Deep-Space Ka-band Link Priority Data Protection: Pre-emptive Retransmission vs. Margin

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Abstract—In this paper the performance of two preemptive retransmission schemes for protection of priority data over deep-space Ka-band links is evaluated. The firs scheme merges the correctly received bit from each transmission to create the most complete set of priority data for each pass (bit merge). The second scheme (symbol combining) combines the soft symbols received from each transmission of the priority data to increase the priority data's signal to noise ratio (SNR), thus increasing the likelihood of their correct reception. These performances were then compared to an equivalent margin scheme in which the data rate used for the transmission of the priority data is reduced by a factor equal to the number of transmissions of the priority data. The performance of each scheme was evaluated through emulation using Water Vapor Radiometer (WVR) and Advanced Water Vapor Radiometer (AWVR) sky brightness temperature measurements along with models for Deep Space Network (DSN) Ka-band capable antenna using Mars Reconniassance Orbiter's DSN tracking schedule and geometry. The results indicate that "bit merge" and "reduced rate" schemes perform roughly the same in terms of availability of the priority data (at least 97% compared to 93% without any data protections scheme) but for "bit merge" priority data losses occur over fewer passes than for the "reduced rate" scheme. The "symbol combining" scheme is superior to both the "bit merge" and the "reduced rate" schemes with at least 98.5% priority data availability with losses over a small number of passes. Receivers have a minimum demodulation threshold SNR and combining algorithms have combining losses; therefore, the performance of the "symbol combining" scheme was also evaluated with respect to these two factors. The results indicate that even with current receivers, the "symbol combining" scheme performs extremely well and the scheme is relatively robust with respect to combining losses.

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1. Introduction

Compared to X-band, Ka-band deep space frequencies are subject to greater degradation due to the weather. Previous studies have indicated that for every dB of loss due to weather at X-band, the Ka-band system would suffer approximately four dB of loss [1]. Because of this, a simple margin policy to protect important data is inefficien and could lead to a severe reduction in the data return. Since there is usually some data onboard the spacecraft that needs to be received by the ground by the end of a pass, we are interested in evaluating methods other than increasing the margin to guarantee delivery of the priority data.

One method to increase the probability that priority data is received correctly is to use preemptive retransmission, that is, to transmit the priority data several times during the pass. Such a preemptive retransmission scheme could be used in two ways. The firs method, refered to as "bit merge" in this paper, is to merge correctly received fragments of the priority data from each transmission to form a more complete set of data. This method is very easy to implement as the ground systems already have the means to combine data from retransmissions. Also, the coding used on the channel could be different for each transmission since the data merge occurs on the information bits after the decoding. The second scheme, refered to as "symbol combining," is to use the same exact coding (this includes same exact block of information bits to generate the same exact block of channel symbols on the spacecraft) for each transmission and then combine the received soft symbols optimally to increase each symbol's signal-to-noise ratio (SNR), thus increasing the likelihood of decoding the information correctly. It should be noted that implementation of such a system could be quite complex since on the spacecraft the same exact channel symbols need to be generated for every transmission and on the ground the soft symbols need to be saved before combining could occur.

Two factors need to be considered for "symbol combining." First is the effica y of the combining process. If combining is ideal, the resulting SNR is equal to the addition of all the SNR values from each transmission of the symbol. However, combining is never ideal and combining losses always exist because of phase jitter on the demodulated signal both because

the spacecraft and the ground receivers. The second factor is the sensitivity of the receiver. Receivers have a minimum symbol SNR (SSNR) threshold in order to lock up and a demodulate symbols. This means that given a real receiver, only the symbols whose SNR is higher than the receiver's minimum symbol SNR could be used for combining. It should be noted that at a minimum, "symbol combining" will work as well as the "bit merge" because every transmission of the priority data could be decoded by itself and its resulting bits merged together under the "bit merge" algorithm.

In order to provide a fair comparison with the standard margin policy, our analysis compares the preemptive retransmission schemes with a case where the data rate for the transmission of the priority data is reduced by a factor equal to the total number of transmissions of the priority data in the preemptive retransmission scheme. So for example, if the preemptive retransmission scheme transmits the priority data in each pass twice, then for the comparable "reduced rate" scheme, the data rate for priority data is reduced by a factor of two over the original link design.

To evaluate these schemes, Mars Reconnaissance Orbiter (MRO) Deep Space Network (DSN) tracking schedule along with models for the DSN antennas Ka-band performance and data from Water Vapor Radiometer (WVR) and Advanced Water Vapor Radiometer (AWVR) were used to emulate the performance of each scheme over the Ka-band link.

