RTCA Special Committee 186, Working Group 5

ADS-B UAT MOPS

Meeting #6

UAT Receiver Model for Multi-Aircraft Network Simulations

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SUMMARY

The following describes the UAT receiver model, for receive bandwidths of 1.26 MHz and 0.8 MHz, used for multi-aircraft network performance modeling at JHU/APL. The model is bit-based to permit analysis of various coding and synchronization designs in time-varying interference conditions.

Introduction

The following describes the UAT receiver model, for receive bandwidths of 1.26 MHz and 0.8 MHz, used for multi-aircraft network performance modeling at JHU/APL. The model is based chiefly on Message Success Rate (MSR) data measured by UPS-AT and reported in WP-4-13 and WP-5-08. These data were re-interpreted somewhat, and extended to more complex environments, based on measurements made on prototype UAT units by JHU/APL in 1999. The model is bit-based to permit analysis of various coding and synchronization designs in time-varying interference conditions.

Analysis of the UPS-AT MSR Data

Eight sets of MSR measurements were taken by UPS-AT: Measurements were taken for the two nominal receive bandwidths, 1.2 MHz and 0.8 MHz, and for two message formats, RS(27,17) and an uncoded ("No FEC") message of the same length, i.e. 27 bytes. Measurements were also taken under two different interference conditions, receiver-noise dominated and other-UAT dominated. For the receiver-noise case, no interference was introduced, whereas for the other-UAT case, interference "modulated like a UAT signal" was introduced at a level (-39 dBm) more than 60 dB above the receiver noise. The receiver-noise data, reported in Figure 10 of WP-4-13, and the other-UAT data, reported in Figures 6 and 7 of WP-5-08, are re-plotted in Figures 1 and 2 below. The horizontal axis in Figure 2 is the (desired) signal-to-interference ratio (SIR) in dB.

Bit Error Rates (BERs) were then estimated from these MSR values, assuming that all missed messages were due to failure to decode the 27-byte message (i.e. assuming that the synchronization header was always successfully recognized if the message could be decoded). For the "No FEC" message, BER was computed as:

$$BER_{NoFEC} = 1 - MSR^{\left(\frac{1}{216}\right)}. \tag{1}$$

For the RS(27,17) message, a simulation was run assuming that bit errors were independent and identically-distributed, and that message failure occurred if and only if more than 5 of the 27 bytes in the message contained bit errors. This yielded the BER-vs.-MSR curve shown in Figure 3. (Note that 1-MSR = Message Error Rate, or MER, is plotted in Figure 3.) BER values for the RS(27,17) messages were interpolated from the measured MSR values using this curve.

For comparison, Figure 3 also plots the BER vs. MSR results for a corresponding simulation of the 27-byte No-FEC message and the analytic relation given by equation (1).

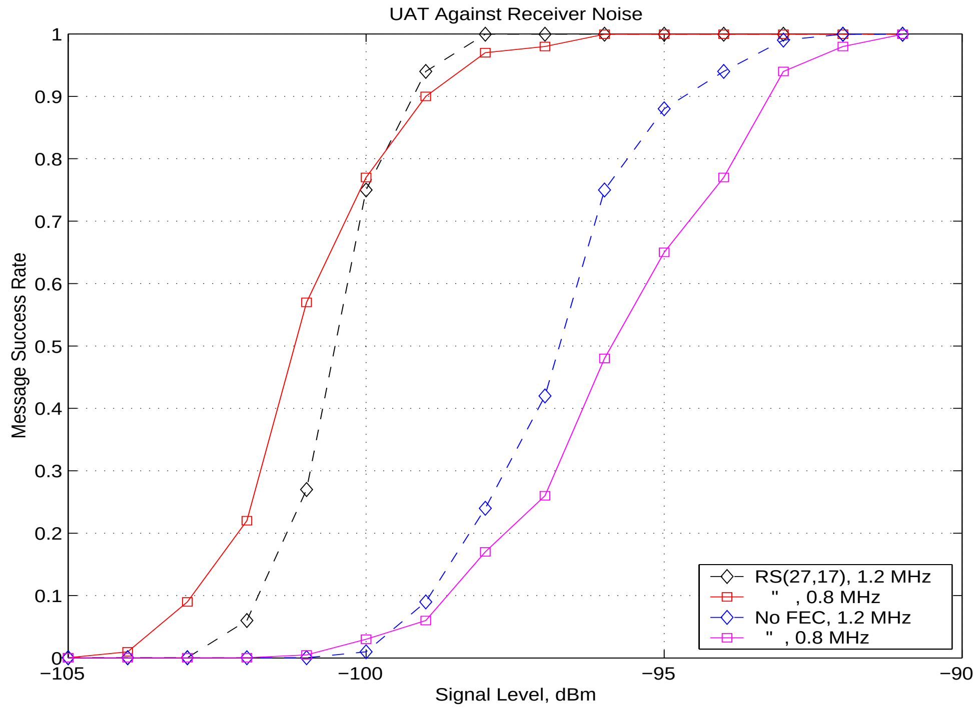

Figure 1. MSR vs. Signal Level (Interference = Receiver Noise)

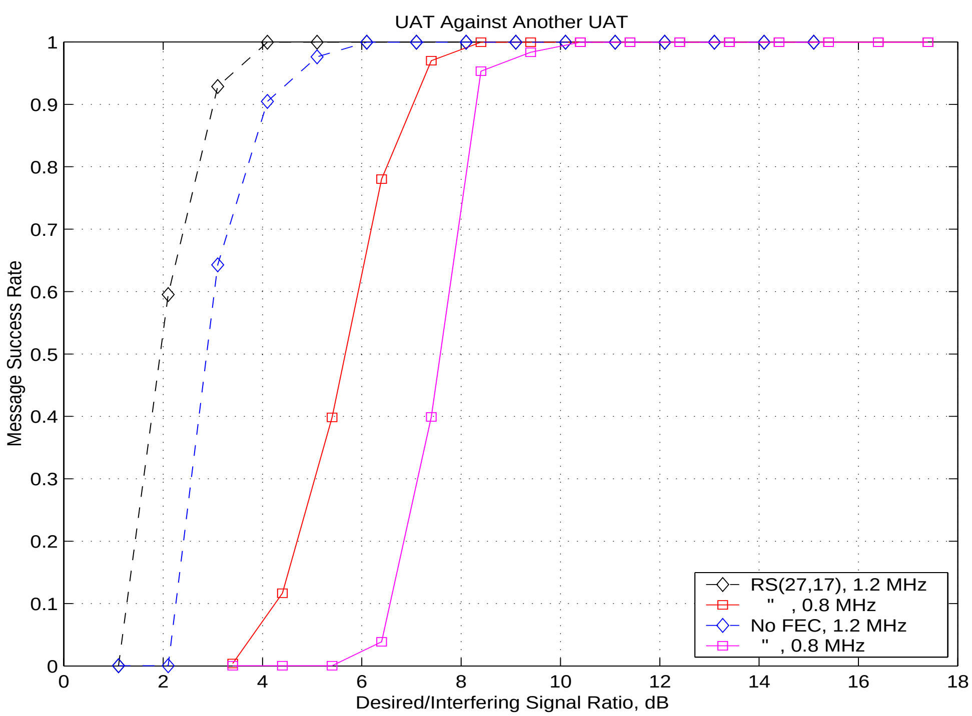

Figure 2. MSR vs. SIR (Interference = Other UAT)

