EXPERIMENTAL RESULTS FOR PCM/FM, TIER 1 SOQPSK, AND TIER II MULTI-H CPM WITH TURBO PRODUCT CODES

Mark Geoghegan
Nova Engineering Inc., Cincinnati, OH

ABSTRACT

Improving the spectral-efficiency of aeronautical telemetry has been a principal area of research over the last several years due to the increasing demand for more data and the limitation of available spectrum. These efforts have lead to the development of the ARTM Tier 1 SOQPSK and Tier II Multi-h CPM waveforms which improve the spectral efficiency by two and three times, as compared to legacy PCM/FM, while maintaining similar detection efficiency. Now that more spectrally efficient waveform options are becoming available, another challenge is to further increase the detection performance. Better detection efficiency translates into additional link margin that can be used to extend the operating range, support higher data throughput, or significantly improve the quality of the received data.

It is well known that Forward Error Correction (FEC) is one means of achieving this objective at the cost of additional overhead and increased receiver complexity. However, as mentioned above, spectral efficiency is also vitally important meaning that the FEC must also have a low amount of overhead. Unfortunately, low overhead and high coding gain are generally conflicting trades, although recent work has shown that Turbo Product Codes (TPC) are a particularly attractive candidate. Computer simulations predict that very impressive gains in detection performance are possible for a relatively small increase in bandwidth. The main drawbacks are the additional complexity of the decoding circuitry and an increase in receive side latency. This paper presents the latest simulation and hardware performance results of PCM/FM, SOQPSK, and Multi-h CPM with TPC.

KEY WORDS

PCM/FM, Tier 1, SOQPSK, Tier II, Multi-h CPM, FEC, Turbo Coding

INTRODUCTION

The objective of this effort is to evaluate the potential benefit of adding Turbo Product Coding (TPC) to three telemetry waveforms, namely legacy PCM/FM, Tier 1 SOQPSK, and Tier II Multi-h CPM. In particular, this paper investigates the performance gains attainable with an off-the-shelf TPC decoder chip from Advanced Hardware Architectures (AHA^{TM}) [1]. Simulation models as well as a hardware evaluation platform were used to perform this study. Although all of the above modulations could be treated as a concatenated coding scheme (phase coding + TPC code), joint detection is not considered here due to the increased complexity and the fact that a large interleaver is not generally suitable for military telemetry applications due to the latency involved at the transmitter. Therefore, the modulation and coding will be processed separately to maximize the use of existing demodulator hardware and a commercially available AHA TPC decoder chip. Simulations and hardware results are presented in the following sections.

WAVEFORM DESCRIPTIONS

Several recent papers have been published describing these particular modulations [2] [3] [4], so they will only be briefly described here. The objective of the Tier 1 and Tier II waveforms was to improve the spectral efficiency as compared to legacy PCM/FM while maintaining similar detection efficiency. Figure 1 shows the measured BEP performance of the three modes and demonstrates that PCM/FM (with traditional detection), SOQPSK, and Multi-h CPM all require around 13 dB Eb/No to achieve an error rate of 10^{-6}. However, if a more sophisticated multi-symbol detector is used with PCM/FM, the performance can be improved by roughly 3 dB.