This paper is organized as follows. In Section 2, the methodology for our analysis, including the link design, seleciton of the priority data, selection of transmission time and performance metrics are discussed. In Section 3, the results of the analysis are presented. In Section 4 conclusions are reached.

2. METHODOLOGY

Pass Selection and Link Design

For the purposes of this analysis, 207 passes were selected from the MRO's DSN tracking schedule from April 1, 2006 through July 31, 2007. The passes were selected such that on the average one pass per week per DSN complex (DSN Communication Complexes are located at Goldstone, California; Canberra, Australia and Madrid, Spain) for a total of 69 passes per complex. Actual MRO-Earth geometry was used for each pass.

It was assumed that the spacecraft has the same 101.3 dBm equivalent isotropic radiated power (EIRP) as MRO. However, the available data rates for the link design are different from MRO's. In this analysis, the spacecraft has information data rates from 330 Kbps to 26 Mbps in 1 dB steps. This is illustrated in Fig. 1.

The initial link design is based on maximizing the expected throughput per pass using at most two data rates subject to 85% minimum availability requirement (MAR). This method

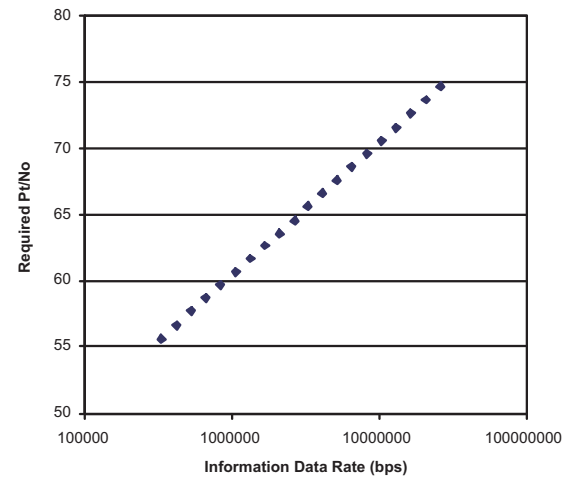

Figure 1. Required P_t/N_0 for Different Data Rates for (8920,1/6) Turbo Code

has been outlined perviously in [1], [2] and [3]. The 85% MAR value is selected so that near-maximum data return could be achieved without too much loss of data [3]. Note that when the data rates are originally selected for the pass, priority consierations are not yet taken into account.

Selection of the Priority Data

For all passes, a fraction of data transmitted over the pass is declared as priority. This fraction, p_p, is the same for all passes and is one of the free variables in our analysis. Another free variable is the number of transmissions (for "bit merge" and "symbol combining" schemes)/data rate reduction factor (for the "reduced rate" scheme), n. These parameters are used to calculate the total amount of unique data, d_u, that is transmitted during the pass. Let d_t be the total number of bits transmitted during a pass based on the two data rates selected according to the link design. Then d_u is given by

$$d_u = \frac{d_t}{1 + (n-1)p_p} \tag{1}$$

and the amount of priority data, d_p, is given by

$$d_p = d_u \cdot p_p = \frac{d_t \cdot p_p}{1 + (n-1)p_p} \tag{2}$$

So for example if d_t is 1.1 Gbits, $n = 2$, and $p_p = 0.1$, then d_u is 1 Gbits and d_p is 100 Mbits.

Selection of Priority Data Transmission Periods for the Preemptive Retransmission Schemes

Given the number of transmissions, n and the amount of priority data, d_p, the transmission periods for the priority data are selected such that there is maximum bit separation between the transmissions, subject to a minimum elevation

mask. Maximum bit separation is desirable in order to assure some degree of independence in the channel conditions between different transmissions of the priority data. The minimum elevation mask is desirable because the weather effects under the same weather conditions are more severe at lower elevations than at higher elevations.