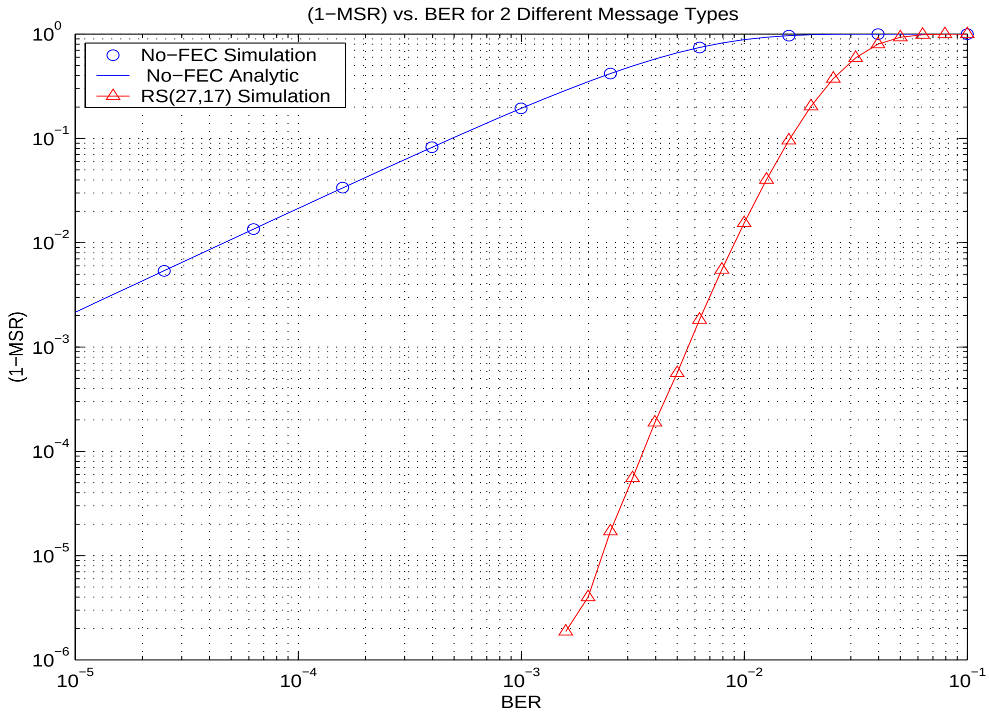

Figure 3. MSR vs. BER for RS(27,17) and No-FEC Messages

Using the MSR-to-BER conversion plotted in Figure 3, the data measured by UPS-AT are re-plotted in terms of BER in Figures 4 through 7.

At the bit level, message coding is irrelevant, so it is to be expected that the No-FEC and the RS(27,17) curves would lie on top of one another for each receiver bandwidth and for each interference case. Note, in comparing No-FEC and RS(27,17) data in Figures 4 through 7, that for these curves, only measured MSR values between 0 and 1 are plotted with diamond and square symbols joined by solid lines. MSR values of 0 were replaced with their largest probable value, 0.5/1260, since they were based on 1260 attempted message receptions. Similarly MSR values of 1 were replaced with their smallest probable value, 1259.5/1260. These data points are plotted with 'x' and '+' symbols joined by dashed lines and are to be interpreted only as lower or upper bounds (depending on whether they are to the left or right end of the data, respectively) on the true expected BER.

It can be seen that the BER curves do generally agree for the two message types, although there appears to be a systematic discrepancy in the other-UAT case (Figures 6 and 7). These curves show the estimated BER at higher SIR values to be significantly lower for the No-FEC message than for the RS(27,17) message. The cause of this discrepancy has not been determined.

