VI. CONCLUSION

The distributions of loop lengths in the graphical models for turbo decoding were analyzed and simulated. Short loops (e.g., of length $c \leq 8$) occur with relatively low probability at any randomly chosen node. As the loop length increases, there is a threshold effect and the probability of finding a loop of length c or less approaches 1 (e.g., for $c > 20$). For turbo codes, as K, the number of information bits, becomes large, the probability that a loop of length c or less exists at any randomly chosen node behaves approximately as $e^{-\frac{2^{C-1}-4}{K}}$, $c \geq 4$. In summary, the results in this correspondence demonstrate that the loop lengths in the graphical models of turbo codes and LDPC codes have a specific distributional character. We hope that this information can be used to further understand the workings of iterative decoding.

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Constructions for Perfect 2-Burst-Correcting Codes

Tuvi Etzion, *Senior Member, IEEE*

***Abstract*—In this correspondence, we present two constructions. In the first construction, we show how to generate perfect linear codes of length 2^{r-1}, $r \geq 5$, and redundancy r, which correct a single burst of length 2. In the second construction, we show how to generate perfect linear codes organized in bytes of length 2^{r-1}, $r \geq 5$, with redundancy divisible by r, which correct a single burst of length 2 within the bytes.**

***Index Terms*—Byte-organized memory, perfect codes, syndromes, 2-burst-correcting codes.**

I. INTRODUCTION

In many memory systems the most common error is a burst of errors. Some memories are byte-oriented and in these memories the burst can occur only within the bytes. In this correspondence, we consider constructions of perfect 2-burst-correcting codes of these types.

All codes considered in this correspondence are binary codes. Let (n, k) code denote a linear code of length n and dimension k. The redundancy r of such a code is $r = n - k$. A code is called a b-*burst-correcting code* if it can correct any single burst of length b or less. A code is called *cyclic* b-*burst-correcting code* if it can correct any single cyclic burst of length b or less. Note that in other papers, e.g., [1], a b-burst-correcting code can correct cyclic bursts. Reiger [8] has proved that an $(n, n-r)$ b-burst-correcting code (or cyclic b-burst-correcting code) must satisfy

$$r \geq 2b. \tag{1}$$

For an $(n, n-r)$ cyclic b-burst-correcting code, there are $n2^{b-1}$ different cyclic bursts of length up to b, each one corresponding to a different nonzero syndrome. Since the number of nonzero vectors of length r is $2^r - 1$, it follows that $2^r - 1 \geq n2^{b-1}$. Abramson [2] noted that this inequality, along with the fact that n is an integer, implies

$$n \leq 2^{r-b+1} - 1. \tag{2}$$

A cyclic b-burst-correcting code which satisfies (2) with equality is said to be *optimum*. Abramson [2] has constructed optimum cyclic 2-burst-correcting codes for any $r \geq 3$. Elspas and Short [5] constructed such codes for $b = 3$ and $b = 4$, Abdel-Ghaffar, McEliece, Odlyzko, and van Tilborg [1] have shown that infinitely many optimum codes exist for each $b \geq 1$. It is clear that if a code satisfies (2) with equality then $2^r - 1 > n2^{b-1}$ (when $b > 1$), i.e., not all nonzero vectors of length r are syndromes obtained as sums of at most b adjacent columns. Therefore, these optimum codes are not perfect. For an $(n, n-r)$ b-burst-correcting code, there are $(n-b+2)2^{b-1} - 1$ different bursts of length up to b, each one corresponding to a different nonzero syndrome. Again, since the number of nonzero vectors of length r is $2^r - 1$, it follows that $2^r - 1 \geq (n-b+2)2^{b-1} - 1$, i.e.,

$$n \leq 2^{r-b+1} + b - 2. \tag{3}$$

A b-burst-correcting code which satisfies (3) with equality is said to be *perfect* (or “complete”as called by Reiger [8]). No perfect b-burst-

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The author is with the Computer Science Department, Technion–Israel Institute of Technology, Haifa 32000, Israel (e-mail: etzion@cs.technion.ac.il).

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correcting code is known to date. In this correspondence, we will give constructions for perfect 2-burst-correcting codes. Some of these codes will be byte-oriented codes. For more information on byte-oriented error-correcting codes, burst-correcting codes, and their applications, the reader is referred to [3], [4], [7].

The rest of this correspondence is organized as follows. In Section II, we will construct a $(2^{r-1}, 2^{r-1}-r)$ perfect 2-burst-correcting code for each $r \geq 5$. In Section III, we construct perfect codes which correct a single burst of length 2 within bytes of sizes 2^{r-1}, $r \geq 5$, for each redundancy which is divisible by r. We also construct perfect codes which correct a single burst of length 2 within bytes of length 3 for each redundancy divisible by 4. Conclusion and a list of open problems are given in Section IV.

