Comparison between Analog Joint Source-Channel Coded and Digital BICM Systems

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Abstract—Recently, the use of analog joint source-channel coding for the transmission of data samples at high rates has been proposed in the literature. Simulation results have shown that when using this analog scheme over AWGN channels, its performance is close to the theoretical capacity limits for several source distributions and transmission rates. In this paper we study the performance of such a system in comparison with optimized capacity approaching digital Bit Interleaved Coded Modulation (BICM) schemes. We show that the analog transmission performs better than the digital scheme with a much lower encoding and decoding complexity when considering Gaussian and Laplacian source distributions.

I. INTRODUCTION

A digital communication system based on separation between source and channel coding is optimal for information transmission along many channels such as the Additive White Gaussian Noise (AWGN) channel [1]. However, these systems present some disadvantages when they are implemented in practical applications. First, their complexity increases considerably when we try to reach a performance close to the Shannon capacity limit. Also, a full redesign of the digital system is required whenever we want to change the code rate or the distortion target. Moreover, digital systems introduce significant delays due to the long block lengths required to approach the theoretical limits, and they experience a non-graceful degradation when the channel quality decreases.

Analog communications based on the transmission of continuous amplitudes in discrete-time is an interesting alternative to digital systems that overcomes these limitations. It is well known that analog communications are optimal under some circumstances. For instance, the optimal way to transmit samples from a Gaussian source over an AWGN channel is the direct transmission of the uncoded Gaussian samples [2]. Recently, several works [3]–[6] have focused on studying analog communications to find an efficient way to encode the analog samples and transmit the resulting encoded symbols over an AWGN channel at different rates. These analog joint source-channel coding schemes perform analog compression at the symbol level and, thus, no delays are introduced. They also exhibit very low encoding complexity, making them very attractive for practical implementations. However, up to the authors knowledge, there are no studies comparing these analog schemes with capacity approaching digital signaling schemes in order to quantify the advantages of the former with respect to the latter.

In this paper we make a comparison study between analog joint source-channel coded systems and optimized capacity approaching digital Bit Interleaved Coded Modulation (BICM) schemes. The aim is to quantify the performance gain of the analog system in order to determine under which circumstances it is more convenient to use each communication setup. We measure the performance of both analog and digital systems in terms of Signal-to-Distortion Ratio (SDR) versus Channel Signal-to-Noise Ratio (CSNR) when Gaussian and Laplacian distributed sources are transmitted. Notice that Gaussian and Laplacian sources are of interest for reasons beyond their theoretical significance. In fact, images represented in transform domains (e.g., wavelets) can be accurately modeled using these distributions, which makes the analog joint source-channel coding system very relevant for image communications [7].

The paper is organized as follows. In Section II we describe an analog system that uses a type of parameterized spirals to encode the source samples and provides high transmission rates. Section III focuses on digital BICM systems while its design and optimization to approach capacity is addressed in Section IV. The performance of the analog and digital systems is compared in Section V. Finally, Section VI contains the conclusions.

II. ANALOG JOINT SOURCE-CHANNEL CODED SYSTEM

We consider the analog transmission of discrete-time continuous-amplitude sources over an AWGN channel. At the transmitter, $N$ independent and identically-distributed (i.i.d.) source symbols are encoded into $K$ channel symbols. Such symbols are transmitted through an AWGN channel with noise variance $\sigma^2$. At the receiver, the symbols are recovered using either Maximum Likelihood (ML) or Minimum Mean Square Error (MMSE) decoding. Due to its better performance [6], MMSE decoding will be chosen in this work.

The distortion between source symbols $X = \{x_i\}_{i=1}^N$ and decoded symbols $\hat{X} = \{\hat{x}_i\}_{i=1}^N$ is calculated according to the
MSE, defined as
\[
\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} ||x_i - \hat{x}_i||^2.
\]
Consequently, the system performance can be measured in terms of the output Signal-to-Distortion Ratio (SDR) with respect to the CSNR, with SDR defined as
\[
\text{SDR} = 10 \log \left( \frac{1}{\text{MSE}} \right),
\]
where the source symbols are normalized to unit mean power.

Given \( N \) and \( K \), the Optimum Performance Theoretically Attainable (OPTA) is calculated by equating the rate distortion function to the AWGN channel capacity [8]. For example, for Gaussian sources we have
\[
N \log \left( \frac{1}{\text{MSE}} \right) = K \log \left( 1 + \frac{1}{\sigma_n^2} \right),
\]
where it is assumed unit transmit power.

Figure 1 shows the block diagram of an \( N:1 \) analog joint source-channel coding system where the source generates blocks of \( B \) i.i.d. symbols that are encoded into \( B/N \) channel symbols. In this paper, we focus on memoryless Gaussian and Laplacian sources.

