Constrained Interleaving of Serially Concatenated Codes with Inner Recursive Codes

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***Abstract*—A novel constrained interleaving technique is proposed to improve serially concatenated codes (SCCs) with inner recursive convolutional codes (IRCCs). In this study, constrained interleavers are designed to achieve a minimum Hamming distance (MHD) for the SCC, d_{SCC}, between $d_o d_i$ and $d_o^2 d_i$ while simultaneously maximizing the interleaver gain, where d_o and d_i are the MHD of the outer and inner codes respectively. Constrained interleavers can be constructed to achieve $d_{SCC} = d_o d_i$ while almost maintaining the interleaver gain of uniform interleaving. By imposing additional inter-row constraints, d_{SCC} of constrained interleaving is increased beyond $d_o d_i$ up to $d_o^2 d_i$, however, at the expense of some interleaver gain. Numerical results demonstrate that constrained interleaving is an efficient way to construct SCCs with low error floors while achieving interleaver gain at relatively short interleaver sizes.**

***Index Terms*—Serial concatenation, interleaving, inner recursive codes.**

I. Introduction

SERIAL concatenation (SC) is a well-known technique that is capable of generating powerful serially concatenated codes (SCCs) [1]–[6]. In fact, SC can generate codes that are more powerful than those generated from parallel concatenation (PC) [1], [2]. In SC, coded bits of an outer code are interleaved and fed into an inner code to generate the coded bits of the concatenation. The outer code is preferably a non-recursive convolutional code or a block code, while the inner code is preferably a recursive convolutional code [1], [2].

Reviewing the literature on interleaver design in SC that involve convolutional codes (CCs) [1]–[6], [4] and [5] consider product CCs by treating the coded sequence of the outer CC as a single codeword of a block code. Such studies that deal with product CCs can be improved by applying the constrained interleaving technique discussed in [7]. In addition, studies [3], [6] focus on searching for an interleaver that achieves the highest possible minimum Hamming distance (MHD) for the concatenation while making the path multiplicity a secondary focus. The algorithm presented in [3], that has been developed for outer convolutional codes, fails to find a SC with a high MHD when the outer code is a block code and multiple codewords of it are present in the interleaver. The study in [6], which can be viewed as an advancement of [3], allows use of any outer code in the concatenation. However, it treats path multiplicity as a secondary factor, and when applied to outer block codes, its complexity increases rapidly with the codeword length and interleaver size. In [7], a constrained interleaving technique has been presented to achieve the product distance while maintaining an interleaver gain close to that of uniform interleaving (UI), thereby performing better than traditional row-column interleaving (RCI) and UI. In this study, we show constrained interleaving (CI) presented in [7] can be modified for SCCs with inner recursive convolutional codes (IRCCs). In contrast to [6], CI discussed here easily finds an interleaver that achieves a desired MHD of SCC while simultaneously maximizing the interleaver gain allowed by that designed distance and the interleaver size.

In this study, we consider the general concatenation of an (n_1, k_1) outer block code with MHD d_o and an (n_2, k_2) IRCC with free MHD d_i to construct a concatenated code with MHD of d_{SCC}. Using a first set of interleaver constraints, a constrained interleaver (CIr) is designed to guarantee d_{SCC} of $d_o d_i$ for the SCC. By additionally imposing inter-row constraints, d_{SCC} of this CIr is increased above $d_o d_i$ up to $d_o^2 d_i$. In this study, CI with $d_{SCC} = d_o d_i$ and $d_o d_i < d_{SCC} \le d_o^2 d_i$ are called CI-1 and CI-2 respectively, while their respective interleavers are called CIr-1 and CIr-2. In order to assist the analysis, we denote the minimum distance that can be achieved by the inner code with an input weight j by $d_{i,j}$, and hence, $d_i = \min_j d_{i,j}$. A CIr has a row-column structure and is characterized by the number of rows of the interleaver L, and the number of codewords of the outer code placed along any single row in the interleaver ρ. Hence, the above combination of component codes can construct a $((L\rho n_1/R_i), L\rho k_1)$ SCC with CI, where $R_i = k_2/n_2$ is the rate of the inner code. The interleaved bits with the termination bits are read along columns and passed through the inner code to form the final coded sequence of the SCC.

