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Meeting #2

Preliminary Results on
Possible Enhancements to the Universal Access Transceiver (UAT)

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SUMMARY

This paper describes a number of possible UAT system enhancements designed to increase robustness in the face of bursty interferers, particularly JTIDS/MIDS transmitters. These changes, which are primarily changes to the error detection and correction schemes, are examined in the context of a simulation which has been validated using data measured on actual UAT and JTIDS equipment. The results obtainable through relatively minor changes seem very promising.

1. Introduction

This paper presents some *preliminary* results of work being done to improve the performance of the Universal Access Transceiver (UAT) in the presence of pulsed interference. Although there could be several types of such interference, this paper will focus on the interference provided by JTIDS/MIDS transmitters. The original experimental version of UAT operated at 966 MHz, and the current transceivers have been modified to operate at 981 MHz. Thus, the operational frequency has moved from just outside the JTIDS band to an actual JTIDS frequency. So, whatever interference existed previously will only be exacerbated by the frequency shift. There is some concern that JTIDS/MIDS interference will limit the usefulness of the overall UAT system in environments where they coexist.

The paper will begin with a description of the models used to describe the interference phenomena. It will then show the results of comparing simulation results with measurements made on actual JTIDS and UAT equipment. That exercise will validate the correctness of the simulation (which is implemented in the Mathematica® programming language). The model will be used to assess the performance of the current version of UAT in a particular JTIDS interference environment. A number of simple ways to improve the performance of UAT versus interference will then be suggested and evaluated using the simulation with the same "standard" interference environment. This paper will focus primarily on changes to the error correction and detection mechanisms built into the system. The suggested changes will be incremental in nature and will not greatly diminish system capacity or system throughput. They will not, for the most part, necessitate changes to the current hardware implementation of UAT. The end of the paper will contain a summary and some suggestions for continued work.

2. Background

In this section we will describe the important assumptions about JTIDS and UAT needed to create an accurate simulation. We begin with JTIDS. It is assumed that the reader has some familiarity with this system.

The important features of JTIDS, from the point of view of our model are (1) the transmitted power, (2) the distance between the JTIDS transmitter and the UAT receiver, (3) the frequency difference between the JTIDS transmitter and the UAT receiver, (4) the JTIDS time slot duty factor, and (5) the transmitted spectrum of JTIDS. Our assumptions are as follows:

1. The transmitted power of JTIDS is assumed to be 200 watts. We will assume that cable losses and antenna gains or losses add up to 0 dB, i.e., the effective radiated power (ERP) is also assumed to be 200 watts.
2. The UAT/JTIDS separation can be any value; however, we will assume it is 3 nmi in many of the examples described below. We will use a free-space propagation model throughout.

3. JTIDS frequencies are chosen pseudorandomly from among 51 frequencies situated between 969 MHz and 1206 MHz (inclusive). In particular, the former UAT frequency of 966 MHz was just below the lowest JTIDS frequency while 981 MHz *is* one the JTIDS hopping frequencies. While there is some correlation between one frequency and the next in an actual JTIDS radio, this correlation is assumed to have a negligible effect on the simulated results.
4. The time slot duty factor of the JTIDS interferer used in many of the examples given below is assumed to 100%. We are assuming that each of the slots is occupied by a train of 258 JTIDS pulses in the standard double pulse format.
5. The transmitted spectrum of a JTIDS pulse is required to conform to a spectral mask provided in the JTIDS specification. In order to meet the specification, the expected minimum shift keying (MSK) spectrum needs to be reduced by filtering. We will assume that the specific type is a four-pole Butterworth filter, so that the JTIDS spectrum is described by equation (1) given below. Here, T is the JTIDS "chip" time of 200 nanoseconds. In addition to the spectrum associated with the modulation and filtering, we assume that there is a noise floor whose effect can be summarized by adding a constant –73 dB to equation (1). The JTIDS specification requires only that the noise floor be less than –60 dB; however, it has been shown that the actual noise floor should be less than –67 dB in order to avoid triggering the interference protection feature (IPF) which is included in every JTIDS/MIDS terminal. Allowing for 6 dB production margin, etc., gives us the –73 dB figure. The resulting spectrum, together with the spectral mask, is given in Figure 1.

$$S(f)=\left(\frac{1}{1+(0.7\,fT)^8}\right)\left(\frac{\cos(2\pi fT)}{1-16(fT)^2}\right)^2 \qquad (1)$$

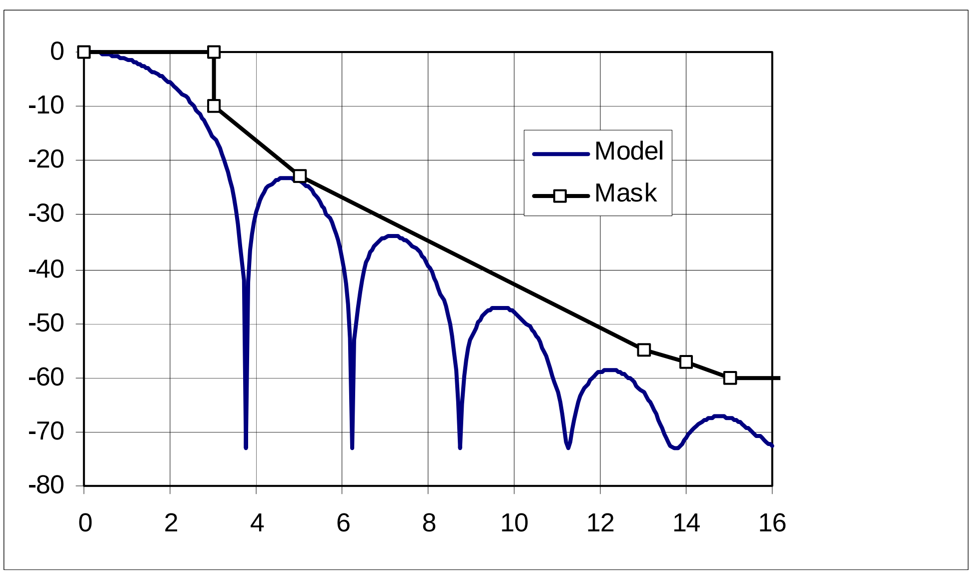

Figure 1: Assumed JTIDS Spectrum

The important aspects of the UAT system incorporated into the simulation are (1) transmitter power, (2) receiver selectivity, (3) receiver sensitivity, and (4) the types of error correction and detection built into the UAT signal formats. Note that although there are other parts of a UAT burst other than the message payload (i.e., the synchronization bits and the ADS-B message length identifier), the susceptibility of these parts can be shown to have a minimal impact on performance. Thus, the attention of the model will focus on those parts of the UAT bursts protected by error correction and detection. Other important assumptions are explained below.

