Parallel concatenated joint source-channel coding

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A novel approach for robust source transmission where variable-length source and channel encoding are concatenated in parallel is presented. Simulation results show that for waveform source signals the proposed scheme shows a strong increase in decoding performance compared to the typically applied serially concatenated scheme.

Introduction: Joint source-channel coding (JSCC) approaches have recently emerged as a good alternative to the strict application of Shannon's source-channel separation principle for delay-constrained transmission scenarios. A subset of these techniques is given by joint source-channel decoding, where residual source redundancy increases the error-correction capability of the decoder [1, 2]. Especially, the serial concatenation of implicit source redundancy and explicit redundancy from a channel code can be decoded in an iterative fashion analogous to the decoding of serially concatenated channel codes [3, 4]. However, parallel concatenated JSCC (PCJSCC) schemes could be an alternative to serially concatenated approaches when one aims to increase the decoding performance especially for high bit error rates [5].

In this Letter a novel joint source-channel coding scheme for the reliable transmission of variable-length encoded waveform signals over additive white Gaussian noise (AWGN) channels is proposed. Instead of using a standard serial concatenation of source and channel encoder we employ a parallel concatenation of variable-length codes (VLCs) and channel encoding. Simulation results show that this new scheme outperforms a previously published serially concatenated VLC JSCC approach [6] in terms of reconstruction signal-to-noise ratio (RSNR).

The transmission model is shown in Fig. 1. The vector $\mathbf{U} = [U_1, \ldots, U_k, \ldots, U_K]$ represents a packet of K correlated source symbols U_k, where after quantisation with M bits we obtain the resulting index vector $\mathbf{I} = [I_1, I_2, \ldots, I_K] = [i_{1,1}, i_{1,2}, \ldots, i_{K,M}]$ with $I_k \in \mathcal{I}$, $\mathcal{I} = \{0, 1, \ldots, 2^M - 1\}$, and $i_{k,\ell} \in \{0, 1\}$, $\ell = 1, \ldots, M$, denoting the ℓth bit of I_k. Owing to the assumed source correlation the indices I_k show dependencies, which may, for example, be modelled as a first-order stationary Gauss-Markov process. The VLC encoder in Fig. 1 maps each fixed-length index I_k to a variable-length bit vector $\mathbf{c}(\lambda) = \mathcal{C}(I_k = \lambda)$ for $\lambda \in \mathcal{I}$ and the variable-length codetable $\mathcal{C}$, leading to the binary sequence $\mathbf{w} = [w_1, \ldots, w_n, \ldots, w_{N_S}]$, $w_n \in \{0, 1\}$, of length N_S. Also, a bit-interleaved version of $\mathbf{I}$ is applied to a terminated rate-R_c recursive systematic convolutional (RSC) channel code. As for turbo codes we only consider the parity bits $v_{p_m} \in \{0, 1\}$ of each codeword resulting in a length-N_C binary sequence $\mathbf{v}_p = [v_{p_1}, \ldots, v_{p_m}, \ldots, v_{pN_C}]$, which leads to a channel code rate of R_{C_p}. The sequences $\mathbf{w}$ and $\mathbf{v}_p$ are then multiplexed and transmitted over a BPSK-modulated AWGN channel with noise variance $\sigma_e^2 = N_0/2E_s$.

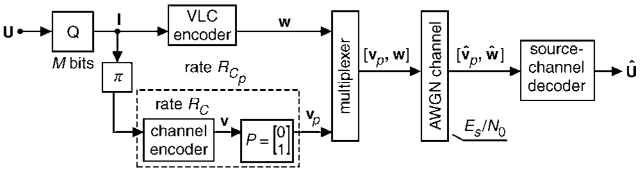

Fig. 1 *Transmission system*

Iterative decoding: From Fig. 1 we can observe that the encoding scheme is very similar to a turbo encoder with the difference that the explicit redundancy from the upper channel encoder is replaced by the residual source redundancy inherent in the bit sequence $\mathbf{w}$ after VLC encoding. Thus, an iterative decoding scheme can be applied where one constituent decoder is replaced by the symbol-level soft-input soft-output (SISO) VLC source decoder derived in [6], which is capable of exploiting the index dependencies within the vector $\mathbf{I}$ for error correction.