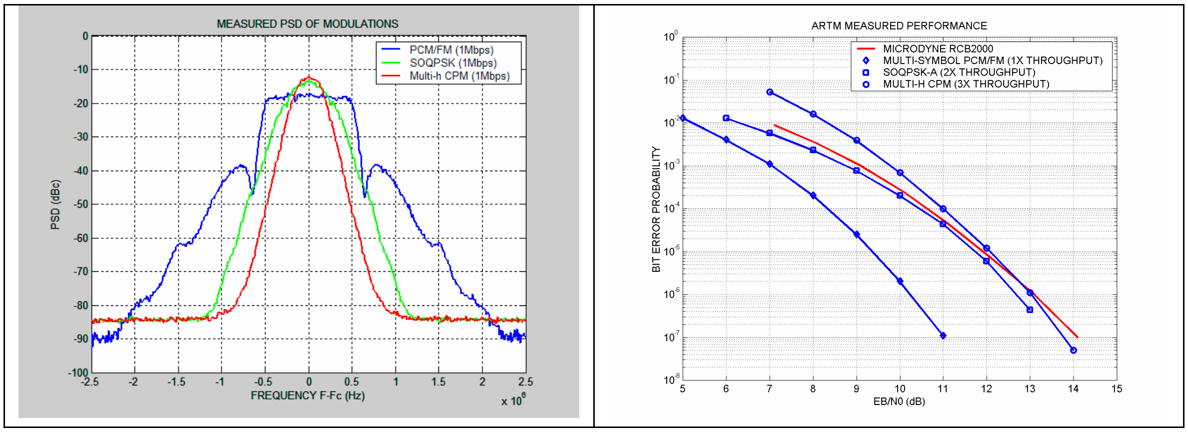

Figure 1. PSD and BEP performance of the modulations.

TURBO PRODUCT ENCODING AND DECODING

There are many types of FEC that could be used in this architecture including Reed-Solomon, Convolutional, concatenated Reed-Solomon and Convolutional, BCH, as well as many others. However, Turbo Product Codes appear particularly attractive due to their large coding gain, rate flexibility, simple structure, modest synchronization requirements, and availability of commercial encoder and decoder integrated circuits. Interleaving will not be used in this study since the added latency at the transmitter may not fit typical mission requirements.

Figure 2 illustrates a simple (7,4)x(7,4) product code constructed from multiple (7,4) codewords. For each block, 16 information bits are used to compute the 33 parity bits. The algorithm performs encoding row-by-row and then column-by-column. Note that the completed block contains parity bits calculated on other parity bits. After the encoding process is finished, 49 bits of information and parity are serialized and sent to the modulator. The code rate for this example, ratio of source bits to source bits plus parity, is 0.327 (=16/49).

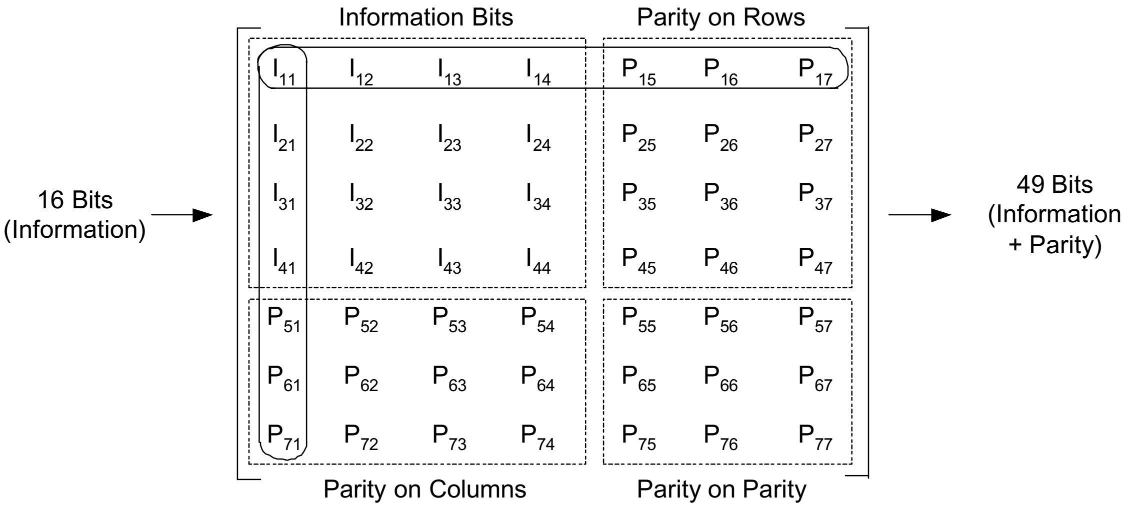

Figure 2. (7,4) x (7,4) Product Code Example

A ‘Turbo’ decoding procedure is used to recover the information bits from the 49 bits of noisy received data. The rows are decoded using a soft (7,4) decoder that outputs not only the decoded bit, but also the confidence on the decision. Similarly, the columns are decoded using the soft information from the decoded rows. This iterative process of decoding the rows followed by the columns continues until the decoder converges on the best answer. Issues that affect the decoder performance include the code parameters, channel characteristics, modulation type, soft decision quality, and number of iterations.