II. CI-1 with $d_{SCC} = d_o d_i$

CI-1 is designed to maintain $d_{SCC} = d_o d_i$ by 1) selecting an appropriate number of rows L, 2) for each row, randomly selecting ρ n_1-bit codewords of the outer code, and 3) uniformly interleaving the selected ρn_1 outer-encoded bits to map them to their selected row. Note that the possible permutation rules of the resulting Clr-1 will be constrained as compared to applying UI to the $L\rho n_1$ outer encoded bits. The above steps ensure that any coded bit has the possibility of being placed anywhere in the interleaver array. The value of L can be selected solely based on the inner code to ensure that the MHD of CI-1 is $d_o d_i$. Specifically, L is selected to ensure that the weight of the coded sequence generated by any input sequence that merges with the all zero path and has the length of the merging event equal to λ input bits (where $jL < \lambda \le (j+1)L$ and $j = 0, 1, .., (d_o - 1)$) is at least $(j+1)d_i$. Even under the worst case placement of 1s along d_o consecutive columns in

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the CIr, the above choice of L guarantees a weight of at least $d_o d_i$ at the output of inner code. When the IRCC is a rate-1 code, only $L = 2$ rows are needed regardless of the choice of the outer code.

The performance of CI-1 at mid to high signal to noise ratios (SNR) is dominated by the codewords with the minimum weight $d_o d_i$. Codewords with weight $d_o d_i$ of the concatenation can be generated by s number of codeword of the outer code with weight d_o and considering contributions corresponding to $s = 1$ and 2. When $s = 1$, the placement of 1s of a weight d_o codeword of the outer code in pairs along a row can generate a weight $d_o d_i$ codeword of the SCC. Following [2], the bit error rate (BER) contribution made by such codewords of the SCC, over an additive white Gaussian noise (AWGN) channel with two-sided power spectral density $N_0/2$, can be written as

$$P_{1,CI-1} \approx \frac{m\binom{N_a}{d_a}C_{d_o}}{k_1\binom{n_1\rho}{d_o}} Q\left(\sqrt{2Rd_o d_i \gamma}\right) \qquad (1)$$

where, $m = \min(k_1, d_o)$ is the maximum number of message bits that can generate a codeword of the outer code with weight d_o, $N_a = n_1\rho$ when d_o is even and $N_a = (n_1\rho - 1)$ when d_o is odd, $d_a = \lfloor d_o/2 \rfloor, R = k_1k_2/(n_1n_2)$ is the overall rate of the concatenation, C_{d_o} is the number of codewords of the outer code with weight d_o, $\binom{n}{x} = \frac{n!}{x!(n-x)!}$, $Q(\cdot)$ is the standard Q-function, γ is the bit SNR, and $\lfloor \cdot \rfloor$ denotes the floor function.

In addition, $s > 1$ number of codewords of the outer code each with weight d_o can generate codewords of the concatenation with minimum weight $d_o d_{i,s}$ when the non-zero coded bits of all s codewords of the outer code are placed in the interleaver so that they can generate d_o number of error events in the inner code each with distance $d_{i,s}$. Since such error events can start from any of the L rows and any selection of d_o columns, the BER contribution made by such combinations of s codewords of the outer code each with weight d_o can be written as

$$P_{s,CI-1} \approx \frac{sm\binom{L\rho}{s}\binom{n_1\rho}{d_o}C_{d_o}^s}{k_1\rho\left[L\binom{n_1\rho}{sd_o} + \binom{L}{s}\binom{n_1\rho}{d_o}^s\right]} Q\left(\sqrt{2Rd_o d_{i,s}\gamma}\right) \qquad (2)$$

It is noticed that variations in (1) and (2) achieve interleaver gain as those BER contributions can be lowered by increasing ρ, and these gains are more significant with increasing d_o. Specifically, the error coefficient of $P_{1,CI-1}$ in (1) is on the order of $\rho^{-(d_o/2)}$, while that of $P_{s,CI-1}$ in (2) is on the order of $\rho^{-(sd_o - s - d_o + 1)}$. Hence, the dominant BER contributions with CIr-1 come from $P_{1,CI-1}$ in (1) and $P_{2,CI-1}$ with $s = 2$ in (2). It also follows from (1) and (2) that, for a given total interleaver size $L\rho n_1$, it is desirable to use a smaller value of L, which depends solely on the inner code to ensure d_{SCC} of $d_o d_i$, along with a higher value of ρ to increase the interleaver gain.

