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Improving Spatially Coupled LDPC Codes by Connecting Chains

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Abstract—In this paper, we study ensembles of connected spatially coupled low-density parity-check codes (SC-LDPCs), i.e., ensembles described by graphs in which regular SC-LDPC chains of various lengths serve as edges. We show that, by carefully connecting individual SC-LDPC chains, we obtain LDPC code ensembles with improved iterative decoding thresholds compared to those of a single coupled chain, in addition to reducing the decoding complexity required to achieve a specific bit error probability. Moreover, we show that, like the component SC-LDPC chains, the proposed constructions have a typical minimum distance that grows linearly with block length.

I. INTRODUCTION

Recently, iterative processing on spatially coupled sparse graphs has received a lot of attention in the literature. The concept of coupling a sequence of identical small structured graphs into a chain with improved properties, first demonstrated in the context of low-density parity-check (LDPC) convolutional codes [1], has been shown to be applicable to a diverse list of topics, such as compressed sensing [2], multiuser communication [3] [4], quantum codes [5], relay channels [6], [7], wiretap channels [8], and models in statistical physics [9]. Ensembles of spatially coupled LDPC codes (SC-LDPCs) can be obtained by terminating regular LDPC convolutional code ensembles [10]. The slight irregularity resulting from the termination of the convolutional codes has been shown to lead to substantially better belief propagation (BP) decoding thresholds compared to corresponding block, or uncoupled, code ensembles for a variety of channels [10]–[13]. Further, it has recently been proven analytically for the binary erasure channel (BEC) that the BP decoding thresholds of a class of regular SC-LDPC ensembles approach the maximum a posteriori (MAP) decoding thresholds of the corresponding LDPC block code ensembles [14].

In this work, we extend the results presented in [15], [16] and show that by carefully connecting individual SC-LDPC chains, we can obtain LDPC code ensembles with improved iterative decoding thresholds for a wide variety of rates. Communication over the binary erasure channel (BEC) and the additive white Gaussian noise (AWGN) channel have been considered. Moreover, we show that this new code construction also decreases the decoding complexity required to achieve specific decoding error probabilities in the near threshold region. Finally, we show that the constructed ensembles, like the individual component SC-LDPC chains, are asymptotically good, i.e., they have the property that their minimum distance increases linearly with block length.

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II. CODE CONSTRUCTION

A protograph [17] is a small Tanner graph described by an \( n_c \times n_v \) incidence matrix \( B \), known as a base matrix, that consists of non-negative integers \( B_{i,j} \) that correspond to \( B_{i,j} \) parallel edges in the graph. A protograph-based code is obtained by taking an \( M \)-fold graph cover of a given protograph and can be described by an \( M n_c \times M n_v \) parity-check matrix obtained by replacing each non-zero entry \( B_{i,j} \) by a sum of \( B_{i,j} \) non-overlapping permutation matrices of size \( M \times M \) and a zero entry by the \( M \times M \) all-zero matrix. Therefore, a protograph with a lifting factor of \( M \) describes an ensemble of LDPC codes.

A. SC-LDPC Ensembles

Fig. 1. The protographs of several SC-LDPC chains of length \( L = 8 \): (a) \((3, 6)\)-regular, (b) \((4, 8)\)-regular, (c) \((3, 9)\)-regular, and (d) their simplified representation.

A protograph of a \((3, 6)\)-regular SC-LDPC chain of length \( L = 8 \) is depicted in Fig. 1(a). The green circles in the figure illustrate check nodes and the black circles illustrate variable nodes. Note that each variable node is connected to 3 parity check nodes, while the parity check nodes in the middle are connected to 6 variable nodes. The check nodes located at the beginning and at the end of the chain, however, are
only connected to either 2 or 4 variable nodes. Figs. 1(b) and (c) show the coupling concept for (4,8)- and (3,9)-regular graphs, respectively. A simplified illustration of the protographs of a length \( L = 8 \) chain is given in Fig. 1(d). Each magenta node illustrates a segment of the \((J, K, L)\)-regular SC-LDPC chain. We will denote the ensemble associated with a \((J, K, L)\)-regular SC-LDPC chain of length \( L \) by \( C(J, K, L) \).