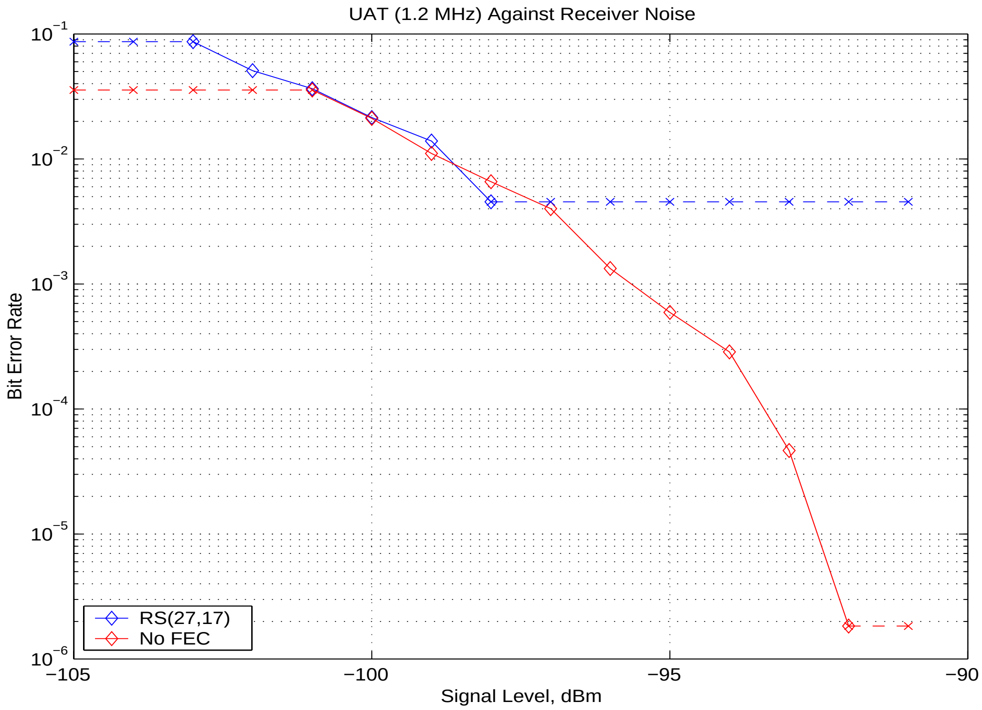

Figure 4. BER vs. S for UAT (1.2 MHz) Against Receiver Noise

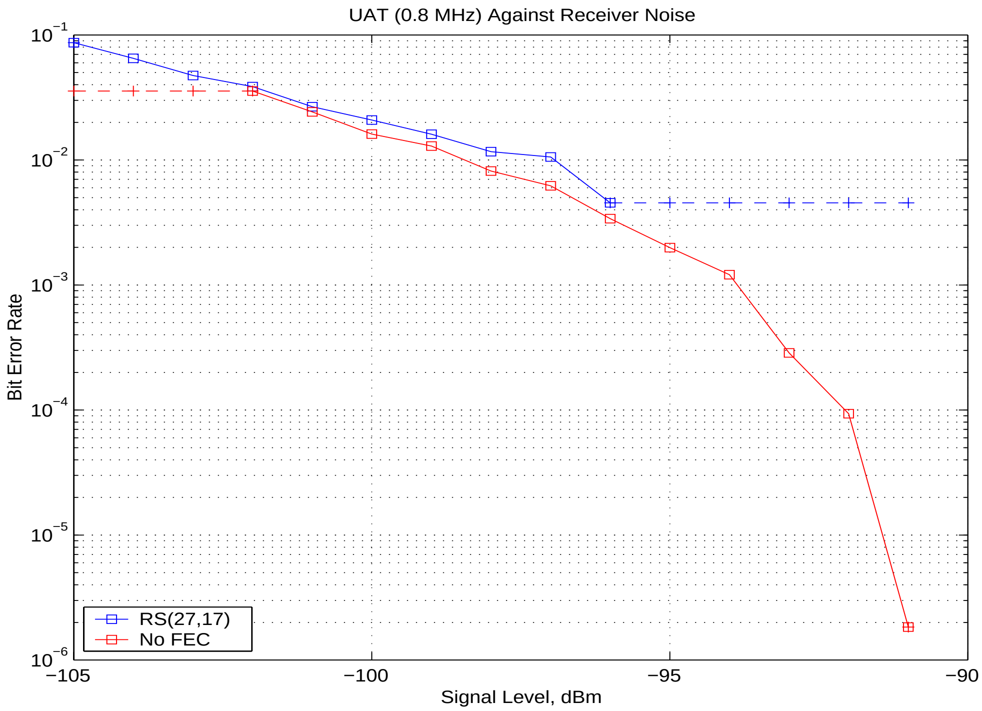

Figure 5. BER vs. S for UAT (0.8 MHz) Against Receiver Noise

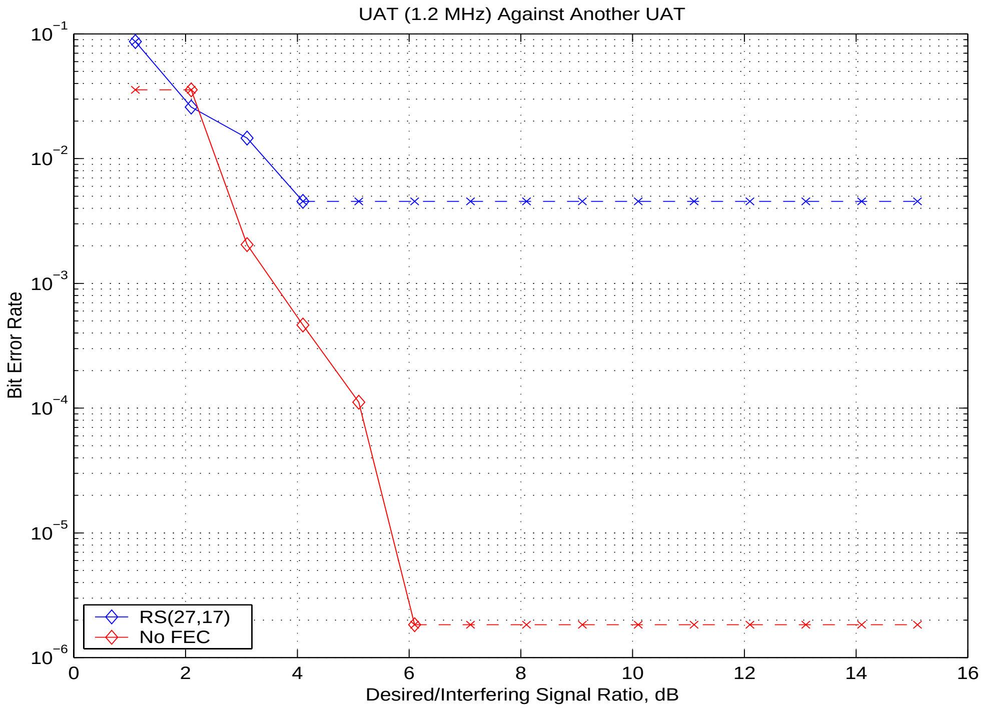

Figure 6. BER vs. SIR for UAT (1.2 MHz) Against Another UAT

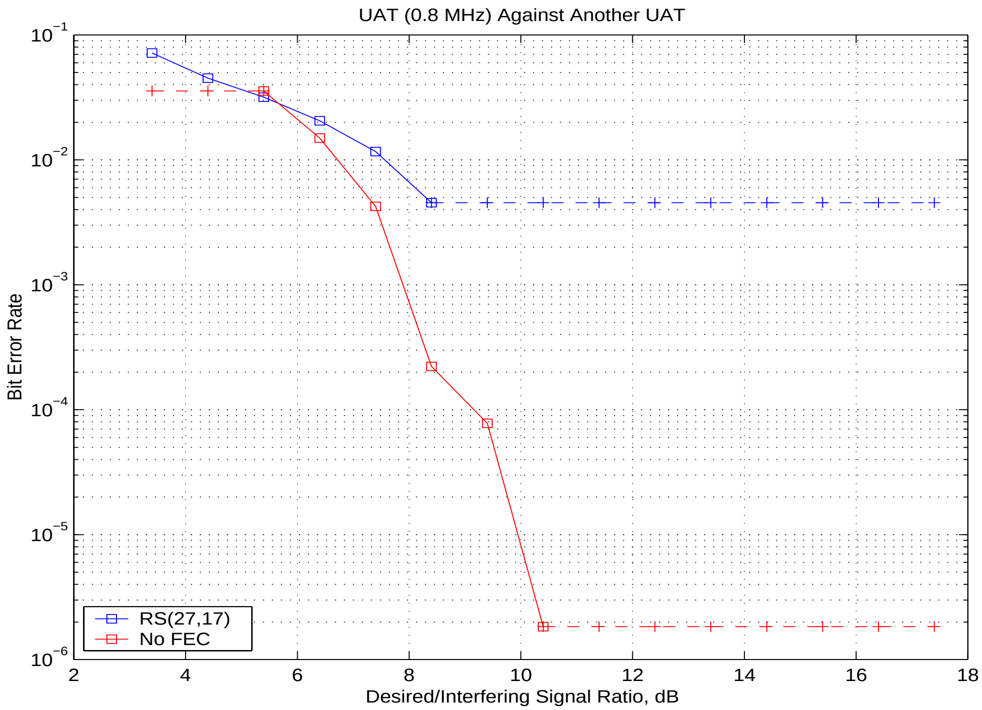

Figure 7. BER vs. SIR for UAT (0.8 MHz) Against Another UAT

Each pair of RS(27,17) and No-FEC values in Figures 4 through 7 were merged into a single, best-BER-estimate by (a) using the non-limited value when the other value was limited and consistent with it, or (b) combining the BER values when both curves gave non-limited values, or when a limited value wasn't consistent with the other value. In the latter case, "combining" was done by averaging the "log-log-BER" values and then converting back to BER, i.e.:

$$BER = 0.5 \cdot [1 - 10^{(-10^{\{llBER_1 + llBER_2\}/2})}], \tag{2}$$

where:

$$llBER_i \equiv \log_{10}\{-\log_{10}(1 - 2 \cdot BER_i)\}. \tag{3}$$

(Converting BER values to log-log-BER values significantly reduces the curvature of measured performance data when plotted against S level or SIR, in dB. Log-log-BER conversion thereby reduces linear interpolation/extrapolation errors.)

The resulting best-BER-estimates for each S or SIR value (plotted as log-log-BER values vs. S or SIR in dB) were then adjusted by eye to make them lie on as straight a curve as possible, and extrapolated at each end with a straight line. The resulting (combined, smoothed and extrapolated) curve fits represent the estimated BER curves and are compared to the BER data of Figures 4 through 7 in Figures 8 through 11.