III. CI-2 WITH $d_o d_i < d_{SCC} \leq d_o^2 d_i$

A. Inter-row Constraints: In this section, CIr-2 interleavers are designed to guarantee d_{SCC}, in the range $d_o d_i < d_{SCC} \leq d_o^2 d_i$ by increasing the number of rows of a CIr-1 and imposing additional inter-row constraints among rows. In order to simplify the description, we assume a rate-1 IRCC, however, it can be extended to other inner codes too. For example, recall from section II that a CI-1 of an SPC outer code ($d_o = 2$) and a rate-1 IRCC ($d_i = 1$) achieves d_{SCC} of 2. The value of d_{SCC} of this concatenation can be increased to 4 by increasing the number of rows to 4 and adding an inter-row constraint that coded bits of any two codewords on adjacent rows share no more than one common column. Fig. 1 illustrates how coded bits of sixteen codewords of an outer (3,2) SPC code, denoted by letters *a* through *p*, can be placed on such an interleaver by denoting coded bits of any codeword by its codeword letter to achieve d_{SCC} of 4.

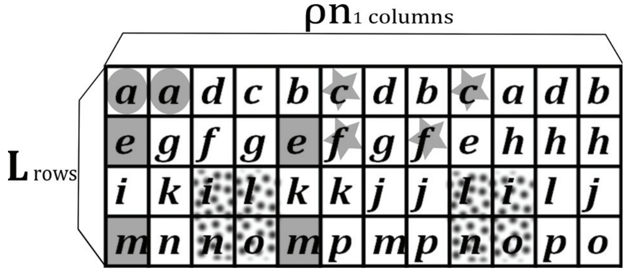

Fig. 1. CI-2 interleaver with $L = 4, \rho = 4$ for (3,2) SPC outer code.

The inter-row constraints can be extended to include rows beyond the immediately previous row. In general, the assignment of coded bits on any i^{th} row can be made dependent up to l_{max} number of previous rows. In this structure, due to the cyclic nature of feeding bits into the inner code by going back to the first row after the L^{th} row, the placement of bits on any $(L-i)^{th}$ row $(i < l_{max})$ depends not only on the l_{max} previous rows and but also on the first $(l_{max} - i)$ rows. In general, any specific inter-row constraint on the i^{th} row $1 < i \leq (L - l_{max})$ can be expressed as: coded bits of any codeword on the i^{th} row can share no more than $k(l)$ common columns with coded bits of any codeword placed on the $(i-l)^{th}$ row, where $l = 1, 2, ..., l_{max}$. As stated before the set of inter-row constraints must be imposed in a cyclic manner meaning that the impact of the inter-row constraints on the k^{th} column of the i^{th} row, for $(L - l_{max}) < i < L$, comes not only from the k^{th} column of $(i-l)^{th}$ row but also from the $(k+1)^{th}$ column of the $(l - L + i)^{th}$ row, for $1 \leq l \leq l_{max}$ and $i > (L - l_{max})$. The value of l_{max} and the set of values $k(l) < d_o, l = 1, 2, ..., l_{max}$, define all parameters of the CI-2. For example, Fig. 1 illustrates a CI-2 with $L = 4, \rho = 4, l_{max} = 1$ and $k(1) = 1$. As with CI-1, CI-2 allows any coded bit to be placed anywhere in the interleaver array, however, due to the inter-row constraints, the number of possible permutations is further limited.

B. Interleaver Construction: Fig. 2 describes the systematic construction of a CIr-2 by placing coded bits of codewords of the outer code one at a time and filling rows one by one. Every coded bit of the outer code is placed on the selected row of the interleaver by (a) removing all columns that would violate any applicable inter-row constraint by placing that bit on any of those columns, and (b) placing that bit on a randomly selected column among the all remaining columns, thereby maximizing the available interleaver gain. The removal of columns is done systematically by considering every applicable inter-row constraint one at a time. The last row, which requires consideration of inter-row constraints from rows $(L - l_{max})$ through

Fig. 2. Systematic construction of CIr-2 with L rows and ρn_1 columns

A. 1^{st} row:

Place ρ randomly selected codewords and uniformly interleave all ρn_1 bits.