B. Connecting Two Coupled Chains: The Loop

In this paper, we will construct the protograph of an LDPC code ensemble by interconnecting the protographs of two \((J, K)\)-regular SC-LDPC chains.\(^1\) The connected protograph, depicted in Fig. 2, is called the loop and is denoted by \( L(J, K) \). Here, the last segment of chain one is connected to an inner segment of chain two, while the first segment of chain two is connected to an inner segment of chain one. It was shown in [16] that, when connecting SC-LDPC chains, the performance is sensitive to the position of the connecting points. In this paper, we will connect the chains at positions \( \max(2, \lfloor L/3 \rfloor) \). The particular connections made between the chains will vary depending on the component chains, and we will see in Section IV that the threshold and speed of convergence can be improved by carefully choosing where to place the connecting edges.

\[ \text{Fig. 2. Two connected } (J, K)\text{-regular SC-LDPC chains of length } L = 15. \]

III. ANALYSIS OF CONNECTED SC-LDPC CHAINS

A. Iterative Decoding Analysis

The analysis of the iterative decoding performance of codes described by protographs can be obtained via density evolution, which, for the case of the BEC, is explained as follows.

We denote the set of variable nodes connected to check node \( k \) in the protograph by \( \mathcal{V}(k) \) and the set of check nodes connected to variable node \( j \) by \( \mathcal{C}(j) \). The probability that the message passed from check node \( k \) to variable node \( j \) in iteration \( i \) is an erasure is denoted by \( q_{kj}^{(i)} \). The probability of an erasure message from variable node \( j \) to check node \( k \) is similarly denoted by \( p_{jk}^{(i)} \). The following equations relate the erasure probabilities of the messages at different iterations:

\[ q_{kj}^{(i)} = 1 - \prod_{j' \in \mathcal{V}(k) - j} (1 - p_{j'k}^{(i-1)}) , \quad (1) \]

\[ p_{jk}^{(i)} = \epsilon \prod_{k' \in \mathcal{C}(j) - k} q_{k'j}^{(i)} . \quad (2) \]

The variable node messages are initialized as \( p_{jk}^{(0)} = \epsilon \) at iteration 0. The bit error probability of variable node \( j \) at iteration \( i \) can be calculated as

\[ P_b(j) = \epsilon \prod_{k \in \mathcal{C}(j)} q_{kj}^{(i)} . \quad (3) \]

\(^1\)Constructions consisting of more than two connected chains are also possible [15], [16].

B. Asymptotic Minimum Distance Analysis

In [18], Divsalar presented a technique to calculate the average weight enumerator for protograph-based block code ensembles. This weight enumerator can be used to test if an ensemble is asymptotically good, i.e., if the minimum distance typical of most members of the ensemble is at least as large as \( \delta_{\text{min}} n \), where \( \delta_{\text{min}} > 0 \) is the minimum distance growth rate of the ensemble and \( n \) is the block length. In [19], it was shown that ensembles of \((J, K)\)-regular SC-LDPCs (i.e., individual chains) are asymptotically good. In Section IV, we present the results of a similar protograph-based analysis for ensembles of connected SC-LDPCs to see if they share the good distance properties of the individual chains.

IV. RESULTS

In this section, we present the iterative decoding threshold and asymptotic minimum distance results obtained for several SC-LDPC loop ensembles. We will first show that the \( L(J, 2J, L) \) loop ensembles have the same rate but better thresholds than the individual \( C(J, 2J, L) \) ensembles. We then proceed to show that this same improvement is visible as we increase the rate of the component SC-LDPC chains.

A. The \((3, 6)\) SC-LDPC Loop Ensemble \( L(3, 6, L) \)

The first component chain we consider is the \((3, 6)\)-regular SC-LDPC chain shown in Fig. 1(a). We take two of these chains and connect them together as shown in Fig. 2. The connections are made as shown in Fig. 3. Note that, at the connection points, the two check nodes at the end of the chain have an additional 2 and 4 edges (shown in red) that connect to the variable nodes of the adjacent chain. As a result, the loop construction \( L(3, 6, L) \) has reduced check node degrees only at the open ends of the loop. However, at each connection point, there are 6 variable nodes that have degree 4. Consequently, for the loop ensemble \( L(3, 6, L) \), the average check node degree is \( 6(L+1)/(L+2) \) and the average variable node degree is \( 3(L+1)/L \). We note that, just as in the case of a single \((3, 6)\)-regular SC-LDPC chain, the degree distribution approaches that of a \((3, 6)\)-regular code as \( L \) grows. The rates of both the loop ensemble \( L(3, 6, L) \) and the single chain ensemble \( C(3, 6, L) \) are equal and are given by \( R_L = (L-2)/2L \).