In order to predict UAT performance in the presence of Link 16 transmissions, the assumption is made that Link16 interference is like Gaussian noise in a 1.2 MHz or 0.8 MHz UAT receive bandwidth, and that the BER will be the same as measured against receiver noise for the same signal-to-noise ratio (SNR), when noise power is measured in the receiver bandwidth. It is therefore of interest to derive BER-vs.-SNR curves for UAT, based on the BER-vs.-S curves, e.g. of Figures 8 and 9. This conversion simply requires an estimate for the actual level of receiver noise present during the measurements of WP-4-13.

In WP-5-08, the noise level was estimated assuming a receiver noise figure of 6.5 dB, resulting in a receiver noise of – 106.5 dBm for the 1.2 MHz bandwidth or –108.5 dBm for the 0.8 MHz bandwidth. This estimate was not supported by measurements.

In order to avoid the uncertainty due to assuming a noise figure, an alternate approach is to directly measure performance under controlled SNR conditions, i.e. by injecting known levels of noise. This had been done in 1999 at JHU/APL with prototype LDPU-based UAT units. There are also uncertainties associated with this approach, as those measurements were made on a UAT with a different bandwidth (about 3 MHz) and using a different message coding (RS[41,35]), but it was expected that both of these differences could be compensated for.

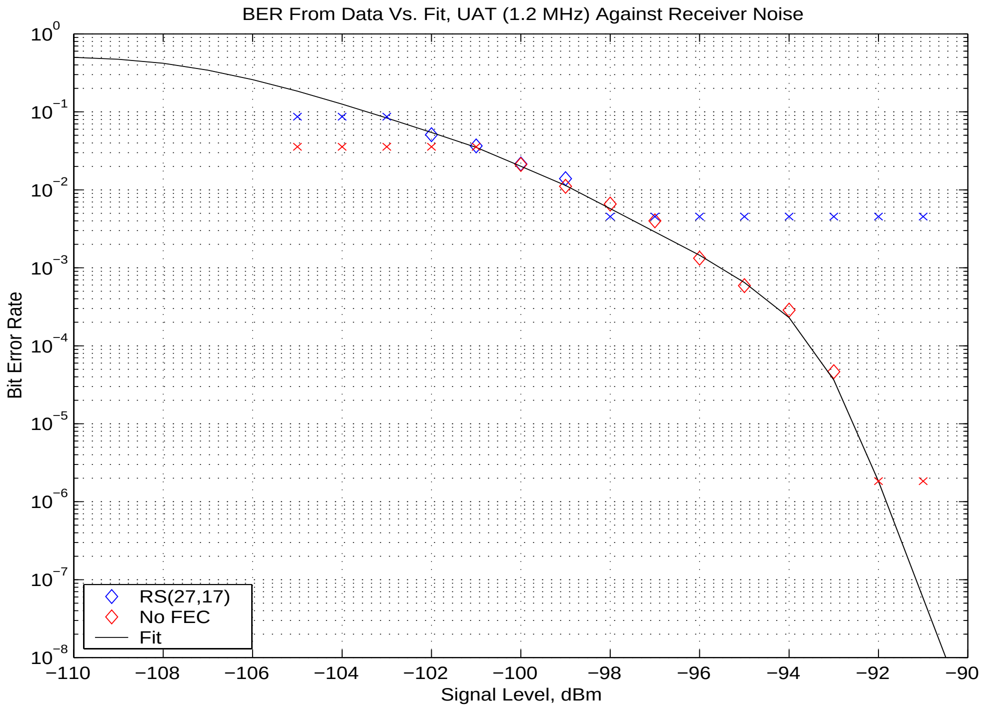

Figure 8. BER Data Compared to Estimated Curve
(1.2 MHz Bandwidth, Interference = Receiver Noise)

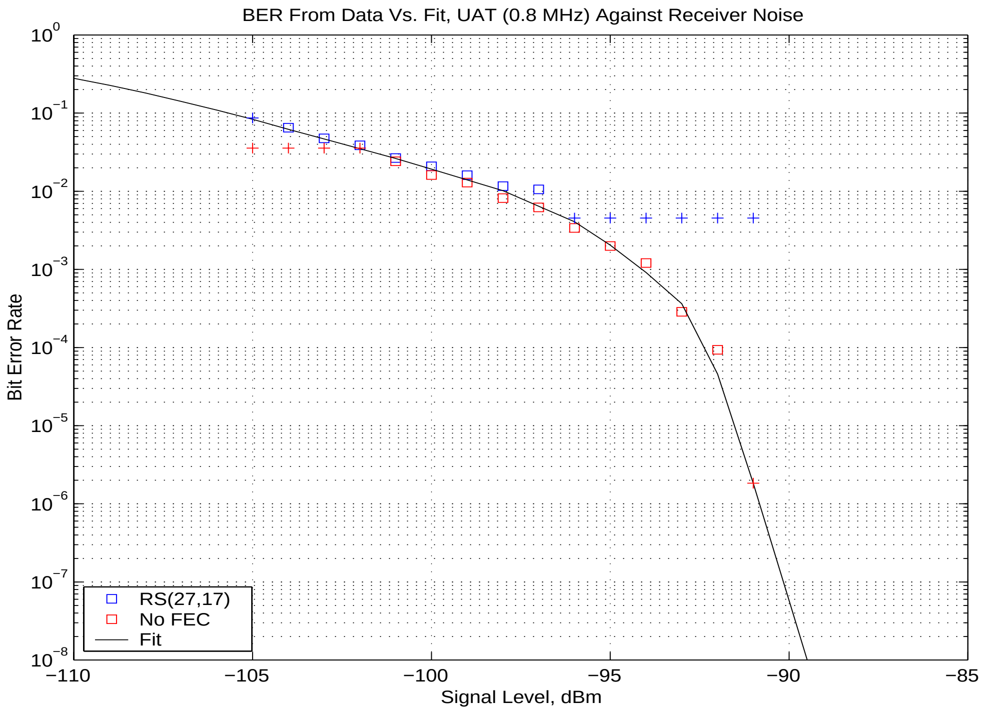

Figure 9. BER Data Compared to Estimated Curve
(0.8 MHz Bandwidth, Interference = Receiver Noise)