B. $1 < i \le (L - l_{max})$ rows:

1) Randomly select ρ codewords from the remaining codewords and randomize coded bits of each codeword separately.
2) Randomly place the first $k_l = \min_l k(l)$ coded bits of all ρ codewords on the i^{th} row.
3) When placing the $k^{th}(k_l < k \le n_1)$ coded bit of any $j^{th}(1 \le j \le \rho)$ codeword: (a) For each $l = 1, 2, ..., l_{max}$ (or applicable), search for codewords on the $(i-l)^{th}$ row that share $k(l)$ columns with already placed $(k-1)$ coded bits of the j^{th} codeword on the i^{th} row. (b) If such codeword/codewords are found, remove all n_1 columns occupied by them. (c) Randomly select a column among the remaining columns for the k^{th} coded bit.

C. $(L - l_{max}) < i \le L$ rows:

Follow the steps in *B*, but modifying steps 3(a) and 3(b) to include searching for codewords on $(l - L + i)^{th}$ row and noticing that column k on i^{th} row corresponds to column $(k + 1)$ on the $(l - L + i)^{th}$ row.

$(L-1)$ and rows 1 through l_{max}, determines the minimum requirement on ρ. Realizing that some of the columns removed due to inter-row constraints from rows $(L - l_{max})$ through $(L-1)$ and rows 1 through l_{max} can be the same, the last (n_1^{th}) bit of a codeword on the L^{th} row requires elimination of at least $\sum_{l=1}^{l_{max}} \lfloor \frac{n_1}{k(l)} \rfloor$ columns of the interleaver array due to all inter-row constraints. Considering filling up the last row, a CI-2 that satisfies all inter-row constraints can be successfully found with a value of

$$\rho \ge 1 + \frac{(n_1 - 1)}{n_1} \sum_{l=1}^{l_{max}} \left\lfloor \frac{n_1}{k(l)} \right\rfloor. \tag{3}$$

The above approach can find a valid CIr-2 numerically with a value of ρ closer to the bound in (3) particularly for larger values of n_1. Further, as with CI-1, the interleaver gain of any CI-2 can be increased by increasing the value of ρ. Since the value of ρ grows with n_1 in a linear manner, in order to limit the size of the interleaver $N = L\rho n_1$, the CI-2 technique is practically limited to only small to medium size outer codes whereas CI-1 can be used with any size of an outer code with any integer ρ.

C. d_{SCC}: The parameters of a CIr-2 are selected to achieve a specific d_{SCC} in the range $d_o d_i < d_{SCC} \le d_o^2 d_i$. The Lemma presented below assists the selection of d_{SCC} and the corresponding parameters.

***Lemma* 1.** *d_{SCC} with CI-2 can be increased up to $d_o^2 d_i$.*

Proof: Starting with a rate-1 IRCC ($d_i = 1$) and considering the codewords of the SCC generated in the following three scenarios: (a) by a single non-zero codeword of the outer code with weight $2\lfloor (d_o + 1)/2 \rfloor$ when all its 1s are placed in pairs on any row (for example, see bits highlighted by (●) as 1s in Fig. 1), (b) by two codewords of the outer code each with weight d_o when placed on rows in the form i and $(i - l_{max} - 1)$ without any influence from inter-row constraints and also placed their 1s on the same set of d_o columns (for example, see bits highlighted by (■) as 1s in Fig. 1), and (c) by two codewords of the outer code each with weight d_o when placed on rows in the form i and $(i - l)$ (where, $l \le l_{max}$) while placing $k(l)$ 1s of each codeword on the same set of columns and the remaining 1s in pairs in consecutive columns (for example, see bits highlighted by (★) as 1s in Fig, 1), d_{SCC} can be bounded as

$$d_{SCC} \le L \left\lfloor \frac{d_o + 1}{2} \right\rfloor, d_{SCC} \le d_o(l_{max} + 1). \tag{4}$$

$$d_{SCC} \le lk(l) + [d_o - k(l)](L - l), l = 1, 2, ..., l_{max}. \tag{5}$$

In addition, even when $k(1) = 1$, two groups of d_o codewords, each with weight d_o, can position their d_o^2 1s in two adjacent rows in the same set of d_o^2 columns without violating any inter-row constraints. Such a codeword of the SCC has distance d_o^2 enforcing the condition $d_{SCC} \le d_o^2$. Noticing that the right hand side of (4) and (5) can be increased by changing its parameters, a CIr-2 can always be designed to increase d_{SCC} to d_o^2. Extending this result to an IRCC with any d_i, the equations similar to (4) and (5) can increase d_{SCC} by adjusting the parameters of CIr-2. However, d_{SCC} is limited by the codeword of the SCC with weight $d_o^2 d_i$ generated by d_o^2 number of columns while each column separately generates a sequence with weight d_i in the inner code, thereby proving the Lemma. ■

