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ADVANCED CODING AND MODULATION SCHEMES FOR TDRSS

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ABSTRACT — This paper describes the performance of the Ungerboeck and pragmatic 8-Phase Shift Key (PSK) Trellis Code Modulation (TCM) coding techniques with and without a (255, 223) Reed-Solomon outer code if they are used for Tracking Data and Relay Satellite System (TDRSS) S-Band and Ku-Band return services. The performance of these codes at high data rates is compared to uncoded Quadrature PSK (QPSK) and rate 1/2 convolutionally coded QPSK in the presence of Radio Frequency Interference (RFI), self-interference, and hardware distortions. This paper shows that the outer Reed-Solomon code is necessary to achieve a 10^{-5} Bit Error Rate (BER) with an acceptable level of degradation in the presence of RFI. This paper also shows that the TCM codes with or without the Reed-Solomon outer code do not perform well in the presence of self-interference. In fact, the uncoded QPSK signal performs better than the TCM coded signal in the self-interference situation considered in this analysis. Finally this paper shows that the E_b/N_0 degradation due to TDRSS hardware distortions is approximately 1.3 dB with a TCM coded signal or a rate 1/2 convolutionally coded QPSK signal and is 3.2 dB with an uncoded QPSK signal.

I. INTRODUCTION

TDRSS users are expected to require higher data rates in the future than are currently supported today. It has been suggested that 8-PSK Ungerboeck and pragmatic TCM codes can support data rates that are twice as high as the data rates currently supported by TDRSS in the same bandwidth. This paper presents the results of an analysis which considers the performance of these codes for S-Band and Ku-Band return services in RFI, self-interference, and hardware distortions. The analysis also considers using the (255, 223) Reed-Solomon code that is recommended by the Consultive Committee for Space Data Systems (CCSDS) as an outer code. This code was selected because it can be easily implemented with TCM and is effective in protecting against burst errors due to RFI. It is also bandwidth efficient since it only requires 14% overhead. Figure 1 shows the channel model used in the analysis.

The analysis only considers high data rate signals since only high data rate signals require the bandwidth efficiency of TCM codes. The lower data rate signals can achieve better performance with less complexity using a rate 1/2 code.

II. BACKGROUND

The design of the coding and modulation functions were performed separately in traditional communication systems. Ungerboeck presented the concept in [1] that the communications performance could be improved without increasing the bandwidth requirements by designing the coding and modulation functions together. He found that the performance of an uncoded QPSK signal in Additive White Gaussian Noise (AWGN) can be improved by coding the signal and increasing the number of phases modulated onto the carrier. Ungerboeck selected the rate 2/3 convolutional code for use with 8-PSK modulation. Essentially this code maps every two data bits into three symbols and then the three symbols select one of eight phases to be modulated onto the carrier. ([1] describes the approach that is to be used to map each of the two data bits into one of the eight phases so that the resulting code is optimum.) This code with Viterbi decoding can achieve a 10^{-5} BER in AWGN with approximately 3 dB less power than is required for an uncoded QPSK signal without any additional bandwidth. Viterbi showed in [2] that another TCM code can be implemented by coding one data bit into two symbols with a rate 1/2 convolutional code and leaving one data bit unchanged, rather than coding both bits with a rate 2/3 con-