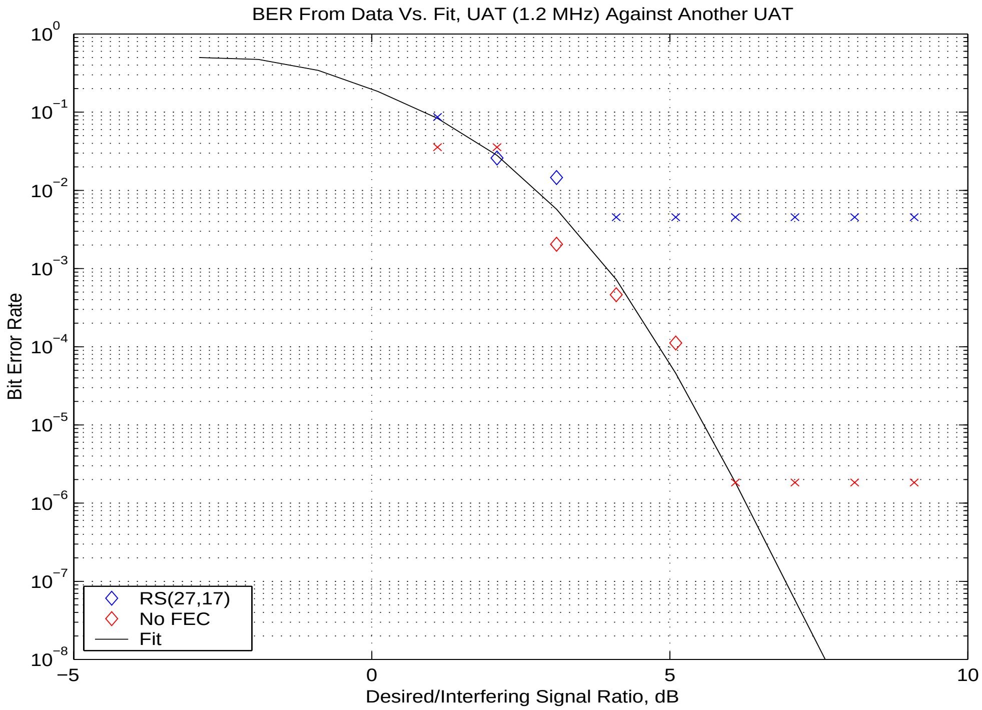

Figure 10. BER Data Compared to Estimated Curve
(1.2 MHz Bandwidth, Interference = Another UAT)

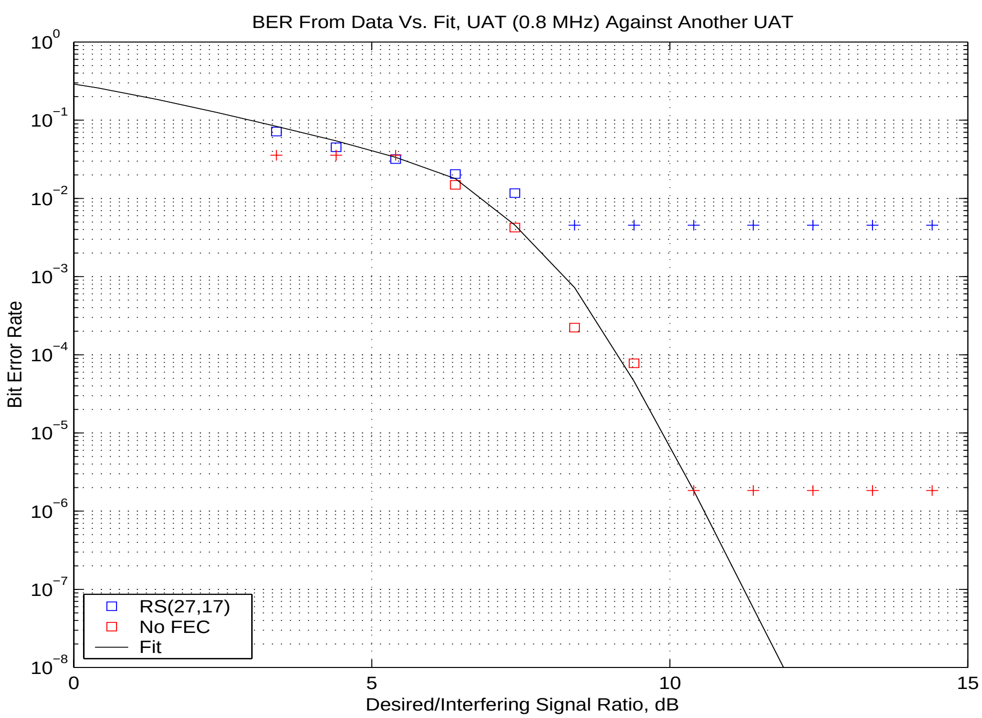

Figure 11. BER Data Compared to Estimated Curve
(0.8 MHz Bandwidth, Interference = Another UAT)

A BER-vs.-MSR simulation, like the one whose results are plotted in Figure 3, was run for RS(41,35), and used to convert the JHU/APL-measured 90% MSR point to a BER of ~ $5.5x10^{-3}$. This occurred at an SNR (in a 3 MHz bandwidth) of ~ 10 dB. The UPS-AT measurements show $5.5x10^{-3}$ BER occurring at ~ -98 dBm for the 1.2 MHz UAT against receiver noise, so if this too corresponded to a 10 dB SNR (in a 1.2 MHz bandwidth), the UPS-AT receiver noise would be ~ -108 dBm and the noise figure would be ~ 5 dB, about 1.5 dB lower than assumed in WP-5-08. As a result, the performance against Link 16 noise would be ~ 1.5 dB worse than predicted based on WP-5-08.

In light of the foregoing, the BER-vs.-S curves were converted to BER-vs.-SNR curves assuming a 5 dB noise figure for the UPS-AT measurements, rather than the 6.5 dB value of WP-5-08. Although, there is some uncertainty in this choice, justifications for it are:

- The JHU/APL measurements were much more extensive than the UPS-AT measurements of WP-4-13.
- Sensitivity measurements were also made at JHU/APL in 1999. Although they gave variable results, probably due to experimental difficulties, they indicated noise figures as low as 3 dB in some cases.
- Assuming the lower noise figure provides conservative predictions of Link 16 impact. (It doesn’t affect the predictions of performance against receiver noise under current protocols, since receiver noise is always adjusted in the multi-aircraft network simulations to provide a fixed level of performance at a given signal level—90% MSR for the long ADS-B message at –93 dBm signal level).

The resulting BER-vs.-SNR curves, together with the corresponding BER-vs.-SIR curves for comparison, are plotted in Figures 12 and 13. These curves represent the results of the UPS-AT tests as far as the JHU/APL UAT receiver model for the multi-aircraft network simulations is concerned.

