EXTENDING THE RANGE OF PCM/FM USING A MULTI-SYMBOL DETECTOR AND TURBO CODING

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ABSTRACT

It has been shown that a multi-symbol detector can improve the detection efficiency of PCM/FM by 3 dB when compared to traditional methods without any change to the transmitted waveform. Although this is a significant breakthrough, further improvements are possible with the addition of Forward Error Correction (FEC). Systematic redundancy can be added by encoding the source data prior to the modulation process, thereby allowing channel errors to be corrected using a decoding circuit. 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. This paper investigates the detection efficiency that can be achieved using a multi-symbol detector and turbo product coding. *The results show that this combination can improve the detection performance by nearly 9 dB relative to conventional PCM/FM systems*. The increase in link margin is gained at the expense of a small increase in bandwidth and the additional complexity of the encoding and decoding circuitry.

KEY WORDS

PCM/FM, Forward Error Correction, Turbo Coding, Range Extension

INTRODUCTION

Binary PCM/FM has been widely adopted as a standard by the telemetry community. It offers a reasonable balance between detection efficiency and spectral efficiency, with very simple implementation in both the transmitter and receiver. It was shown in [1] that the detection performance of PCM/FM could be improved by 3 dB using a multiple symbol demodulator as opposed to a traditional single-symbol detector. No change was required to the transmitter equipment. To address the need for improved data quality at longer ranges or higher throughputs, a system using a multi-symbol detector with turbo product coding will be investigated. The resulting system will use traditional PCM/FM for its robustness and existing logistical infrastructure and will provide a significant increase in link margin that can be used to either extend the range or enhance the data quality.

SYSTEM DESCRIPTION

Conceptual block diagrams of several PCM/FM communication systems are shown in Figure 1. First, a typical system that uses a conventional demodulator requires a nominal amount of bandwidth (1x) and an Eb/No of roughly 14 dB to achieve a bit error probability (BEP) of 10^{-7}. Next, by switching from a conventional to a Multi-Symbol Demodulator (MSD), 3 dB less Eb/No is required to achieve the same 10^{-7} BEP. Finally, a Turbo Product Code (TPC) encoder and decoder are added that can further reduce the Eb/No required to achieve a BEP of 10^{-7}. However, note that the transmitted bandwidth increases proportional to the amount of overhead created by the encoder. Several codes will be studied with overheads ranging from around 10 to 20 percent. The penalty for better detection performance with the TPC approach is a small increase in bandwidth along with the increased complexity of the encoder and decoder circuitry.

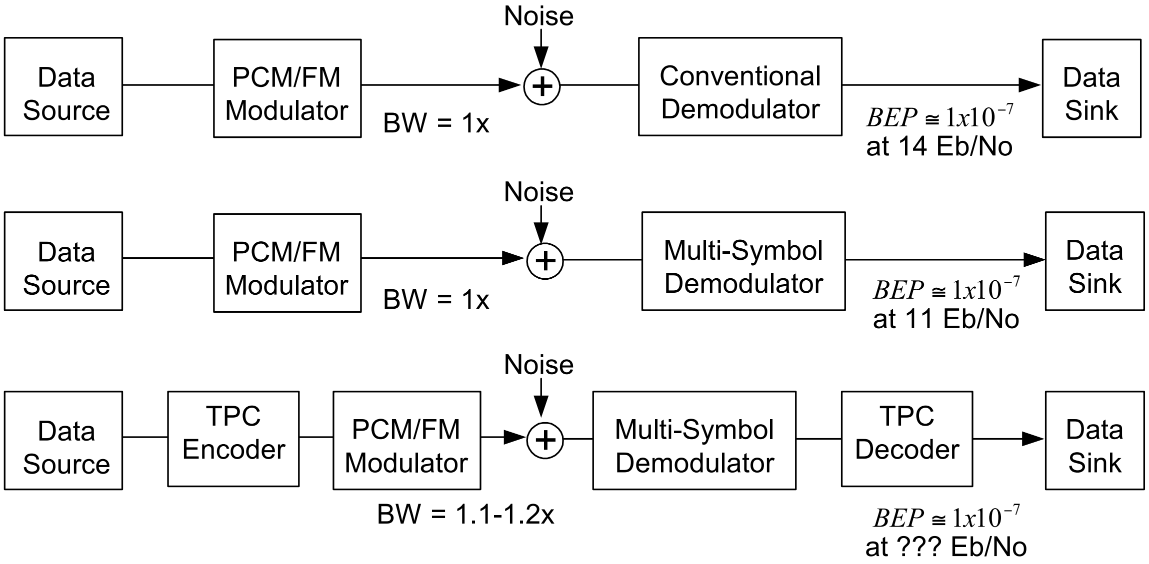

Figure 1. Possible PCM/FM Systems (Conventional, MSD, MSD + TPC)

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).