The ERP of an airborne UAT transmitter (transmitting long and short ADS-B messages) is assumed to be 25 watts. The ERP of a ground radio (transmitting ground messages) is assumed to be 125 watts. This could be based on a 25 watt transmitter together with a 7 dB gain antenna.

Measurements on the UAT transceivers that were used in our tests indicate that the effective bandwidth of those receivers is approximately 3 MHz. (This number is probably bigger than necessary.) Outside of this bandwidth the effect of external signals falls rapidly, so it appears that the possibility of a large out-of-band JTIDS signal reducing receiver performance via desensitization, reciprocal mixing, or otherwise is negligible. In other words, the main effect of a JTIDS transmitter can be estimated by determining the amount of interfering power within the effective (3 MHz) receiver bandwidth.

The sensitivity of a UAT receiver depends on the relationship of the input signal-to-noise ratio to the channel bit error rate. We will assume that this connection is given (approximately) by the text-book formula for orthogonal keying:

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{\gamma_b}{2}}\right). \tag{2}$$

The factor, γ_b, is just the signal power divided by the noise power. In the presence of thermal noise only, this is given by

$$\gamma_b = \frac{S}{N} = \frac{LS_R}{FkT_0 B} \tag{3}$$

where

$S_R =$ received power level at the receiver input,

$L =$ implementation loss factor (-2 dB),

$F =$ receiver noise figure (4.2 dB), and

$B =$ 3 MHz.

The numbers for the implementation loss and noise figure were chosen to fit measured data as described in the next section. (Actually, only the total of 4.2 dB + 2 dB = 6.2 dB was determined. The estimated split between L and F was somewhat arbitrary. The particular choice does not strongly effect the results of this paper.) If, in addition to thermal noise, there is an interferer, then the denominator of equation (3) becomes

$$N = \left(FkT_0 + J\right)B \, .$$

J is the average of the interfering noise density over the bandwidth, B. If the interferer is a JTIDS transmitter, then JB is proportional to the integral of the spectrum given in Figure 1 over the appropriate 3 MHz bandwidth.

3. Validation

A number of tests were performed at the MITRE facilities in Bedford, MA (by J. C. Moody and J. Devine) to determine if the models of JTIDS and UAT were correct. Originally, the UAT operating frequency was 966 MHz. In later tests we used UAT units tuned to 981 MHz. We determined the sensitivity of the UAT receivers (at 981 MHz) using long ADS-B messages (which are coded using a Reed Solomon (RS) (41,35) code) and ground messages (which are coded using a pair of RS(255,235) code words). Because the two types have different lengths and different coding schemes, their performance is not identical. The results of the tests on a particular unit are shown in Figure 2.

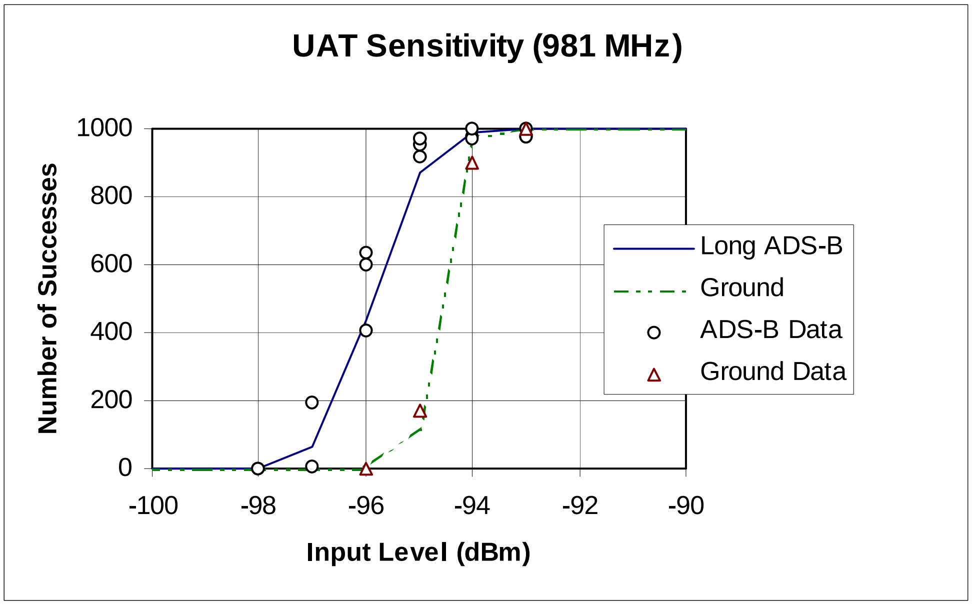

Figure 2. UAT Sensitivity Measurements

In each case, 999 messages were sent and the number of successful receptions was recorded. For the ground messages, success was defined as having two correct RS code words. In the figure the lines are based on equations (2) and (3), with the effects of coding included. The circles and triangles represent the data. The measurement of the long ADS-B performance was repeated three times in order to get some idea of the repeatability of the measurements, and the variability in the ADS-B data may be related to the steepness of the performance curve. Note that the only free parameter used in generating the curves was F/L, which was set at a value equivalent to 6.2 dB. The agreement between the model and the data seems good. If we define sensitivity to be the level where the success rate is 90%, then the sensitivity for long ADS-B messages is about –95 dBm and the sensitivity for ground messages is about –94 dBm. (Of course, choosing 90% is somewhat arbitrary, we might just as well have chosen 50%.) Another unit was tested, and its sensitivity was within 1 dB of the first one.

The UAT radios were also tested with JTIDS interference present. Using JTIDS terminals which were temporarily at our disposal, we subjected UAT receivers to JTIDS interference at various power levels and at various duty factors. For example, we operated a UAT receiver at 966 MHz and subjected it to JTIDS interference at an input level of –33 dBm. When the UAT level was varied, the results shown in Figure 3 were obtained.