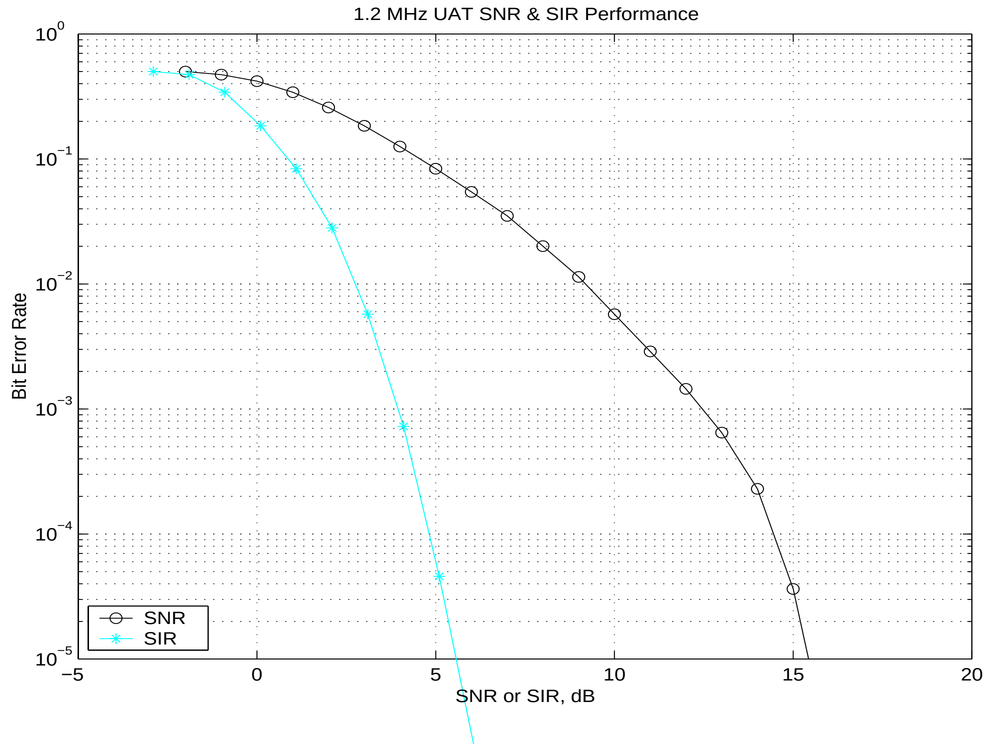

Figure 12. Estimated BER vs. SNR or SIR for 1.2 MHz UAT

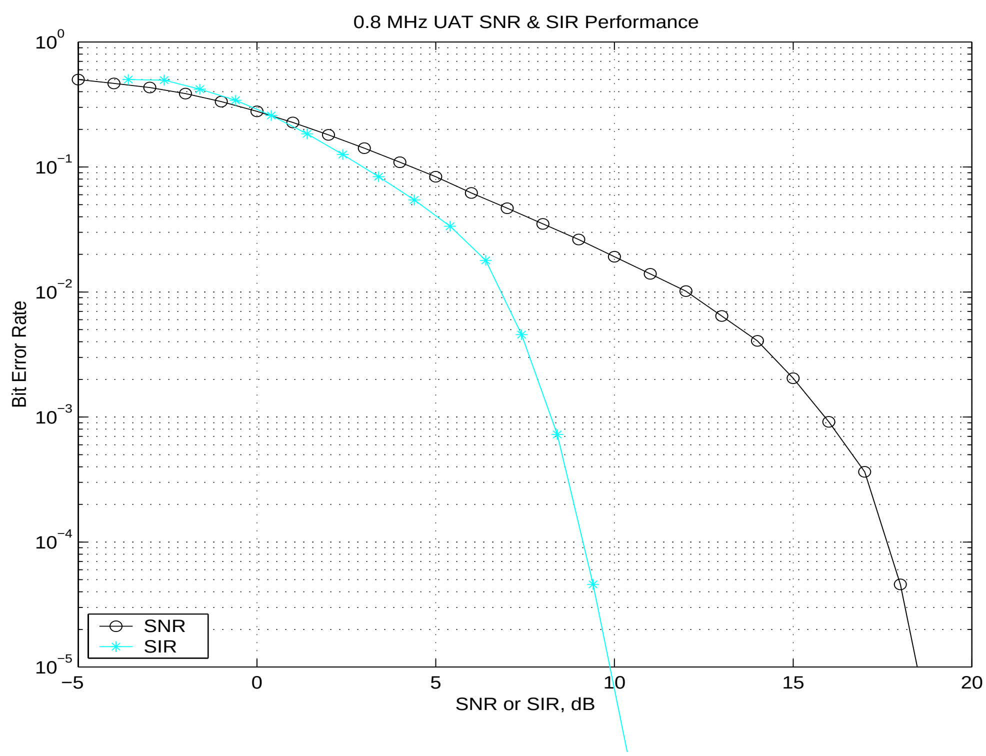

Figure 13. Estimated BER vs. SNR or SIR for 0.8 MHz UAT

Performance Against Mixed Noise Plus One or More UAT Interferers

Figures 12 and 13 describe performance against interference that is either pure Gaussian noise or a single UAT. When UAT interference is received below ~ - 80 dBm, it sums with receiver noise to produce an interference with intermediate properties. Also, when multiple UAT interferers occur at the same time and at levels within ~ 20 dB of one another, they create a waveform that is more noise-like than a single UAT interferer. In both these cases, the BER impact of the interference lies between the SNR and SIR curves of Figures 12 and 13. To handle such cases, these curves must be generalized.

In the absence of any measured data for the performance in mixed interference environments of the 1.2-MHz or 0.8-MHz UAT, the model developed at JHU/APL for mixed interference impact on the UAT receiver is used as a guide. It was based on two distinct sources of JHU/APL-measured information about the operation of the 3-MHz LDPU-based prototype UAT:

1) Simulations of MSR-vs.-SIR in multi-UAT-interferer environments based on waveforms measured at the UAT frequency discriminator output during reception of a single UAT at high SNR.

2) Extensive MSR-vs.-SNR/SIR measurements made in mixed noise-plus-single-UAT-interferer environments.

The above data were analyzed and empirically modeled. It was found that the measured MSR-vs.-SNR and MSR-vs.-SIR curves were nearly parallel, related by a fixed 7 dB offset, over the range of interest (MSR between ~5% and 99%). In other words, over this MSR range, the impact of a single UAT interferer was close to that of Gaussian noise 7 dB weaker.

Since many simultaneous UAT interferers will sum to near-Gaussian noise, it was concluded that the impact of mixed interference environments could be modeled by assuming that the summed UAT interference is equivalent to a Gaussian noise, n_{eff}, with power between 0 and 7 dB weaker than the actual summed interference power:

$$BER = BER_{snr}\left\{\frac{s}{n+n_{eff}} = \frac{s}{n+i}\cdot\left(\frac{n+i}{n+n_{eff}}\right)\right\}, \tag{4}$$

where

$$n_{eff} \equiv i \cdot 10^{\left(\frac{-k\cdot(7dB)}{10}\right)}, \tag{5}$$

and s, n and i represent the signal, noise and summed UAT interference power in linear units (not dB). $BER_{snr}(x)$ is the BER measured for pure noise, as a function of the argument $x = s/n$. The only parameter that needs to be estimated then is k, the fraction of the way from pure noise (0 dB weaker) behavior to pure-single-UAT-interference (7 dB weaker) behavior.

With the simplification represented by equations (4) and (5), the empirical results on mixed interference environments can be summarized as:

1) Multiple UAT interferers at equal powers combine so that their impact sums according to:

$$k = \left\{ \frac{1}{(m_I)^{0.4}} \right\}, \tag{6}$$

where m_I is the number of simultaneous equal-power interferers. So, for example, a single interferer gives k = 1 (i.e. 7 dB less impact than pure noise), 2 equal interferers give k = 0.76 (i.e. 5.3 dB less impact than pure noise, or 1.7 dB more than a single interferer), and so on (the more interferers, the closer k approaches to 0).

2) Mixed noise and multiple UAT interferers at arbitrary levels have a combined impact given roughly by equation (6) if the equivalent number of simultaneous interferers is given by:

$$m_I = \frac{\left(1.5 \cdot \sqrt{n} + \sum_j \sqrt{i_j}\right)^2}{(n+i)}, \tag{7}$$

where i_j is the jth interference power, again in linear units. (It can be seen that equation (7) is like a peak-to-average power ratio of the mixed interference waveform, with the Gaussian noise term replaced by a fixed level with amplitude 1.5 times its rms value.)

Equations (4), (5), (6) and (7) describe the BER impact of a mixed noise-plus-multiple-UAT-interferer environment for the prototype 3-MHz UAT. In the absence of any further information, a minimum modification was made to these equations to make them consistent with the 1.2-MHz and 0.8-MHz UAT performance curves of Figures 12 and 13. Specifically, the dB difference between the noise power and the single interferer power with the same BER impact was interpolated from the data in Figures 12 and 13 and this value, Δ (plotted in Figure 14) , replaced the 7 dB term in equation (5):

$$n_{eff} \equiv i \cdot 10^{\left(\frac{-k \cdot \Delta}{10}\right)}. \tag{8}$$

Equations (4), (6) and (7) were not changed.

