The Performance of a Space-Based AIS System

James K.E. Tunaley

***Abstract*—A recent theory of space-based AIS performance is extended and compared with data presented by COMDEV at the ASAR-2011 conference. This simulated data was derived from a comprehensive AIS system emulator. The predictions of the theory appear to be consistent with the simulations if account is taken of message losses due to both signal collisions and other mechanisms, such as thermal noise.**

***Index Terms*—space-based AIS, performance model, signal collision.**

I. Introduction

Space-based AIS performance has been analyzed by the Norwegian Defence Establishment (FFI) [1]. The analysis applies to the case where the receiving system cannot resolve signal collisions due to the inability of the Self-Organizing Time Domain Multiple Access (SOTDMA) protocols to handle a large number of cells in the antenna Field Of View (FOV). Recently this has been extended to cover situations where the effects of signal collisions can be resolved by signal processing and messages recovered [2]. Signal processing provides a significant improvement in performance as measured by the probability of receiving an AIS message correctly.

At the recent ASAR-2011 conference, COMDEV presented the results of simulations of their AIS system using a comprehensive emulator [3]. This included the effects of signal collisions associated with SOTDMA failures as well as those due to messages from ships at different ranges to the satellite, which produce "signal overlap". In addition the effects of thermal noise were included. Results relevant to a single satellite-borne receiving system coupled to a ground-based signal processing scheme are shown in Fig. 1. The ordinate γ represents the fraction of AIS messages correctly extracted by their system. The data for this figure were derived from a similar figure in their presentation.

The theory in [2] includes the effects of signal collisions but does not include message loss due to thermal noise or any other effects, such as interfering terrestrial signals and so it will be extended to cover this case. Other clarifications and minor improvements will also be included.

J.K.E. Tunaley is President of London Research and Development Corporation, Ottawa, ON, Prof. Emeritus, Physics Dept., University of Western Ontario, London, ON and Adjunct Prof., Physics Dept., Royal Military College, Kingston, ON.
Email: manager@london-research-and-development.com

Initially published: June 20th, 2011. Published with additions and minor modifications: August 8th, 2011.

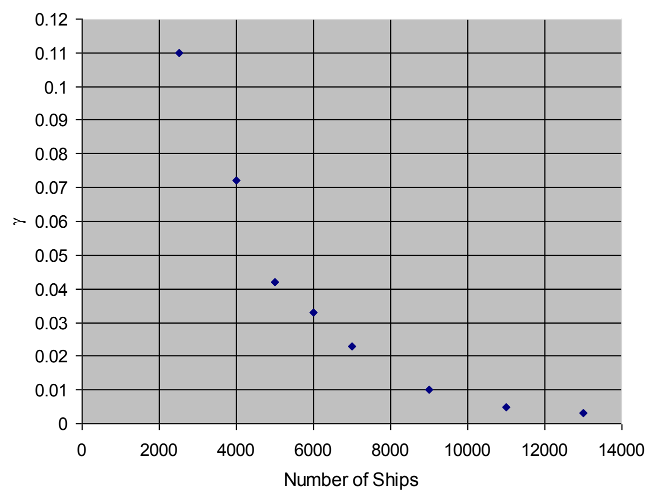

Fig. 1. The fraction of uncorrupted messages as a function of the number of ships in the FOV.

II. Extended Theory

Each ship in the satellite receiver FOV transmits a signal regularly and those ships roughly within its line of sight and which lie within its SOTDMA cell do not interfere with it. We can pick a ship at random and estimate the probability that a signal from another ship does not corrupt it. Picking a single ship at random implies that ships outside of that ship's SOTDMA cell act as a source that provides interfering signals that arrive randomly and the number of signals is Poisson distributed.