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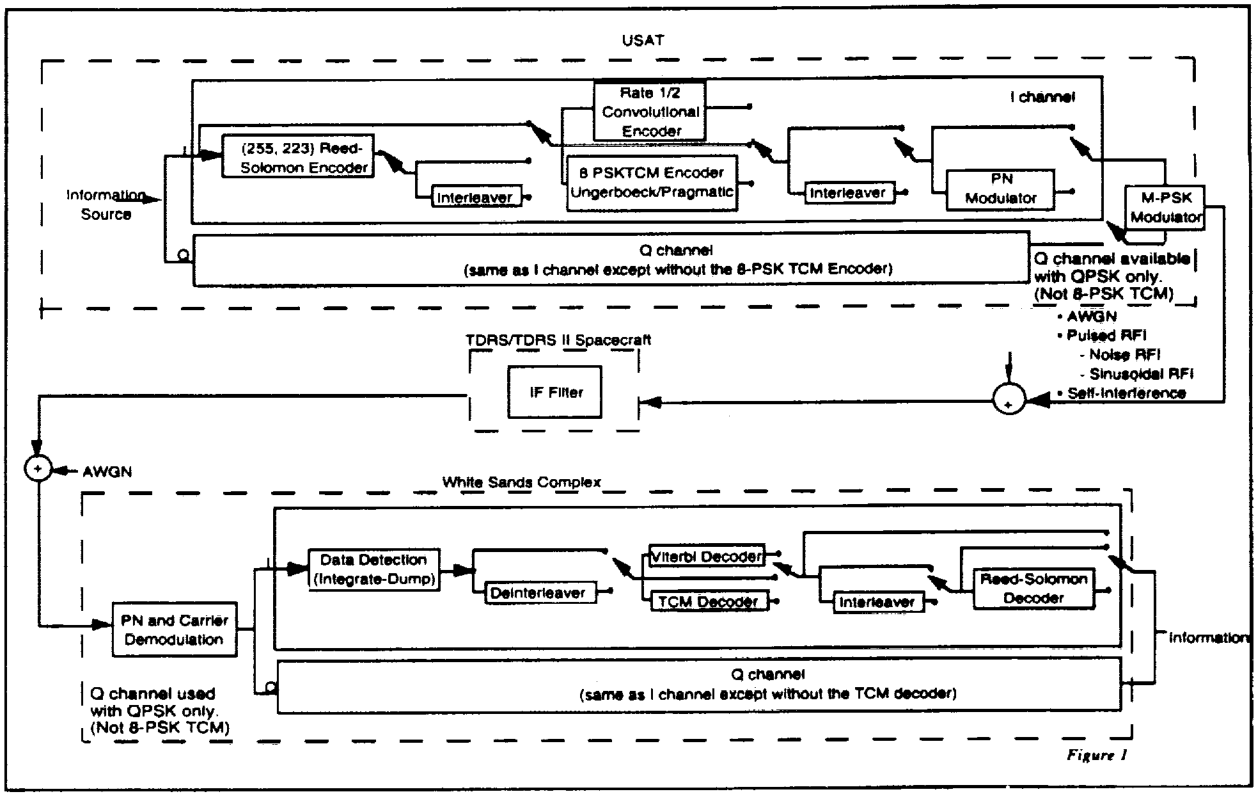

Figure 1. TDRSS Coding and Modulation Channel Model

volutional code. This TCM code, which is referred to as a 8-PSK pragmatic code, is easier to implement and more versatile than the Ungerboeck code, but it's performance in AWGN is approximately the same as can be obtained with the Ungerboeck code. Figure 2 shows the BER performance of these two TCM codes in AWGN compared with the performance of uncoded QPSK and rate 1/2 convolutionally coded QPSK.

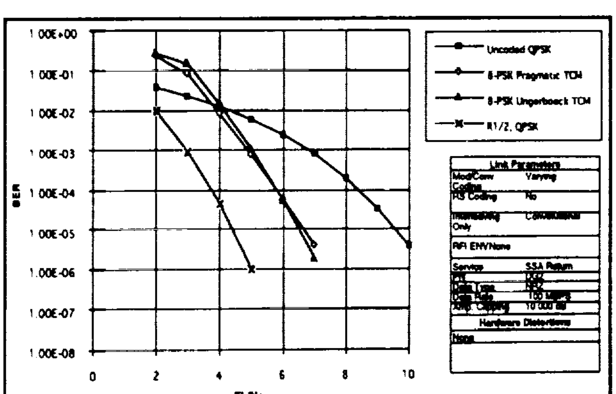

Figure 2. Performance of TCM and Rate 1/2 Convolutional Codes in AWGN

III. ANALYSIS TOOL

The performance of the TCM and Reed-Solomon codes in the presence of RFI, self-interference and hardware distortions was assessed using a Monte-Carlo simulation package that is described in [3].

