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Joint-decoding-complexity-oriented collaborative design for joint source-channel coding system based on double protograph-LDPC codes

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Although the code designs for the joint source-channel coding (JSCC) systems based on double protograph low-density parity-check (DP-LDPC) codes have been widely investigated over various coding channels, they tend to emphasize performance enhancements rather than the decoding complexity [1–3]. In the current landscape, the challenge associated with designing the DP-LDPC JSCC system with low decoding complexity [4] remains an open question. Moreover, the optimization of the coding and decoding sides in the DP-LDPC JSCC system is considered separately regardless of standard [2] or non-standard [3] coding channels. The superiority of collaborative design has been verified in the separated source-channel coding system [5]. However, the realization of the collaborative design framework for the DP-LDPC JSCC system remains another open question.

In this study, in an effort to address the above challenges, a joint-decoding-complexity-oriented collaborative design for the DP-LDPC JSCC system is proposed and validated. The major contributions are listed as follows: (1) This study introduces, for the first time, a collaborative design framework based on joint decoding complexity for the DP-LDPC JSCC system, effectively utilizing the property from the decoding side as a guiding principle in the code design. (2) The joint decoding complexity for the DP-LDPC JSCC system is defined for the first time. In the collaborative design framework, joint decoding complexity is used as the guiding principle. To quickly validate the new framework, the channel code in the joint base matrix is redesigned. (3) In the collaborative design process, the joint decoding thresholds are calculated by the joint protograph extrinsic information transfer (JPEXIT) algorithm, which is limited by the maximum number of iterations. The modified genetic algorithm (GA) is used in the search process, and the joint decoding thresholds are utilized as the objective function. Both simulation results and decoding threshold analyses reveal that the system with the proposed channel code performs well in terms of error correction, decoding complexity, and throughput. Specifically, the proposed channel code achieves a coding grain of more than 0.4 dB and reduces the average converged iteration number by 12.5%–16.8% compared with its counterparts, thereby verifying the superiority and effectiveness of the collaborative design framework.

System model. In this system, a joint base matrix $\boldsymbol{B}_J$ of size $(m_{\rm sc}+m_{\rm cc})\times(n_{\rm sc}+n_{\rm cc})$ is defined as

$$\boldsymbol{B}_J=\begin{bmatrix}\boldsymbol{B}_{sc} & \boldsymbol{B}_{L1}\\ \boldsymbol{B}_{L2} & \boldsymbol{B}_{cc}\end{bmatrix}, \tag{1}$$

where $\boldsymbol{B}_{sc}$ is the base matrix of source protograph low-density parity-check (P-LDPC) code, $\boldsymbol{B}_{cc}$ is the base matrix of channel P-LDPC code, $\boldsymbol{B}_{L1}$ represents the edges connecting the check nodes (CNs) of the source P-LDPC code to the variable nodes (VNs) of the channel P-LDPC code in the joint Tanner graph, and $\boldsymbol{B}_{L2}$ represents the edges connecting the CNs of channel P-LDPC code to the VNs of the source P-LDPC code in the joint Tanner graph. The joint parity-check matrix $\boldsymbol{H}_J$ with size $(M_{\rm sc}+M_{\rm cc})\times(N_{\rm sc}+N_{\rm cc})$ can be obtained from $\boldsymbol{B}_J$. The details of the system model can be found in Appendix B.

Collaborative design based on joint decoding complexity. Following [4, 5], the joint decoding complexity of the DP-LDPC JSCC system (denoted by JDC) is defined as

$$\begin{aligned}&{\rm JDC}\propto E\cdot I_{\max}={\rm Sum}\left(\boldsymbol{H}_J\right)\cdot I_{\max}\\&={\rm Sum}\left(\boldsymbol{H}_{sc}+\boldsymbol{H}_{cc}+\boldsymbol{H}_{L1}+\boldsymbol{H}_{L2}\right)\cdot I_{\max}.\\&={\rm Sum}\left(\boldsymbol{B}_{sc}\cdot q_{sc}+\boldsymbol{B}_{cc}\cdot q_{cc}+\boldsymbol{B}_{L1}\cdot q_1+\boldsymbol{B}_{L2}\cdot q_2\right)\cdot I_{\max},\end{aligned} \tag{2}$$

where ${\rm Sum}\left(\boldsymbol{H}_J\right)$ represents the sum of the entries in the joint parity-check matrix of this system and $I_{\max}$ represents the maximum number of iterations. As previously stated, $\boldsymbol{H}_J$ consists of four parts: $\boldsymbol{H}_{sc}$, $\boldsymbol{H}_{cc}$, $\boldsymbol{H}_{L1}$, and $\boldsymbol{H}_{L2}$; they

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are obtained from $\boldsymbol{B}_{sc}$, $\boldsymbol{B}_{cc}$, $\boldsymbol{B}_{L1}$, and $\boldsymbol{B}_{L2}$ via a lifting operation with lifting factor q_{sc}, q_{cc}, q_1, and q_2, respectively; generally, $q_{sc} = q_{cc} = q_1 = q_2$. The detail of JDC can be found in Appendix C.1. Through the analysis with a limited iteration number, we discovered that the channel code for this system needs to be redesigned when considering the joint decoding complexity; the details of the analysis process can be found in Appendix C.2.