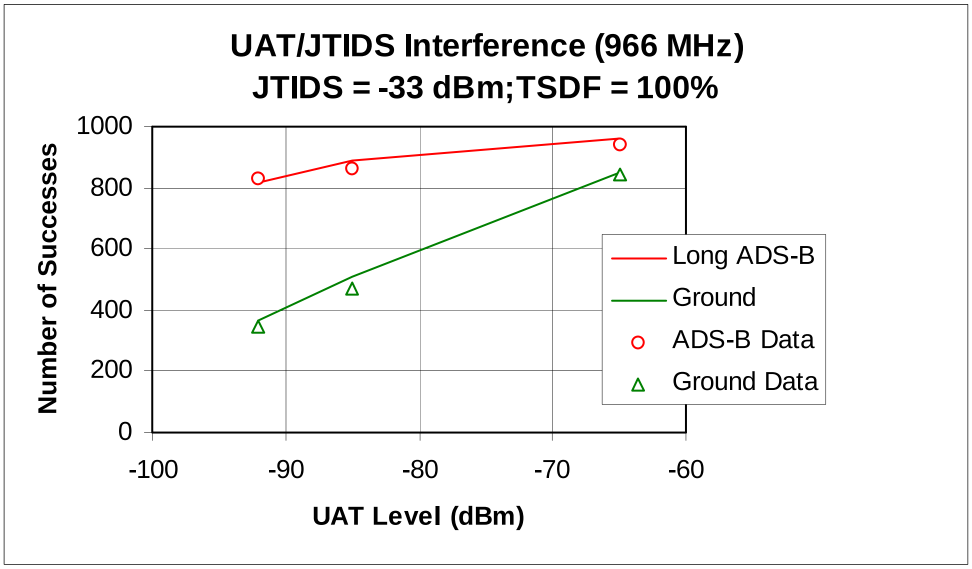

Figure 3. JTIDS/UAT Interference at 966 MHz

The solid lines represent the predictions of the simulations and the circles and triangles are the measured data. There appears to be very good agreement between the simulation and the data for both the long ADS-B messages and the ground messages.

A similar test was done with the UAT receiver operating at 981 MHz. In this case the level of the UAT signal was set at –90 dBm and the level of the JTIDS interferer was varied. The results of the measurements for the long ADS-B message are shown in Figure 4. In this case the measurements were again repeated three times in order to visualize the variability in the data. This variability arises because of the statistical nature of the bit error performance engendered by the probability curve of equation (2), and because the amount of overlap between the JTIDS signal and the UAT signal can vary from pulse to pulse. Because the transmit time of the ADS-B message is well randomized with respect to the JTIDS interference, there is not too much variability. There appears to be very good agreement between the model and the measured data.

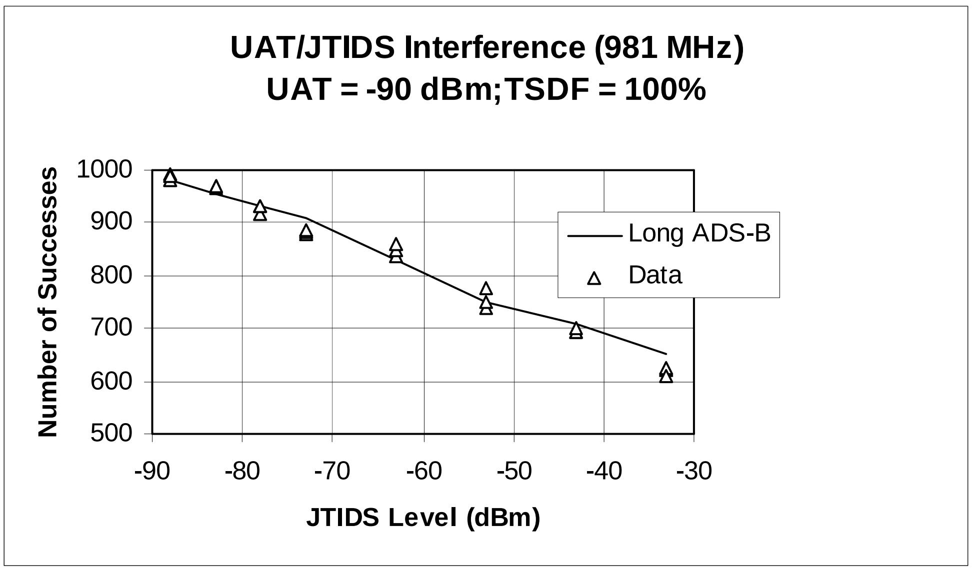

Figure 4. JTIDS/UAT Interference at 981 MHz. Long ADS-B Message.

We can compare Figures 3 and 4 at the points where JTIDS is at –33 dBm and UAT is at –90 dBm. At 966 MHz the probability of success for the ADS-B message is about 85%. At 981 MHz the same probability is only about 65%. This is an expected result because the lower frequency is at the edge of the JTIDS band, while the higher frequency is in the midst of the JTIDS frequencies. Thus, the probability of being "hit" by a JTIDS pulse is much higher at 981 MHz. This points to the fact that it will be more difficult to protect UAT at the higher frequency.

The up link performance at 981 MHz was also measured; however, interpretation of these results is a little more problematical. In the case of these measurements, the timing of the up link messages was changed from that of the test at 966 MHz so that the relative timing between the UAT up link and the JTIDS interferer was no longer well randomized on any particular test run. This meant UAT/JTIDS timing could vary from very good to very bad for the duration of a test, leading to a great deal of performance variability from run to run. This is apparent from the data shown in Figure 5. One line in Figure 5 shows the performance expected when averaged over all possible time relationships, and the other shows an approximation to the worst case relative timing. (Note that another difference between this figure and most of the others is that the JTIDS TSDF was 50% instead of 100%.) All of the data fall within the expected region.