Neglecting range overlap, the probability of receiving an uncorrupted message in a time slot is given in [2] (5) as:

$$e^{-\lambda\tau_0(1-q)} \tag{1}$$

where λ is the mean rate of random messages arriving in that slot, τ_0 is the length of the time slot, and q is the probability that a single message will be uncorrupted by the simultaneous arrival of another singleton message. The mean rate of random message arrivals can be expressed in terms of the total number of ships, N, in the FOV, the number of ships, M, inside the ships cell, the number of VHF channels, n_{ch}, and the mean time between message transmissions, ΔT:

$$\lambda = \frac{N-M}{n_{ch}\Delta T} \tag{2}$$

In many cases of interest, M is a small fraction of N and can be ignored; this is the case here.

An alternative model is discussed in the Appendix.

However, if messages are corrupted by thermal noise, interference from neighboring channels or even interference in the same channel from terrestrial transmitters, the probability, γ, of extracting an uncorrupted message is reduced to:

$$\gamma = \gamma_0 e^{-\lambda\tau_0(1-q)(1+s)} \tag{3}$$

where γ_0 is the probability of receiving an uncorrupted message at the input of the receiving system, regardless of collisions. The effect of overlap has been added as in [1] and [2] by including the factor $(1 + s)$.

Therefore we see that a plot of $\ln(\gamma)$ against the number of ships in the FOV should be a straight line. This is shown in Fig. 2. A trend line is included with a value of R^2 of 0.9957, which demonstrates that the data are an excellent fit. The value of the intercept is -1.3157; this indicates directly that γ_0 = 0.2683. The slope, m, is -0.000354. The number of ships in a SOTDMA cell is assumed to be negligible.

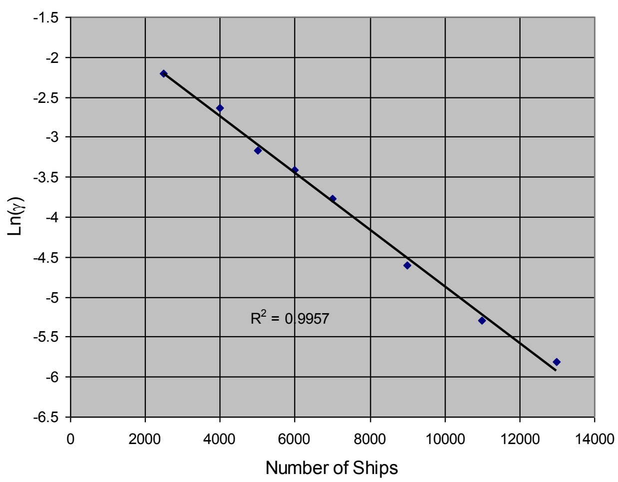

Fig. 2. Plot of the natural logarithm of γ against N.

III. Discussion

Firstly it is emphasized that the data in Fig. 1 apply only to Class A AIS messages for the receiver design, including antenna and processing method, of a proposed exactEarth AIS system; it is not applicable in general [4].

It is perhaps surprising that γ_0 is so small; over 70% of the messages are corrupted by thermal noise or for some other reason (including Class B messages) at the receiver input. However, this depends on the transmitting and receiving antenna patterns. The overall pattern is likely to taper off at the edge of the swath, which is expected to coincide roughly with the horizon. If the ships are dispersed uniformly over the FOV, there will be a disproportionate number of ships in an annulus near the horizon and this could partly account for the result.

The slope permits a value of q to be estimated:

$$q = 1 - \frac{m n_{ch} \Delta T}{\tau_0 (1+s)} \tag{4}$$

Assuming that the satellite altitude is 800 km, a value of s is provided in [1] as 0.674 (see also Table 1). If the time interval between transmissions is taken as 6 s [3], we have q = 0.904. This seems rather large but the value of q is influenced by the value of γ_0. This is because collisions with low level signals arising from the edge of the antenna pattern will be resolved easily.

The space-based AIS performance in terms of the probability, p, that at least one correct AIS message will be received during an observation time T_{obs} is now given by:

$$p = 1 - \left(1 - \gamma_0 e^{-\lambda\tau_0(1-q)(1+s)}\right)^{T_{obs}/\Delta T} \tag{5}$$

Using values in Table 1, the probability of detecting a single correct message from a ship in the FOV is presented in Fig. 3. This is optimistic in that ships near the edge of the swath will not be in the FOV for the nominal length of time in Table 1. If T_{obs} is reduced to 150 s, the maximum number of ships in the FOV that can be accommodated with a 90% probability of detection falls to about 3000.

