A Strategy for Successful Deep Space Information Transmission in Bad Weather

L. Swanson and J. H. Yuen
Communications Systems Research Section

To retrieve data during bad weather, most missions slow the data rate to accommodate a certain amount of attenuation, or to allow for all but a very small percentage of all-weather conditions. This system has two well-known and balancing disadvantages: no data is received reliably during very bad weather, and the data rate is slowed during good weather. We propose a system of processing that encodes the most critical data more heavily, allowing it to be retrieved under bad conditions, while at the same time allowing most of the data to be sent at a higher data rate.

I. Introduction

A brief look at past progress in data transmission from space shows that a lot of improvement has come from frequency increases and associated technology. From 108 MHz, through L-band and S-band to our current X-band of the Voyager spacecraft, telemetry capability measured in bits per second at a given range has improved by a factor of 10^{18} since the first free-world satellite, Explorer I in 1958 (Ref. 1).

In the near future, use of Ka-band (32 GHz) will undoubtedly allow even further improvements in data rate. But as frequency increases, data rate increases must be weighed against performance degradations due to weather and atmospheric effects. Clouds are almost transparent at S-band; weather causes virtually no degradation. At the current X-band, data rate must be chosen for a weather trade-off. By lowering the data rate, a mission can be more nearly certain of clear reception, but the cost is less telemetry. For example, as shown in Table 1, total weather degradation for X-band data at the Madrid 64-meter antenna, 90% weather, 30° elevation angle, is 1.1 dB. This means that to ensure reception under 90% of all weather conditions, data must be slowed to a factor of 0.78 compared to what it would be if we assumed clear, dry weather. To ensure reception under 99% of all weather conditions (at the same station and elevation), a mission would have to accept a loss of 4.2 dB, or a data rate factor of 0.38, compared to clear, dry weather.

At Ka-band, while increased data rate is available in clear, dry weather, degradation due to bad weather is worse than at X-band. There is little experimental data currently available to quantify the losses, but in any case the same principle applies.

The current Voyager and Galileo communication systems employ the concatenated Reed-Solomon/convolutional code, which is very sensitive to even a small degradation in signal-to-noise ratio. For example, bit error rate rises from 10^{-5} to 10^{-2} as E_b/N_0 drops from 2.3 dB to 1.9 dB (Ref. 2). This means that 0.4 dB can be the difference between successful data transmission and failure. Future deep-space channel coding schemes are likely to be just as sensitive.

II. Protecting Critical Data

One way to design a reliable telemetry system is to provide extra margin. For example, at the Madrid 64-meter antenna 30° elevation, one could adjust the data rate to allow $E_b/N_0 =$ 3.4 dB, allowing a margin of 1.1 dB over the 2.3 dB required for a bit error rate of 10^{-5}. This would mean that, during 90% of all weather conditions, E_b/N_0 is sufficient to expect a decoded bit error rate of 10^{-5}. In fact, even in the absence of weather degradation, we must provide some margin for other system uncertainty (Ref. 1). The Voyager and Galileo missions provide about 2.0 dB for these nonweather effects. Thus a total of 5.4 dB of E_b/N_0 is needed to assure reliable communication 90% of the time.

This system has two obvious drawbacks. One is that no useful data is received 10% of the time. The other is that the 1.1 dB is unnecessarily conservative most of the time, and so some data rate is being sacrificed. These drawbacks play off against each other: the higher data rate during good weather means a higher likelihood that the reception of any useful data is precluded during bad weather.

We propose an information transmission system that will allow certain data, viewed by the mission as critical or "must receive," to be retrieved under the worst of circumstances (e.g., 99% weather) while allowing a reasonably high data rate for all data during most weather. Another goal, such as maximizing the expected total data return, might lead to a different coding scheme.

Each mission has different scientific and mission objectives, and so different critical data. Our scheme is to encode this critical data separately so that it is recoverable under very bad circumstances. We call the rest of the data "normal" data. (E. C. Posner (Ref. 3) refers to the two types as "base" and "bonus" data, respectively.)

Our coding scheme does not require a completely new deep-space telemetry system, but builds upon the existing concatenated Reed-Solomon/convolutional code, requiring only simple additional equipment. Hence it is an efficient and economically effective way to enhance data reception capability.

The current deep-space telemetry coding scheme, as used on JPL missions and adopted as the guideline of the International Consultative Committee on Space Data Standards, can be seen in Fig. 1.

