TURBO-CODED APSK FOR TELEMETRY

Christopher Shaw and Michael Rice
424 Clyde Building
Brigham Young University
Provo, UT

ABSTRACT

This paper considers the use of Amplitude-Phase Shift Keying (APSK) for a telemetry system. Variable rate turbo codes are used to improve the power efficiency of 16- and 32-APSK. We discuss compensation techniques for power amplifier nonlinearities. Simulation results show the improved spectral efficiency of this modulation scheme over those currently defined in telemetry standards.

KEY WORDS

Turbo codes, amplitude-phase shift keying, spectral efficiency

INTRODUCTION

The classical tradeoff in a wireless communication system is between power efficiency, spectral efficiency, and complexity. The use of error-correcting codes improves power efficiency (coding gain) at the expense of decreased spectral efficiency and increased complexity [1]. Higher order modulation increases the size of the signal set to improve spectral efficiency but causes a decrease in power efficiency and requires greater complexity [2]. The designer of a telemetry system must consider the available power, bandwidth, and computational resources in order to satisfy constraints on bit rate and bit-error rate (BER).

Turbo codes have been an important focus of research since they were first proposed in [3] because they produce coding gains that approach the Shannon limit. Although the original design was based on the parallel concatenation of convolutional codes (PCCC) [4], serially concatenated convolutional codes (SCCC) have also been considered [5]. In addition, analysis and simulation have produced useful results in code design [4], [6], interleaver design [4], and puncturing [7].

Combining error-correction coding with higher order modulation has also been investigated. Ungerboeck first proposed a technique called trellis-coded modulation (TCM) in [8] in which codewords are mapped to signals in an expanded signal set. This technique provides coding gains to improve power efficiency but without a corresponding loss in spectral efficiency. Zehavi later proposed a simpler technique which came to be known as bit-interleaved coded modulation (BICM) and showed that this technique performs almost as well as TCM over an additive white Gaussian noise (AWGN) channel and outperforms TCM over a Rayleigh fading channel [9], [10]. This technique inserts an interleaver between the binary encoder and the signal mapper and uses soft detection at the receiver.

Amplitude-phase shift keying (APSK), recently included in the ETSI second generation Digital Video Broadcasting (DVB-S2) standard [11], is almost as spectrally efficient as corresponding quadrature amplitude modulation (QAM) constellations assigned to a square grid [12]. APSK also has the advantage of being more resilient to channel AM/AM and AM/PM nonlinearities since the constellation points lie on concentric circles [13].

In this paper we present a system for aeronautical telemetry that maps the output of a binary turbo encoder through BICM to a 16- or 32-APSK constellation and transmits over an AWGN channel. At the receiver we use a soft demodulator followed by an iterative decoder. Simulation results demonstrate the performance of this system which is compared to systems defined in the current ARTM Tier 0 and Tier 1 telemetry standards. The next section includes a high-level system overview. Afterwards, we define the error-correcting turbo code and corresponding encoder and decoder designs. We then discuss the APSK constellations used and specify the soft demodulator employed by the receiver. Simulation results are presented later and conclusions are drawn in the last section.

SYSTEM DESCRIPTION

A telemetry system is used to transmit data from a transmitter to a receiver. Our proposed system is illustrated in Figure 1. A stream of bits is input to the transmitter and passed to a rate k/n turbo encoder which adds redundancy to the bitstream by generating n output bits for every k input bits ($k/n < 1$). The output of the encoder is then permuted by a random interleaver. This permuted bit-stream is passed to the APSK modulator which divides the bits into blocks of 4 bits for 16-APSK or 5 bits for 32-APSK. Each block of bits is mapped to a signal in the 16- or 32-APSK signal set represented by the constellations shown in Figures 5 and 6 respectively. The signal is transmitted wirelessly over a channel to the receiver. For the purposes of this paper we assume that there is an additive white Gaussian noise (AWGN) channel between the transmitter and receiver.