Table 1
Parameters

τ_0 (s)	0.0267
ΔT (s)	6
T_{obs} (s)	300
n_{ch}	2
s	0.674
q	0.904
γ_0	0.2683

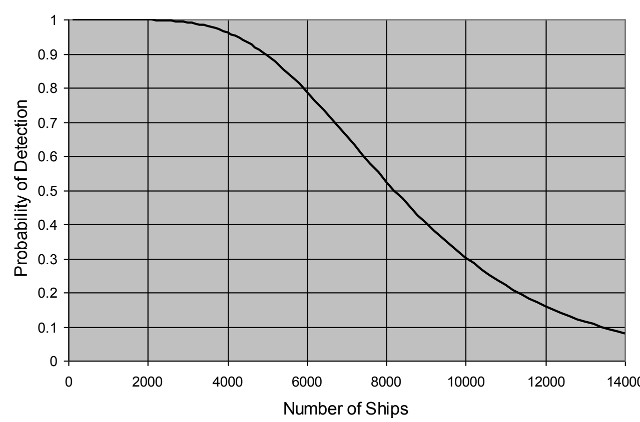

Fig. 3. Probability of Detection against Number of Ships.

If the details of the antenna pattern were available, it would be possible to calculate the actual probability of detection and to estimate an effective value of T_{obs}.

IV. Conclusion

The theory of space-based AIS performance has been extended to include messages that are corrupted by thermal noise and other effects at the receiver input as well as signal collisions. It has been compared with data from COMDEV simulations and the predicted dependence of the fraction of arriving messages that can be deciphered as a function of the number of ships has been demonstrated. The probability that a message will be overcome by thermal noise and other effects is perhaps unexpectedly large along with the probability that a collision can be resolved.

The data supplied by COMDEV is consistent with their performance claims but some caution must be exercised because simulated data is not necessarily reliable and real data is always preferable.

ACKNOWLEDGMENT

The author thanks Ian D'Souza for making his presentation available and for his helpful comments.

REFERENCES

[1] G. Hoye, Observation modelling and detection probability for space-based AIS reception - Extended observation area, FFI/Rapport 04390, 2004.

[2] J.K.E. Tunaley, Space-Based AIS Performance, London Research and Development Corporation Technical Report, May 28th, 2011.

[3] I. D'Souza, Single Satellite, Single Pass AIS Performance, Presentation at ASAR-2001 Conference, Canadian Space Agency, June 2011.

[4] I. D'Souza, Private Communication, August, 2011.

APPENDIX

An alternative to the theory in [2] can be based on the concept that a processor can readily separate the AIS messages into categories. For example, a message from far astern of the satellite should be separable from a message arising from far ahead of it; this is based on the maximum Doppler separation of about 7 kHz compared to the bandwidth required to extract the message of about 9 kHz. Polarization is a useful attribute that can be employed and should yield another two disjoint categories at least under some ionospheric conditions. Therefore we suppose that there are c categories into which a signal will fall at random.

If we pick a ship at random, the probability that there will be a message collision with another single signal arising from outside of its SOTDMA cell is equal to $1/c$. If there are n potentially colliding signals distributed randomly among the c categories, the probability, q_n, that there will not be a collision with our chosen signal is given by:

$$q_n = \left(1 - \frac{1}{c}\right)^n \tag{6}$$

However, n itself is a random variable with a Poisson distribution so that the probability that there will not be a collision and the message will be uncorrupted is now:

$$\sum_{n=0} q_n e^{-\lambda\tau_0} \frac{(\lambda\tau_0)^n}{n!} = e^{-\lambda\tau_0 / c} \tag{7}$$

Comparing this with (1), we see that $1/c$ has simply replaced 1-q and the practical effect is similar to that of the previous theory.