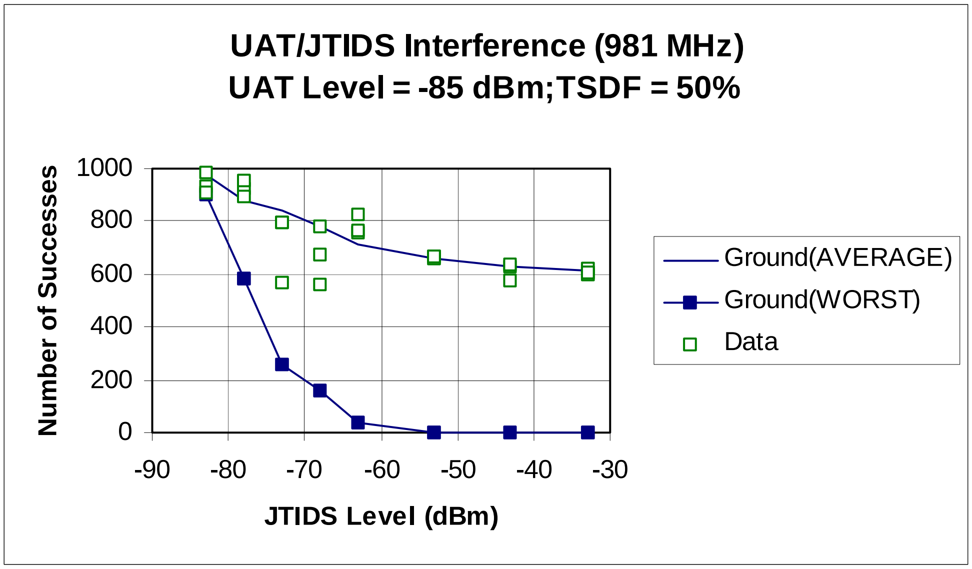

Figure 5. JTIDS/UAT Interference at 981 MHz. Ground Message.

This phenomenon points to a potential performance limitation for the up link UAT messages. Since the timing of JTIDS and the UAT up link can both have a periodicity of exactly one second, the worst case timing may repeatedly occur in a real scenario unless the timing of the UAT up link is somehow varied in order to break up the synchronism with JTIDS. For example, a particular application such as a weather map might use the same transmission time each second at a particular ground site and be repeatedly hit by JTIDS transmissions. This situation could be resolved by using a slightly different transmission time each second. Of course, this type of timing agility might require coordination between different ground sites. Unless otherwise stated, the ground message performance curves presented below assume randomization.

In summary, based on the generally good agreement between the simulation and the measured data, it seems that we can safely use the simulation to investigate the effects of possible UAT enhancements on system performance.

4. Potential Enhancements

In this section we look at potential enhancements to UAT based on adjustments to the error correction and detection schemes. As a basis for comparison we will look at UAT performance in a standard scenario in which a single JTIDS transmitter is 3 nmi from the UAT receiver and is transmitting with a duty factor of 100%. The model can easily incorporate other interference environments; but for the sake of simplicity we will focus on just one, which may be near the high end of the likely interference scenarios. Within the given scenario, we will show the probability of a successful UAT burst versus the UAT distance, i.e., the distance between the UAT transmitter and receiver. Note that when the JTIDS interferer is at 3 nmi the –73 dB noise floor attributed to the JTIDS spectrum does not really come into play since the floor is lower than contribution of the receiver noise. However, its effect will increase in importance if the distance separation is decreased.

Beginning the investigation, Figures 6 and 7 show the expected performance at 966 MHz of the long ADS-B message and the ground message (average values), respectively. In general, the performance is moderately good. The 90% success range for the long ADS-B message is about 100 nmi; and the 90% success range for the ground message is about 60 nmi. Note that the rapid fall-off in ADS-B performance after 100 nmi is due to the sensitivity of the receiver. The graph for the ground message does not show such an effect because the ERP of a ground transmitter is 7 dB higher than that of an aircraft transmitter.

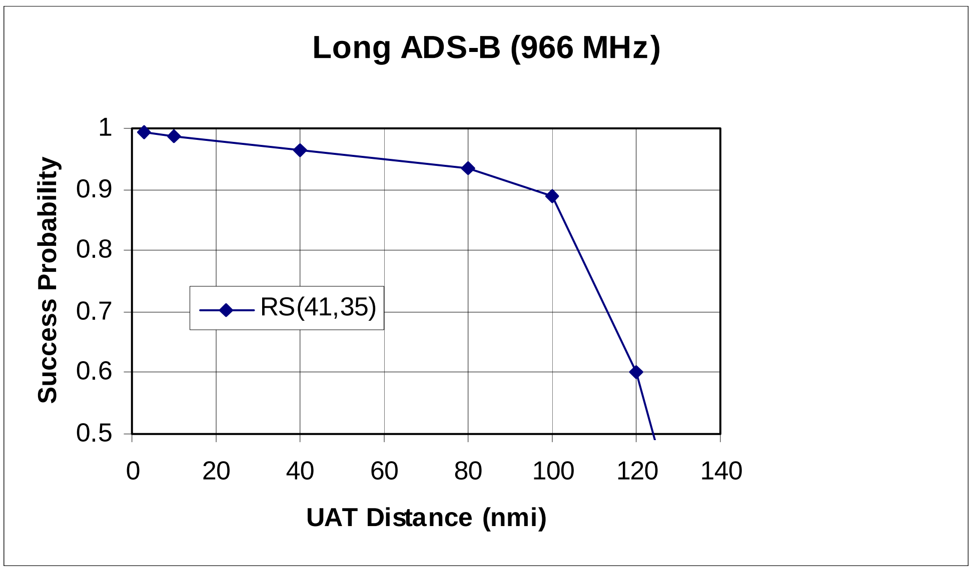

Figure 6. Long ADS-B Message Performance at 966 MHz
(JTIDS@3 nmi, 100% TSDF)

It is assumed that the UAT requirements can be included as some sort of mask (i.e., a line above which the actual performance curve should lie) in graphs like these. Note that the graphs only include the performance degradation due to JTIDS (and to receiver sensitivity). Other limitations on performance such as UAT self-interference in a dense traffic environment are not included. If additional sources of interference are present, all that we can say for sure is that the JTIDS-only curve represents an upper limit to the combined effect. A rough rule of thumb might be to estimate the total effect by multiplying together the success probabilities generated by each contributing effect separately, but a more precise analysis should include all interference effects in a single simulation.