At the receiver, the signal goes through a soft-demodulator. Rather than producing a maximum likelihood bit decision, the soft-demodulator generates a bit metric for each bit. For the ith bit, the

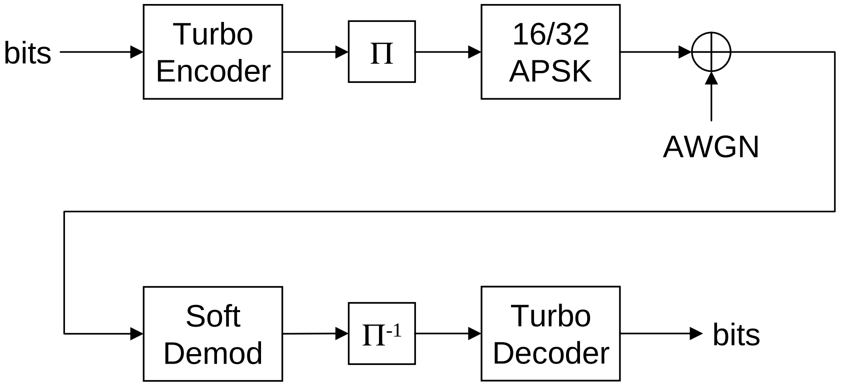

Figure 1: Block diagram of a turbo-coded APSK system.

demodulator calculates $p(r|b_i = 0)$ and $p(r|b_i = 1)$. These bit metrics are deinterleaved and fed into the turbo decoder which calculates an estimate of the transmitted bits. This illustrates the need for the bit-wise interleaver between coding and modulation. If a bad symbol is received, several consecutive bits may be corrupted at the output of the demodulator. After the deinterleaver, these bits are likely no longer adjacent and the decoder is more able to recover the corrupted data. This becomes even more important in the case of fading channels so that adjacent bits in the coded bitstream experience uncorrelated fades.

TURBO CODE

A turbo encoder based on the PCCC concept is illustrated in Figure 2. A single stream of bits is input to the encoder and three streams are produced at the output. The first output stream is a direct copy of the input stream. The second and third output streams are generated by recursive systematic convolutional (RSC) encoders. An example of an RSC encoder is shown in Figure 3. The code is called "recursive" because it includes a feedback path. Codes of this type are analogous to infinite impulse response (IIR) filters. It is called "systematic" because the input stream appears in the output stream as shown in Figure 2. The code is called "convolutional" because the encoder structure in Figure 3 looks like a filter.

The encoder shown in Figure 2 is a rate $1/3$ encoder. In other words, for every bit input to the encoder, three bits are output. The code rate can be increased by puncturing some of the output bits. In order to maintain the systematic nature of the code, only bits in the second and third streams can be punctured. For example, without puncturing, the output stream would be $\mathbf{v} = \{(v_0^0, v_0^1, v_0^2), (v_1^0, v_1^1, v_1^2), \ldots\}$. If the even blocks included only the second stream and odd

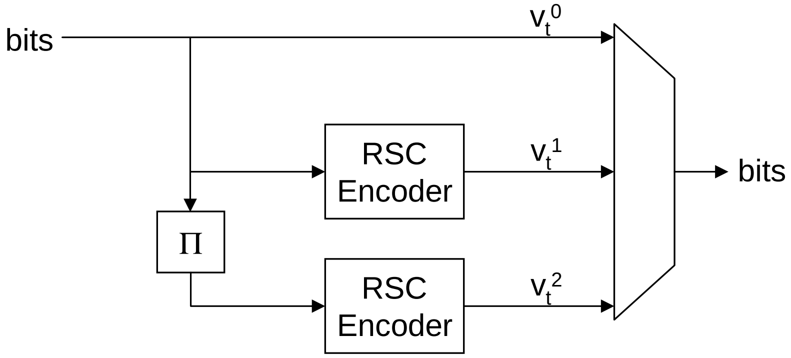

Figure 2: Block diagram of a turbo encoder.