Let d_{mb} be the transmitted bit number at which the elevation of the pass firs exceeds the minimum elevation mask and let d_{me} be the bit number at which the elevation of the pass becomes lower than the minimum elevation mask. If the elevation of the pass never falls below the minimum elevation mask before the pass ends, then d_{me} is equal to d_t . Given that there are a total of n transmissions for the priority data, then the number of non-priority bits between two transmissions is given by

$$d_{gap} = \frac{d_{me} - d_{mb} - n \cdot d_p}{n-1} \tag{3}$$

and the *i*th transmission of the priority data starts on bit

$$d_{sp}^{(i)} = d_{mb} + (i-1) \cdot (d_p + d_{gap}) \tag{4}$$

Fig. 2 illustrates this for a simple example. In this case, $d_t = 57960\text{Mbits}$, $p_p = 0.1$ and $n = 2$. Then $d_u = 5269$ Mbits and $d_p = 5269$ Mbits according to eqs. 1 and 2, respectively. The minimum elevation for this case is 20 degrees. This leads to $d_{mb} = 4083$ Mbits and $d_{me} = 40069$ Mbits. Using these values, according to 4, $d_{sp}^{(1)} = 4083$ Mbits and $d_{sp}^{(2)} = 49421$ Mbits.

Note that because of equation 3, the minimum elevation mask can only be satisfie if

$$d_{me} - d_{mb} \geq n \cdot d_p \tag{5}$$

For the analysis presented here, the minimum elevation was selected such that for all the passes under consideration, condition in 5 was satisfie for the selected p_p and n values, with the minimum elevation not exceeding 25 degrees.

Selection of Priority Data Transmission Period for the Reduced Data Rate Scheme

For the reduced data rate scheme, the priority data is transmitted near the maximum elevation of the pass in order to reduce the adverse weather affects on the link. In this case, given the original, priority-less link design, let $t(d)$ be the time when the *d*th bit is transmitted and $d_{\max}$ be the bit number at which the pass achieves its maximum elevation for the link design without the priority schemes. Then the priority data starts transmission at

$$t_s^{(rr)} = \begin{cases} t(1) & d_{\max} < \frac{n \cdot d_p}{2} \\ t(d_t - n \cdot d_p) & d_{\max} > d_t - \frac{n \cdot d_p}{2} \\ t\left(d_{\max} - \frac{n \cdot d_p}{2}\right) & \text{otherwise} \end{cases} \tag{6}$$

and the priority data stops transmission at

$$t_e^{(rr)} = \begin{cases} t(n \cdot d_p) & d_{\max} < \frac{n \cdot d_p}{2} \\ t(d_t) & d_{\max} > d_t - \frac{n \cdot d_p}{2} \\ t\left(d_{\max} + \frac{n \cdot d_p}{2}\right) & \text{otherwise} \end{cases} \tag{7}$$

During this period, $\left[t_s^{(rr)}, t_e^{(rr)}\right]$, the data rates that were calculated according to the original priority-less link design are reduced by a factor of n, thus reducing the required P_t/N_0 by a factor of n as well. Fig. 3 illustrates this for the same example used for Fig. 2, *i.e.*, $d_t = 57960\text{Mbits}$, $p_p = 0.1$ and $n = 2$. In this case, $t_s^{(rr)} = t\left(d_{\max} - \frac{n \cdot d_p}{2}\right) = 18:41:05$ and $t_e^{(rr)} = t\left(d_{\max} + \frac{n \cdot d_p}{2}\right) = 20:08:54$. Note that this is 5269 seconds at the reduced data rate (from 2 Mbps) of 1 Mbps, resulting in 5269 Mbits of data.

Analysis of the Preemptive Retransmission Schemes

WVR and AWVR data along with DSN models for 34-m BWG antennas gains and equipment noise temperature [4] were used to emulate the link performance. For the "bit merge" case, during the firs transmission, a list of correctly received bits is constructed. This list is merged with a similar list made from the second transmission. On subsequent transmissions, the list of correctly received bits is merged with the merged list obtained after the previous transmission. The merged list obtained after the last transmission is the list of priority data that were obtained through this scheme.

Note that since it is assumed that the spacecraft is sequenced well in advance, the times at which priority data are transmitted are assumed to be known before the transmission actually takes place. This along with the frame sequence identificatio tags facilitates making the list of the correctly received bits.

For the "symbol combining" scheme, the SNR margins for the priority symbols are calculated after each transmission and saved. These values are then added together (not in dBs) and reduced by the combining loss to produce the overall SNR margin of each symbol. Note that only those SNR values that are greater than the minimum SSNR threshold value of the receiver are used for calculating the combined SNR margins. From these margin values it is then determined which priority bits are correctly received.