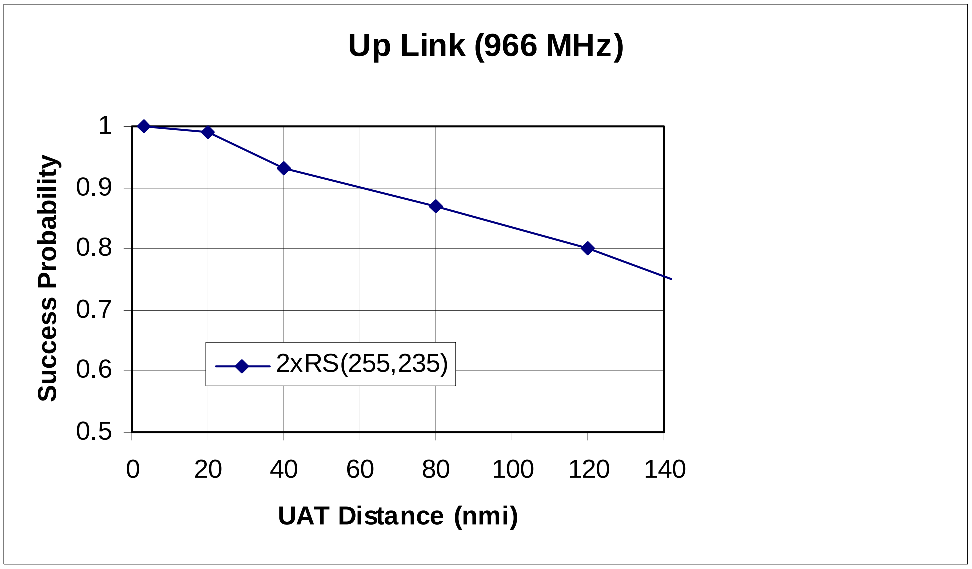

Figure 7. Ground Message Performance at 966 MHz
(JTIDS@3 nmi, 100% TSDF)

When the operating frequency of UAT is at 981 MHz, the predicted performance of the current system is shown in Figures 8 and 9. In each case the performance of the current system (with no changes) is the lower curve. A comparison of Figures 6 and 7 with 8 and 9 indicates that performance is *substantially* degraded when the frequency is moved from 966 MHz to 981 MHz---the probability of failure at any particular range more than doubles.

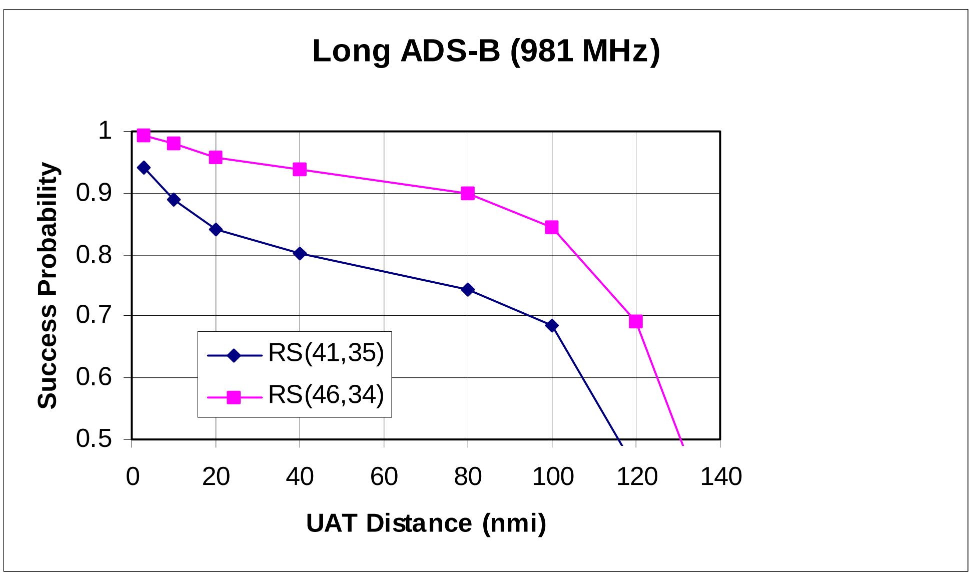

Figure 8. Long ADS-B Message Performance at 981 MHz

(JTIDS@3 nmi, 100% TSDF)

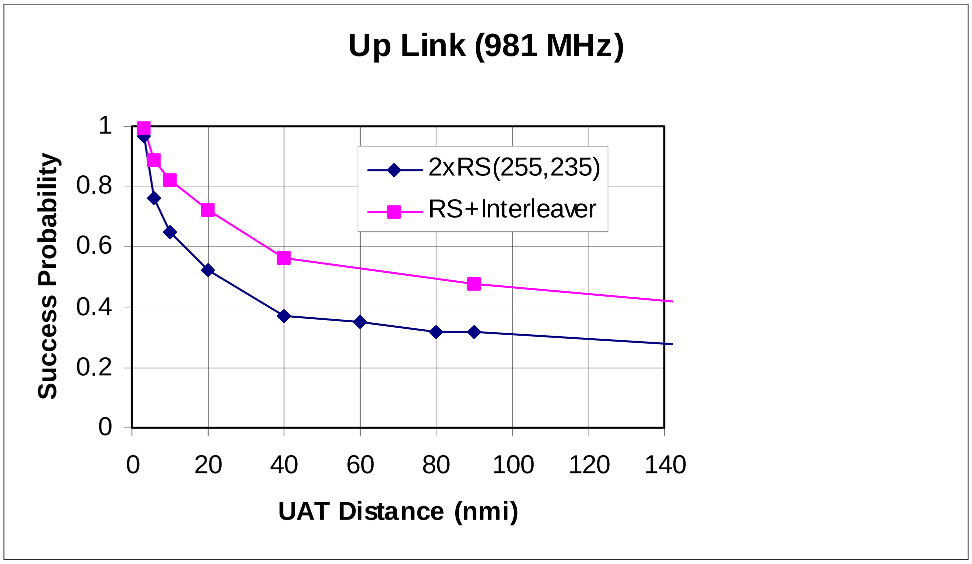

Figure 9. Ground Message Performance at 981 MHz
(JTIDS@3 nmi, 100% TSDF)

The upper curves in Figures 8 and 9 illustrate two ways of improving the performance of UAT. Figure 8 shows the result of changing the coding of the long ADS-B message from RS(41,35) to RS(46,34). The number of parity bytes was increased from 6 to 12 and the apparent information content of the message was reduced from 35 to 34. The information was not really reduced; instead, the size of the error-detecting CRC code was reduced from 24 bits to 16 bits. The error detection performance of UAT will be discussed in the next section. Doubling the number of parity bytes significantly improves performance. The particular choice of the RS(46,34) code was driven by the fact that it can correct up to 6 errors and the fact that JTIDS interference tends to cause byte errors to come in pairs. The error pairing is related to the fact that the duration of a JTIDS pulse is roughly the same as the duration of a UAT byte. Thus, we expect a code that corrects an even number of byte errors to have disproportionately better performance than one that corrects an odd number of byte errors.

