ships outside its self-organizing cell often limit performance. A probabilistic approach based on Poisson statistics is adopted to predict this. The method takes account of the ability of a system to resolve signal collisions and the model is applied to explain the curves presented in ITU-R M.2169, which applies to the introduction of message 27; this is designed for space-based receivers.**

Index Terms— Automatic Identification System, space-based AIS, stochastic, Poisson, performance.

I. Introduction

Space-based AIS reception promises to be an important component of maritime wide-area surveillance. The swath width of a satellite-borne receiver can be over 5000 km and, with a ground speed close to 7 km/s, the Area Coverage Rate (ACR) is very much larger than can be achieved using other methods. For example, the range of terrestrial AIS is typically 35 km, though ducting of the VHF signals can extend it greatly.

However, AIS is designed as a ship collision avoidance system for terrestrial use and uses a communication scheme called Self-Organized Time Domain Multiple Access (SOTDMA). The messages are transmitted at VHF frequencies on two channels at 161.950 MHz and 162.050 MHz. The range is basically limited to line of sight; only those ships within a cell of size roughly equal to the signal range transmit into a fixed number of time slots. The signal protocols ensure that interference cannot occur with normal shipping densities.

The timing of the signals is important so that they fit into the TDMA time slots. The AIS transponders are typically synchronized to UTC from a GPS receiver. Each message is 256 bits in length transmitted at 9600 bits/s; it starts with a 24 bit training sequence (for receiver synchronization) and ends with a 24 bit buffer that contains 12 bits as a distance delay buffer. The frame length is 60 s and within each frame there are 2250 time slots; each message just fits into a time slot.

A space-based receiver typically receives signals from a large number of cells over the receiving antenna footprint. Therefore the allocation of messages from individual ships into a time slot is not coordinated and can be considered to be random. This results in signal collisions. In addition, the range to the satellite can vary from a minimum value when a ship is at nadir to values that are much greater for ships near the horizon; the difference can be more than 1000 km.

The Norwegian Defence Establishment (FFI) has developed a model for handling the two problems [1], [2]. It is assumed that signal collisions cannot be resolved. Where there is time-slot synchronization but no self-organization the messages from ships are assumed to arrive in a time slot completely at random though they all start at a time corresponding to the beginning of the slot. When time-slot synchronization fails due to excessive range overlap beyond the buffer and training sequence, the theory is modified to accommodate the excess signal collisions.

However, the situation is more complicated than this [2] because the signal strengths are likely to vary due to differences in range; strong signals are likely to be processed correctly in the presence of weak interfering signals. Moreover, the frequency of the received signal is Doppler shifted by the motion of the satellite. This can be a problem with a simple receiver because the bandwidth must be increased. On the other hand, the Doppler shift can be exploited to disentangle the messages using signal processing techniques. Similarly, Faraday rotation in the ionosphere changes the plane of polarization and this can be employed to separate signals from ships at different positions on the ocean. Therefore a space-based AIS receiver should be capable of handling some signal collisions and be able to extract the information in spite of them.

II. Theory

First we consider the situation where all messages are synchronized to their time slots and any range overlap can be accommodated by the training sequence and the buffer. It is assumed that there is an average of N ships in the antenna footprint. The effect of the lack of coordination in slot allocation over the entire footprint is to distribute the ship messages evenly over the slots. Thus the distribution of messages over the slots will be close to uniform in spite of the correlation induced by SOTDMA protocols within each individual cell.

The average rate, λ, at which ships are transmitting into a channel is given by:

$$\lambda = \frac{N}{n_{ch}\Delta T} \quad (1)$$

where n_{ch} is the number of VHF channels (presently two) and ΔT is the time between messages averaged over the ships. The

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Published: May 28th, 2011.

average number of messages arriving in a slot is just $\lambda\tau_0$ where τ_0 is the length of a slot (26.67 ms), which as noted also happens to be equal to the length of a message.

Because the ships are transmitting at random into the time slots, the number of messages arriving at a single slot is closely Poisson distributed. The probability, P_n, of receiving exactly n messages is given by:

$$P_n = e^{-\lambda\tau_0} \frac{(\lambda\tau_0)^n}{n!} \quad (2)$$

Now consider the case where a random message is received. A collision will occur if another one or more messages are received. Because the messages arrive entirely randomly, the presence of a message already in the time slot does not affect the arrival of more messages. From (2) the probability of a collision involving one or more additional signals is just:

$$\sum_{n=1}^{\infty} P_n = 1 - P_0 = 1 - e^{-\lambda\tau_0} \quad (3)$$

If no collisions can be tolerated, the event of a collision is identical to the event of a corrupted message. Therefore the probabilities of a collision and a corrupted message are the same.

On the other hand, if just one collision can be tolerated, the probability of a corrupted message is somewhat less:

$$\sum_{n=2}^{\infty} P_n = 1 - P_0 - P_1 = 1 - e^{-\lambda\tau_0} - \lambda\tau_0 e^{-\lambda\tau_0} \quad (4)$$

In a sequence of independent trials over time T_{obs}, the probability of receiving at least one uncorrupted message is now:

$$p_k = 1 - \left(\sum_{n=k}^{\infty} P_n \right)^{T_{obs} / \Delta T} \quad (5)$$

where k is the number of message collisions that can be tolerated in each trial. This contains the equivalent Norwegian formula [1] as the case where $k = 1$.

