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Performance of Trellis Coded Modulation with 8PSK Through TDRSS

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Abstract

The need to increase data-rate capabilities of the Tracking and Data Relay Satellite System (TDRSS) has prompted NASA to investigate bandwidth-efficient modulation schemes. Based upon current technology the most promising scheme is Trellis-Coded Modulation (TCM) operating with Octal Phase Shift Keying (8PSK). In conjunction with NASA, New Mexico State University's Manuel Lujan Jr. Center for Space Telemetering and Telecommunications Systems has constructed a system to test this new candidate TDRSS modulation scheme, TCM 8PSK. This system was tested through the TDRSS channel to demonstrate that this coding scheme operates as well over the actual channel as it has in lab experiments and simulations. Two interchangeable codecs, implementing separate TCM techniques, were tested. The results of this experiment and subsequent data analysis are presented in this paper.

Background

As the National Aeronautics and Space Administration moves into the 21st century with programs like Space Station Freedom and the new Landsat mission, transmission demands on the Tracking and Data Relay Satellite System (TDRSS) will very likely exceed the available bandwidth. Under NASA grant NAG 5-1491, the Manuel Lujan Jr. Center for Space Telemetering and Telecommunications Systems at New Mexico State University is studying techniques for increasing the data-rate capabilities of TDRSS. These techniques include the use of advanced bandwidth-efficient modulation formats to increase the data rate that can be sustained in a TDRSS transponder and the use of lossless bandwidth compression of the data to be transmitted to lower the data rate required from the user spacecraft.

Currently, TDRSS operates with coded QPSK. Use of uncoded 8PSK would decrease the bandwidth requirement by a factor of 3, while allowing more information to be transmitted with each symbol. The problem with implementing uncoded 8PSK is a significant decrease in performance. The error rates experienced by an uncoded 8PSK system are much higher due to constellation points in closer proximity to one another. In order to make up for the lost performance, error-correction coding must be used. But coding decreases the amount of information carried by individual symbols and therefore decreases the data throughput.

The best solution to this problem is a code that performs well with a minimum of bandwidth expansion. A coding scheme that meets these tough requirements is Trellis-Coded Modulation (TCM). In fact, laboratory tests have shown that 8PSK operating with TCM can perform at error rates lower than uncoded QPSK while transmitting at least as much information in each symbol. This scheme had never been tested through the actual TDRSS channel. It was not known if the channel would affect the coding scheme in a way that was unaccounted for in previous laboratory tests and simulations.

Tests were performed through the TDRSS channel with the help of the White Sands Ground Terminal (WSGT) and NASA. For the test, two TCM codecs (coders/decoders) were developed. One, built by NMSU, is a rate 2/3 Pragmatic Codec [3], while the other is a rate 5/6 TCM codec built by the University of Notre Dame and the University of South Australia [2]. Whereas the NMSU codec focuses on minimizing the system's error rate while maintaining two data bits per symbol, as in uncoded QPSK, the UND/USA codec transmits two and one-half data bits per symbol while still exhibiting a gain in system performance.

All tests were performed at 1 million symbols per second (1Msps). The rate was limited by the operational range of the support hardware and not by the codecs themselves.

Test System Configuration & Operation

A block diagram of the test system constructed by NMSU along with its interface with the WSGT network is shown in Figure 1. This network uses a small dish antenna from which the test signal is transmitted to simulate a user satellite. The signal is then received through TDRSS and routed back to the transmitter for analysis. The test system was designed to interface directly with this equipment. This required only two connections between the test system and the WSGT network. A 370MHz 8PSK data signal was supplied by the test system to the transmission side of the network. That data signal was then converted to the S or K band frequency and routed through the TDRSS channel. The signal was recovered at 370MHz from the network at the return point.

As shown in Figure 1, the system starts and ends with the Bit Error Rate (BER) Test Set, where the pseudo-random bit sequence to be transmitted is created. This data sequence is supplied to the codec in operation and the PN Generator, which is used to create parallel channels of pseudo-random data for uncoded tests. Three parallel bits of coded or uncoded data are then supplied to the Vector Modulator for 8PSK modulation. The data is modulated on a 370MHz carrier for transmission over the channel and supplied to the WSGT network or routed directly to the test system's receive side or laboratory tests.