The upper curve in Figure 9 shows the beneficial effect of interleaving the data (in a byte-wise fashion) when multiple RS blocks comprise a burst. Because errors caused by burst interference tend to come in contiguous pairs, overall performance can be improved by an interleaver that splits each pair between two RS blocks. In Figure 9 the interleaver distributes contiguous bytes so that one byte is in one RS(255,235) block and the other byte is in the other RS(255,235) block.

In spite of the fact that the upper curve in Figure 9 is much better than the lower curve, it still represents somewhat poor performance for the ground message. To improve performance we can increase the number of parity bytes in each burst. A possible change would be to replace the two RS(255,235) blocks with six RS(85,65) blocks. The total number of bytes is the same, but the number of parity bytes increases from 40 to 120. (Note that the reason that we chose 6xRS(85,65) instead of 2xRS(255,195), which would have better performance, is that it is typically difficult to do the necessary processing when there are large numbers of parity bytes. The hardware in the current UAT implementation is believed to be limited to 20 parity bytes per block.) The performance of ground messages with the stronger coding is shown in Figure 10.

In Figure 10 we also show the performance when an interleaver is included. The interleaver need not be very complex. The interleaver assumed in Figure 10 consists of an 85x6 matrix in which the *bytes* are fed in row-wise so that each RS block occupies one row. (It is important that all the processing at this stage be done in terms of the 8-bit bytes constituting the RS code symbols.) Prior to modulation and transmission the bytes are read out column-by-column. On reception the process is reversed. The result is that every contiguous pair of bytes transmitted over the channel is split between two separate RS blocks. As shown in Figure 10, this simple interleaver, coupled with the stronger coding, improves performance considerably. The cost of this improvement is that the number of bytes carried by each burst is reduced from 470 to 390.

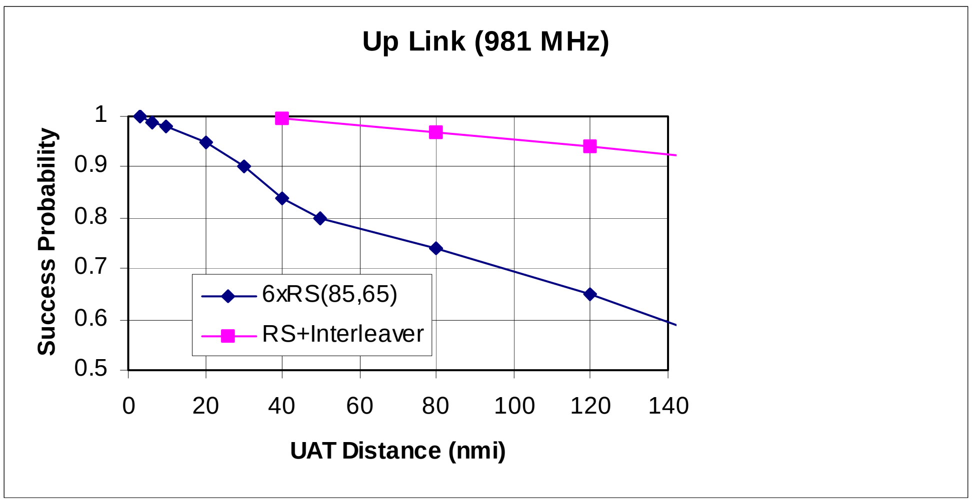

Figure 10. Enhanced Ground Message Performance at 981 MHz
(JTIDS@3 nmi, 100% TSDF)

We can also improve the performance of the short ADS-B message by changing the coding from RS(25,19) to RS(26,18). This change reduces the number of CRC bytes from 3 to 2. It also increases the number of parity bytes from 6 to 8, so that the number of correctable errors is increased from 3 to 4. As discussed previously, it appears to be most efficient to allow for a code that can correct an even number of errors. The error detection performance of the CRC code will be discussed in the next section. The improved performance of the short ADS-B message is shown in Figure 11.

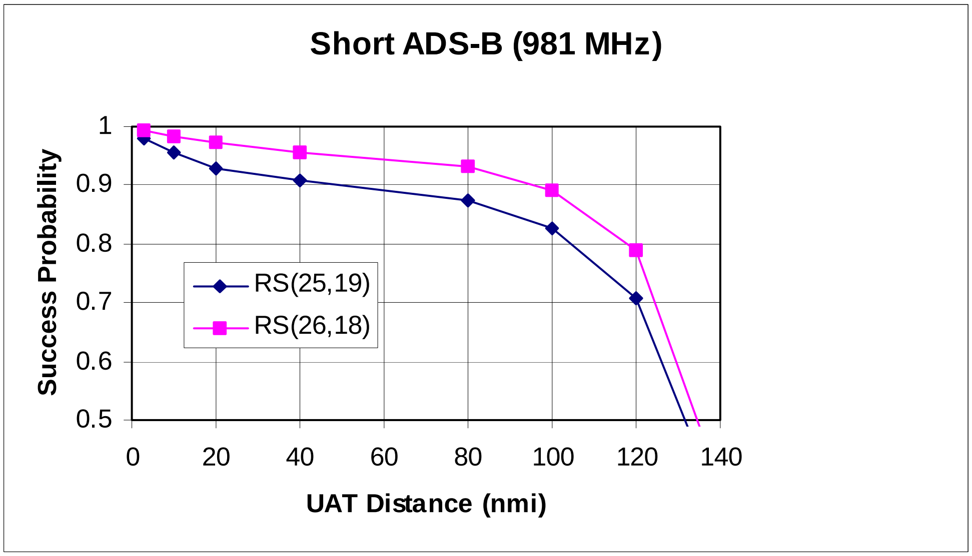

Figure 11. Short ADS-B Message Performance at 981 MHz
(JTIDS@3 nmi, 100% TSDF)