We propose adding a repetition code to the critical data, yielding the system depicted in Fig. 2. On the ground, critical data is identified and the repetition code decoded. During good weather, all data is Viterbi and Reed-Solomon decoded. During bad weather, only critical data can be decoded. (Critical data must be sent in whole frames in order that the outer decoders can work during bad weather.)

The performance of our system is a parametric function of the repetition code rate and of the amount of critical data. Of course, the extra power given to the critical data means that there is less power available to the normal data; again the amount of power lost to the normal data is a function of the repetition code rate and of the amount of critical data. Table 2 shows the loss of power in overall data (for critical and normal data combined) in a system using our scheme, compared to the current concatenated convolutional/Reed-Solomon system, as a function of repetition code rate and the amount of critical data. When x of the data is repeated n times, the loss of power in overall data is just $(n - 1)x$, which is shown on Table 2 in dB.

The fact that a concatenated Reed-Solomon/convolutional/repetition code is a good low-rate code for low symbol signal-to-noise ratios was first called to our attention by Pil Lee during a technical discussion. Indeed, this seemingly almost trivial repetition code works quite well. We compared it to other low-rate coding schemes (orthogonal and biorthogonal codes); this comparison is shown in Appendix A.

The scheme described above is different from the one proposed by E. C. Posner (Ref. 3), and first suggested by T. M. Cover (Ref. 4), which uses a single "cloud" code to protect some data more than others. The Cover-Posner scheme is a theoretical one, giving bounds on the data rates for the two kinds of data, while ours is a concrete, easy-to-implement system based on a very minor addition to the existing proven deep-space coding system. A comparison of the performance of a time-multiplexed system like ours to the optimum is given in Appendix B.

Aside from the obvious critical data protection, a scheme like ours offers several advantages. Of course, a mission can determine what data is critical. For example, some science data and some highly compressed imaging data might be the critical data on a mission. Also, a mission can determine how heavily to encode the critical data, and how much critical data to send, trading these off against power for the normal data. There could even be different levels of critical data: five repetitions for very critical data, three repetitions for less critical data, etc. Also, the amount of redundancy can be changed in flight, in case of hardware changes on the ground or even on account of short-term weather predictions.

What does our protection cost in terms of data rate during good weather? The fact that the critical data has been expanded means that overall data rate must suffer in some way. Three ways to deal with this loss present themselves: (1) compressing the rest of the data, (2) sacrificing the least desirable data, and (3) lowering the probability that normal data will be received reliably. We examine each in the paragraphs below.

Current missions use data compression for imaging data.[1] Depending on the amount of redundancy in the original data, data compression can allow a large increase in the amount of information communicated at a given data rate. If the normal data being sent are redundant, further data compression would present little problem. If all possible data compression has already been done, source coding could be done to code the information bits. This, however, adds substantially to the bit error rate. So data compression should be used only if redundancy exists in the normal data.

The simplest idea is just to sacrifice (never transmit) the least desirable data, lowering the real data rate. This gives each transmitted normal bit exactly the same power it had before the critical bits were heavily encoded.

The last possibility is to speed channel symbols, increasing their rate. This means that each channel symbol carries slightly less power. Thus the normal data is received under slightly more restrictive weather conditions, in exchange for the critical data being received under less restrictive conditions.

[1]E. Hilbert et al., *BARC Data Compression for Galileo Imaging*. Publication GLL-625-301, Jet Propulsion Laboratory, Pasadena, California, 1979 (internal document).

III. Conclusions

We have proposed a coding system to protect a mission's critical data against very low signal-to-noise ratio conditions. This system is simple to implement, easy to change, and is based on a proven, reliable, existing coding system. It allows a small amount of data to be protected against very bad attenuation, while allowing all of the data to be sent at a higher data rate than would be the case if all data were protected against such bad attenuation. Critical data is heavily encoded and then embedded in the normal data. If only a small amount of data is critical, the effect on the power available for the rest of the data is minimal. Besides protecting critical data against bad weather, another goal might be to maximize expected total data return. This goal might lead to a different coding scheme.

There are other means of dealing with weather effects, which are operational in nature. Our method does not in any way preclude the use of these. It does offer additional protection to any link. Historically, this protection has been offered by the use of a lower frequency link, like S-band, which is virtually independent of weather, for critical data. In the future, such weather-transparent links may not be available, but in any case our scheme can be viewed as additional protection.