\[ \text{Fig. 3. Graphs depicting (a) two connected spatially coupled } (3, 6)\text{-regular protograph chains, and (b) the simplified representation. The connecting edges are shown in red.} \]
In the next section, we will see that a loop constructed using results for the single chain ensembles for comparison. We observe that the thresholds of the loop ensembles are generally superior with the exception of large $L$. In particular, we observe a dramatic threshold improvement for ensembles with rates in the region $0.3571 \leq R_L \leq 0.4375$. For large values of $L$, the improvement diminishes. The thresholds of the single chain ensembles $C(3, 6, L)$ and $C(4, 8, L)$ can be observed to converge to values close to the MAP threshold of the underlying $(J, K)$-regular LDPC code as $L$ becomes sufficiently large. (Recall that it has been shown in [14] that the BP thresholds of a class of SC-LDPC ensembles on the BEC are equal to the (optimal) MAP thresholds of their corresponding LDPC block code ensembles.) As a result, for large $L$, we observe the surprising behaviour that the iterative decoding thresholds of the $C(4, 8, L)$ ensembles are larger than the $C(3, 6, L)$ thresholds (unlike the corresponding LDPC block code ensembles). However, even in this region, we observe that the thresholds of the $L(3, 6, L)$ ensemble remain above the $C(4, 8, L)$ thresholds for rates between 0.4 and 0.45. In the next section, we will see that a loop constructed using $(4, 8)$-regular SC-LDPC chains achieves further performance improvement.

AWGN channel thresholds for the loop ensembles $L(3, 6, L)$ are given in Table I for $L = 12, 15$, and 18. The results for the single chain ensembles $C(3, 6, L)$ are shown for comparison. We notice that the thresholds of the loop ensembles are significantly better than these for corresponding single chains.

In addition to an improvement in threshold, we also find that connecting two chains may improve the speed of convergence of the chains at the connecting points. The evolution of the bit error probability for the variable nodes of the loop ensemble $L(3, 6, 15)$ is illustrated in Fig. 5. The red curves correspond to the error probability at each node position at iterations 1, 6, 11, . . . , 36 (from top to bottom). The green curves correspond to the error probability as a function of the node position for the single chain ensemble $C(3, 6, 15)$ and iteration numbers 1, 6, 11, . . . , 36. The BEC erasure probability is fixed to be 0.488. We note that the red curves achieve low bit error probabilities much faster than the green curves. In addition, it takes fewer decoding iterations for the loop ensemble $L(3, 6, 15)$ to converge to a given bit error probability.

![Fig. 4. BEC thresholds calculated for the $L(3, 6, L)$ loop ensembles as well as some $C(J, K, L)$ ensembles and $(J, K)$-regular LDPC ensembles.](image)

![Fig. 5. Logarithm of the bit error probability for the variable nodes of a) chain one of the ensemble $L(3, 6, 15)$ (red curves), and b) ensemble $C(3, 6, 15)$ (green curves), as a function of the position of the node in the chain. The curves (either red or green) are computed for decoding iterations 1, 6, 11, . . . , 36 (from top to bottom). The position where chain one is connected to the end of chain two is shown by the red triangle.](image)

<table>
<thead>
<tr>
<th>Rate</th>
<th>Ensemble</th>
<th>$(E_b/N_0)^*$</th>
<th>Ensemble</th>
<th>$(E_b/N_0)^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4167</td>
<td>$L(3, 6, 12)$</td>
<td>0.6520dB</td>
<td>$C(3, 6, 12)$</td>
<td>1.1167dB</td>
</tr>
<tr>
<td>0.4333</td>
<td>$L(3, 6, 15)$</td>
<td>0.7281dB</td>
<td>$C(3, 6, 15)$</td>
<td>1.0431dB</td>
</tr>
<tr>
<td>0.4444</td>
<td>$L(3, 6, 18)$</td>
<td>0.7850dB</td>
<td>$C(3, 6, 18)$</td>
<td>0.9659dB</td>
</tr>
</tbody>
</table>

Table I
AWGN channel thresholds $(E_b/N_0)^*$ calculated for the $L(3, 6, L)$ loop ensembles and the $C(3, 6, L)$ ensembles for $L = 12, 15$, and 18.
length $L$. We see the same behaviour as for the $(3, 6)$ loops: for short $L$ and low rates, the ensemble $C(4, 8, L)$ has the largest threshold; for a large rate region in the middle of the achievable range, the loop ensembles have significantly better thresholds; and, finally, the improvement observed for the loop ensembles diminishes as $L$ becomes large and the thresholds converge at a value slightly below the MAP threshold of the underlying ensemble. The threshold difference between ensembles $\mathcal{L}^A(4, 8, L)$ and $\mathcal{L}^B(4, 8, L)$ indicates that the performance is sensitive to the choice of additional edges connecting the chains.