IV. RESULTS WITHOUT THE OUTER REED-SOLOMON CODE

In the presence of RFI. The performance of the TDRSS return service with the TCM codes was assessed in the presence of the S-Band Multiple Access (SMA) and Ku-Band Single Access (KuSA) terrestrial RFI environments shown in Table 1.

Figure 3 shows the performance of the TCM codes for a 3 Mega bits per second (Mbps) signal in the presence of the SMA RFI environment. This figure shows that the Ungerboeck and pragmatic TCM codes do not perform well in RFI. In fact, the performance of the pragmatic code is not much better than can be achieved with an uncoded QPSK signal. This is because the performance of the pragmatic TCM code is driven by the perfor-

Table 1. RFI Environments for TDRSS SMA and KuSA Return Services

SMA RFI ENVIRONMENT		
5 Pulsed noise RFI sources		
The power spectral density of the noise RFI is uniform within the 6 MHz bandwidth		
Each RFI pulse has a Poisson distributed arrival time and a pulsewidth of 3.5μs		
The received power level and duty cycle for each RFI source is as follows:		
RFI Source	P_{rec} Above TDRS Noise Floor (dB)	Duty Cycle (%)
Source 1	35	0.1
Source 2	25	0.4
Source 3	15	1.5
Source 4	5	2.0
Source 5	0	5.0
KuSA RFI ENVIRONMENT		
1 Pulsed sinusoidal RFI source		
The frequency of the sinusoidal RFI is a constant during each pulse, but it changes from pulse to pulse with a probability that is uniform over the 225 MHz channel bandwidth		
Each RFI pulse has a Poisson distributed arrival time		
The received power level of each pulse is 50 dB above the TDRS noise floor		
The RFI duty cycle is 0.1%		

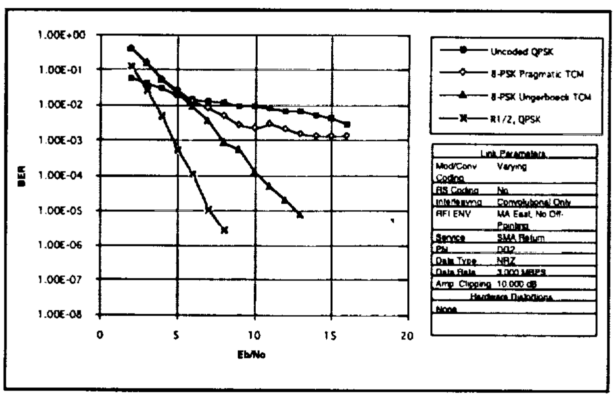

Figure 3. Performance of TCM and Rate 1/2 Convolutional Codes in SMA Return Service RFI

mance of the uncoded bit. The performance of the Ungerboeck TCM code is significantly better than the performance of the pragmatic TCM code because this code does not have any uncoded bits. However, it still suffers about 6 dB degradation at a 10^{-5} BER due to the RFI. (The E_b/N_0 required to achieve a 10^{-5} BER with the Ungerboeck TCM code is approximately 6.6 dB in AWGN and 12.6 dB in the SMA RFI). The problem with the Ungerboeck code is that the rate 2/3 code does not provide sufficient error correction. A lower rate code is needed. A comparison of Figures 2 and 3 shows that the performance with the rate 1/2 convolutional code is only degraded by 2.6 dB due to the RFI. (The E_b/N_0 required to achieve a 10^{-5} BER with rate 1/2 convolutional coding is 4.4 dB in AWGN and approximately 7 dB in the SMA RFI). This explains why rate 1/2 convolutional coding is currently required for TDRSS SMA return links. The SSA return service performance with TCM codes would be degraded by RFI even more than the SMA return service since the SSA RFI environment is even more severe than the SMA RFI environment.

Figure 4 shows the performance of the TCM codes for a 10 Mbps signal in the presence of the KuSA RFI environment. This figure shows that the Ungerboeck and pragmatic TCM codes do not perform much better than the uncoded QPSK in the KuSA return service RFI environment. The coding is unable to correct the errors due to the RFI. However, the rate 1/2 code can correct the errors due to RFI.