In practice, the occurrence of a collision may or may not corrupt the existing message. It is possible to model this by specifying the probability, q, that an additional signal does not corrupt the message. For simplicity, we assume that multiple additional signals do not interact: if there are n additional signals, the probability that the original message remains uncorrupted is q^n. Therefore the probability of an existing message *not* being corrupted is now:

$$\sum_{n=0}^{\infty} q^n P_n = e^{-\lambda\tau_0} \sum_{n=0}^{\infty} \frac{(q\lambda\tau_0)^n}{n!} = e^{-\lambda\tau_0(1-q)} \quad (6)$$

The probability that at least one uncorrupted message will be received in a sequence of trials now becomes:

$$p = 1 - \left(1 - e^{-\lambda\tau_0(1-q)}\right)^{T_{obs} / \Delta T} \quad (7)$$

Clearly, if $q = 0$, (5) is recovered with $k = 1$ and the formula is identical to the equivalent in [1]. Also the ability of a space-based AIS receiver to handle some collisions has the effect of increasing the number of ships in the antenna footprint that can be detected; the maximum number of ships for a fixed detection rate is increased in inverse proportion to $1 - q$.

The overlap of signals due to variations in range can be treated as in [1] by introducing an overlap factor, s. Therefore the final result is:

$$p = 1 - \left(1 - e^{-(1+s)\lambda\tau_0(1-q)}\right)^{T_{obs} / \Delta T} \quad (8)$$

III. Performance

When the ships are distributed uniformly at random over an AIS receiver antenna footprint that is very broad, the signal strength of those signals from the near range will be much higher than those in the far range by up to 12 dB. The weaker signals are unlikely to have much impact on the stronger ones. The probability that the strength of any received signal will be less that that of another single interfering signal is 0.5.

The signals can also be separated by the Doppler shifts as a result of the satellite motion. This creates shifts of up to ±3.5 kHz compared with the bandwidth of the AIS signal, which is somewhat less than 10 kHz. Signals arising from far forward of the satellite can be shifted by up to 7 kHz from those from far aft. It should be possible to separate these without corruption even when they have comparable strength.

Polarization should permit signal separation because Faraday rotation can occur over quite different parts of the ionosphere and this should introduce large differences in the orientations of the planes of polarization. A dual polarized receiver should be very effective in mitigating the effects of signal collisions.

Because some parts of each signal can be predicted in advance, the loss of symbol synchronization associated with the time-slot overlap could also be exploited to extract interfering signals.

Whether small values of 1 - q can be realized depends partly on the receiver; this is typically based on software-defined radio technology and both non-coherent and coherent methods of detection can be employed. The former can be used when carrier reconstruction is difficult as is the case when there is deep fading and a loss of phase coherence. Coherent detection is preferred because of the better Bit Error Rate (BER) that is achievable as well as the performance in the presence of interference [3].

This suggests that achievable values of q could range from about 0.5 upwards to about 0.8, say. However, this is contingent upon the distribution of ships in the field of view. If the shipping density is large and the number is highly concentrated in one area, the separation techniques may be ineffective and the realizable value of q may be close to zero. Performance may be extraordinarily poor in such areas as Galveston, Chesapeake Bay and the east coast of the US.

The results can be illustrated for the present AIS channels 1 and 2 designated for terrestrial AIS as well as for those advocated for space-based AIS, namely 3 and 4. We assume the parameters in Table 1 for the current channels.

Fig. 1 shows the probability of detecting a message according to (8) as a function of the number of ships in the field of view of the receiving antenna; this is for a satellite at 1000 km altitude. The value of q ranges from 0 to 0.8. It can be seen that the performance is critically dependent on how signal collisions are handled by the receiving system.

Table 1
Parameters for AIS 1 AND 2

Parameter	
Message Time, τ_0 (ms)	26.77
Average Message Interval, ΔT (s)	6
Observation Time, T_{obs} (min)	15
Number of Channels	2
Overlap Factor	0.7

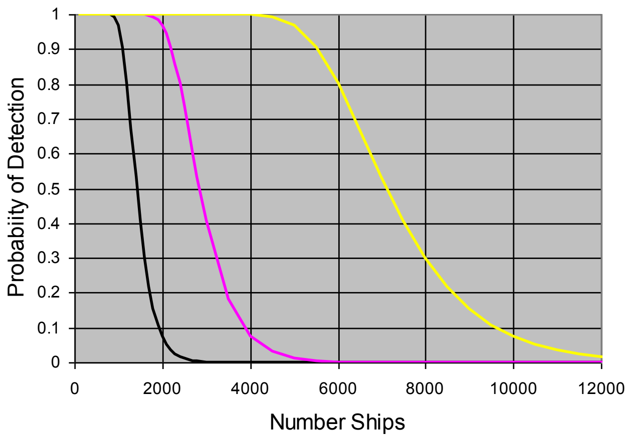

Fig. 1. Probability of detection versus number of ships for AIS 1 and 2. q = 0 (—), q = 0.5 (—), q = 0.8 (—).