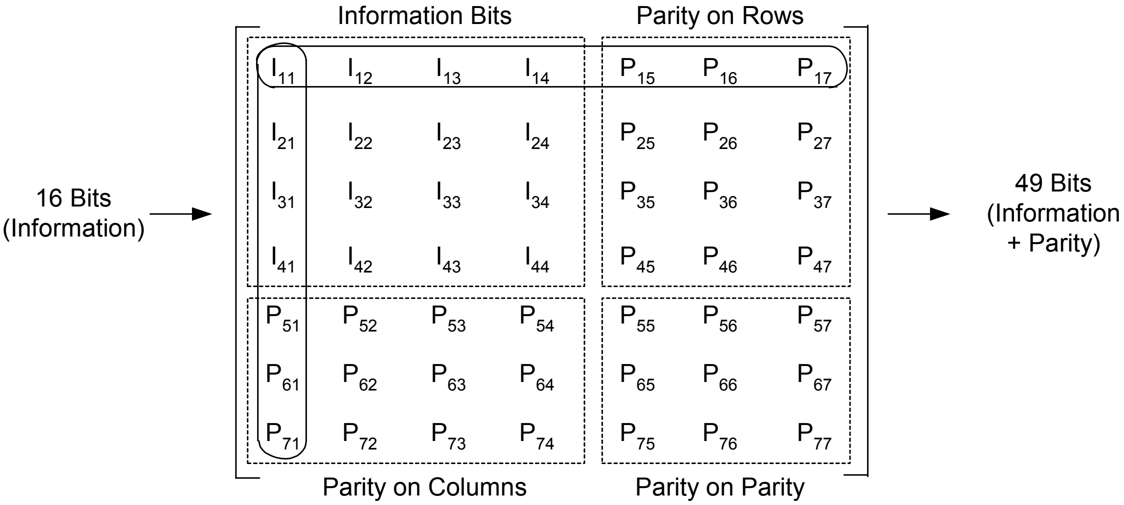

Figure 1. (7,4) x (7,4) Product Code Example

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. 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 with PCM/FM modulation in an additive white Gaussian noise (AWGN) channel with perfect synchronization.

SELECTION OF PRODUCT CODES

Since the next step of this research may be to develop a prototype system, only codes with a convenient hardware solution were investigated. Of particular interest are codes supported by the line of Turbo coding products from Advanced Hardware Architectures (AHA^{TM}). Codes that have large coding gains, overhead rates of approximately 10 to 20 percent, and can support multi-megabit data rates are very attractive for typical telemetry applications. Table 1 lists some of the codes supported by the AHA integrated circuits [2] and their projected performance with coherent BPSK for a AWGN channel at an error rate of 10^{-6} using a sufficient number of decode iterations. Some degradation can be expected using non-coherent PCM/FM instead of coherent BPSK.

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

SOFT DECISION APPROACHES

The decoder requires soft-decision inputs from the PCM/FM 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. A second approach for computing x(k) is to replace the max function with the mean function. In other words, the soft decision is based on the difference of the average magnitudes of the set of the '0' and '1' correlations. The 'mean' approach was determined via computer simulation to be inferior by at least 1 dB and was not considered further. The 'max' soft-decision method was used for the following simulation results.

SIMULATION RESULTS

This section presents simulation results for a PCM/FM multi-symbol detector with Turbo product coding. Figure 2 compares the BEP performance of a conventional and multi-symbol detector without coding to a system with a multi-symbol detector using three different product codes, namely a (64,57)x(64,57), (128,120)x(64,57), and (128,120)x(128,120). ***The Multi-Symbol detector with TPC improves the BEP performance by nearly 9 dB over the conventional system***. This dramatic increase in link margin can be used to extend the operating range of the system, support increased data throughput, or significantly enhance the data quality. The performance results for each system are summarized in Table 2. Figure 3 shows the slight increase in transmitted bandwidth necessary to support the coding overhead.