SIMULATION MODEL

Computer simulations with different code parameters and soft decision techniques were used to evaluate the system performance. Codes with low to moderate overhead were evaluated in an additive white Gaussian noise (AWGN) channel with perfect synchronization. Table 1 lists some of the codes supported by the AHA 4540 integrated circuit [1] and their projected performance with coherent BPSK for an AWGN channel at an error rate of 10^{-6} using a sufficient number of decode iterations. However, this level of performance will not be realized since the modulations, although much more spectrally-efficient, are not as power-efficient as BPSK. Figure 3 shows the simulation model with and without TPC.

Code $(n_1,k_1)x(n_2,k_2)$	Block Size (Bits)	Data Size (Bits)	Rate	Coding Gain (dB) for BPSK
(64,57)x(64,57)	4096	3249	0.793	7.1
(128,120)x(64,57)	8192	6840	0.845	6.8
(128,120)x(128,120)	16384	14400	0.879	6.6

Table 1. Attractive TPC candidates supported by AHA integrated circuits

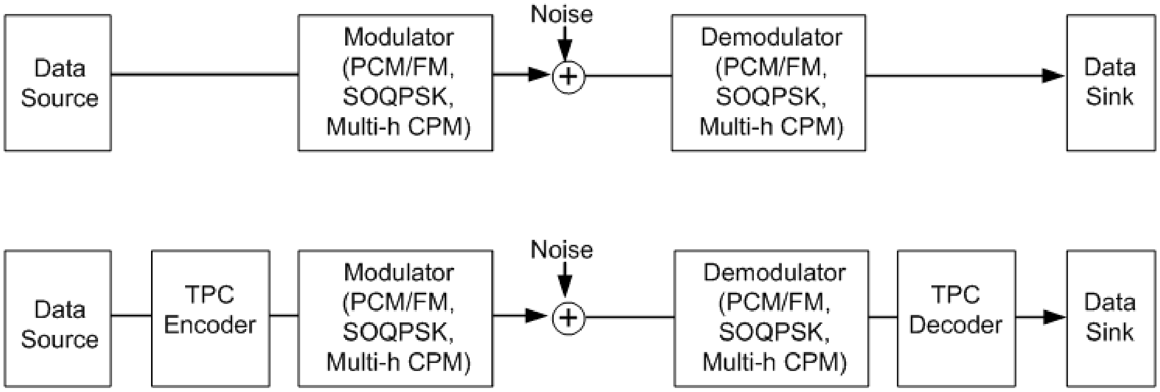

Figure 3. Simulation Model with and without TPC

SOFT DECISION APPROACHES

PCM/FM

The decoder requires soft-decision inputs from the demodulator. For coherent BPSK, a simple decision slicer that quantizes the matched filter output is suitable for creating the soft decision values. For PCM/FM, the multi-symbol detector compares the received input signal with the ideal transmitted values over several symbols and computes a score for all possible transmitted patterns. The correlation with the largest magnitude determines the recovered data bit (hard decision). Two methods of creating a soft decision output were investigated. The first approach takes the difference between the magnitudes of the largest '0' filter and the largest '1' filter which can be normalized and quantized to be compatible with the input requirements of the Turbo decoder. The soft decision x(k) can be expressed mathematically as

$$x(k) = quant\left(\frac{\max\left|C^{0}\right| - \max\left|C^{1}\right|}{A} \right)$$

where $C^{i} = \left(c_{1}^{i}, c_{2}^{i}, c_{3}^{i}, \ldots, c_{N}^{i}\right)$ is the set of correlations that produce the binary output (i) and A is a normalization factor based on the size of the correlator scaling and the quantization scheme desired.