The receive side of the test system starts with a channel simulator that adds white noise to the data signal, rotates the data's phase for elimination of phase ambiguity, and conditions the signal for interface with the demodulator. The signal is then demodulated by a Harris High Rate

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Demodulator modified for 8PSK operation [1]. After demodulation, the bit clock is recovered from the demodulated signal by the Symbol Synchronizer, which also converts the received analog data signal into 5 bits of digital phase information. This data is then decoded and returned to the BER Test Set for measurement.

The two codecs used in the test operate similarly. The NMSU Pragmatic Codec uses the pragmatic TCM standard invented by Viterbi [4] to implement TCM using a currently available binary Viterbi decoder. The codec was implemented using two separate channels. The inboard channel processes a pseudo-random bit sequence using a standard rate 1/2, constraint length 7 convolutional encoder, creating two of the three symbol bits. The outboard channel simply passes a parallel pseudo-random bit sequence to the output as the third symbol bit. When the TCM sequence is decoded, the Viterbi decoder returns the convolutionally encoded bit while the outboard bit is returned by independent decision logic. Since the performance of the inboard bit alone is of most interest, these channels were kept separate in order to measure their performances individually.

The UND/USA codec uses a 4-dimensional signal set, each symbol consisting of a pair of 2-dimensional 8PSK signals [2]. Five data bits are encoded onto the 4-dimensional symbol, thereby achieving a code rate of 5/6 — 6 codebits per 5 data bits. This gives the code a slightly higher spectral efficiency. Differential encoding is used to achieve phase invariance.

System Gain Measurement

System gain is a performance measure defined as the gain in error rate performance seen at the output of the decoders, compared to an equivalent uncoded QPSK modem's performance. More precisely, system gain is the gain in bit energy to noise ratio (Eb/No) at an error rate of 1×10^{-5} demonstrated by the coded 8PSK system over an equivalent uncoded QPSK system.

In order to measure system gain as defined, an equivalent QPSK performance curve must be developed from the uncoded 8PSK performance curve. This is done by mapping from the 8PSK curve to the equivalent QPSK curve through a function of the BER. Each point on the measured curve is translated by ΔdB, where Δ is a function of BER defined by the graph in Figure 2.

Verification of this technique was performed by mapping the theoretical 8PSK BER curve to an equivalent QPSK curve. This curve was then compared to QPSK theory. As shown in Figure 3, the equivalent QPSK curve and the theoretical QPSK curve are identical to within a tenth of a decibel.

Uncoded System Performance

The first test performed was the measurement of the unmodified system performance. The performance of the unmodified HRD was measured and compared to similar data supplied with the equipment. Figure 4 shows the BER curve measured in the laboratory. These curves correspond to well within acceptable measurement error.

Once modifications were made to the HRD to allow it to demodulate 8PSK data, a baseline uncoded performance curve was measured. This curve is shown in Figure 5. Included in this figure is the uncoded QPSK curve measured before modification and the translated equivalent QPSK curve. An important feature of this graph is the slight flare present in the equivalent curve as Eb/No increases, as compared to the measured QPSK curve. This is to be expected, since the 8PSK modem also flares. This flare is due to increased sensitivity of an 8PSK system to phase noise. With smaller values of Eb/No, this phase noise is swamped by the white noise and is not a factor in the maximum likelihood decision process. The 8PSK uncoded baseline curve and its equivalent QPSK curve will be used to measure system gain for all in-lab codec tests.

The baseline measurement was repeated through both the S-band and K-band channels to allow proper system gain measurement under these conditions. Figure 6 and Figure 7 show the S-band and K-band uncoded 8PSK baseline performance curves. The in-lab baseline curve is included in both to demonstrate the additional flare present in each channel. This is due to the significant levels of phase jitter on the channels that were not present during the in-lab test. The K-band channel shows less flare, indicating that the equipment in this link contributed less phase noise to the channel than the corresponding equipment in the S-band link.

NMSU Pragmatic Codec Performance

While in the laboratory, the performance of the NMSU Pragmatic Codec was measured. The resulting curve is shown in Figure 8. Included in this graph are the measured performance of the codec, the uncoded baseline measured in the lab and the equivalent uncoded QPSK curve. The system gain is 2.5dB at a BER of 1×10^{-5}, as shown. This measurement is slightly below theoretical predictions.