System Description	Eb/No (dB) required for 10^{-7} BEP	Req'd Bandwidth (Relative to uncoded case)	Code Rate	Block Size (Bits)	Detection Improvement (dB)
Conventional (uncoded)	14	1.0	1	-	Reference
Multi-Symbol (uncoded)	11	1.0	1	-	3
MSD+TPC (64,57)x(64,57)	5.25	1.26	0.793	4096	8.75
MSD+TPC (128,120)x(64,57)	5.125	1.198	0.835	8192	8.875
MSD+TPC (128,120)x(128,120)	5	1.137	0.879	16384	9

Table 2. Summary of PCM/FM System Results

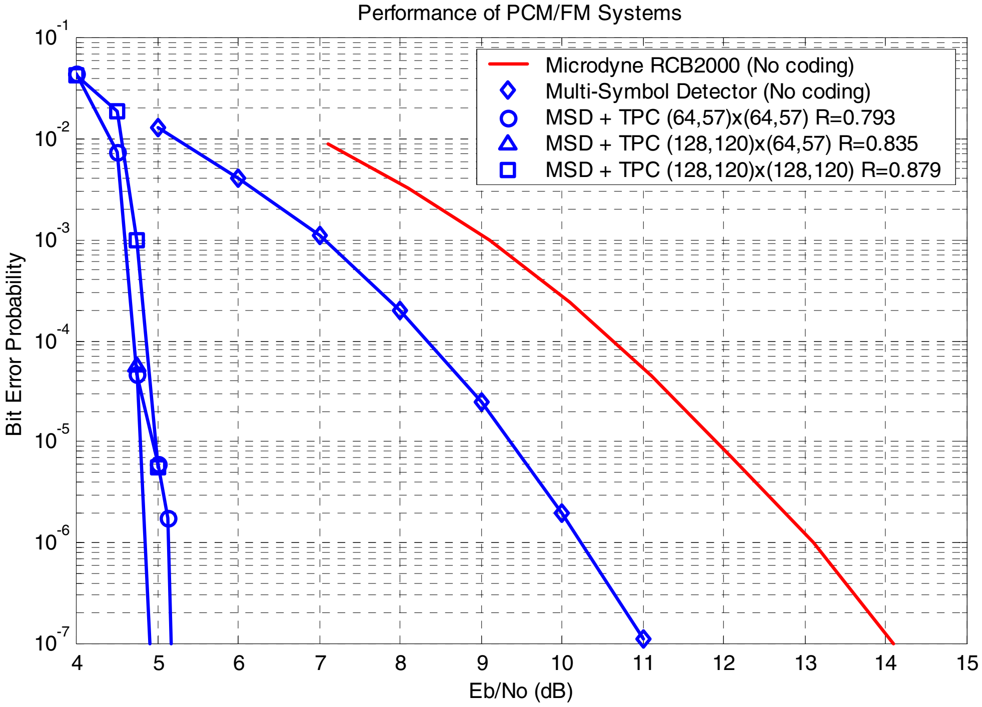

Figure 2. Performance of PCM/FM Systems
(Conventional, MSD, MSD+TPC(16 iterations per decode, 6 bit quantization))