5. Error Detection

Among the suggested changes to improve UAT performance are reductions in the sizes of the cyclic redundancy check (CRC) codes for the ADS-B messages. This seems like a viable option because there is already a lot of error detection implicitly included in the performance of the RS coding. The error detection performance of RS codes has been studied, and it has been shown that an upper bound on the probability of undetected error for a RS(n,k) code is given by

$$P_U \leq \frac{256^k - 1}{256^n} \sum_{j=0}^{t} \frac{n!}{j!(n-j)!} 255^j \tag{4}$$

with t = IntegerPart[(n-k)/2]. This upper limit is achieved when the bit error rate is 0.5. For any other channel bit error rate the probability of undetected error is even lower. When applied to the codes under consideration in this paper, the maximum probabilities are given in Table 1.

Current UAT		Enhanced UAT	
Code	Maximum P_U	Code	Maximum P_U
RS(41,35)	6.28×10^{-4}	RS(46,34)	3.25×10^{-8}
RS(25,19)	1.36×10^{-4}	RS(26,18)	3.43×10^{-6}
RS(255,235)	2.13×10^{-7}	RS(85,65)	2.49×10^{-12}

Table 1. RS Error Detection Performance

From the table we can see that the probabilities, which are already very small in the current system, are extremely small if the suggested coding changes are made. In general, it can be said that a CRCn code provides a probability of undetected error whose upper limit is given by

$$P_{CRC} \approx 2^{-n}, \qquad (5)$$

which is 1.53×10^{-5} if n=16 and 5.96×10^{-8} if n=24. The combination of the RS and CRC performance is summarized in Table 2. Note that the table indicates that we are suggesting the elimination of the CRC from the ground message.

Current UAT			Enhanced UAT		
RS Code	CRCn	Overall P	RS Code	CRCn	Overall P
(41,35)	24	3.74×10^{-11}	(46,34)	16	4.96×10^{-13}
(25,19)	24	8.11×10^{-12}	(26,18)	16	5.23×10^{-11}
(255,235)	24	1.27×10^{-14}	(85,65)	---	2.49×10^{-12}

Table 2. Overall Error Detection Performance: Maximum Probabilities

All these probabilities are extremely small, so it seems as if reducing the CRC lengths will do no harm. As a matter of fact it might be useful to reduce the CRC lengths even further. An examination of the undetected error tolerances of the system may shed light on this issue.

6. Summary/Future Work

The changes to the UAT message formats that have been suggested in this paper are as follows:

> The coding of the ground message should be changed to 6xRS(85,65), and an 85x6 byte interleaver should be added. All six bytes of CRC should be removed. This reduces the payload of a ground burst from 464 bytes to 390 bytes, a reduction of 16%. The burst length remains the same.
>
> The coding of the long ADS-B message should be changed to RS(46,34), and the CRC should be reduced to 2 bytes. This increases the length of a long ADS-B burst (including overhead for synchronization bits and Length ID) by 11%. The information content remains the same.
>
> The coding of the short ADS-B message should be changed to RS(26,18), and the CRC should be reduced to 2 bytes. This increases the length of a short ADS-B burst (including overhead for synchronization bits and Length ID) by 3%. The information content remains the same.

The change in performance (in the standard JTIDS interference scenario of this paper) can be seen by comparing the two summary charts of Figures 12 and 13. Note that the vertical scales on the two graphs are very different. Two curves for the ground message are shown in each graph. The upper one assumes that the timing between UAT and JTIDS interference is randomized. The curve labeled (WORST) shows the performance for the worst-case relative timing. This gives an estimate of the potential value of varying the ground message timing on a second-to-second basis.

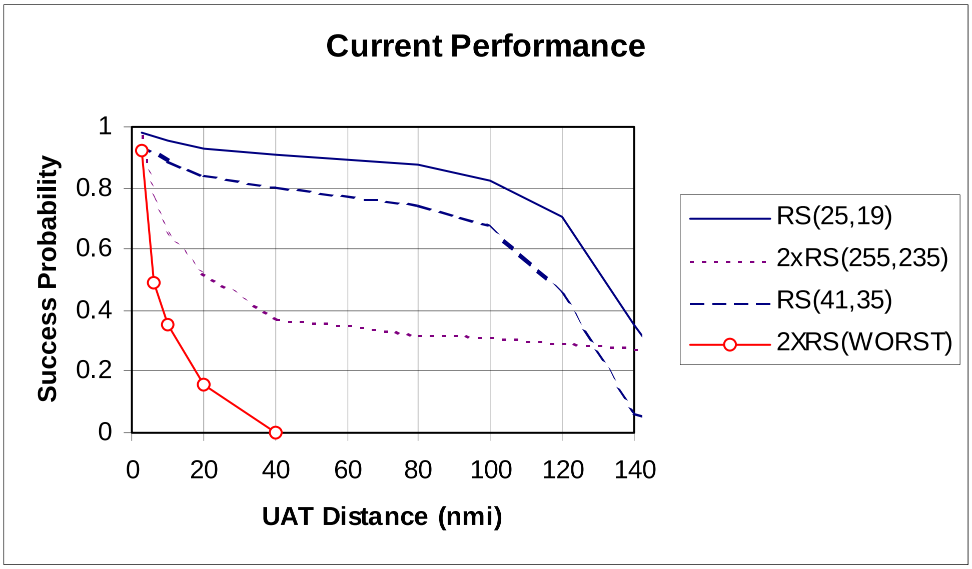

Figure 12. Summary of Current UAT Performance at 981 MHz
(JTIDS@3 nmi, 100% TSDF)