SOQPSK

For the uncoded case, SOQPSK uses differential encoding to resolve the carrier phase ambiguity. Although this degrades the BEP performance by only a factor of 2 at high SNR, the loss in dB is much worse at the lower SNR's where the coding starts to become effective. Furthermore, not only is the BEP curve worse but the soft-decisioning is complicated by the fact that the output is also a function of the previous symbol. One option is to not differentially encode SOQPSK and use the FEC structure to resolve the phase ambiguity. This scheme will perform better, but it will take longer to acquire and it will have to resynchronize if the carrier slips.

If differential encoding is used, the soft decision is a function of the current and previous symbols. Several methods of creating a soft output exists based on algebraic rotation, angular difference, and metric combining. One approach is to use the minimum quality of the two matched filter outputs that make up the overall bit decision as shown below. If differential encoding is not used, the soft decision is simply the quantized matched filter output.

$$i(k) = \min\left(quant\left(\frac{I(k)}{A}\right), quant\left(\frac{Q(k-1)}{A}\right)\right) \ , \ q(k) = \min\left(quant\left(\frac{Q(k)}{A}\right), quant\left(\frac{I(k-1)}{A}\right)\right)$$

Multi-h CPM

Since Multi-h CPM is demodulated by forming a phase trellis and using the Viterbi algorithm, soft-decision generation is somewhat more difficult. Typically, at each add, compare, select (ACS) operation, only the index of the surviving path is saved and a traceback algorithm is used to determine the data bit, thereby resulting in a hard decision output. One method for generating a soft output is to use a soft output Viterbi algorithm (SOVA). The basic premise is that the confidence in the decision is a function of how close the path metric comparisons were that would have produced a different decision. Ideally, one could save all comparisons that could have produced a different result and use the minimum as the confidence measure of the traceback output. Although this approach can be included in a multi-h CPM computer simulation, modification of the existing hardware demodulator has not completed at the time of this publication.

SIMULATION RESULTS

TPC simulation results for PCM/FM with TPC and perfect synchronization are shown in Figure 4. Included for comparison are some measured hardware results for the uncoded case using both a traditional detector (RCB2000) and Nova's multi-symbol detector. The multi-symbol detection algorithm was used in the simulation when the TPC was added. Even though the TPC results assume perfect synchronization , the conclusion is that TPC has the potential to provide a significant improvement in detection efficiency.

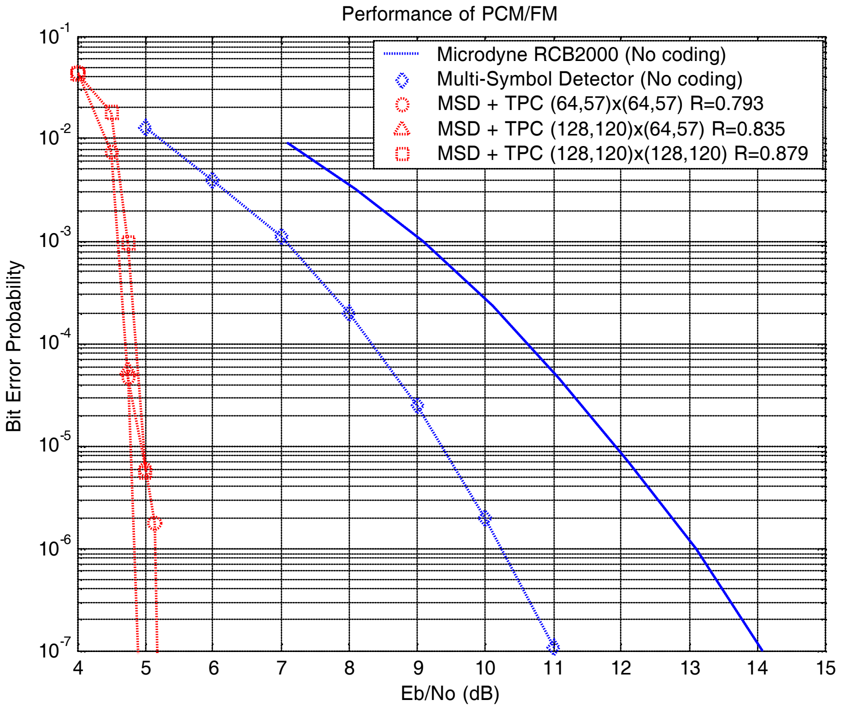

Figure 4. Performance of PCM/FM Systems
(Conventional, MSD, MSD+TPC(16 iterations per decode, 6 bit quantization))