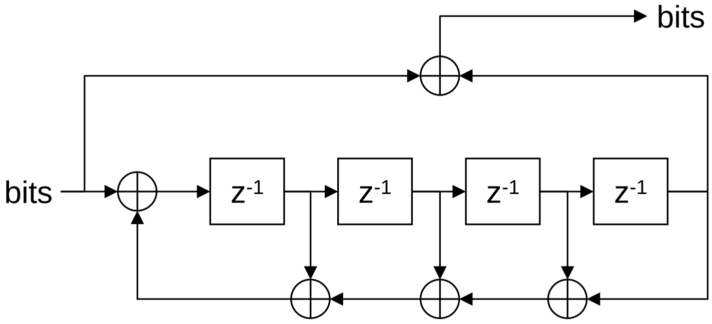

Figure 3: Block diagram of the RSC used in the turbo encoder.

blocks included only the third stream, the code rate would be $1/2$ and the output would be $\mathbf{v} = \{(v_0^0, v_0^1), (v_1^0, v_1^2), \ldots\}$. At the receiver, bit metrics can be inserted where bits have been punctured that assign equal likelihood to a 0 and a 1.

The decoder for a PCCC turbo code is shown in Figure 4. The decoder uses two maximum *a posteriori* (MAP) detectors based on the BCJR algorithm [14]. Each of the detectors computes an estimate of the transmitted bits and passes information back to the other. This process continues for a specified number of iterations. On the first iteration, the first MAP detector is given an initial prior distribution on the transmitted bits. Since the receiver does not have prior knowledge of the transmitted bits, the prior distribution is $p(b_t = 0) = p(b_t = 1) = 1/2$. The detector then calculates an estimate of the transmitted bits based on the first and second streams of bit metrics. Extrinsic

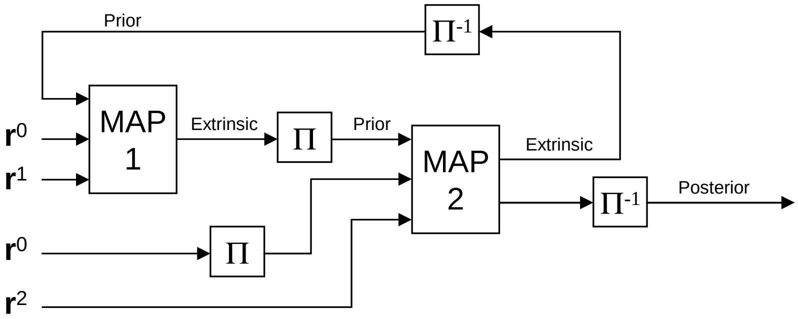

Figure 4: Block diagram of a turbo decoder.

information derived from the code is then used as an initial prior distribution for the second MAP detector. The second MAP detector then calculates an estimate of the transmitted data based on this prior distribution and the first and third streams of bit metrics. This detector then passes the extrinsic information to the first MAP detector as a new prior distribution. After the specified number of iterations has passed, the second MAP detector computes a posterior probability for each transmitted bit given the entire received signal, $p(b_i = 0|\mathbf{r})$ and $p(b_i = 1|\mathbf{r})$.

By introducing redundancy into the transmitted bitstream, the receiver can recover data that has been corrupted by noise. Thus, the system can achieve a given BER with a lower signal-to-noise ratio (SNR) than an uncoded system. However, there is a corresponding rate loss because more coded bits must be transmitted than the uncoded information bits. Various coding gains and rates can be achieved using different puncture patterns. These turbo codes can greatly improve the power efficiency of the APSK modulation used in our telemetry system.

AMPLITUDE-PHASE SHIFT KEYING

Amplitude-phase shift keying was proposed in [12] for use in a satellite communication system due to its increased spectral efficiency over phase shift keying (PSK). It has also been shown that APSK is well-suited for use over a nonlinear satellite channel [12], [13]. Since all of the constellation points lie on concentric circles (see Figure 6), the transmitter may pre-compensate for the power amplifier AM/AM and AM/PM nonlinearities. In this paper, we leave pre-compensation to future study and use only a constant back off at the transmitter to drive the power amplifier in a linear range. We show in our results section that this is an appropriate technique.