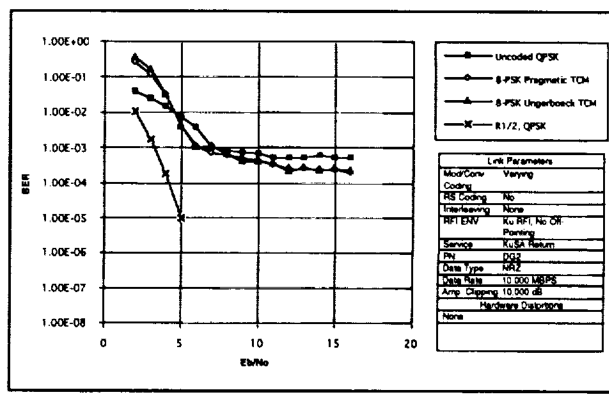

Figure 4. Performance of TCM and Rate 1/2 Convolutional Codes in KuSA Return Service RFI

The performance of the TCM codes in RFI is very important for S-Band return services as RFI can be present for a significant portion of the time a user is in orbit. For example, the SMA return service RFI environment considered in this analysis can be present up to 6% of the time. (This is total time and does not take into account visibility periods.) Ku-Band RFI statistics cannot be generated, but RFI events are much less frequent at

Ku-band than at S-band. This is why TDRSS supports uncoded signals on Ku-Band return links, despite the fact that uncoded signals do not perform well in RFI.

In the presence of Self-Interference. Figure 5 shows the TDRSS return service performance with the TCM codes in the presence of an interfering signal, where the interfering signal has a lower symbol rate than the desired signal. (This is the worst-case situation since none of the interference is filtered at the receiver. But it is also the most likely situation to occur since only the high data rate signals require the bandwidth efficiency of TCM codes.) It was assumed that the desired signal has a 7 dB E_b/N_0 margin, which is sufficient to ensure that noise is insignificant relative to the interference at high signal-to-interference ratios. This figure shows that both the Ungerboeck and pragmatic TCM code's BER performance is worse than the uncoded QPSK signal performance. This is because the decision regions for 8-PSK TCM are closer together than they are for the uncoded QPSK signal.

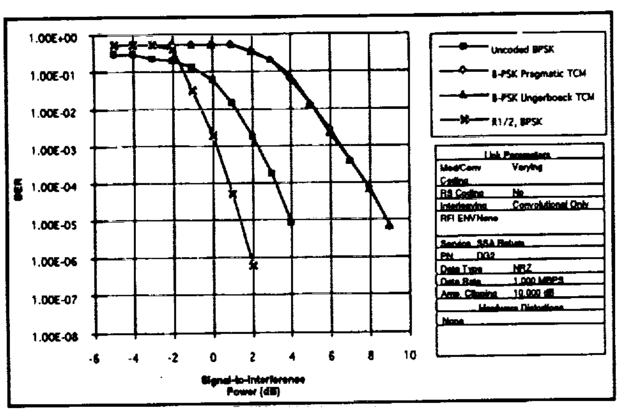

Figure 5. Performance of TCM and Rate 1/2 Convolutional Codes in the Presence of an Interfering Signal with a Lower Symbol Rate than the Desired Signal

The performance of the return services in self-interference is very important for S-Band return services as there are many users operating at the same frequency at S-Band. Self-interference is less of a concern for Ku-Band return services as there are not as many users currently operating at this frequency and beamwidths are narrower at Ku-Band than they are at S-Band. However, self-interference events are expected to increase as more users operate at the Ku-Band frequency.

In the presence of Hardware Distortions. Table 2 shows the hardware distortions considered in this analysis and the return service performance achievable with the pragmatic TCM coded, uncoded QPSK, and rate 1/2 QPSK signals in the presence of each hardware distortion individually and combined together. This table shows that the E_b/N_0 degradation due to all of the hardware distortions combined is 1.3 dB for the coded signals and 3.2 dB for the uncoded QPSK signal.