We have assumed that synchronization will not be a problem. This and the ability of the deep-space telemetry system to recover channel symbols under very bad weather conditions are questions that still need to be addressed.

References

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Table 1. Total weather degradation (including effects of both increased atmospheric attenuation and increased system noise temperature) in decibels; Madrid X-band 64-meter[a]

Percent weather	Elevation angle, degrees														
	10	12	14	16	18	20	25	30	35	40	50	60	70	80	90
10.0	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
20.0	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
30.0	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
40.0	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
50.0	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
60.0	0.9	0.8	0.7	0.6	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2
70.0	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.3
75.0	1.6	1.4	1.2	1.1	1.0	0.9	0.7	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.3
80.0	2.1	1.7	1.5	1.3	1.2	1.1	0.9	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3
85.0	2.6	2.2	1.9	1.7	1.5	1.3	1.0	0.9	0.7	0.7	0.5	0.5	0.4	0.4	0.4
90.0	3.4	2.9	2.4	2.1	1.9	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.5	0.5	0.5
95.0	5.0	4.2	3.6	3.2	2.8	2.5	2.0	1.6	1.4	1.2	1.0	0.8	0.8	0.7	0.7
98.0	7.7	6.6	5.8	5.2	4.6	4.2	3.4	2.9	2.5	2.2	1.8	1.6	1.4	1.3	1.3
99.0	10.3	9.0	7.9	7.1	6.5	5.9	4.9	4.2	3.7	3.3	2.7	2.4	2.2	2.1	2.0
99.5	14.6	12.6	11.2	10.1	9.3	8.6	7.3	6.3	5.6	5.1	4.3	3.9	3.5	3.4	3.3

[a]This table is one of a set of tables, describing weather attenuation under many circumstances at many Deep Space Network antennae, prepared by P. Kinman of the Jet Propulsion Laboratory in an internal memorandum to N. Burow.

Table 2. Loss of power (in decibels) to data because of repetition of critical data

Code repetition	2	3	5	10
Attenuation allowed critical data, dB	3	4.7	7	10
Critical data, %				
1	0.04	0.09	0.18	0.41
2	0.09	0.18	0.36	0.86
5	0.22	0.46	0.97	2.60
10	0.46	0.97	2.20	10.00