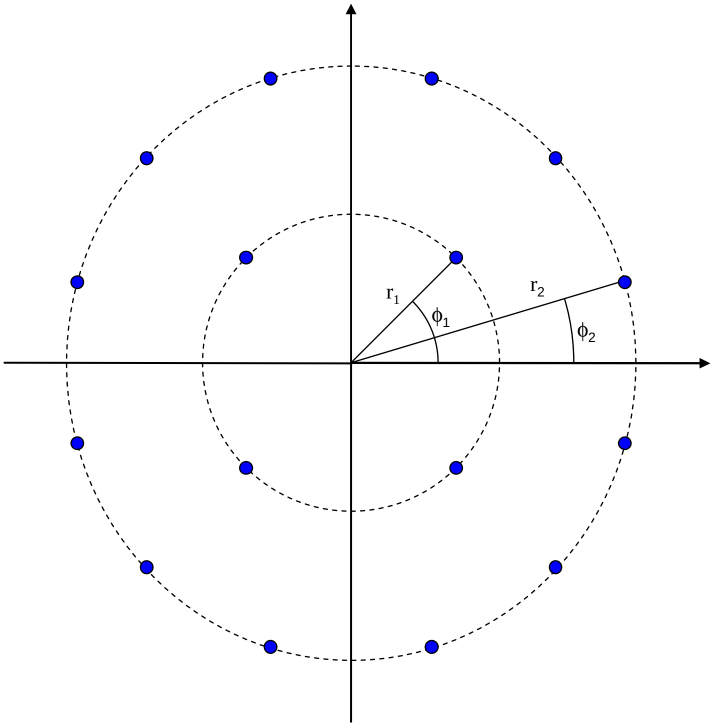

Figure 5: 16-APSK constellation as defined in [11].

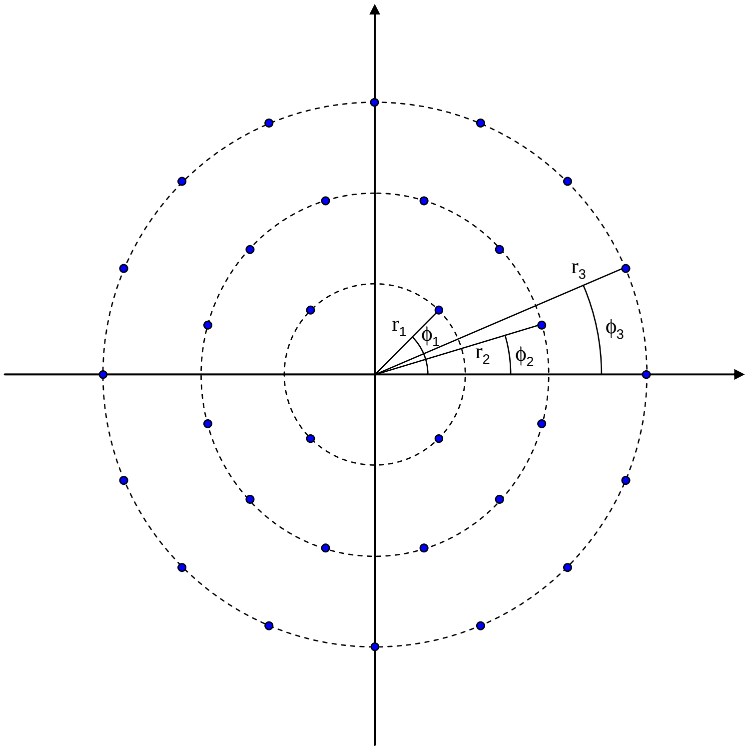

Figure 6: 32-APSK constellation as defined in [11].