II. Perfect Burst-Correcting Codes

In this section, we show that for each $r \geq 5$ there exists a $(2^{r-1}, 2^{r-1}-r)$ perfect 2-burst-correcting code. For a parity-check matrix $H = [h_1, h_2, \ldots, h_n]$ of an (n, k) code C, let $S(H)$ denote the set of syndromes obtained from single columns and two adjacent columns, i.e.,

$$S(H) = \{h_i \colon 1 \leq i \leq n\} \cup \{h_i + h_{i+1} \colon 1 \leq i \leq n-1\}.$$

C is a perfect 2-burst-correcting code if every nonzero column vector of length r belongs to $S(H)$ and

$$\{h_i \colon 1 \leq i \leq n\} \cap \{h_i + h_{i+1} \colon 1 \leq i \leq n-1\} = \emptyset.$$

By (1) there is no 2-burst-correcting code for redundancy less than 4. It can be easily verified by simple backtracking that an $(8, 4)$ 2-burst-correcting code does not exist. Perfect 2-burst-correcting codes for redundancies 5 and 6, i.e., perfect $(16, 11)$ and perfect $(32, 26)$ 2-burst-correcting codes, respectively, were obtained by computer search. Their parity-check matrices are given below.

$$\begin{bmatrix} 1000101010000101 \\ 0100001001101011 \\ 0010101000110010 \\ 0001000110101101 \\ 0000010101010110 \end{bmatrix}$$

$$\begin{bmatrix} 10001001110101110011110010011100 \\ 01000101000110110000100101101111 \\ 00101001000000001011011010101010 \\ 00010100100100000101101011011111 \\ 00000010010010101010111011111110 \\ 00000000001001010101010101010101 \end{bmatrix}.$$

Given an $r \times 2^{r-1}$ parity-check matrix H for a perfect 2-burst-correcting code we construct the following four matrices:

$$\tilde{H}_1 = \begin{bmatrix} H \\ T_1 \end{bmatrix} \text{ where } T_1 = \begin{bmatrix} 1 & 1 & 1 & 1 & \cdots & 1 & 1 \\ 0 & 1 & 0 & 1 & \cdots & 0 & 1 \end{bmatrix}$$

$$\tilde{H}_2 = \begin{bmatrix} H \\ T_2 \end{bmatrix} \text{ where } T_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 \end{bmatrix}$$

$$\tilde{H}_3 = \begin{bmatrix} H \\ T_3 \end{bmatrix} \text{ where } T_3 = \begin{bmatrix} 1 & 0 & 1 & 0 & \cdots & 1 & 0 \\ 1 & 1 & 1 & 1 & \cdots & 1 & 1 \end{bmatrix}$$

$$\tilde{H}_4 = \begin{bmatrix} H \\ T_4 \end{bmatrix} \text{ where } T_4 = \begin{bmatrix} 0 & 1 & 0 & 1 & \cdots & 0 & 1 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 \end{bmatrix}$$

Lemma 1: Each column vector of length $r+2$ which does not begin with r zeros appears exactly once either as a column of one of the $\tilde{H}_i$'s or as a sum of two adjacent columns from one of the $\tilde{H}_i$'s.

Proof: The proof follows immediately from the following observations.

- In each position the four T_i's have exactly the four possible 2-tuples.
- In each pair of adjacent positions, the adjacent columns in the four T_i's sum exactly to the four possible 2-tuples.
- Each nonzero column vector of length r appears exactly once either as a column or as sum of two adjacent columns from H. $\square$

For an $r \times n$ matrix

$$F = [\, f_1 \quad f_2 \quad f_3 \quad \cdots \quad f_{n-2} \quad f_{n-1} \quad f_n \,]$$

let

$$\begin{aligned} p(F) &= [\, f_1 + f_2 \quad f_2 \quad f_3 \quad \cdots \quad f_{n-2} \quad f_{n-1} \quad f_n \,] \\ s(F) &= [\, f_1 \quad f_2 \quad f_3 \quad \cdots \quad f_{n-2} \quad f_{n-1} \quad f_{n-1} + f_n \,] \\ e(F) &= [\, f_1 + f_2 \quad f_2 \quad f_3 \quad \cdots \quad f_{n-2} \quad f_{n-1} \quad f_{n-1} + f_n \,] \\ F^R &= [\, f_n \quad f_{n-1} \quad f_{n-2} \quad \cdots \quad f_3 \quad f_2 \quad f_1 \,]. \end{aligned}$$

The following lemma is a simple observation.

Lemma 2: For any $r \times n$ parity-check matrix H

$$S(H) = S(p(H)) = S(s(H)) = S(e(H)) = S(H^R).$$

We are now in a position to state our main result.

Theorem 1: If $H = [h_1 \, h_2 \cdots h_n]$ is an $r \times n$, $n = 2^{r-1}$, parity-check matrix of a perfect 2-burst-correcting code then the matrix shown at the bottom of the page is an $(r+2) \times 2^{r+1}$ parity-check matrix of a perfect 2-burst-correcting code.

Proof: Clearly, we need only to prove that every nonzero vector of length $r+2$ is a column of $\tilde{H}$ or the sum of two adjacent columns of $\tilde{H}$.