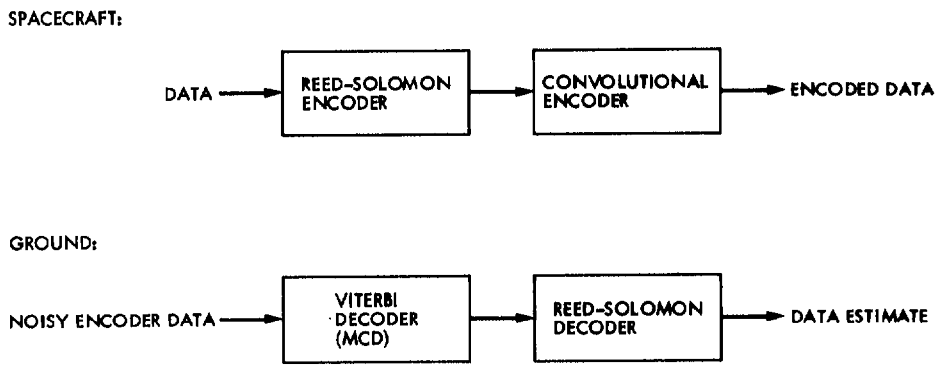

Fig. 1. The current deep-space telemetry coding system

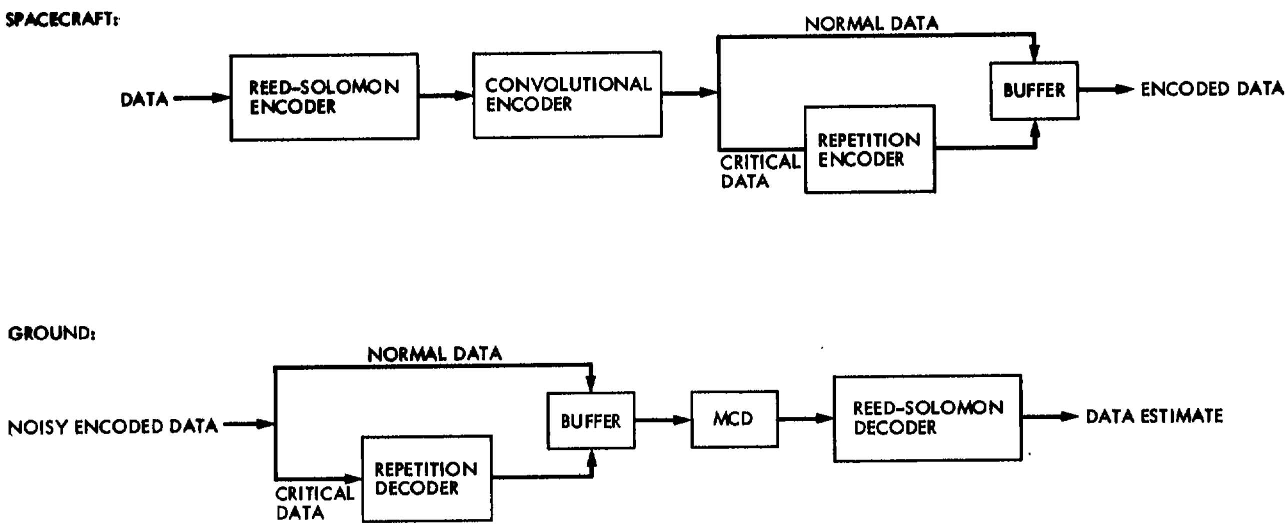

Fig. 2. Proposed new deep-space telemetry coding system

Appendix A
Choice of Code for Critical Data

The codes suggested in this article are simple to implement in a mission using concatenated Reed-Solomon/convolutional coding. Other low-rate codes could be considered for the critical data. Prominent examples of low-rate codes are orthogonal and bi-orthogonal codes (Ref. 5). Bi-orthogonal and orthogonal codes of appropriate rates are considered, along with concatenated Reed-Solomon/convolutional/repetition codes, in Table A-1.

For each of these three types of codes, we have chosen several specific codes to examine. Of course, rate balances against performance at low symbol signal-to-noise ratio.

Table A-1 gives these attributes for several codes of each type. In addition to code rate, expansion 7/(16 × rate) is given. This is the ratio of the number of channel symbols required for transmission of one critical bit under a given low-rate code to that required for a normal bit under Reed-Solomon/convolutional coding.

Table A-1 also gives performance, in terms of decoded bit error rate, of each code at two symbol signal-to-noise ratios: −4.4 dB and −6.5 dB. These were chosen because they represent 99% weather and 99.5% weather (X-band, Madrid 64-meter antenna, 30° elevation) when normal data is reliable in 90% weather. A choice among these codes for critical data would then depend on a balance between the expansion of the code and its performance. Of course, this balance gets more difficult if there is much critical data (which makes expansion touchier), or if a very low symbol signal-to-noise ratio must be considered. Performance for orthogonal and bi-orthogonal codes was obtained by interpolation from tables in Appendix 4 of Ref. 5; performance for the concatenated code was obtained from Ref. 2.

Comparison of codes for these purposes is different from normal comparison for error correcting codes. One usually compares codes by considering the bit signal-to-noise ratio (E_b/N_0) required for a given decoded bit-error rate (or conversely, the decoded bit-error rate for a given E_b/N_0). When one can adjust the data rate in order to control E_b/N_0, this is the logical way to compare codes. But we are assuming that the symbol rate has been adjusted to control E_b/N_0 for Reed-Solomon/convolutionally encoded normal data under certain weather conditions, so that symbol signal-to-noise ratio E_s/N_0 is determined entirely by weather conditions. Once we decided how much attenuation we wish to accommodate, we have determined the *symbol* signal-to-noise ratio. We can then choose a code, weighing the probability of error at that symbol signal-to-noise ratio vs code rate or expansion. The lower the code rate, of course, the more expansion, or the more channel space will be used by the critical data, lowering the power available for normal data. Notice that the error rates in Table A-1 show that the concatenated Reed-Solomon/convolutional/repetition codes perform better than the orthogonal and bi-orthogonal codes. (All error rates assume perfect carrier and subcarrier tracking, and perfect code synthronization.)