The performance was measured again through the TDRSS S-band and K-band channels. As shown in Figures 9 and 10, neither channel adversely affected the codec's performance.

Compared to the in-lab results, the system gain was measured to be higher through each of the TDRSS channels. These results, shown in graphs similar to the in-lab measurement, are shown in Figures 11 and 12. The S-band and K-band results demonstrate a system gain of 3.1dB and 2.9dB compared to the in-lab measurement of 2.5dB.

The increase in system gain is due to the ability of the codec to operate at lower levels of Eb/No where it is unaffected by the phase jitter that produces the flare associated with the uncoded system. In effect, the coded system is credited with fixing one of the major problems with the uncoded 8PSK system — flare caused by phase jitter at high signal-to-noise ratios.

The variation in system gain from one channel to the other is a result of to the difference in phase jitter in the different systems. Recall that the K-band network produced less phase noise than the S-band network. Although the codec operates almost identically through the two channels, it corrects for more performance loss in the S-band channel. Therefore, the coded system receives more credit, in the form of a higher system gain, through the S-band channel.

UND/USA Rate 5/6 TCM Codec

The in-lab tests showed that the UND/USA codec performs with a system gain of 1.8dB. The measurements made are shown in Figure 13. This system gain is less than that measured for the NMSU codec, but the UND/USA codec operates with a higher spectral bandwidth efficiency.

Due to time and scheduling constraints, this codec was only tested through the S-band TDRSS channel. As shown in Figure 14, this codec was also unaffected by the TDRSS channel, operating with performance almost identical to that measured in the laboratory.

Again, the system gain through the actual channel was measured to be slightly higher than that measured in the laboratory tests. The UND/USA codec performed with 2.4dB of system gain through the S-band channel, as shown in Figure 15. This increase in system gain of .6dB corresponds to the same increase for the NMSU codec when measured through the S-band channel.

Conclusion

Through its research in conjunction with NASA, New Mexico State University's Center for Space Telemetering and Telecommunications believes it has found a strong candidate for a modulation scheme to be used for high data-rate applications through the TDRSS channel in the near future. The test of 8PSK TCM through the satellite system proved to be successful.

The test performed at WSGT by NMSU demonstrated that 8PSK with trellis coding is a modulation scheme that will increase the data-rate capabilities through the TDRSS spacecraft while still achieving better BER versus signal-to-noise ratio performance than uncoded QPSK. This will help with the high demands expected to be placed on the TDRSS network by programs such as Space Station Freedom and the new Landsat mission.

Two TCM codecs, implementing different levels of bandwidth efficiency, were tested and proved to be unaffected by the TDRSS channel. The codec designed and built by NMSU achieved a system gain of approximately 3dB over the S-band and K-band channels while increasing the data rate per unit of occupied bandwidth by a factor of 2. The second codec, built by the University of Notre Dame with the University of South Australia, demonstrated a coding gain of 2.4dB over the S-band channel with a 2.5-to-1 increase in data rate per unit bandwidth.

The modulation technique was not fully tested. Further tests performed at rates higher than 1Msps are required to stress the channel. S-band service should be tested at 6 or 12Msps, while K-band service should be tested with data rated in the 300 to 600Msps range. Tests must also be performed to investigate the effects of RFI and burst errors on the performance of TCM.

Overall, the proof-of-concept test was deemed a success. It was shown that the TDRSS channel did not degrade the TCM format in any unusual way. The researchers at NMSU are confidant that this modulation scheme will pass all future tests and can safely be selected as one of the modulation schemes for future high-rate TDRSS applications.

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[2] Pietrobon, Steven S., "Trellis Coding With Multidimensional Signal Sets and Rotationally Invariant Trellis Codes," Doctoral Dissertation, University of Notre Dame, Illinois, December 1990.