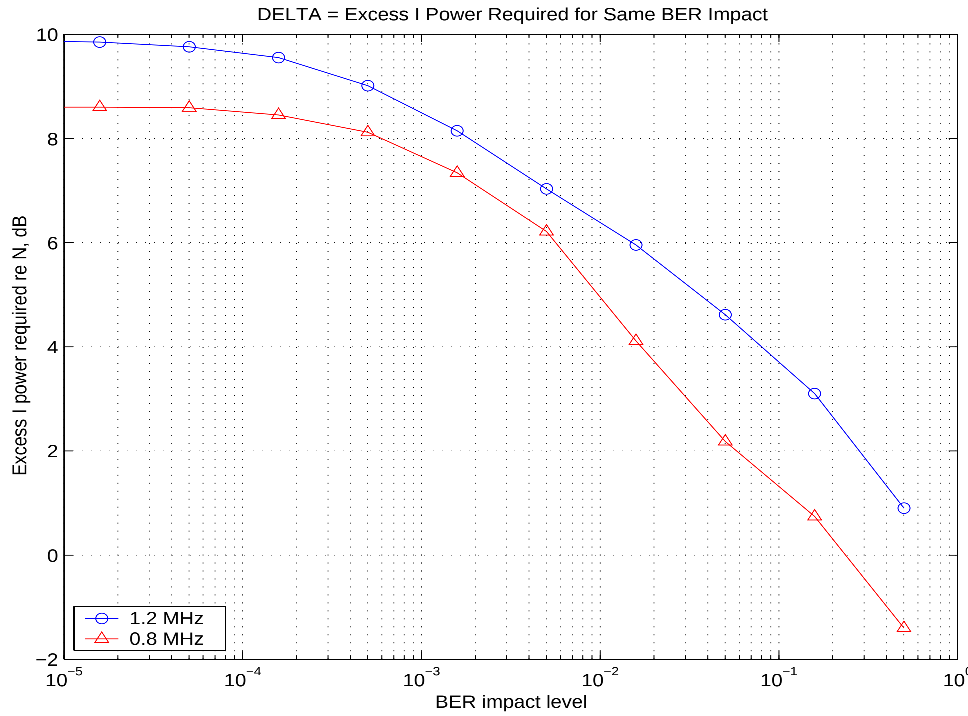

Figure 14. Excess I Required for Same BER Impact (Δ)

In equation (8), Δ is no longer a constant 7 dB, but a function of BER. As a result, equation (4) is no longer a closed-form expression for BER. Inverting it gives:

$$sinr \equiv \left(\frac{s}{n+i}\right) = \left(\frac{n+n_{eff}(BER)}{n+i}\right)\cdot sinr_{snr}\{BER\}, \tag{9}$$

where the function $sinr_{snr}(BER)$ is the inverse of BER_{snr}, the empirical function shown in black in Figure 12 or 13, and $n_{eff}(BER)$ is the empirical function defined by equation (8) and the function $\Delta(BER)$, plotted in Figure (14).

The procedure for estimating BER is therefore to use these two empirical functions BER_{snr} and $n_{eff}(BER)$, together with the values of n and the set $\{i_j\}$ to determine the empirical function *sinr(BER)* from equations (6) through (9) and then to use that function (inverted) as a look-up table to determine *BER* for a given input *sinr* value. To keep the number of entries small, interpolation between table entries is used. To improve the accuracy of linear interpolation, the BER values are converted to log-log-BER values in the look-up table, as described in equation (3), and the interpolated result is then converted back to BER. This lookup procedure permits fast computation. Sample MATLAB code is included in the Appendix.

Comparison With Measured Data for Noise Plus A Single UAT Interferer

As a check, this BER estimation procedure was used to estimate BER values for the mixed (injected) Gaussian noise and single UAT interference conditions measured at JHU/APL in 1999. The 1.2 MHz bandwidth receiver was used since its behavior is expected to be close to the 3-MHz receiver actually tested, when SNR is computed for the appropriate receiver bandwidth. These estimated BER values were then converted to RS(41,35) MERs in order to compare them with the measured MER values. It was found that the best fit to the measured data was obtained with a 0.5 dB increase in assumed interference power. This estimate is compared with the measured data in Figures (15) and (16). The 0.5 dB error does not appear large in view of the differences between the 1.2 and 3-MHz receivers and given the variability of the measured data.

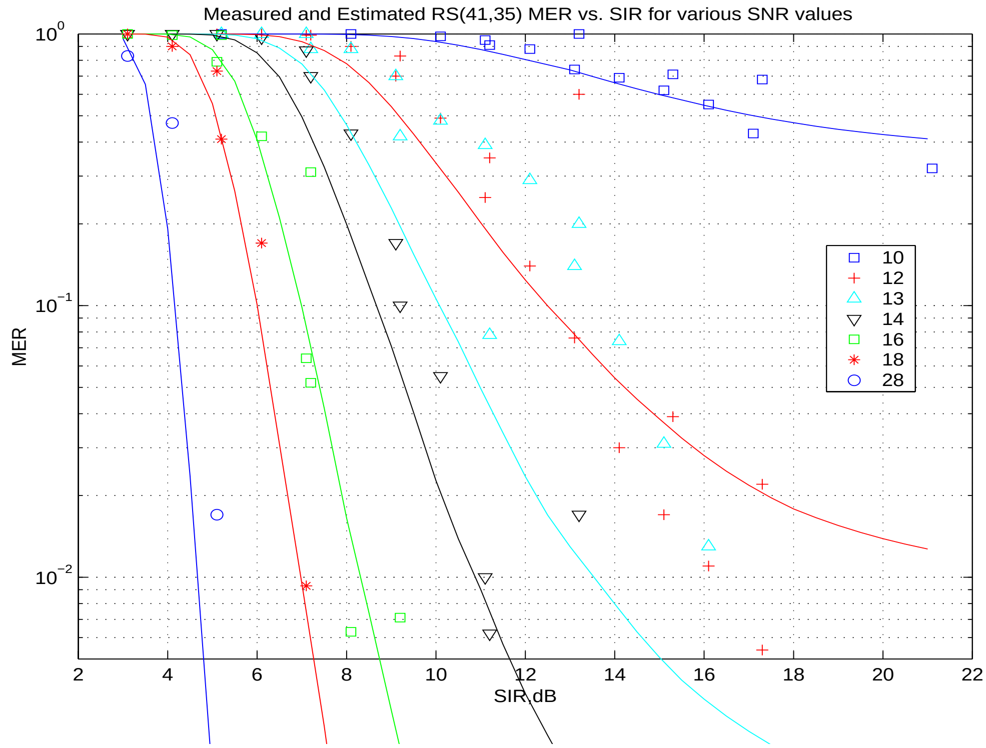

Figure 15. Comparison of Estimated and Measured MER vs. SIR, at various SNRs (see text)