A particular type of parameterized space-filling continuous curves, called spiral-like curves [3]–[5], can be used to encode the \( X = (x_1, x_2) \) source samples. For the case of 2:1 compression (i.e., \( N = 2 \)), they are formally defined as
\[
\begin{align*}
    x_{\theta,1} &= \frac{\alpha}{\pi} \theta \sin \theta \\
    x_{\theta,2} &= \frac{\Delta}{\pi} \theta \cos \theta
\end{align*}
\]
for \( \theta \in \mathbb{R} \), where \( \Delta \) is the distance between two neighboring spiral arms, and \( \theta \) is the angle from the origin to the point \( X_\theta = (x_{\theta,1}, x_{\theta,2}) \) on the curve. Therefore, each pair of source samples, \( x_1 \) and \( x_2 \), represent a specific point in \( \mathbb{R}^2 \) that is matched to the closest point \( X_\theta = (x_{\theta,1}, x_{\theta,2}) \) on the spiral. The angle from the origin to that point on the spiral, \( \theta \), will be the channel symbol for \( x_1 \) and \( x_2 \), i.e.,
\[
\hat{\theta} = M_\Delta(X) = \arg \min_\theta \left\{ (x_1 \pm (\Delta/\pi) \theta \sin \theta)^2 + (x_2 - (\Delta/\pi) \theta \cos \theta)^2 \right\}.
\]
These curves were proposed for the transmission of Gaussian sources over AWGN channels [5]. Laplacian sources can be either mapped directly to the curves or transformed to Gaussian prior to the mapping. Results obtained with both approaches show a similar performance in terms of SDR [6], so we will focus on direct mapping.

Since our goal is the minimization of the MSE, the bi-dimensional space has to be filled by the spiral in the best possible way for every CSNR value. On one hand, by changing the \( \Delta \) value, we manage to optimize this matching and to improve the system performance. On the other hand, it is possible to achieve higher compression rates (i.e. \( N:1 \)) by extending (1) to generate more complex curves [9], [10].

The next step consists in defining an invertible function of \( \hat{\theta} \) — with the corresponding normalization factor to ensure the transmit power constraint. In [3], [5], [11], the invertible function \( T_\alpha(\hat{\theta}) = \text{sign}(\hat{\theta})|\hat{\theta}|^\alpha \), with \( \alpha = 2 \), was proposed. However, as shown in [6], the system performance can be improved if \( \alpha \) and \( \Delta \) are numerically optimized for each different CSNR value. Therefore, the channel symbol is \( T_\alpha(\hat{\theta})/\sqrt{\gamma} \), where \( \sqrt{\gamma} \) is the normalization factor. In summary, the received symbol \( y \) at the decoder can be expressed as
\[
y = T_\alpha(M_\Delta(X)) + n\sqrt{\gamma},
\]
where \( n \) is Gaussian noise.

Given a received symbol \( y \), MMSE decoding is performed at the receiver to calculate an estimation of the corresponding source symbol. Optimal MMSE decoding can be expressed as
\[
\hat{X}_{\text{MMSE}} = E\{X|y\} = \int X p(X|y) dX = \frac{1}{p(y)} \int X p(y|X)p(X) dX,
\]
where the mapping function \( M_\Delta(\cdot) \) is used to obtain the conditional probability \( p(y|X) \). Note that the integral in (2) can only be calculated numerically because \( M_\Delta(\cdot) \) is discontinuous and highly non-linear. To do so, \( X \) is first discretized using a uniform step and a mapped value is calculated for each discretized point according to (1). As a result, we obtain a discretized version of \( p(y|X) \). Next, \( p(X) \) is also computed for each point and, hence, the calculation of the integral reduces to multiplicative and additive operations. Since this discretization does not depend on the received symbol, it is calculated once off-line and stored in the decoder.

Although in this paper we focus on 2:1 systems, the proposed system can be readily modified to adapt the compression rate from \( N:1 \) to \( N:K \) [12].
III. Bit Interleaved Coded Modulation (BICM)

Trellis Coded Modulation (TCM) [13] and Bit Interleaved Coded Modulation (BICM) [14], [15] are the two most prominent examples of digital transmission schemes using coded modulation. Both are capable of approaching the Shannon capacity limit over the AWGN channel. In this work we have chosen BICM as a capacity approaching representative digital transmission scheme because of its larger simplicity and lower complexity. In addition, BICM outperforms TCM when transmitting over Rayleigh channels.