A CIr-2 can be systematically constructed by (a) selecting a desired d_{SCC} $(d_o d_i < d_{SCC} \le d_o^2 d_i)$, (b) selecting the parameters L, ρ, l_{max}, and $k(1), k(2), ..., k(l_{max})$ to maintain that d_{SCC}, (c) selecting ρ according to (3), and (d) following steps in Fig. 2. In CIr-2 design, it is also desirable to use $k(l) = 1$ for all $l = 1, 2, .., l_{max}$ to maximize the interleaver gain despite a slight increase in interleaver size.

D. Performance: Similar to CI-1, the performance of CI-2 with a rate-1 IRCC is dominated by the contributions made by one or two codewords of the outer code with weight d_o when $d_o > 2$. These contributions can be found from (1) and (2), however by adjusting them according to the inter-row constraints. Following the construction of CI-2, the number of ways one or two codewords with weight d_o can be placed in the interleaver is reduced by the inter-row constraints. Considering the worst case on the last row, the total number of ways a weight d_o codeword can be placed in the interleaver according to the CI-2 constraints can be bounded as $N_{CI-2}(d_o) > \frac{L}{d_o!} \prod_{j=0}^{d_o - 1} (n_1\rho - xj)$, where, $x = 2\sum_{l=1}^{l_{max}} \lfloor \frac{n_1}{k(l)} \rfloor$. Hence, the performance of a CI-2 scheme with $k(l) = 1$ for $l = 1, 2, .., l_{max}$ can be found by modifying (1) and (2) as

$$P_{1,CI-2} \approx \frac{m\binom{N_a}{d_a} C_{d_o}}{k_1[N_{CI-2}(d_o)]/L} Q\left(\sqrt{2Rd_{1,CI-2}\gamma}\right) \tag{6}$$

$$P_{2,CI-2} \approx \frac{2m\binom{L\rho}{2}\binom{n_1\rho}{d_o}[2^{d_o} - 1]C_{d_o}^2}{D_{P_{2,CI-2}}} Q\left(\sqrt{2Rd_o(l_{max} + 1)\gamma}\right) \tag{7}$$

respectively, where $d_{1,CI-2} = Ld_o/2$ when d_o is even and $d_{1,CI-2} = 1 + L(d_o - 1)/2$ when d_o is odd, and $D_{P_{2,CI-2}} = k_1\rho[\frac{L}{(2d_o)!} \prod_{j=0}^{(d_o - 1)} (n_1\rho - jx)(n_1\rho - jx - n_1) + \binom{L}{2} [N_{CI-2}(d_o)/L]^2]$. When $d_o = 2$ (as with an SPC code), the contribution from four codewords, two each on two consecutive rows (as illustrated by (dots) as 1s in Fig. 1), which can be calculated by extending that of two codewords, should

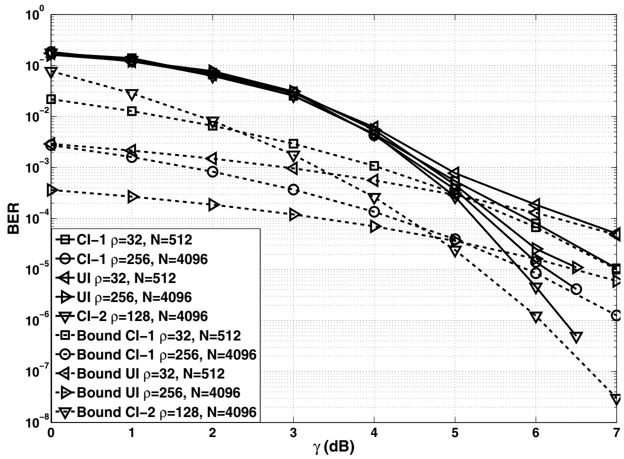

Fig. 3. Numerical results of a (8,7) SPC outer code and a rate-1 inner code.