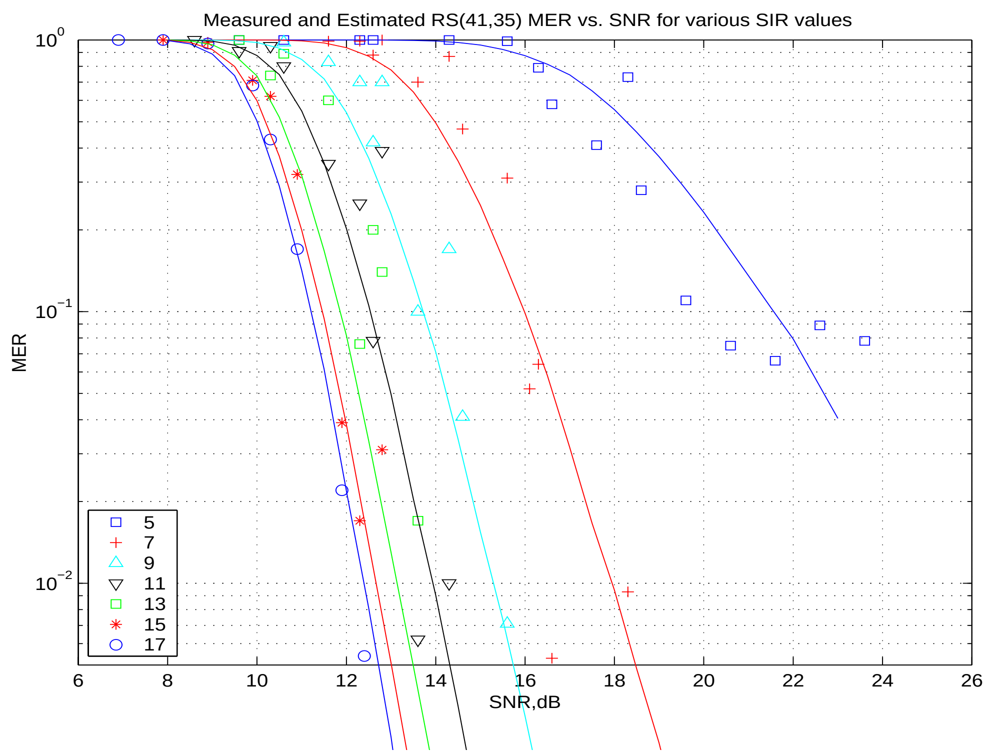

Figure 16. Comparison of Measured and Estimated MER vs. SNR at Various SIRs (see text)

Appendix: MATLAB Code for BER Estimation

```
function BER = BER_UAT2(B,I_U,I_16,S,N)
%  BER = BER_UAT2(B,I_U,I_16,S,N)
%
%  Estimates the UAT BER for a desired UAT signal
%  against single or multiple interferers,
%  both other UATs and noise-like ones such as Link 16,
%  based on BER & MER curves
%  for various SNR and SIR conditions
%  with a single interferer, measured
%  both at UPS-AT and at JHU/APL, and on
%  the results of the UAT LDPU receiver simulation.
%
%  B is the UAT receive 3-dB bandwidth in MHz
%
%  I_U is the UAT interference level in dBm
%     (assumes TX bandwidth = RX bandwidth,
%     otherwise only the portion within the RX bandwidth
%     should be included)
%     (a row vector with one element for each UAT interferer)
%
%  I_16 is the sum of all Link 16 interference in dBm
%     within the receiver bandwidth
%     (must be computed for each TX hop frequency
%     and for the RX bandwidth)
%
%  S is the desired UAT signal level in dBm.
%
%  N is the equivalent UAT receiver noise level in dBm
%     in a 1-MHz bandwidth and referred to the antenna input,
%     i.e. 3 dB higher than at the receiver input.
%
%----------------------------------------------

%  Look-up tables from Figures 12, 13 and 14.
%  1st column is log10(-log10(1-2*BER))
%  2nd column is SNR from Figure 12 or 13
%  3rd column is Δ from Figure 14

if B==1.2
   llB_SNR_INR = [-realmax realmax 9.9; ...
      -9.3612   18.0000    9.9000
      -8.8612   18.0000    9.9000
      -8.3612   17.7075    9.9000
      -7.8612   17.3741    9.9000
      -7.3612   17.0408    9.9000
      -6.8612   16.7075    9.9000
      -6.3612   16.3741    9.9000
      -5.8612   16.0408    9.9000
      -5.3612   15.6624    9.8759
      -4.8612   15.2778    9.8484
      -4.3612   14.8265    9.7588
      -3.8611   14.2014    9.5505
      -3.3610   13.2466    9.0125
```

```
      -2.8605   11.8683    8.1455
      -2.3590   10.1967    7.0311
      -1.8542    8.4168    5.9537
      -1.3385    6.1923    4.6154
      -0.7810    3.4051    3.1026
       1.1946   -1.0000    0.9000
      realmax   -realmax   0.9000];
elseif B==0.8
   llB_SNR_INR = [-realmax realmax 8.6; ...
   -9.3612   21.0000    8.6000
   -8.8612   21.0000    8.6000
   -8.3612   20.7075    8.6000
   -7.8612   20.3741    8.6000
   -7.3612   20.0408    8.6000
   -6.8612   19.7075    8.6000
   -6.3612   19.3741    8.6000
   -5.8612   19.0408    8.6000
   -5.3612   18.6866    8.6000
   -4.8612   18.3294    8.6000
   -4.3612   17.9568    8.5892
   -3.8611   17.4012    8.4503
   -3.3610   16.6524    8.1183
   -2.8605   15.3157    7.3401
   -2.3590   13.5450    6.2133
   -1.8542   10.6015    4.1111
   -1.3385    6.7573    2.1825
   -0.7810    2.5464    0.7412
   1.1946   -4.0000   -1.4000
   realmax  -realmax  -1.4000];
else
   error('B must be 1.2 or 0.8 (MHz)')
end

%------------------------------------------------------------

%  Translate signal, noise and interference values to linear (mW)
s = (10^(S/10));  %desired UAT signal power in mW
n1 = B*(10^(N/10)) + sum(10.^(I_16/10));  %Gaussian noise sum in mW
i = (10.^(I_U/10));  %UAT interferer powers in mW
ni = n1 + sum(i); %total noise + interference power
inr = sum(i)/n1;  %UAT to Gaussian noise power ratio (linear units)

% Compute empirical parameters used to determine
%  mixture of BER(SNR) vs. BER(SIR) curves to use
%     - mI = equivalent number of interferers
%        used for MER model of prototype UAT
%        (reduces to # of interferers when all are equally strong
%        and much stronger than receiver noise)
%     - k determines how noise-like (k = 0)
%        or interference-like (k = 1)
%        BER behavior is expected to be
mI = ((1.5*sqrt(n1)+sum(sqrt(i)))^2)/ni;
k = (1/(mI^0.4));
```

```
% Compute loglogBER to SINR look-up table for given inr and k values
%  and using loglogBER to SNR and SIR curves from measurements
llB0 = llB_SNR_INR(:,1);
SINR0 = llB_SNR_INR(:,2) + 10*log10( ...
   (1+inr*(10.^(-k*llB_SNR_INR(:,3)/10)))./(1+inr));

% Use table just created to look up loglogBER from known SINR
%  and get BER
SINR = S - 10*log10(ni);      %sig to noise+interference ratio, dB
BER = 0.5*(1-(10^(-10^interp1(SINR0,llB0,SINR))));
```