Figure 2 shows the block diagram of a digital BICM system. We assume a discrete-time source that produces Gaussian and Laplacian independent and identically distributed (i.i.d.) real-valued analog symbols $X_n$. These continuous samples are mapped to a discrete set of values using an optimum $Q$-level scalar quantizer. Both, the quantization levels and the partition regions can be obtained using the well-known Lloyd-Max algorithm [16], [17]. Although better performance could be obtained with vector quantization, we discarded this possibility to keep the overall quantizing complexity at a low level.

Next, the quantized discrete-time symbols are converted into a binary representation using a suitable source encoder. Again, among the many existing source encoding methods, we decided to use Huffman encoding because it is a simple algorithm and approaches the source entropy. The input alphabet to the Huffman encoder is made up of the $Q$-levels of the scalar quantizer, i.e., no grouping is performed prior to the encoding. The length of the average Huffman codeword used to represent each source sample will be denoted by $L_m$.

The output bit sequence is encoded with a rate $r$ capacity-approaching channel encoder. Due to their low encoding and decoding complexity, we decided to use Irregular Repeat Accumulate (IRA) codes [18].

Finally, the channel encoded bits are modulated using a real-valued $M$-PAM constellation and Gray mapping. Notice that an interleaver between the channel encoder and the modulator is not strictly necessary since we are transmitting over an AWGN channel. A one-dimensional PAM constellation has been chosen to keep the same signaling as the analog system in Section II where real analog encoded symbols are transmitted. The constellation size $M$ limits the maximum attainable data rate over the channel. We chose the value $M = 256$ which allows the transmission of a maximum of 8 bits per channel use, a transmission rate high enough for the comparison carried out in the ensuing section. Higher values of $M$ could be used but they yield to extremely complex PAM constellations that are not feasible in practice.

At the receiver, an optimum detector calculates the LLRs of the transmitted bits and passes them to the sum-product IRA decoding algorithm. After a maximum number of decoding iterations, the resulting bits are hard-decoded and dequantized to the corresponding levels.

IV. BICM System Design

Let us consider a 2:1 analog joint source-channel coding transmission system. In this practical setup, two source samples are encoded into one channel symbol and transmitted in one channel use. In the digital system, each source sample is quantized with a $Q$-level quantizer and represented with a codeword whose average length is $L_m$. Thus, $2L_m$ source bits are used to represent the two source samples. The digital system is designed in such a way that the information rate is less than the channel capacity so that no errors occur during the transmission. Thus, the SDR is determined by the number of quantization levels, $Q$.

When transmitting over an AWGN channel, the CSNR should be high enough so that the channel capacity is higher than the data rate. Two different expressions of the AWGN channel capacity will be used in this work: the unconstrained channel capacity that assumes Gaussian input symbols and the constrained channel capacity that takes into account that the channel symbols are modulated with a PAM constellation. In the digital system, the information data rate is $2L_m$ bits per channel use, so that the number of channel uses is the same as in the analog scheme. Thus, it is easy to obtain the minimum CSNR necessary to achieve an error-free transmission since both the unconstrained and constrained capacity limits are known for the AWGN channel. Notice that the minimum CSNR necessary to achieve the constrained channel capacity is slightly higher than that of the unconstrained one because the mutual information over an AWGN channel is maximized when the input is Gaussian.

The digital system uses a $M = 256$ PAM constellation, i.e., 8 bits per channel use. If $2L_m < 8$, an error-free transmission over an AWGN channel is possible provided the channel SNR is high enough. Moreover, there is room enough to introduce redundant channel bits that are necessary to achieve the channel capacity. Notice that in order to keep the same number of channel uses as in the analog scheme ($2L_m/8r = 1$), the rate of the channel encoder should be $r = L_m/4$ which, in turn, depends on the number of quantization levels, $Q$, and, hence, on the target SDR. This means that in the digital transmission system a different channel encoder should be used each time the target SDR is changed.

In a practical system, a rate $r = L_m/4$ channel encoder capable of approaching the capacity of an AWGN channel should be designed. Such a channel encoder can be optimized using EXtrinsic Information Transfer (EXIT) analysis [19]. In particular, we have optimized IRA codes for certain rates and obtained their threshold values, i.e., the minimum CSNR necessary for the IRA codes to correct all channel errors. The maximum variable and check node degrees were limited to 100 and 12, respectively, in order not to increase the decoding complexity excessively. These threshold values are higher than those obtained from the channel capacity because practical IRA codes always incur in some performance losses.

Tables I and II show the parameters of the resulting BICM digital transmission systems designed for Gaussian and Laplacian sources, respectively. The first column of Tables I and II contains the number of scalar quantization levels, $Q$. The second column is the SDR provided by the optimum MMSE Lloyd-Max scalar quantizer. The third column shows the
TABLE I

PARAMETERS OF A 2:1 DIGITAL BICM SYSTEM WITH GAUSSIAN SOURCES, SCALAR QUANTIZATION, Huffman source coding, IRA CHANNEL CODING AND 256-PAM MODULATION, SDR, Capacities and Thresholds in dB.