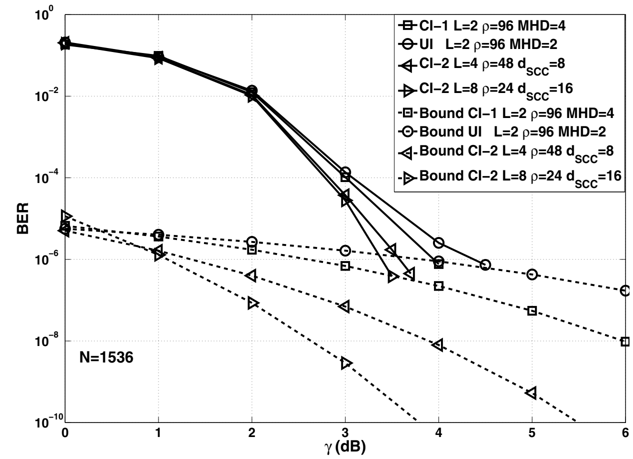

Fig. 4. Numerical results of a (8,4) BCH outer code and a rate-1 inner code.

also be considered. Compared with CI-1, it is noticed that CI-2 increases d_{SCC}, however, at the expense of some interleaver gain.

IV. Comparison and Numerical Results

In this section, we compare CI-1 and CI-2 with UI for the same combination of component codes and interleaver size $N = L\rho n_1$. The primary BER contribution with UI is generated by sequences of weight $d_p d_{i,2}$ originated by a single codeword with weight $2d_p$ of the outer code, where $d_p = \lfloor (d_o+1)/2 \rfloor$. Following the analysis in the previous sections, the contribution made by such codewords with weight d_p of the concatenation with UI is

$$P_{1,uni} \approx \frac{m_{2d_p}\binom{N}{d_p}C_{2d_p}}{k_1\binom{N}{2d_p}} Q\left(\sqrt{2Rd_p d_{i,2}\gamma}\right) \qquad (8)$$

where, m_{2d_p} is the average number of message bits that can generate a codeword of the outer code with weight $2d_p$. Focusing on the dependence of the error coefficients of (1) and (8) on ρ, it can be seen that they all have the same order of dependence of $\rho^{-d_o/2}$, while (1) of CI-1 has a higher distance. Hence, CI-1 performs better than UI due to increased d_{SCC}, while preserving most of the interleaver gain achieved by UI.

Figs. 3 and 4 show the BER variations of CI-1, CI-2 and UI techniques, when the inner code is a rate-1 IRCC, which is also known as the accumulator [1], and the outer code is an (8,7) SPC code and an (8,4) BCH code (that has $d_o = 4$) [1] respectively. In Figs. 3 and 4, we present the performance bounds of CI-1 (given by the combination of (1) and (2)) and of UI (given by (8)) along with the respective simulations. It is seen that the simulation results match well with the bounds, and CI-1 performs significantly better than UI particularly at higher SNR values lowering the error floor. It is also seen that CI-1 achieves interleaver gains similar to those of UI and they can perform similar to UI even at much lower interleaver sizes. Figs. 3 and 4 also present the performance of CI-2. Specifically, Fig. 3 shows the performance of CI-2 with $L = 4$, $l_{max} = 1$ and $k(1) = 1$ which achieves $d_{SCC} = 4$, while Fig. 4 shows the performance of CI-2 with $L = 4$, $l_{max} = 1$, $k(1) = 1$, $d_{SCC} = 8$ and $L = 8$, $l_{max} = 3$, $k(1) = k(2) = k(3) = 1$, $d_{SCC} = 16$. The performance bounds of CI-2 are calculated as explained in section III by modifying (1) and (2). Comparing schemes with CI, it is seen that CI-2 can perform significantly better than CI-1. All schemes considered here are decoded using the standard soft-in soft-out (SISO) decoding [1], [2] with four iterations and exchanging extrinsic information between component codes. Finally, as with the construction of any random interleaver, any specific interleaver designed according to CI-1 and CI-2 can have a MHD above their respective minimum possible values.

V. Conclusions

A CI technique has been proposed to improve serially concatenated codes (SCCs) with inner recursive convolutional codes (IRCCs). CI that uses a first set of constraints, CI-1, to achieve a MHD for the SCC, d_{SCC}, equal to $d_o d_i$ while preserving most of the benefits of UI has been discussed, where d_o and d_i are the MHD of the outer and inner code respectively. In addition, by imposing additional inter-row constraints on CI-1, a CI-2 technique that trades off some interleaver gain to increase d_{SCC} up to $d_o^2 d_i$ has also been presented. Performance bounds with CI-1 and CI-2 have been derived and verified numerically. It has been demonstrated that CI-1 and CI-2 techniques can generate powerful SCCs with high MHD and high interleaver gain at smaller interleaver sizes.

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