Table 2. E_b/N_0 Degradation due to Hardware Distortions

Hardware Distortion		**Degradation at a 10^{-5} BER (dB)**		
Name	**User Constraint Value**	**Uncoded QPSK**	**8-PSK TCM Pragmatic / Ungerboeck**	**Rate 1/2 Coded QPSK**
Data Asymmetry	3%	0.8	0.3	0.2
Data Jitter	0.1%	0	0	0
Gain Imbalance	.25 dB	0.2	0.2	0.2
Phase Imbalance	6°	0.6	0.5	0.1
Phase Noise	3°	0	0.2	0
Phase Nonlinearity	3°	0 6	0.1	0.1
AM/AM	0.75 dB/dB	0.3	0	0
AM/PM	12°/dB	0	0	0
Jitter Rate	0.1	0	0	0
Gain Flatness	0.3 dB	0.7	0.1	0.1
All Hardware Distortions Combined		3.2	1.3	1.3

V. RESULTS WITH THE OUTER REED-SOLOMON CODE

In AWGN. Figure 6 shows the performance of the concatenated codes using a (255, 223) Reed-Solomon outer code and the TCM codes and rate 1/2 convolutional code as the inner code in the presence of AWGN. This figure also shows the performance of the (255, 223) Reed-Solomon outer code by itself in AWGN.

In the presence of RFI. Figure 7 shows the performance of the concatenated codes with a (255, 223) Reed-Solomon outer code and either the TCM code or the rate 1/2 convolutional code as the inner code in the presence of SMA RFI environment. A comparison of this figure with Figure 6 shows that the concatenated code performance with the Ungerboeck or pragmatic TCM

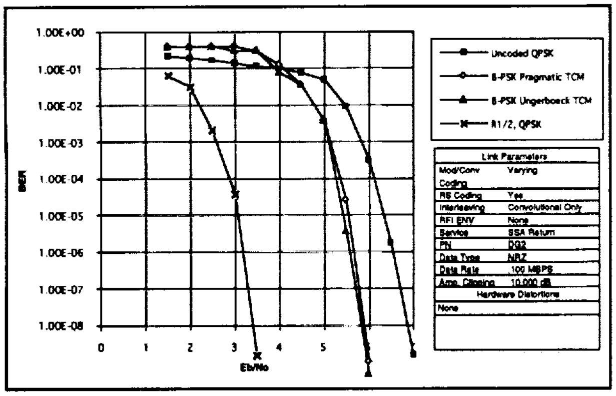

Figure 6. Performance of (255, 223) Reed-Solomon Outer Code with Various Inner Codes in AWGN

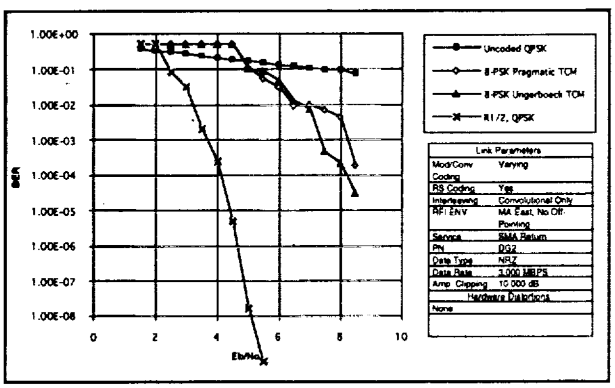

Figure 7. Performance of the Reed-Solomon Outer Code with Various Inner Codes in SMA Return Service RFI

inner code suffers about 3.2 dB degradation at a 10^{-5} BER due to the RFI. (The E_b/N_0 required to achieve a 10^{-5} BER with the Ungerboeck TCM code is approximately 5.5 dB in AWGN and 8.7 dB in the SMA RFI). A similar comparison shows that the performance with the rate 1/2 convolutional code is only degraded by 1.3 dB due to the RFI. (The E_b/N_0 required to achieve a 10^{-5} BER with rate 1/2 convolutional coding is 3.1 dB in AWGN and approximately 4.4 dB in the SMA RFI). Therefore, the concatenated code using either a TCM inner code or a rate 1/2 convolutional code can achieve the required 10^{-5} BER with an acceptable amount of degradation in the presence of RFI.