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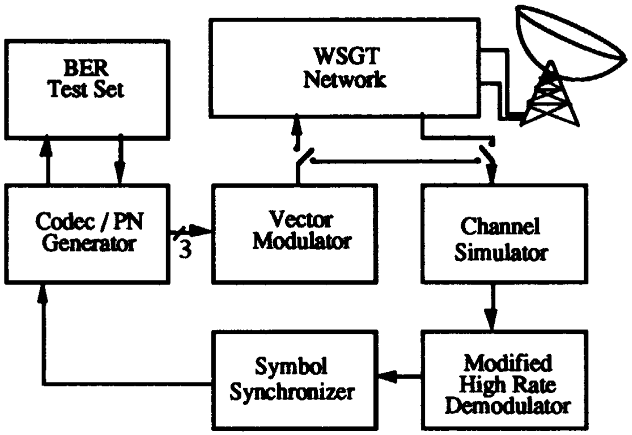

Figure 1/Test System Diagram

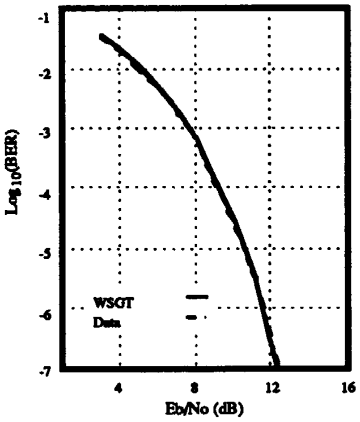

Figure 4/QPSK Baseline

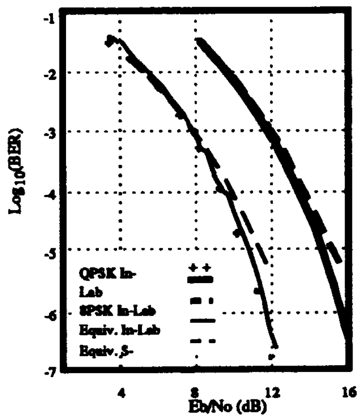

Figure 6/Uncoded S-band Performance

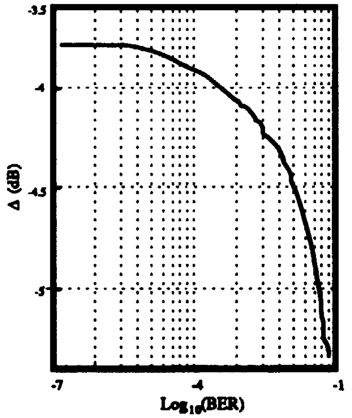

Figure 2/Translation Map

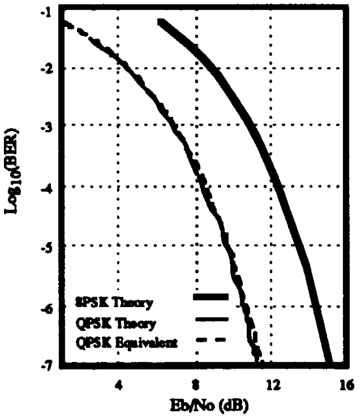

Figure 3/Translation Verification Curve

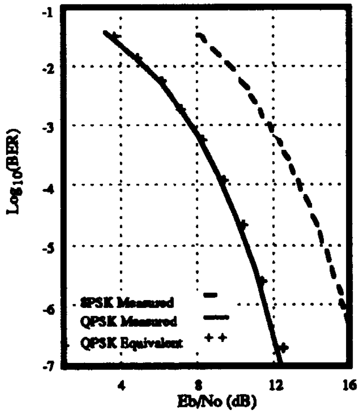

Figure 5/Baseline Comparison

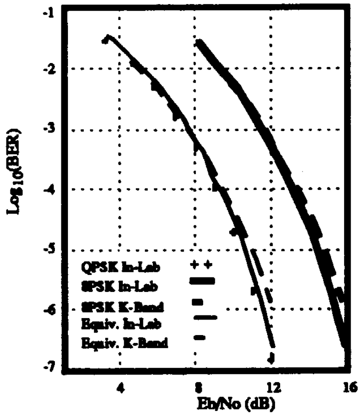

Figure 7/Uncoded K-Band Performance

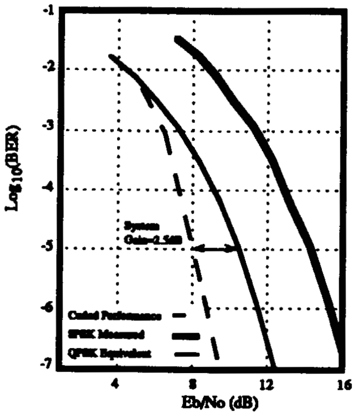