The receiver in our telemetry system uses a soft-demodulator as discussed previously. A typical maximum-likelihood hard decision detector for APSK uses a filter matched to the pulse shape to project the received signal onto the signal space spanned by the APSK signal set. This projection can be represented by a point on Figure 6. The maximum-likelihood detector would then find which constellation point is closest in Euclidean distance to the received point and output the bits corresponding to that signal. However, the turbo decoder performs much better if it is given a stream of bit metrics rather than hard bits. The bit metrics must be calculated by a soft-demodulator as $p(r|b_i = 0)$ and $p(r|b_i = 1)$. Since we assume the channel adds Gaussian noise, we can calculate the density function given that the symbol s_j was transmitted, $p(r|s_j)$, by using the constellation point for s_j as the mean in the Gaussian pdf. In order to calculate $p(r|b_i = 0)$ the demodulator must add together $p(r|s_j)$ for all s_j that have a zero in the ith position. Similarly, $p(r|b_i = 1) = \sum_{s_j \in A_i^1} p(r|s_j)$ where A_i^1 is the set of constellation points that have a one in the ith position.

For our telemetry system, we use a pseudo-Gray mapping to assign blocks of bits to APSK constellation points as defined in [11]. For the 16-APSK constellation shown in Figure 5, we let $\rho = r_2/r_1 = 2.57$, $\phi_1 = \pi/4$, and $\phi_2 = \pi/12$ also as defined in [11]. Similarly, for the 32-APSK constellation shown in Figure 6, we let $\rho_1 = r_2/r_1 = 2.53$, $\rho_2 = r_3/r_1 = 4.30$, $\phi_1 = \pi/4$, $\phi_2 = \pi/12$, and $\phi_3 = \pi/8$.

RESULTS

We have simulated the performance of our proposed telemetry system using both 16- and 32-APSK and various turbo code rates. For our simulations, we use blocks of 10000 bits with the same size random interleaver in the turbo encoder. The RSC used is the 16-state code shown in Figure 3. The BICM interleaver is also randomly generated but the interleaver size depends on the code rate. The turbo decoder runs for 10 iterations. We use a rate-compatible puncture pattern to achieve code rates of $1/3$, $1/2$, $2/3$, $3/4$, $4/5$, $7/8$, and $8/9$. For each of our simulations, we generate 500 blocks of 10000 bits and measure the BER performance at several different SNRs.

For each code rate and each APSK modulation, we find what SNR is necessary to achieve a BER of less than 10^{-6}. This is a measure of the power efficiency of the system. The spectral efficiency of the system is $\frac{k}{n}\frac{log_2(M)}{(1+\alpha)}$ where $\frac{k}{n}$ is the code rate, M is 16 or 32, and α is the excess bandwidth parameter for the square-root raised cosine (SRRC) pulse shape. These two values are used to create a point on a spectral efficiency plot. Figure 7 shows the spectral efficiency of several uncoded linear modulations, the current telemetry standards, and turbo coded 16-APSK. Figure 8 is similar but with turbo coded 32-APSK.