Simulation results for SOQPSK with TPC and perfect synchronization are shown in Figure 5. Curves with and without differential encoding are presented. Although differential encoding only slightly degrades the performance of an uncoded system, it has a much greater effect with TPC. This occurs due to the relatively larger loss in dB at low SNR's and the fact that the soft-decisioning is coupled with the previous bit. These results indicate that differential encoding causes a relatively large penalty in detection efficiency and should not be used if acceptable synchronization can be maintained without it.

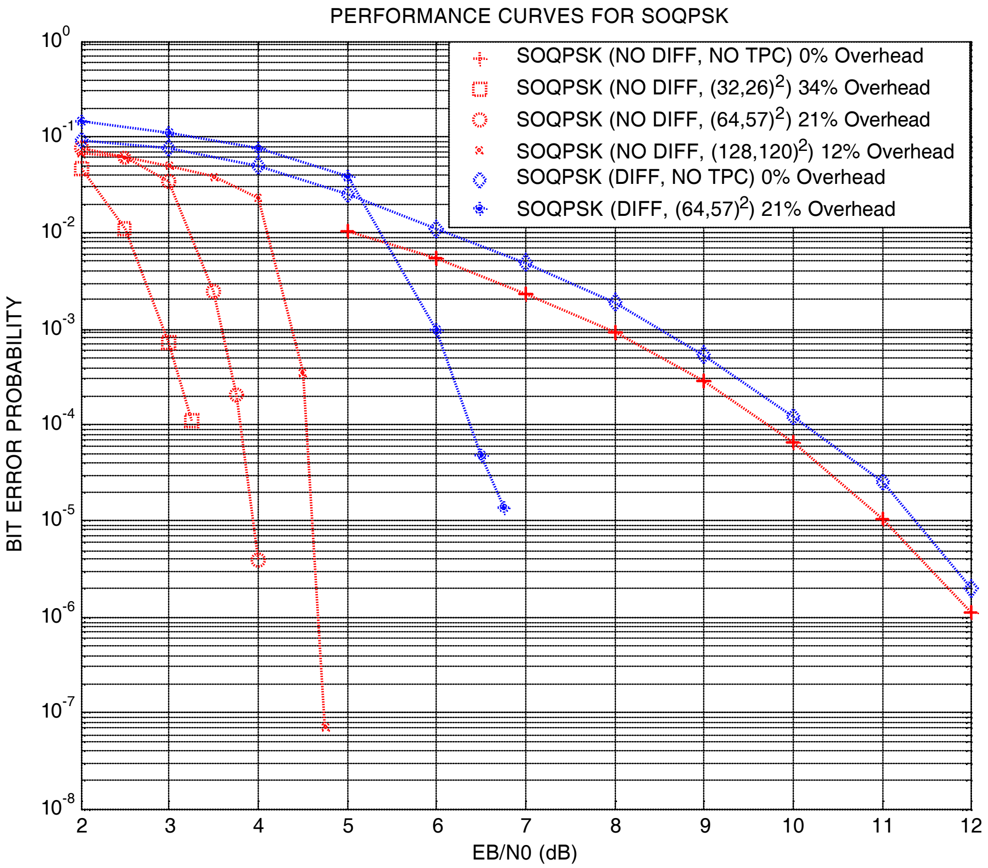

Figure 5. Performance of SOQPSK Systems
(Conventional, MSD, MSD+TPC(16 iterations per decode, 6 bit quantization))

At the time of this publication, the simulation results for CPM have not yet been completed.