With an assumption about the observation time, which has been reduced from 15 min to 13.6 min, Table 2 gives the parameters for AIS channels 3 and 4 designed for space-based AIS.

Table 2
Parameters for AIS 3 AND 4

Parameter	
Message Time, τ_0 (ms)	26.77
Average Message Interval, ΔT (s)	180
Obervation Time, T_{obs} (min)	13.6
Number of Channels	2
Overlap Factor	0

Fig. 2 provides a similar series of performance graphs. However, the case where a single collision does not corrupt the message is also included using (4) and (5). The performances for q = 0.5 and for a single allowed collision are somewhat similar, as might be expected.

The ITU has published a document [4] containing probability of detection curves to justify introduction of the two channels dedicated to space-based AIS reception. The curves in the document are the result of simulations. The results of a calculation are shown in Fig. 3; these are based on the assumption that it is possible to resolve a single collision (one of the curves from the previous figure is repeated). The parameter sets are the same as those in [4]. The two sets of graphs are quite close to each other, though there are minor differences; this suggests that the ITU simulation model and the model developed here for a single allowed collision are comparable.

IV. Conclusions

A new model has been developed for the performance of space-based AIS reception. It is based on Poisson statistics and applies to a receiving system that can resolve a signal chosen at random in spite of multiple signal collisions. This is controlled by an additional parameter that is equal to the probability that a single collision does not corrupt the signal.

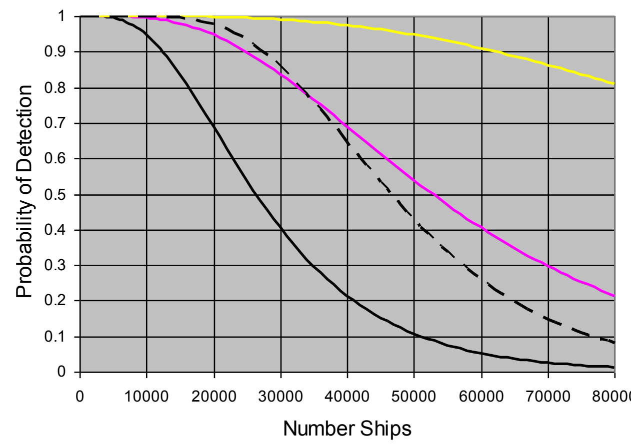

Fig. 2. Probability of detection versus number of ships for AIS 3 and 4. q = 0 (—), q = 0.5 (—), q = 0.8 (—). The dotted line is for a single allowed collision.

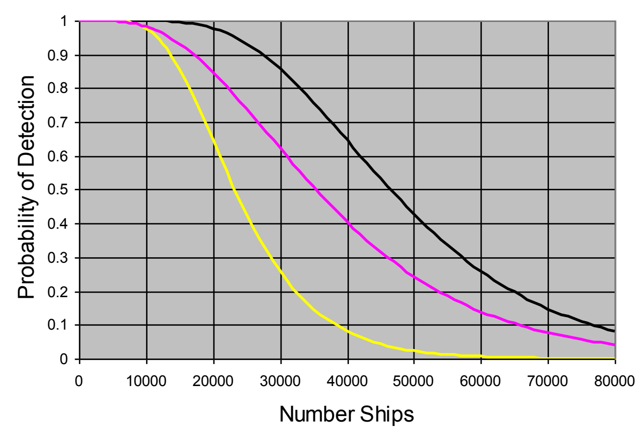

Fig.3. Probability of detection versus number of ships for AIS 3 and 4. T_{obs} = 13.6 min, ΔT = 3 min, #Channels = 1 (—), ΔT = 6 min, #Channels = 1 (—), ΔT = 3 min, #Channels = 2 (—),

The concept has been applied successfully to estimate the probabilities of detection for three cases that are documented by the ITU. The agreement between the calculated and simulations appears to be acceptable, though an important feature of the ITU model is not provided and can only be implied.

Furthermore the new model implies that the performance of space-based AIS in the presence of signal collisions in a high shipping density environment is very sensitive to the ability of the system to resolve collisions. Consequently performance is likely to fall off badly if there are a very large number of ships concentrated in a small area. This problem will be overcome with the introduction of message 27.

REFERENCES

[1] G. Hoye, Space-Based AIS–Theoretical Considerations and System Parameter Optimization, FFI/Rapport 02495, 2006.

[2] G.K. Hoye, T. Eriksen, B.J. Meland, B.T. Narheim, "Space-Based AIS for Global Maritime Traffic Monitoring", Acta Astranautica, Vol. 62, No. 2-3, pp 240-245, 2008.

[3] S. Haykin, *Communication Systems*, 4^{th} Edition, John Wiley & Sons Inc., 2001.

[4] "Improved Satellite Detection of AIS", International Telecommunications Union Recommendation ITU-R M.2169, December 2009.