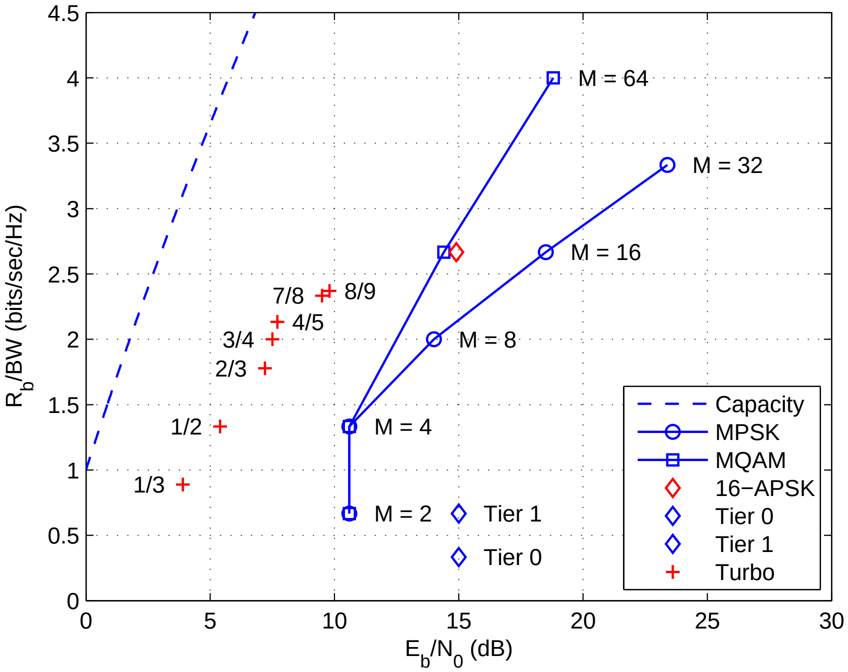

Figure 7: Spectral efficiency of various uncoded modulations and turbo coded 16-APSK.

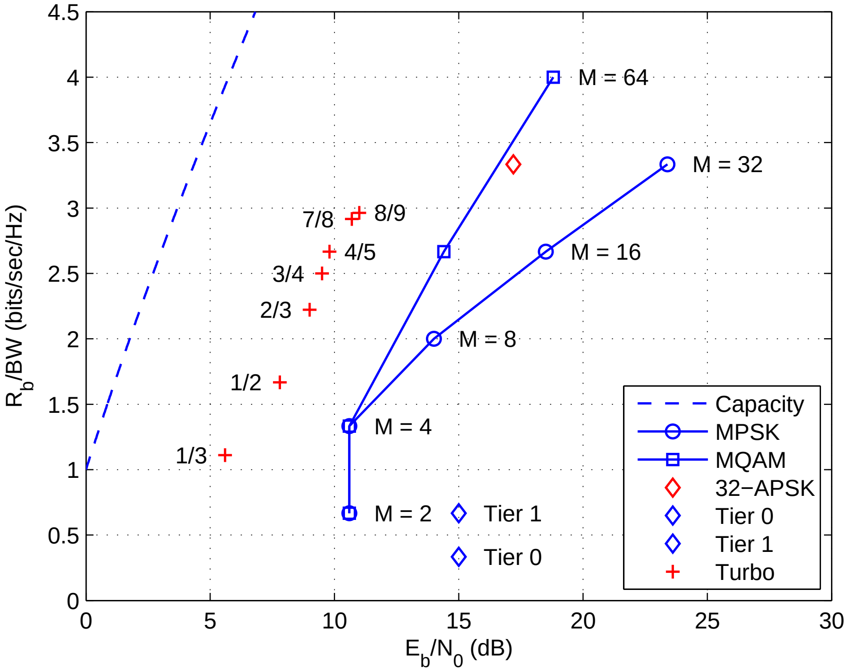

Figure 8: Spectral efficiency of various uncoded modulations and turbo coded 32-APSK.

In order to make a fair comparison between our proposed system and the current telemetry standards, we need to consider power amplifier nonlinearity. The constant envelope modulations used in the ARTM Tier 0 and Tier 1 standards are not affected by a nonlinear channel like the linear APSK modulation is. Whereas current telemetry systems can drive the transmit power amplifier at saturation, doing so with APSK would introduce significant distortion and bandwidth increase to the transmitted signal. As mentioned previously, we will only consider using a constant back off to compensate for amplifier nonlinearity. For example, if a specific amplifier is measured to be mostly linear if the transmitter backs off 6 dB, we can model this by shifting all of the points in Figure 8 to the right by 6 dB except those labeled Tier 0 and Tier 1. Notice that the point representing 32-APSK with a rate $2/3$ turbo code is moved from 9 dB to 15 dB, the same power efficiency as Tier 0 and Tier 1. However, the spectral efficiency of this modulation is more than three times greater than the current telemetry standards. In other words, for the same bandwidth constraint, turbo coded APSK can more than triple the bit rate of a telemetry system. Depending on the power amplifier characteristics, we can back off by a different amount and use a different rate turbo code to achieve the same power efficiency but much greater spectral efficiency than techniques defined in the current ARTM standards.