Figure 8/NMSU In-Lab Performance

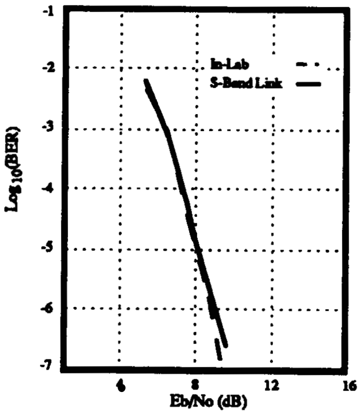

Figure 9/NMSU S-Band Performance Comparison

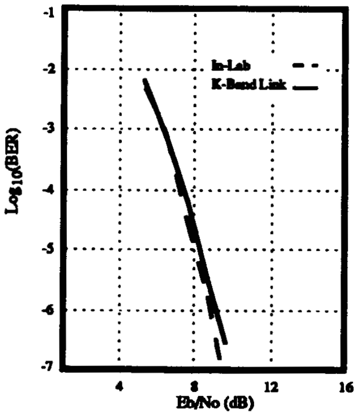

Figure 10/NMSU K-Band Performance Comparison

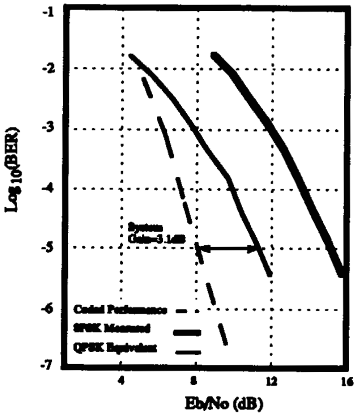

Figure 11/NMSU S-Band Performance

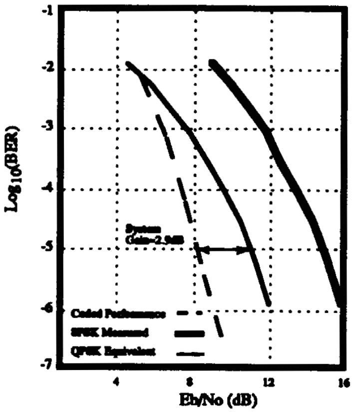

Figure 12/NMSU K-Band Performance

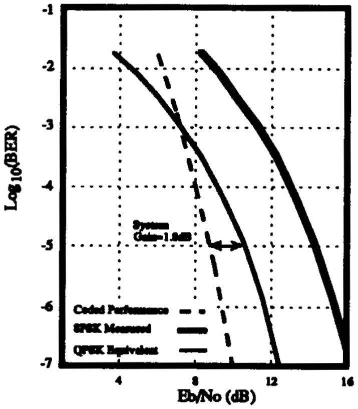

Figure 13/UND In-Lab Performance

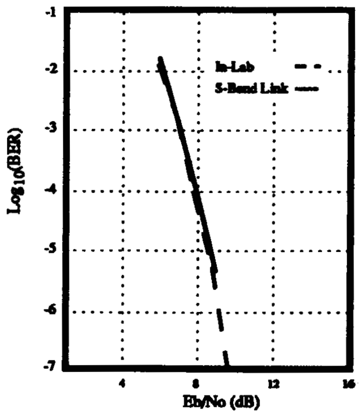

Figure 14/UND S-Band Performance Comparison

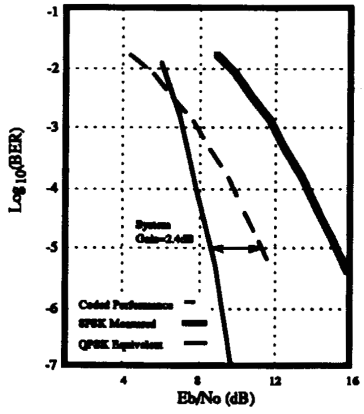

Figure 15/UND S-Band Performance