The proposed decoder structure is shown in Fig. 2. At the beginning of the iterations the VLC source decoder calculates *a posteriori* probabilities (APPs) $P(I_k = \lambda|\hat{\mathbf{w}})$ for the source indices I_k. These APPs are converted to L-values for the source index bits $i_{k,\ell} = \lambda_\ell$ according to

$$L^{(S)}(i_{k,\ell}) = \ln\left(\frac{\sum\limits_{\lambda\in\mathcal{I}:\lambda_\ell=0} P(I_k = \lambda|\hat{\mathbf{w}})}{\sum\limits_{\lambda\in\mathcal{I}:\lambda_\ell=1} P(I_k = \lambda|\hat{\mathbf{w}})}\right) \qquad (1)$$

with $\lambda_\ell \in \{0, 1\}$ representing the ℓth bit of the source hypothesis λ. These L-values can be decomposed according to $L^{(S)}(i_{k,\ell}) = L_e^{(S)}(i_{k,\ell}) + L_a^{(S)}(i_{k,\ell})$ where $L_e^{(S)}(i_{k,\ell})$ contains both reliability information from the AWGN channel output and extrinsic information for the index bit $i_{k,\ell}$, and $L_a^{(S)}(i_{k,\ell})$ denotes the *a priori* term. Owing to the non-systematic property of the VLC the L-values $L_e^{(S)}(i_{k,\ell})$ cannot be further separated into a channel and an extrinsic term. After subtraction of $L_a^{(S)}(i_{k,\ell})$ and after bit-interleaving, the L-values $L_e^{(S)}(i'_{k,\ell})$ for the bits $i'_{k,\ell}$ of the bit-interleaved index sequence $\pi(\mathbf{I})$ are employed as *a priori* information for the SISO channel decoder, where we use the BCJR algorithm [7] for APP channel decoding. Note that in contrast to turbo decoding with systematic codes, where the received information bits are also applied to the second constituent decoder, here this information is provided by the reliabilities for the already source-decoded bits in form of $L_e^{(S)}(i_{k,\ell})$. The feedback to the source decoder is carried out by sending extrinsic information $L_{extr}^{(C)}(i_{k,\ell})$ as in standard turbo decoding. Since the VLC source decoder from [6] needs index-based *a priori* information, the L-values $L_a^{(S)}(i_{k,\ell})$ are converted to index-based probabilities by a simple multiplication of the corresponding bit-based *a priori* probabilities $P_a^{(S)}(i_{k,\ell})$, where we assume that all bits $i_{k,\ell}$ are uncorrelated. After each iteration, reliability values $\tilde{P}(I_k = \lambda|\hat{\mathbf{w}}, \hat{\mathbf{v}}_p)$ emerge at the output of the source decoder, which may be interpreted as approximations for the true APPs. These index reliabilities are then used in a subsequent mean-squares estimation to obtain an estimate of the source symbol U_k as

$$\hat{U}_k = \sum_{\lambda=0}^{2^M-1} U_q(\lambda)\tilde{P}(I_k = \lambda|\hat{\mathbf{w}}, \hat{\mathbf{v}}_p) \qquad (2)$$

where $U_q(\lambda)$ denotes the quantiser reconstruction level corresponding to the index λ.