It should be noted that the WVR/AWVR data that are used to emulate the link performance are sampled at approximated

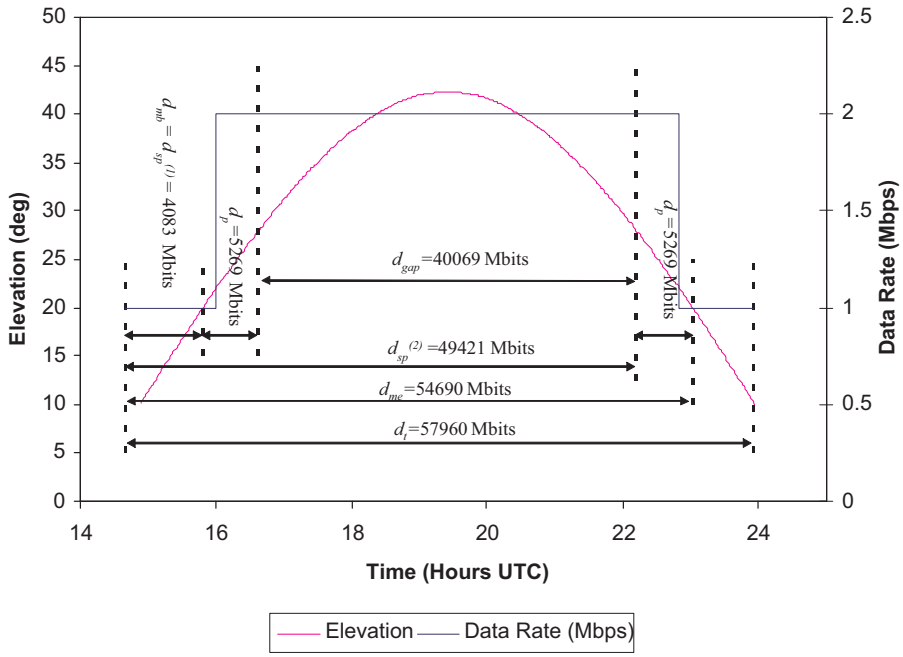

Figure 2. Example for Selection of Priority Data Transimission Times for Pre-emptive Retransmission Schemes

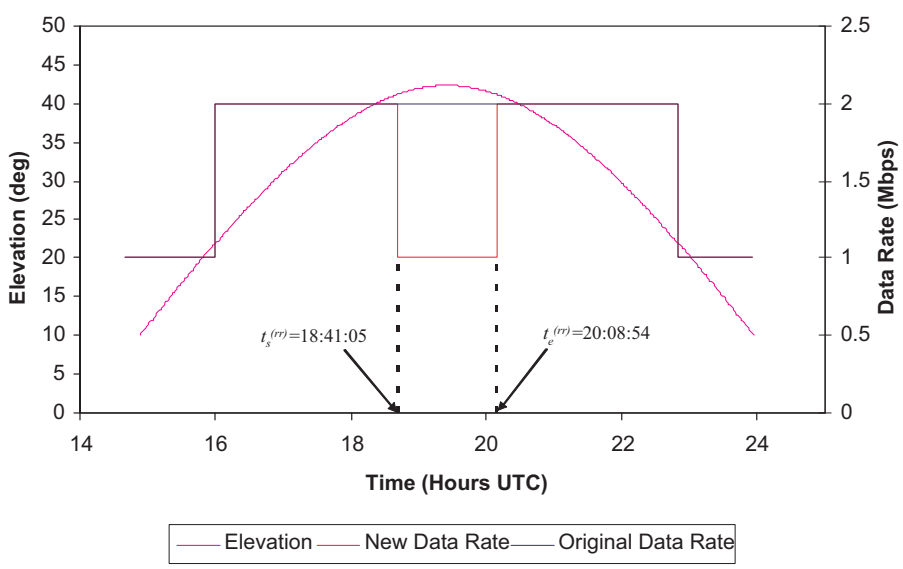

Figure 3. Example for Selection of Priority Data Transmission Times for Reduced Data Rate Scheme

once every f ve minutes and the elevation information for each pass is provided at once every minute. Therefore, a single SNR value calculated applies to all bits transmitted in one specifi minute.

Analysis of the Reduced Data Rate Scheme

This analysis is straightforward. Since the priority data are transmitted only once in this scheme, WVR and AWVR data along with DSN models are used to evaluate the performance of the link during the transmission of the priority data. At the end of the transmission period, it is determined how much of the priority data was successfully received.

Performance Metrics

Two performance metrics are of interest: the completeness of the priority data in terms of the fraction of data received and the number of passes with priority data loss. These two metrics give an understanding of how often and how much of the priority data is lost.