HARDWARE SETUP

In order to evaluate the performance improvement that can be realized in practice, the following equipment was used to construct a communication link. A Rohde and Schwarz modulation generator was loaded with waveform samples corresponding to a TPC encoded test pattern modulated with PCM/FM, SOQPSK, or multi-h CPM. The 70 MHz IF analog signal was corrupted with additive noise and was demodulated using the Hypermod multi-mode demodulator. The recovered clock and soft decisions were passed to an AHA EVB4540 board containing the TPC decoder. Finally, the recovered clock and data output from the decoder was sent to a Fireberd 6000A error rate analyzer. The setup is shown below in Figure 6.

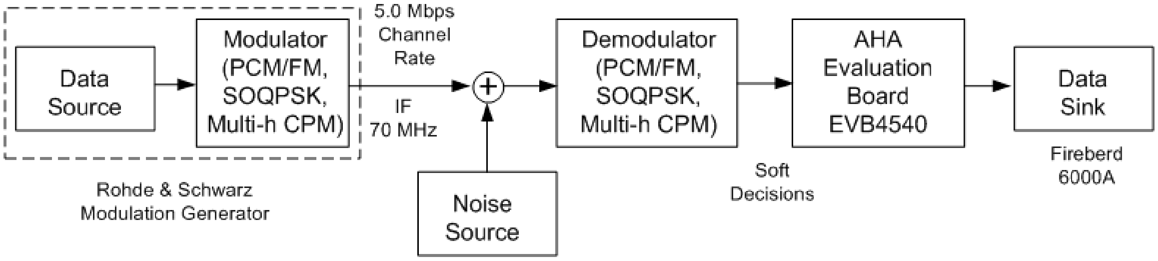

Figure 6. Configuration for Hardware Measurements

HARDWARE RESULTS

At the present time, only hardware results for PCM/FM and SOQPSK with TPC have been measured. These preliminary results indicate that SOQPSK is working very well and PCM/FM is not yet performing as expected. Optimization of the TPC parameters and the soft decision metrics for PCM/FM is expected to produce results closer to that of the computer simulation. Figure 7 shows the PCM/FM results which are approximately 2 dB worse than the simulation performance. This may be attributed to several causes: 1) optimization is not yet complete, 2) synchronization is not perfect as in the simulation, 3) only 4 bit soft-decisions can be used due to interfacing limitations of the evaluation board (8 were used in simulation). However, these results already demonstrate that at least 6 dB of improvement in detection efficiency (as compared to traditional equipment) can be obtained with the $(128,120)^2$ code that only requires 12% of bandwidth overhead.

Figure 8 shows the results for SOQPSK. Adding TPC improves the detection efficiency of non-differential encoded SOQPSK by at least 6 dB as compared to the non-TPC case with differential decoding. The improvement is a result of the TPC as well as being able to eliminate the differential encoding. It also appears that the overall system performance is currently limited by synchronization rather than the capability of the TPC code. Although the synchronization thresholds in the demodulator could be modified to extend the range, a trade-off in resynchronization time would likely be required. Again, this dramatic improvement can be obtained with only 12% of bandwidth overhead using the $(128,120)^2$ code .