CONCLUSIONS

It is well known that high-order linear modulations are spectrally more efficient than the ARTM Tier 0 and Tier 1 standards. However, Tier 0 and Tier 1 are immune to the effects of a nonlinear power amplifier while linear modulations such as APSK are not. To compensate for the amplifier nonlinearity, a telemetry system using linear modulation must back off in order to drive the power amplifier in a linear region. This causes a loss in the power efficiency of the system. We have demonstrated that error-correcting turbo codes can recover the lost power efficiency. Our system, which uses a turbo coded APSK modulation, significantly outperforms the modulations defined in ARTM standards. For the same BER, power efficiency, and bandwidth, our system can achieve at least a three times increase in bit rate. Specific results may be calculated for each power amplifier with models of AM/AM and AM/PM nonlinearities.

REFERENCES

[1] S. B. Wicker, *Error Control Systems for Digital Communication and Storage*, Prentice Hall, 1995.

[2] J. G. Proakis, *Digital Communications*, fourth ed., McGraw-Hill, 2001.

[3] C. Berrou, A. Glavieux, and P. Thitimajshima, “Near Shannon limit error-correcting coding and decoding: Turbo-codes,” in *Proceedings of the IEEE International Conference on Communications*, May 1993, pp. 1064–1070.

[4] S. Benedetto and G. Montorsi, “Design of parallel concatenated convolutional codes,” *IEEE Transactions on Communications*, vol. 44, May 1996, pp. 591–600.

[5] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, “Serial concatenation of interleaved codes: Performance analysis, design, and iterative decoding,” *IEEE Transactions on Information Theory*, vol. 44, May 1998, pp. 909–926.

[6] S. Benedetto, R. Garello, and G. Montorsi, “A search for good convolutional codes to be used in the construction of turbo codes,” *IEEE Transactions on Communications*, vol. 46, September 1998, pp. 1101–1105.

[7] Ömer F. Açıkel and W. E. Ryan, “Punctured turbo-codes for BPSK/QPSK channels,” *IEEE Transactions on Communications*, vol. 47, September 1999, pp. 1315–1323.

[8] G. Ungerboeck, “Channel coding with multilevel/phase signals,” *IEEE Transactions on Information Theory*, vol. IT-28, January 1982, pp. 55–67.

[9] E. Zehavi, “8-PSK trellis codes for a Rayleigh channel,” *IEEE Transactions on Communications*, vol. 40, May 1992, pp. 873–884.

[10] G. Caire, G. Taricco, and E. Biglieri, “Bit-interleaved coded modulation,” *IEEE Transactions on Information Theory*, vol. 44, May 1998, pp. 927–946.

[11] “Digital video broadcasting; second generation framing structure, channel coding and modulation systems for broadcasting, interactive services, news gathering, and other broadband satellite applications (DVB-S2).” European Telecommunications Standards Institute, Std. 302 307, 2006.

[12] C. M. Thomas, M. Y. Weidner, and S. H. Durrani, “Digital amplitude-phase keying with M-ary alphabets,” *IEEE Transactions on Communications*, vol. COM-22, February 1974, pp. 168–180.

[13] R. De Gaudenzi, A. Guillén i Fàbregas, and A. Martinez, “Performance analysis of turbo-coded APSK modulations over nonlinear satellite channels,” *IEEE Transactions on Wireless Communications*, vol. 5, September 2006, pp. 2396–2407.

[14] L. R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, “Optimal decoding of linear codes for minimizing symbol error rate,” *IEEE Transactions on Information Theory*, vol. 20, March 1974, pp. 284–287.