3. Results

The analysis was performed for several different assumptions about the fraction of the priority data, number of transmissions of the priority data and sensitivity of the receivers. The parameter p_p was varied from 0.02 to 0.5. The total number of transmissions of the priority data was varied from 2 to 4. The minimum elevation was selected such that for *all passes* the minimum elevation requirement for the priority data was met (see Fig. 4). For the "symbol combining" algorithm, the performance was evaluated for receivers with minimum symbol SNR (SSNR) values of -11 dB, -11.5 dB, -12 dB, -12.5 dB, -13 dB and -13.5 dB. Note that, currently, the DSN Block V Receiver (BVR) has a minimum SSNR tracking capability of approximately -11 dB with BPSK modulation. In addition, we considered the case with three transmissions of the priority data and $p_p = 0.08$ with combining losses varying from 0 to 1 dB.

If no preference was given to priority data the expected data availability is 0.928 with 73 out of 207 passes suffering some data loss. Figs. 5, 6 and 7 show the availability of the different schemes as a function of p_p for n equal to two, three and four respectively. As seen from these figures all schemes under consideration provide substantial protection for the priority data, increasing the availability of the priority data to at least 0.96 (for $n = 2$). For minimum SSNR values under consideration in this paper, the "symbol combining" scheme outperforms both the "rate reduction" scheme and the "bit merge" scheme. As expected, the lower the minimum SSNR of the receiver, the better is the performance of the "symbol combining" scheme. Similarly, the larger the value of n, the higher is the availability of the priority data. For example, with $n = 4$ and no minimum SSNR for the receiver, the "symbol combining" algorithm suffers no priority data loss for $p_p \leq 0.1$. For all "symbol combining" cases the priority data availability is better than 0.985 for $n = 2$, better than 0.99 for $n = 3$

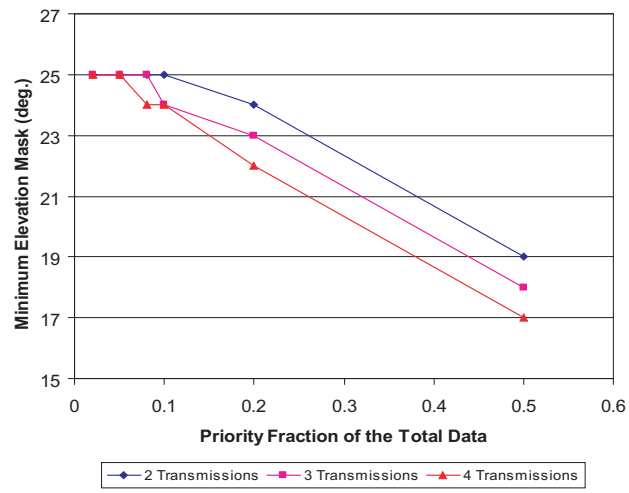

Figure 4. Minimum Elevation Mast vs. p_p for Different Number of Transmissions

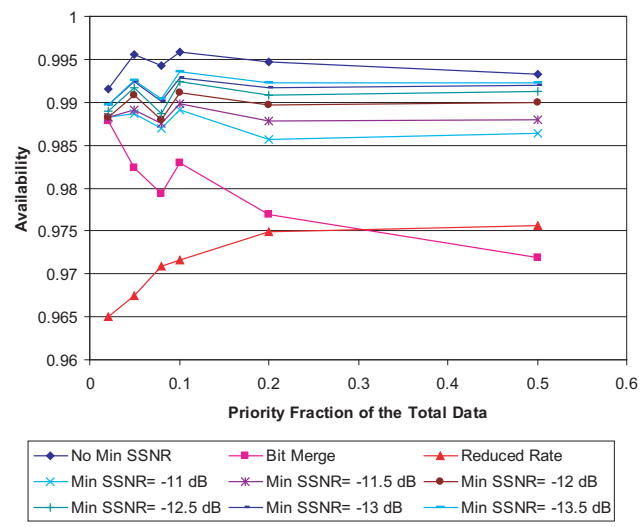

Figure 5. Priority Data Availability for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Two

and better than 0.995 for $n = 4$. In terms of availability of the priority data, the "bit merge" scheme performs better at lower p_p values while the "reduced rate" scheme has better performance at higher p_p values. However, it should be noted that for all number of transmissions/rate reduction factor values, the "bit merge" advantage is significantl higher at smaller p_p than the "reduced rate" advatange at larger p_p values.