The collaborative design process for this system's channel code with low joint decoding complexity can be expressed as an optimization problem with an objective function, with an emphasis on the maximum iteration number; this is expressed by the following equation:

$$\min_{\boldsymbol{B}_J} \quad \boldsymbol{\theta}\left(\boldsymbol{B}_J, I_{\max}^{\text{JPEXIT}}\right), \tag{3}$$

$$\text{s.t.} \quad \mathscr{F}_t\left(\boldsymbol{B}_J\right) \geqslant 0, \quad t = 1, 2, \ldots, T, \tag{4}$$

where the function $\boldsymbol{\theta}\left(\boldsymbol{B}_J, I_{\max}^{\text{JPEXIT}}\right)$ returns the joint decoding thresholds of $\boldsymbol{B}_J$ using JPEXIT analysis with the limitation of $I_{\max}^{\text{JPEXIT}}$. Inequation (4) represents the design constraints for the DP-LDPC JSCC system's channel code. Many relative constraints must be considered when designing channel code for the DP-LDPC JSCC system with low joint decoding complexity. The initial channel base matrix $\boldsymbol{B}_{cc,1}^{(0)}$ can be obtained using these constraints. Through the modified GA algorithm and using the above design method with the constraint conditions, the optimized rate-1/2 channel base matrix $\boldsymbol{B}_{cc}^{\text{opt}}$ with $I_{\max}^{\text{JPEXIT}}$=20 can be obtained as

$$\boldsymbol{B}_{cc}^{\text{opt}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \end{bmatrix}. \tag{5}$$

The joint base matrix corresponding to the code pair $(\boldsymbol{B}_{sc}^{fix}, \boldsymbol{B}_{cc}^{\text{opt}})$ is represented as $\boldsymbol{B}_J^{\text{opt}}$. The code pairs that select the channel base matrix corresponding to (16) and (17) in [2] are defined as $\boldsymbol{B}_J^{\text{comp\_1}}$ and $\boldsymbol{B}_J^{\text{comp\_2}}$, respectively. The details of specific constraints, modified GA algorithm, and $\boldsymbol{B}_{cc,1}^{(0)}$ can be found in Appendix C.3.

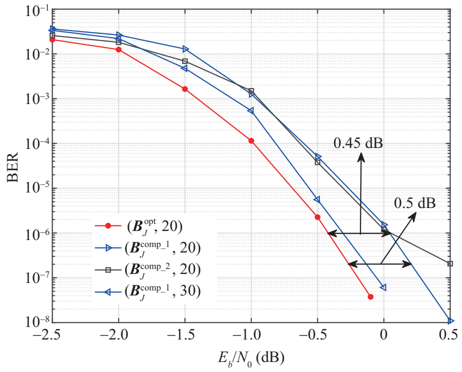

Figure 1 (Color online) Bit error rate (BER) performance comparison at $p_m = 0.04$ over additive white Gaussian noise (AWGN) channel.

Simulation results. The frame length is set to 3200 bits. The label $(\boldsymbol{B}_J, I_{\max})$ in Figure 1 refers to the scheme using $\boldsymbol{B}_J$ with $I_{\max}$ iterations. Figure 1 illustrates that the bit error rate (BER) performance of $\boldsymbol{B}_J^{\text{opt}}$ at $p_m = 0.04$ exhibits coding gains of 0.5 dB at BER $= 2 \times 10^{-7}$ and 0.45 dB at BER $= 1 \times 10^{-6}$ at $I_{\max} = 20$, compared with $\boldsymbol{B}_J^{\text{comp\_1}}$ and $\boldsymbol{B}_J^{\text{comp\_2}}$, which are consistent with the joint decoding thresholds shown in Appendix D. The BER curve of $\boldsymbol{B}_J^{\text{comp\_1}}$ with $I_{\max} = 30$ is also presented in Figure 1. It can be observed that the BER performance of $\boldsymbol{B}_J^{\text{comp\_1}}$ with $I_{\max} = 30$ is inferior to that of $\boldsymbol{B}_J^{\text{opt}}$ with $I_{\max} = 20$, and there is a gap of nearly 0.1 dB between them. This suggests that using the scheme $\boldsymbol{B}_J^{\text{opt}}$ with $I_{\max} = 20$ instead of the scheme $\boldsymbol{B}_J^{\text{comp\_1}}$ with $I_{\max} = 30$ can lead to a reduction in iteration numbers by nearly 33% $\left(\frac{30-20}{30}=33\%\right)$ and a slight performance improvement. Meanwhile, the iteration number directly affects power consumption and throughput, implying that one can reduce power consumption by nearly 33% and increase the throughput [4] by 50% $\left(\frac{1/20-1/30}{1/30}= 50\%\right)$ using the scheme $\boldsymbol{B}_J^{\text{opt}}$ with $I_{\max} = 20$ rather than the scheme $\boldsymbol{B}_J^{\text{comp\_1}}$ with $I_{\max} = 30$. The detailed simulation parameters and additional simulation results are presented in Appendix D.

Conclusion. In this study, we propose a joint-decoding-complexity-oriented collaborative design framework for the DP-LDPC JSCC system. The joint decoding complexity for this system is defined for the first time and used as the design principle for this framework. To validate this framework, the channel code is redesigned, and the other components of the joint base matrix are temporarily fixed to facilitate the design process. The DP-LDPC JSCC system equipped with the proposed channel code exhibits superior waterfall performance, lower decoding complexity, and higher throughput when compared to the system utilizing the conventional channel code and neglecting the joint decoding complexity, which validates the effectiveness of the new framework. Furthermore, this design framework is applicable to other LDPC-based JSCC systems. The multi-elements collaborative design for the DP-LDPC JSCC system in terms of algorithm and hardware will be investigated in the future.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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