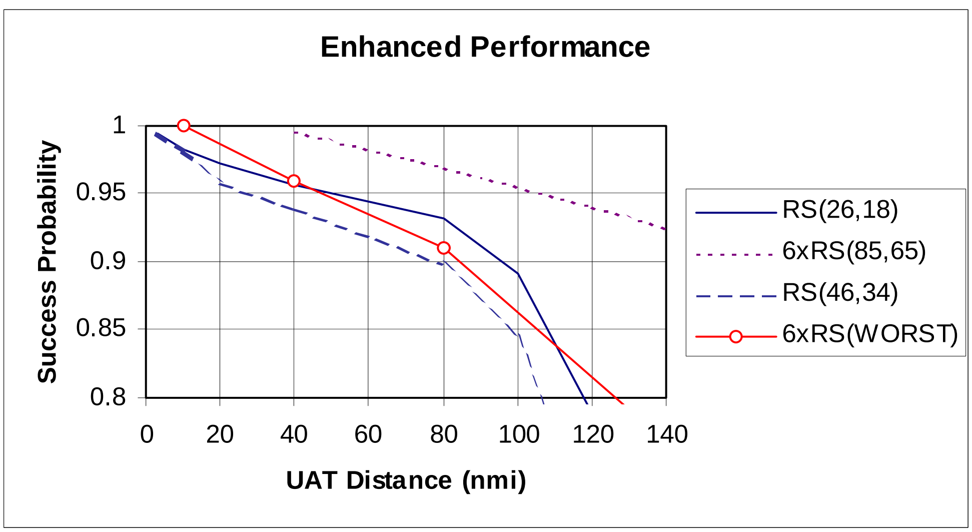

Figure 13. Summary of Enhanced UAT Performance at 981 MHz
(JTIDS@3 nmi, 100% TSDF)

For each of the message types, there is a small price to pay for performance improvement, either a smaller payload in the case of the ground message or a longer burst in the case of the ADS-B messages. It has been pointed out by one of our colleagues at MITRE (Ronald Sea) that if these small costs are not acceptable, the instantaneous data rate of UAT could be increased slightly (say, from 1.041666 MHz to 1.25 MHz). This 20% increase in bandwidth would erase the negative impacts of the suggested format changes. In terms of performance, the price to pay for this change could be a small degradation in sensitivity. On the other hand, changing the bit rate may impose an unacceptable cost impact on the current UAT radios.

One other potential enhancement to the current radio design, which is not just a protocol change, is the possibility of reducing the receiver bandwidth. The design of the current hardware includes an IF filter whose bandwidth is 3 MHz. This manifests itself in the factor B in equation (3). There is no need for this filter bandwidth to be so large. Previous studies have shown that the bandwidth can safely be reduced to 1 MHz or even smaller. By reducing this bandwidth from 3 MHz to 1 MHz, we can improve sensitivity by about 5 dB while simultaneously reducing the impact of JTIDS or other pulsed interference. The resulting performance is shown in Figure 14. *There is no negative impact to system performance if this change is incorporated*. The cost to change the current radio design would be the only impact.

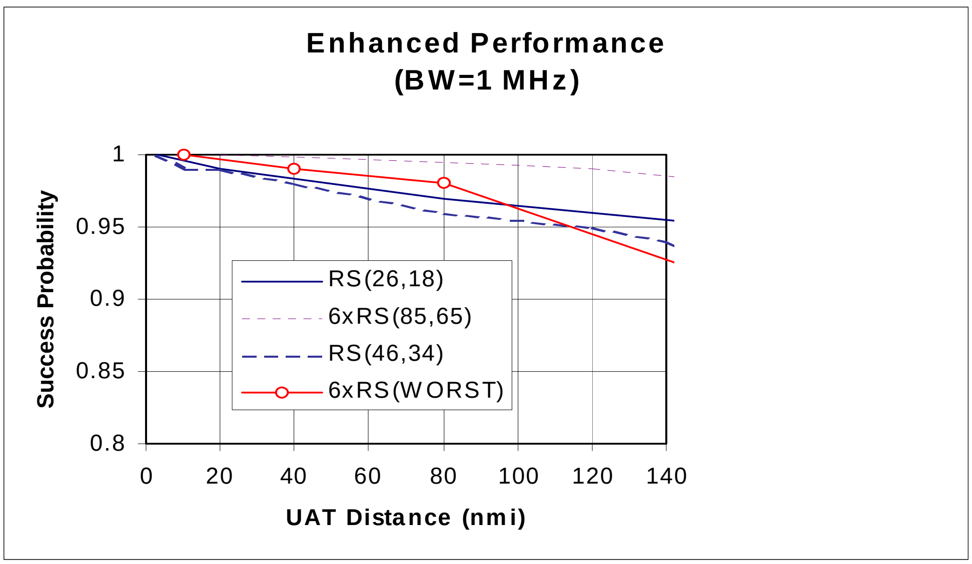

Figure 14. Summary of Enhanced Performance at 981 MHz (IF Bandwidth = 1 MHz) (JTIDS@3 nmi, 100% TSDF)

The above recommendations do not necessarily represent the final word on possible improvements to UAT. Possible future efforts, within the universe of “small changes” to UAT could include the following:

1.Fine tune the error correction and detection schemes

2.Consider more advanced schemes for demodulating the current waveform, including ones that generate erasures for use in error correction

3. Consider additional JTIDS interference scenarios

4. Add other types of interferers (DME, ATCRBS, etc.)

5. Add UAT self-interference to ADS-B curves

6. Include ADS-B probability versus distance requirements in the various performance graphs.

7. Conclusions/Recommendation

This paper has focused on changes to the current UAT definition that make it more tolerant to JTIDS interference (and, by implication, other bursty interference as well). There are, of course, potential changes to JTIDS that could also ameliorate interference problems. For example, the JTIDS frequency plan could be changed to avoid the UAT frequency and possibly neighboring ones. This type of change would likely result in some expense to the JTIDS program. Another potential change to the JTIDS program might be to prohibit the usage of the 20% of the JTIDS time slots that overlap the ground portion of the UAT time structure. (This could be done by judiciously choosing JTIDS block assignments and by supplying a time reference to the appropriate JTIDS radios.) This would be useful since the ground messages are currently the most vulnerable. The resulting 20% drop in JTIDS system throughput would be roughly equivalent to the 16% throughput drop for the ground messages proposed in this paper. Such considerations may be fruitful; nevertheless, JTIDS changes are outside the scope of this paper and are not discussed.

It is recommended that WG5 of SC-186 consider the proposed changes (or similar ones) during its deliberations on the UAT MOPS.