Table A-1. Performance of several low rate codes at low symbol signal-to-noise ratios

Orthogonal codes				
k	Rate	Expansion	Bit-error rate at symbol SNR −4.4 dB	Bit-error rate at symbol SNR −6.5 dB
4	0.25	1.75	0.04	0.11
5	0.15625	2.8	0.004	0.03
6	0.09375	4.7	10^{-5}	0.002

Biorthogonal codes				
k	Rate	Expansion	Bit-error rate at symbol SNR −4.4 dB	Bit-error rate at symbol SNR −6.5 dB
5	0.325	1.4	0.05	0.12
6	0.1875	2.3	0.005	0.04
7	0.109375	4.0	3×10^{-5}	0.003

Repetition codes – inside Reed-Solomon/convolutional				
k	Rate	Expansion	Bit-error rate at symbol SNR −4.4 dB	Bit-error rate at symbol SNR −6.5 dB
2	0.21875	2.0	5×10^{-4}	>0.05
3	0.145833	3.0	$<10^{-5}$	>0.05
4	0.109375	4.0	$<10^{-5}$	$<10^{-5}$
5	0.0875	5.0	$<10^{-5}$	$<10^{-5}$

Appendix B
Time-Multiplexing vs Cloud Coding

We wish to compare a system like ours, which time-multiplexes critical data with normal data, to a cloud coding system (Ref. 4), which is optimal. To avoid comparing apples with oranges, we assume that we have optimal codes in all cases, that is, we are time-multiplexing an optimal code for the critical data with an optimal code for the normal data, and comparing this to an optimal cloud code.

For bandwidth B, signal-to-noise ratio P/N for normal data, signal-to-noise ratio P/AN for critical data, and critical data rate x_2, the normal data rate is bounded by

$$x_1 = B \log_2 \left[1 + A\left(2^{-x_2/B} - 1\right) + 2^{-x_2/B} P/NB\right]$$

in a cloud coded system Ref. 3.

Using time-multiplexing, the critical data rate x_2 uses

$$J = \frac{x_2}{B \log_2 (1 + P/ANB)}$$

of the channel time, leaving $(1 - J)$ of the channel time, at data rate $B\log_2 (1 + P/NB)$, for normal data. Thus the largest possible normal data rate $\hat{x}_1$, for time-multiplexing is

$$\hat{x}_1 = \left(1 - \frac{x_2}{B \log_2 (1 + P/ANB)}\right) B \log_2 (1 + P/NB)$$

We wish to bound the ratio $x_1/\hat{x}_1$.

The ratio $x_1/\hat{x}_1$ approaches 1 as x_2 approaches zero or $B \log_2 (1 + P/ANB)$; so, for fixed B, P/N, and A, it is largest when $d(x_1/\hat{x}_1)/dx_2$ is zero. This occurs when

$$\log_2 \left[1 + A\left(2^{-x_2/B} - 1\right) + 2^{-x_2/B} P/NB\right]$$

$$= \frac{\log_2 (1 + P/ANB) - x_2/B}{1 + A\left(2^{-x_2/B} - 1\right) + 2^{-x_2/B} P/NB} (A + P/NB)\, 2^{-x_2/B}$$

Substituting this into $x_1/\hat{x}_1$, we find that

$$\frac{x_1}{\hat{x}_1} = \frac{\log_2 (1 + P/ANB)}{\log_2 (1 + P/NB)} \cdot \frac{(A + P/NB)\, 2^{-x_2/B}}{1 + A\left(2^{-x_2/B} - 1\right) + 2^{-x_2/B} P/NB}$$

at the x_2 for which $x_1/\hat{x}_1$ is maximized. Since

$$x_2 \leqslant B \log_2 (1 + P/ANB)$$

we get

$$\frac{x_1}{\hat{x}_1} \leqslant \frac{A \log_2 (1 + P/ANB)}{\log_2 (1 + P/NB)}$$

Letting $D = B\log_2 (1 + P/NB)$ represent the largest supportable normal data rate, we get

$$\frac{x_1}{\hat{x}_1} \leqslant \frac{AB}{D} \log_2 \left(1 + \frac{2^{D/B} - 1}{A}\right)$$

For example, if $B = 2{,}000{,}000$, $A = 5$, and $D = 115{,}000$, we find that $(x_1/\hat{x}_1) \leqslant 1.016$, or the maximum loss due to using time-multiplexing (with optimal codes) compared to cloud coding (with optimal codes) is 0.07 dB.