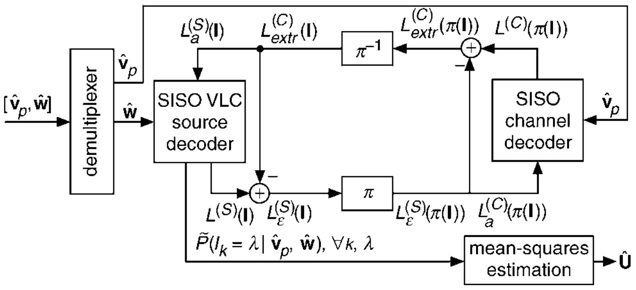

Fig. 2 *Iterative joint source-channel decoder*

Performance comparisons: In the following we illustrate the performance improvement obtained for the PCJSCC technique by comparing it with the serially concatenated JSCC (SCJSCC) approach for robust VLC transmission from [6]. In the simulations the source redundancy is modelled by a strongly correlated AR(1) source process with correlation coefficient $a = 0.9$ quantised with $M = 4$ bits by a uniform scalar quantiser. We employ the same symmetrical reversible VLC (RVLC) with a minimum distance $d_{\min} = 2$ [8] for both schemes in order to provide an equal amount of source redundancy. Furthermore, source packets of length $K = 100$ are used for 50 different realisations of the source signal, where each realisation is averaged over 100 simulated AWGN channel transmissions. We also assume that the sensitive parameters K, N_S and N_C are transmitted without error to the decoder. The RSC codes are selected by a code search based on test simulations for fixed channel SNRs in the waterfall region of the RSNR decoding performance plot, where we limit the search to all unpunctured mother codes with code memory $\mu = 3$ and $R_C = 1/2$. The resulting forward (g_0) and recursive (g_r) generator polynomials giving the best RSNR performance are $(g_0, g_r)_8 = (15, 11)_8$ for the SCJSCC scheme and $(g_0, g_r)_8 = (12, 11)_8$ for the PCJSCC approach, respectively. (The same code polynomials can also be obtained by a code search based on EXIT charts [9]. However, for the short block lengths used here, there may be a strong mismatch between simulated and calculated decoding trajectory.)

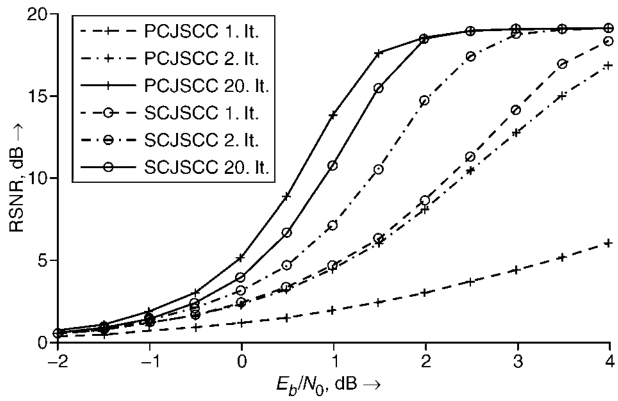

Fig. 3 *Simulation results for mean-squares estimation*

Fig. 3 shows the simulation results for the RSNR against the E_b/N_0 on the channel, where $E_b = E_s/R_{S/P}$ denotes the transmit energy per information bit. The overall code rates R_S and R_P for the serial and parallel JSCC scheme, respectively, are given by

$$R_S = \frac{KR_C H(I_k|I_{k-1})}{K\bar{M}_{VLC} + \mu} \simeq 0.3$$
$$R_P = \frac{KH(I_k|I_{k-1})}{K\bar{M}_{VLC} + (KM + \mu)/R_{C_p}} \simeq 0.3 \qquad (3)$$

where for SCJSCC no puncturing is carried out. The code rates in (3) consider all redundancy exploited for error protection, where the conditional entropy $H(I_k|I_{k-1})$ takes the residual source redundancy into account and the mean VLC word length $\bar{M}_{VLC}$ the explicit RVLC-based redundancy, respectively. We can observe from Fig. 3 that the PCJSCC technique clearly outperforms the SCJSCC approach in the waterfall region, which corresponds well with the observations made in [5] for turbo and serially concatenated channel codes. For larger channel SNR PCJSCC exhibits an error floor at a symbol error rate of 10^{-4}. However, this error floor does not visibly affect the clear channel performance for $E_b/N_0 > 2$ dB in Fig. 3 due to the fact that a few symbol errors within a source packet only lead to an error signal with small energy for the whole frame.

Conclusions: We have shown that robust variable-length encoded transmission of waveform signals can also be achieved by transmitting rate-one channel-encoded source data in parallel with the VLC codewords and subsequent turbo decoding at the receiver. Compared to a typically used serially concatenated approach for channel-encoded VLC transmission the proposed scheme yields up to 3 dB larger reconstruction SNR for strongly distorted channels.

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