As mentioned in Section 2, not only the overall availability of the priority data is important but also the number of passes over which priority data is lost. Figs. 8, 9 and 10 show the number of passes with priority data loss for n equal to two, three and four, respectively. Again these results indicate that all schemes under consideration substantially decrease the number of passes with priority data loss (from 73 passes

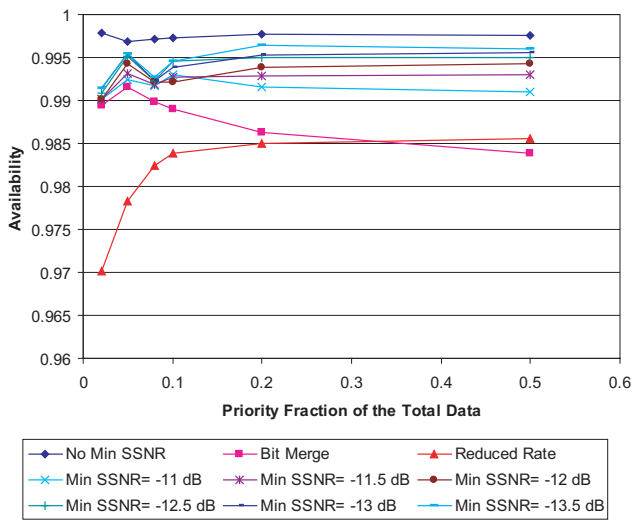

Figure 6. Priority Data Availability for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Three

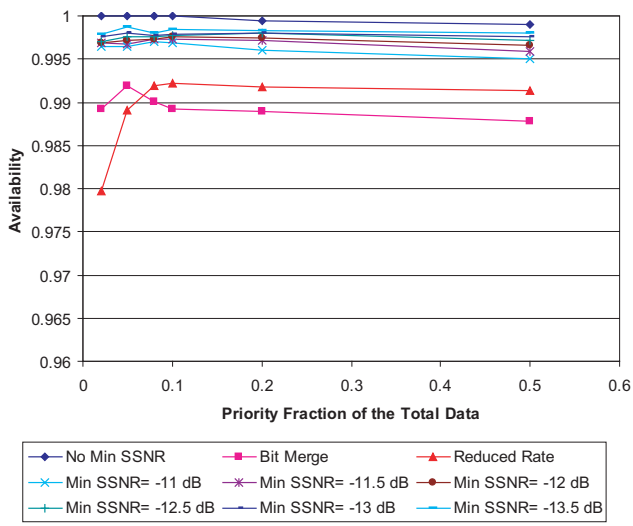

Figure 7. Priority Data Availability for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Three

without priority data protection to at most 26 passes for $n = 2$ and $p_p = 0.5$ with the "reduced rate" scheme). Note that with all the symbol combining schemes, the number of passes with priority data loss is at most 12 passes. This is less than one sixth the total number of passes with data loss without any protection.

Although for $n = 2$ the "bit merge" scheme has roughly the same number of passes with priority data loss as the "reduced rate" scheme, for higher n values it has significantl less. This is because the fundamental nature of the priority data protection is different between the "bit merge" and "symbol combining" on one hand and the "reduced rate" scheme on the other. The "bit merge" and "symbol combining" use time diversity to protect the priority data while the "reduced rate" scheme uses additional margin to protect the data. This implies that for "bit merge" and "symbol combining" all the transmissions of a priority bit have to suffer from bad weather in order for that priority bit not to be received correctly. On the other hand, for the "reduced rate" scheme to fail, the weather degradation has to be greater than the margin available to the priority data. Therefore, priority data losses are associated with presistent bad weather for "bit merge" and "symbol combining," and they tend be concentrated in a few passes because bad weather is not usually very persistent (see [3]). On the other hand, the losses for the "reduced rate" scheme tend to occur over a larger number of passes because it is far more likely for a single deep drop in the SNR to occur during a pass.

It should be noted that because of the way the transmission periods for each scheme is selected, a pass that has a priority data outage for a lower p_p value will also have a priority data loss for a higher p_p value for the "reduced rate" scheme. That is why for the "reduced rate" scheme, the number of passes with priority data loss is a non-decreasing function of p_p. This, however, is not the case for the "symbol combining" since the times at which the priority bits and their duplicates are transmitted vary as a function p_p.