Figure 8 shows the performance of the concatenated codes with a (255, 223) Reed-Solomon outer code and either the TCM code or the rate 1/2 convolutional code as the inner code in the presence of the KuSA RFI environment. This figure also shows the performance of the (255, 223) Reed-Solomon outer code by itself. (The inner code is an uncoded QPSK signal.) A comparison of Figure 8 with Figure 6 shows that a 10^{-5} BER can be achieved with minimal degradation with all of the concatenated codes and with the (255, 223) Reed-Solomon code by itself (no inner code).

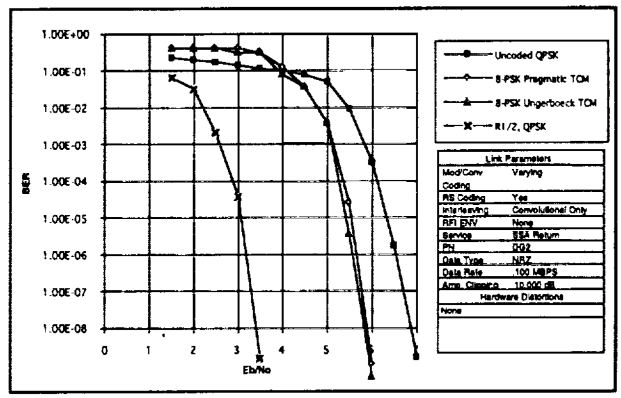

Figure 8. Performance of the Reed-Solomon Outer Code with Various Inner Codes in KuSA Return Service RFI

In the presence of Self-Interference. Figure 9 shows the TDRSS return service performance with the concatenated codes in the presence of an interfering signal, where the interfering signal has a lower symbol rate than the desired signal. It was assumed that the desired signal has a 7 dB E_b/N_0 margin, which is sufficient to ensure that noise is insignificant relative to the interference at high signal-to-interference ratios. This figure shows that the BER performance with a concatenated code and either the Ungerboeck or pragmatic TCM codes as the inner code is worse than the performance without an inner code. The Ungerboeck and the pragmatic TCM codes are more susceptible to decoding errors than an uncoded QPSK signal since the decision regions of an 8-PSK signal are closer together than the decision regions of an uncoded QPSK signal and the Reed-Solomon outer code cannot correct the decoding errors.

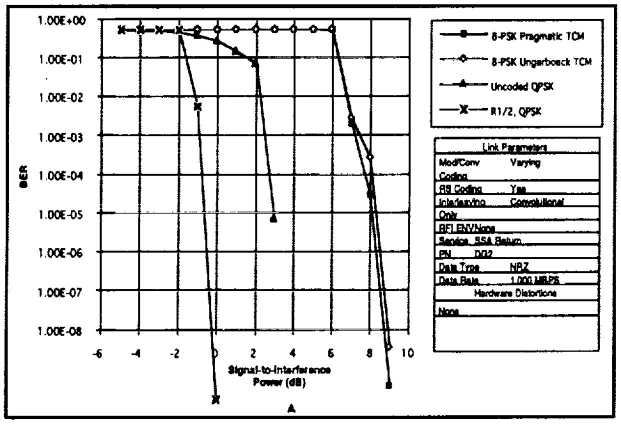

Figure 9. Performance of the (255, 223) Reed-Solomon Code with Different Inner Codes in the Presence of an Interfering Signal with a Lower Symbol Rate than the Desired signal

IV. CONCLUSIONS

The TCM codes without the (255, 223) Reed-Solomon outer code do not perform well in the presence of RFI or self-interference. The concatenated code which has an outer (255, 223) Reed-Solomon code and an inner TCM code can achieve a 10^{-5} BER in RFI, but it's performance is worse than an uncoded QPSK signal in the presence of self-interference. Since RFI and self-interference are often present at S-Band frequencies, the TCM codes with or without the Reed-Solomon code outer code are not recommended for TDRSS S-Band return services. However, RFI and self-interference are not present as often on the Ku-Band return services as they are on the S-Band return services so that TCM codes with or without the Reed-Solomon outer code can be used for TDRSS Ku-Band return services.

V. REFERENCES

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[3] Advanced Coding Techniques Study for TDRS/TDRS II Systems, Kaplan, Ted, Berman, Ted, STel 003R1493, April 23, 1993