<table>
<thead>
<tr>
<th>$L$</th>
<th>$R$</th>
<th>$\mathcal{L}^A(4, 8, L)$</th>
<th>$\mathcal{L}^B(4, 8, L)$</th>
<th>$C(4, 8, L)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.2500</td>
<td>0.5629</td>
<td>0.5709</td>
<td>0.5748</td>
</tr>
<tr>
<td>9</td>
<td>0.3333</td>
<td>0.5342</td>
<td>0.5399</td>
<td>0.5194</td>
</tr>
<tr>
<td>12</td>
<td>0.3750</td>
<td>0.5185</td>
<td>0.5247</td>
<td>0.5021</td>
</tr>
<tr>
<td>15</td>
<td>0.4000</td>
<td>0.5088</td>
<td>0.5138</td>
<td>0.4983</td>
</tr>
<tr>
<td>75</td>
<td>0.4800</td>
<td>0.4975</td>
<td>0.4975</td>
<td>0.4977</td>
</tr>
<tr>
<td>150</td>
<td>0.4900</td>
<td>0.4971</td>
<td>0.4971</td>
<td>0.4977</td>
</tr>
</tbody>
</table>

Fig. 8 shows the evolution of the bit error probability for the variable nodes of chain one for the ensembles $\mathcal{L}^A(4, 8, 12)$ (blue curves) and $\mathcal{L}^B(4, 8, 12)$ (red curves). The BEC erasure probability is fixed to be 0.514, and error probabilities are plotted for iteration numbers $1, 6, 11, \ldots, 56$. We observe that the red curves (corresponding to fewer additional edges at the connecting points) achieve low bit error probabilities much faster than the blue curves, i.e., in addition to improved thresholds, connection method B also enables faster convergence to a specific bit error probability.

![Fig. 6. Asymptotic minimum distance growth rates calculated for the $\mathcal{L}(3, 6, L)$ loop SC-LDPC ensembles as well as some $C(J, K, L)$ SC-LDPC ensembles and $(J, K)$-regular LDPC ensembles.](image)

![Fig. 7. Connected spatially coupled $(4, 8)$-regular protograph chains. The connecting edges are shown in red.](image)

![Fig. 8. Logarithm of the bit error probability for the variable nodes of chain one of the ensembles $\mathcal{L}^A(4, 8, 12)$ (blue curves) and $\mathcal{L}^B(4, 8, 12)$ (red curves), as a function of the position of the node in the chain. The curves (either blue or red) are computed for decoding iterations $1, 6, 11, \ldots, 56$ (from top to bottom). The position where chain one is connected to the end of chain two is shown by the red triangle.](image)
As a final example, we construct some higher rate loop ensembles by connecting two \((3,9)\)-regular SC-LDPC chains. As a result of the boundary effects of spatial coupling, there is some rate loss for finite chain length \(L\). Consequently, a code designer may be tempted to choose a large chain length \(L\), where the design rate of the ensemble is higher and the threshold is closer to capacity. However, the performance of the code is also affected by the size of the lifting factor \(M\) and, for a fixed block length, practical limitations may require a moderate choice of \(L\), where the thresholds are typically further from capacity. For high rate coupled ensembles, in the region of moderate values of \(L\), the loop ensembles are particularly promising, since this is where they provide the largest threshold improvement. A \((3,9)\)-regular SC-LDPC chain is shown in Fig. 1(c). We connect the chains as shown in Fig. 9, using the reduced edge type of connection discussed in Section IV-B.

V. CONCLUSIONS

In this paper, we showed that by connecting individual chains of \((J,K)\)-regular SC-LDPCs we obtain LDPC code ensembles with improved iterative decoding thresholds compared to those of a single coupled chain for a large portion of the achievable rate region. Moreover, we saw that connecting SC-LDPC chains may also reduce the decoding complexity required to achieve a specific bit error probability. We also showed that, like the component SC-LDPC chains, the proposed constructions have a typical minimum distance that grows linearly with block length, and there exists a trade-off between the minimum distance growth rate and the iterative decoding threshold for a particular code rate. Finally, we observed that the iterative decoding thresholds and convergence behaviour can be further improved by carefully designing the connections between the chains.

References