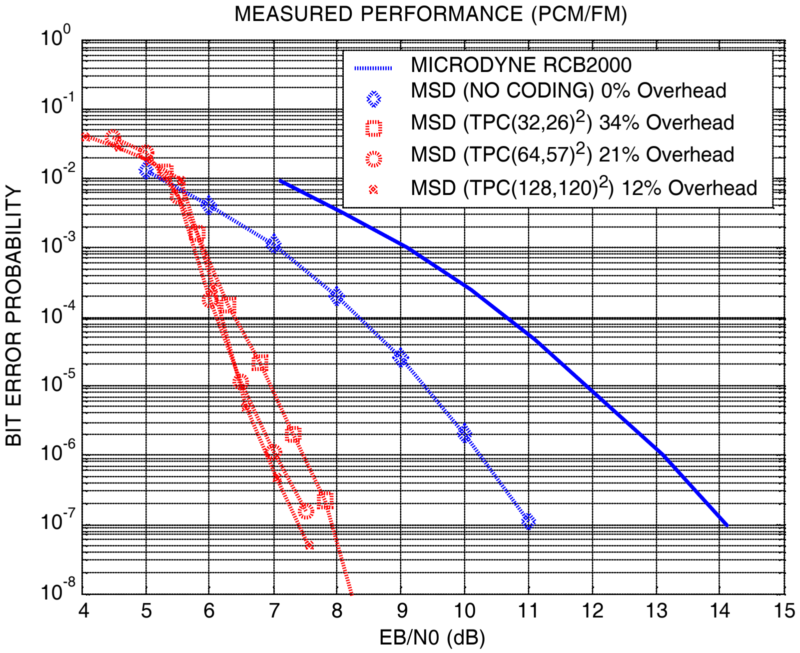

Figure 7. Current Hardware Results for PCM/FM

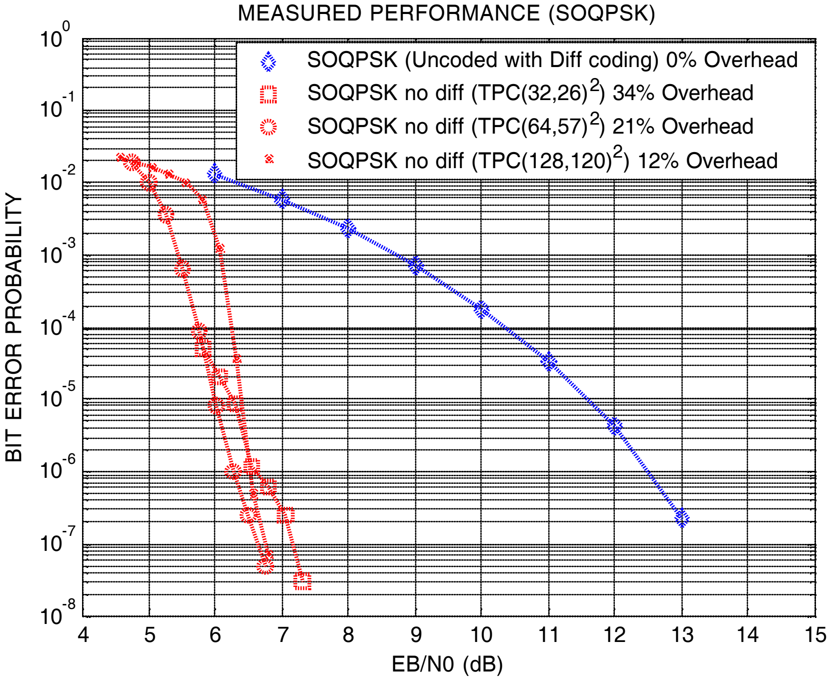

Figure 8. Current Hardware Results for SOQPSK

As mentioned above, no hardware results are yet available for multi-h CPM at this time.

CONCLUSIONS

Simulation and hardware results for PCM/FM and SOQPSK communication systems with turbo product coding have been presented. In PCM/FM, it was found that even without optimization and working under limitations of the evaluation board, the combination of the multi-symbol demodulator and the TPC outperformed a conventional demodulator by at least 6 dB in detection efficiency. For SOQPSK, an improvement of 6 dB was also observed. This was due to the TPC as well as being able to eliminate the need for differential encoding. It was noted that the current configuration was synchronization limited, and that further improvement may be gained through modifying the demodulator thresholds. Performance for both systems may also improve once the embedded TPC decoder is integrated in the demodulator thereby allowing full utilization of the AHA part.

This substantial increase in link margin can be used to extend the operating range, support higher data rates, or significantly improve the data quality. All of this is achieved with no increase in transmitter power or antenna gain. The price for this dramatic detection performance is a slight increase in transmitted bandwidth and the addition of encoding and decoding circuitry.

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