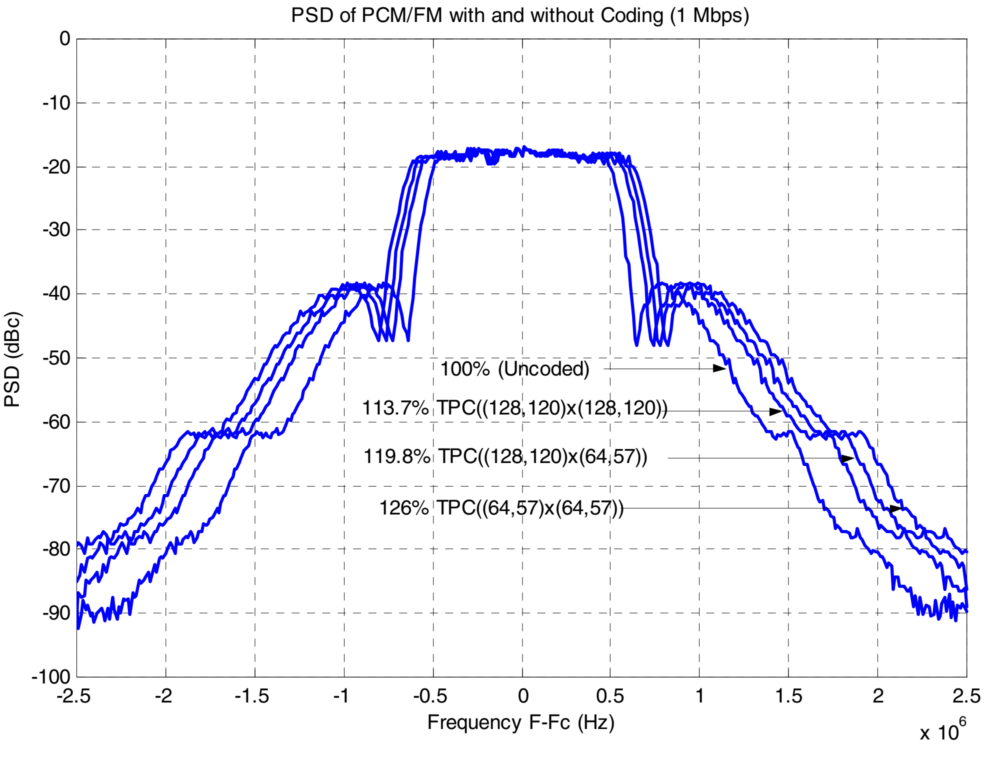

Figure 3. PSD of PCM/FM with and without Coding

In addition to the BEP and PSD performance, synchronization and latency are also important system issues. Synchronization of the TPC decoder can be achieved robustly and quickly without inserting any additional synchronization or framing overhead. Figure 4 illustrates a method of establishing the row and column codeword alignment required by the decoder. First, the row alignment is detected and used to construct possible column alignments. Column alignment, along with the row alignment, identifies the block alignment required by the TPC decoder.

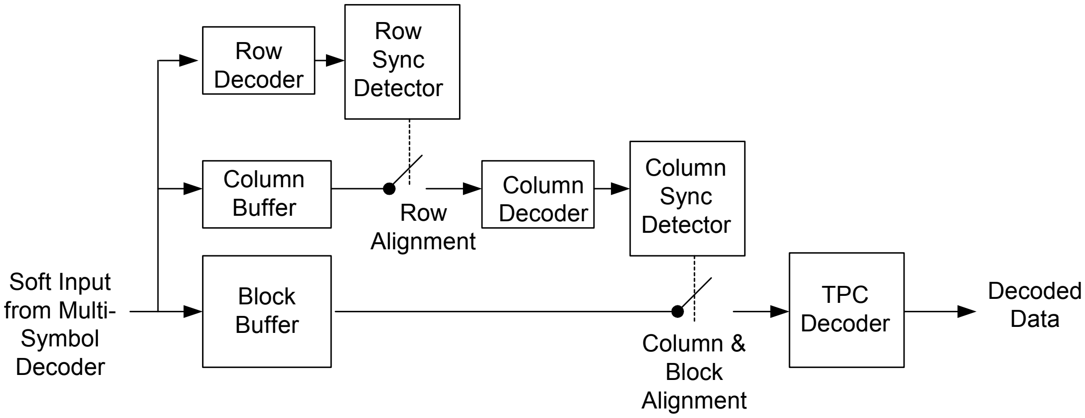

Figure 4. Block Diagram of TPC Decoder Synchronization

The latency of the encoding circuit can be made negligible (on the order of n-k bits) while the decoder latency will be approximately two and a half blocks ($2.5*n_1*n_2$) on average. This assumes that the reception will begin with a partial block, another block will be required for synchronization, and another block of latency will occur due to the decoding process itself. However, although the receive latency will be roughly 2.5 blocks, the only portion of the transmission that will be not be recovered is the initial partial block.

CONCLUSIONS

The performance results for a PCM/FM communication system using a multi-symbol demodulator with Turbo product coding has been presented. ***It was found that the combination of the Multi-Symbol detector and TPC outperformed a conventional demodulator by nearly 9 dB in detection efficiency. 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. Methods for generating suitable soft decision metrics and synchronizing the decoder were presented as well as estimates of the TPC encoder and decoder latency.

ACKNOWLEDGEMENTS

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REFERENCES

1. Geoghegan M.S., “Improving the Detection Efficiency of Conventional PCM/FM Telemetry by using a Multi-Symbol Demodulator”, Proceedings of the 2000 International Telemetry Conference, Volume XXXVI,675-682, San Diego CA, October 2000.

2. Advanced Hardware Architectures, Inc., “Product Specification AHA4540 Astro OC-3 155 Mbits/Sec Turbo Product Code Encoder/Decoder”, 2002.