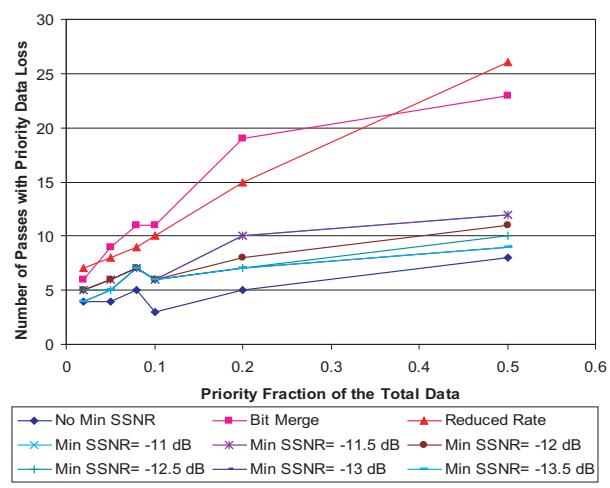

Figure 8. Number of Passes with Priority Data Loss for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Two

Finally, the effects of combining loss on the performance of the "symbol combining" were investigated. For this analysis a value of $p_p = 0.08$ win $n = 3$ was assumed and the combining loss was varied from 0 to 1 dB. The results are plotted in Figs. 11 and 12. As seen from these figures priority data availability is relatively insensitive to combining losses with the receivers with the lower the minimum symbol SNR thresholds being more sensitive to combining losses. Number of passes with priority data loss shows sensitivity to com-

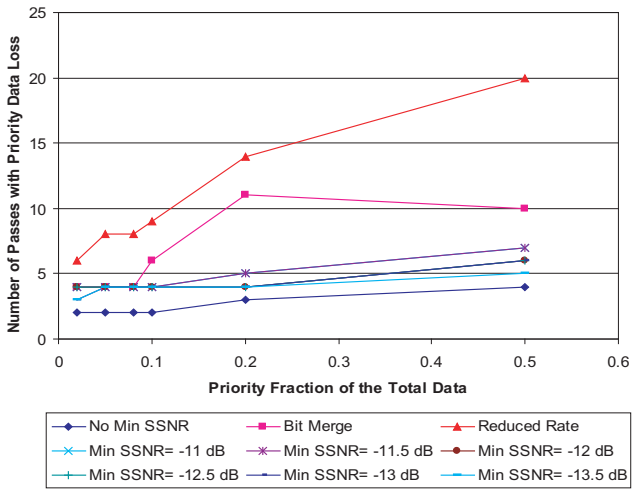

Figure 9. Number of Passes with Priority Data Loss for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Three

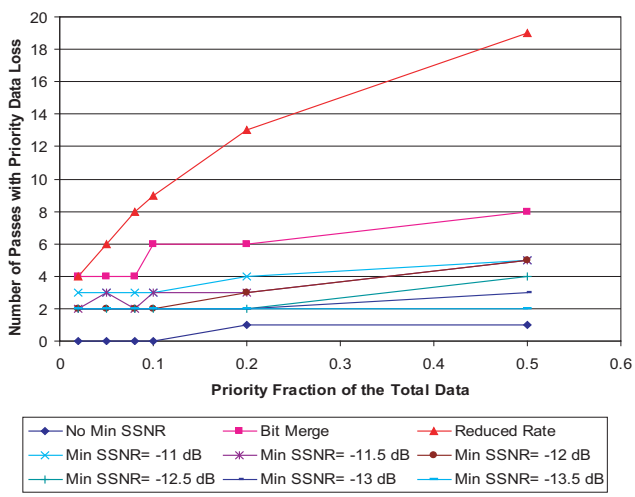

Figure 10. Number of Passes with Priority Data Loss for Reduced Rate, Data Merge and Symbol Combining with Number of Transmissions/Rate Reduction Factor of Three

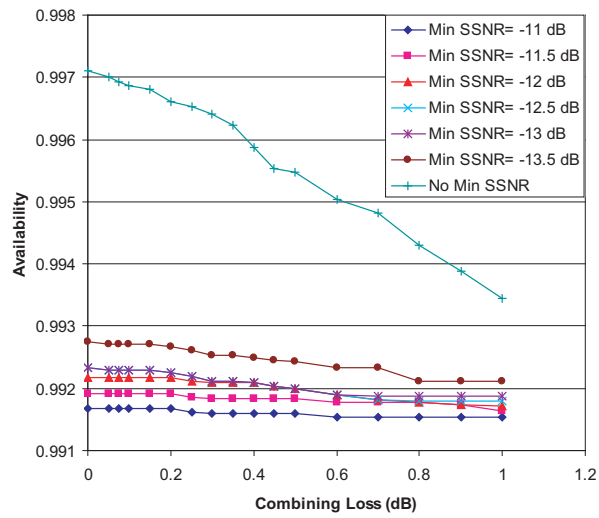

Figure 11. Symbol Combining Priorirty Data Availability vs. Combining Loss for $p_p = 0.08$ and $n = 3$