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resulting entropy after quantization while the fourth column shows the average length values obtained when the sources are Huffman encoded. The fifth column is the channel encoder rate allowed by the 256-PAM modulator. The sixth and seventh columns are the minimum CSNR necessary to achieve the unconstrained and constrained channel capacity, respectively. Since we employ Gray mapping, the BICM capacity corresponds to the symbol-wise mutual information [15]. Finally, the eighth column shows the threshold values obtained when using a practical IRA code.

It should be noticed that other BICM digital transmission systems could be designed with different modulation levels and channel code rates, specially for the case of low number of quantization levels, $Q$. For instance, if an $M = 64$ PAM constellation is used, information transfer is feasible as long as $2L_{in} < 6$. This channel information rate limit forces the maximum achievable SDR value to be $14.617$ dB ($Q = 8$) for Gaussian sources and $14.372$ dB ($Q = 10$) for Laplacian sources. In addition, the rate of the channel encoder should be changed now to $r = L_{in}/3$. Nevertheless, since the constrained capacities for 64 and 256 PAM are very similar in the low SNR regime, the results are almost identical to those in Tables I and II. The same is true for $M = 16$ PAM. On the other hand, higher values of $Q$ would lead to better performance only for very high CSNR, but not for the CSNR range considered in this paper.

V. SYSTEM COMPARISON

Figures 3 and 4 show the SDR versus CSNR performance points that were obtained for the different analog and digital systems discussed in the previous sections. Figure 3 is for the case of Gaussian distributed sources while Fig. 4 is for the Laplacian case. For the same number of channel uses, the different points represent the performance of the analog system, the theoretical limit of a digital system that utilizes scalar quantization (i.e., the ultimate limit with scalar quantization using perfect source and channel coding and optimal signaling), and the performance of a BICM digital system that utilizes scalar quantization when i) Huffman coding and Gaussian signaling is employed, ii) Huffman coding and PAM signaling is used, and iii) the most realistic scenario in which a Huffman code, a PAM constellation and an IRA channel

TABLE II

PARAMETERS OF A 2:1 DIGITAL BICM SYSTEM WITH LAPLACIAN SOURCES, SCALAR QUANTIZATION, Huffman source coding, IRA CHANNEL CODING AND 256-PAM MODULATION, SDR, Capacities and Thresholds in dB.

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Fig. 3. Performance comparison of 2:1 analog joint source-channel coded and digital 256-PAM schemes with the same number of channel uses for Gaussian sources.
encoder are utilized. The OPTA curves have also been included as a benchmark.

From Figs. 3 and 4 it is clear that the performance of the analog joint source-channel coded system is significantly better than that of the digital BICM systems, even when optimal (Gaussian) signaling is used in the latter case. For Gaussian sources, the difference in performance is about 5 dB when considering 256-PAM constellations (3 dB when using Gaussian modulations) for CSNR values above 20 dB. For Laplacian sources, differences are particularly remarkable in the low CSNR regime where the digital BICM system outperforms the analog one in about 6 dB for PAM and 5 dB for Gaussian modulations. Differences are smaller at high CSNR values although still important (2 – 3 dB for the more realistic case of using PAM).

It should be noticed that the superior performance of the analog joint source-channel coding system is achieved with extremely low complexity: the encoding and decoding are carried out on a per symbol basis. Furthermore, not only is the resulting complexity of the digital BICM systems higher, but also the digital design (i.e., number of quantization levels, source encoder, channel encoder rate and degree profile) must change radically when the operating conditions vary, whereas the analog system simply needs to adjust the spiral scaling parameter $\Delta$. Vector quantization can be considered in order to improve the performance of the digital BICM system but this would be accomplished at the cost of an even greater increase in complexity.

VI. CONCLUSION

We have studied the performance of an analog joint source-channel coding system in comparison with optimized digital systems in AWGN channels. The analyzed analog system employs a two-dimensional space-filling curve to map two real-valued samples to an analog amplitude that is transmitted directly through the channel. The digital systems are based on a Bit-Interleaved Coded Modulation (BICM) scheme made up of an optimum scalar quantizer, a Huffman encoder, an optimized Irregular Repeat-Accumulate (IRA) encoder and a 256-PAM mapper. The results show that the analog system performs better and with a significantly lower encoding and decoding complexity than the considered digital systems. Its performance is even better than the theoretical limit for digital systems that have the same number of channel uses and utilize scalar quantization.

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