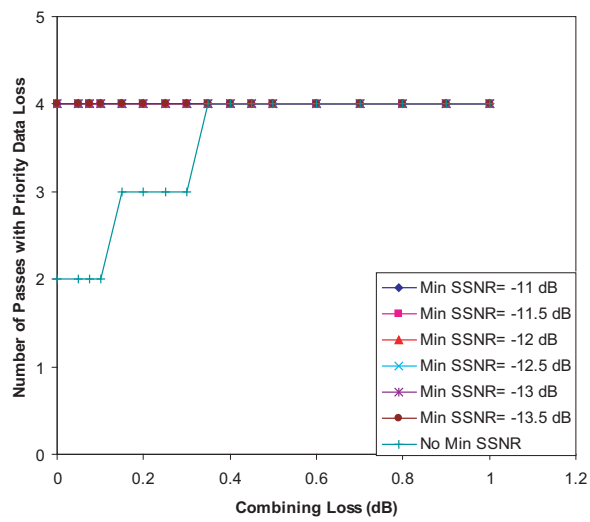

Figure 12. Number of Passes with Priority Data Loss for Symbol Combining vs. Combining for $p_p = 0.08$ and $n = 3$

binining losses only for the case of the perfect receiver (no minimum SSNR). This indicates that for the case under consideration, the symbol combining scheme is relatively robust in the face of combining losses.

4. Conclusions

In this paper we have introduced two schemes that use preemptive retransmission to provide additional protection for priority data and compared their performance with a simple equivalent margin policy implemented through a reduction of the data rate. Performance of each scheme was evaluated using DSN models for Ka-band performance of the ground antennas along with the data from WVR and AWVR. The analysis indicates that if a simple "bit merge" scheme is used without symbol combining, the preemtive retransmission and the "reduced rate" scheme have roughly the same performance in terms of availability of the priority data; however, for the "bit merge" scheme, priority data losses are concentrated in fewer passes than the "reduced rate" scheme. Using "symbol combining" with preemptive retransmission provides signifi cantly superior performance to the "reduced rate" and the "bit merge" schemes, but requires a more complex system both on the ground and onboard the spacecraft. This is to insure that the same channel symbol patterns are transmitted during each transmission of the priority data in order to perform proper symbol combining. Since "symbol combining" could be performed only when the receiver is able to lock onto the symbols, performance of the "symbol combining" scheme was

evaluated for different receiver sensitivities. The results indicate that although with an increase in the receiver sensitivity, the performance of the "symbol combining" scheme improves, even with the least sensitive receiver under consideration, the performance of the "symbol combining" scheme is superior to that of the "reduced rate" scheme. Finally, the effects of combining losses on the "symbol combining" scheme were investigated in this paper. In cases that were considered, the "symbol combining" scheme was relatively robust with respect to combining losses with very little degradation in terms of priority data availability for combining losses of upto 1 dB. The analysis also indicated that more sensitive the receiver is, the larger the effects of combining losses are on the performance of the "symbol combining" scheme.

ACKNOWLEDGMENTS

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BIOGRAPHY

Shervin Shambayati obtained his Bachelors of Science degree in Applied Mathematics and Engineering in 1989 from California State University, Northridge. Subsequently, he obtained his MSEE, Engineer's Degree and Ph.D. from University of California, Los Angeles in 1991, 1993 and 2002, respectively. In 1993, Dr. Shambayati joined the Deep Space Communications Systems Group at Jet Propulsion Laboratory where he took part in development and testing of Deep Space Network's Galileo Telemetry receiver (DGT). In 1997, Dr. Shambayati joined the Information Processing Group at JPL where he has been working ever since. With that group Dr. Shambayati has been involved in various projects including Mars Global Surveyor's Ka-Band Link Experiment II, Deep Space 1 Ka-band testing, 70m antenna Ka-band Task and the Mars Reconnaissance Orbiter Ka-band Demonstration for which he was the Principal Invsetigator. His current research interests and activities include evaluating the effects of weather outages on the spacecraft resources, Ka-band weather forecasting, Ka-band link design and end-to-end system architecture studies for implementation of Ka-band and optical communications services in NASA's Deep Space Network.