Let $\tilde{X} = (x_1, \ldots, x_r, x_{r+1}, x_{r+2})$ be a nonzero vector of length $r+2$ and $X = (x_1, \ldots, x_r)$. Let Y^t denote the transpose of Y. We distinguish between two cases.

Case 1: If X is a nonzero vector then by Lemmas 1 and 2 $\tilde{X}^t$ is either a column of $\tilde{H}$ or the sum of two adjacent columns of $\tilde{H}$.

Case 2: X is the allzero vector.

- If $(x_{r+1}, x_{r+2}) = (1, 1)$ then $\tilde{X}^t$ is the sum of the last column of $\tilde{H}_1$ and the first column of $s(\tilde{H}_2^R)$.
- If $(x_{r+1}, x_{r+2}) = (1, 0)$ then $\tilde{X}^t$ is the sum of the last column of $s(\tilde{H}_2^R)$ and the first column of $e(\tilde{H}_3)$.
- If $(x_{r+1}, x_{r+2}) = (0, 1)$ then $\tilde{X}^t$ is the sum of the last column of $e(\tilde{H}_3)$ and the first column of $p(\tilde{H}_4^R)$. $\square$

Combining Theorem 1, the perfect $(16, 11)$ 2-burst-correcting code, and the perfect $(32, 26)$ 2-burst-correcting code given above we have the following.

Corollary 1: For each $r \geq 5$, there exists a perfect $(2^{r-1}, 2^{r-1}-r)$ 2-burst-correcting code.

$$\tilde{H} = [\, \tilde{H}_1 \quad s(\tilde{H}_2^R) \quad e(\tilde{H}_3) \quad p(\tilde{H}_4^R) \,]$$

$$= \left[\begin{array}{ccccc|ccccc|ccccc|ccccc} h_1 & h_2 & \cdots & h_{n-1} & h_n & h_n & h_{n-1} & \cdots & h_2 & h_2 + h_1 & h_1 + h_2 & h_2 & \cdots & h_{n-1} & h_{n-1} + h_n & h_n + h_{n-1} & h_{n-1} & \cdots & h_2 & h_1 \\ 1 & 1 & \cdots & 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 1 & 0 & \cdots & 1 & 1 & 1 & 0 & \cdots & 1 & 0 \\ 0 & 1 & \cdots & 0 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 1 & \cdots & 1 & 0 & 1 & 1 & \cdots & 0 & 1 \end{array}\right]$$

III. Codes for Byte-Oriented Memories

As said in the Introduction, we are also interested in perfect burst-correcting codes within bytes of size β. If the codes are constructed for a byte-oriented memory with bytes of size β, then when we say that the code is b-burst-correcting meaning that it corrects a single burst of length b within the bytes of size β. One example is a perfect $(9, 5)$ 2-burst-correcting code which corrects a single burst of length 2 or less within bytes of size 3. Its parity-check matrix is

$$\begin{bmatrix} 110 & 110 & 100 \\ 101 & 101 & 000 \\ 111 & 001 & 010 \\ 011 & 110 & 001 \end{bmatrix}.$$

We first want to give a necessary condition for the existence of perfect 2-burst-correcting codes with bytes of length β. The number of different bursts of length 2 or less within a byte is $2\beta - 1$. The total number of nonzero vectors of length r is $2^r - 1$ and hence the total number of bytes in such a code with redundancy r is $\frac{2^r-1}{2\beta-1}$. Therefore,

$$2^r - 1 \equiv 0 \, (\mathrm{mod}\, 2\beta - 1). \tag{4}$$

In the most interesting case, when β is a power of 2, say $\beta = 2^\rho$, the necessary condition (4) implies that $2^r - 1$ is divisible by $2^{\rho+1} - 1$, i.e., $\rho + 1$ divides r. We will show that, in this case, the necessary condition is also sufficient.

Assume now that $2^r - 1 = m(2\beta - 1)$ and there exists a perfect 2-burst-correcting code of length $m\beta$ with m bytes of size β, and redundancy r. We will describe now how to construct the parity-check matrix of a perfect 2-burst-correcting code of length $mt\beta$ and redundancy rs, where $t = (2^{sr} - 1)/(2^r - 1)$, with mt bytes of size β, for any $s > 1$.

Let $H = [h_1\, h_2 \cdots h_n]$, $n = m\beta$, be the parity-check matrix of a perfect $(m\beta,\, m\beta - r)$ 2-burst-correcting code with bytes of size β. Viewing the columns of H as elements of GF$\,(2^r)$ we find a vector $(a_1\, a_2 \cdots a_n)$, where $a_i \in$ GF$\,(2^r)$, such that the sums of at most two adjacent elements within the bytes of size β give each of the nonzero elements of GF$\,(2^r)$ exactly once.

Let α be a primitive element of GF$\,(2^{rs})$. Then it has the subfield

$$\mathrm{GF}\,(2^r) = \{0\} \cup \{\alpha^{jt}:\, 0 \le j \le 2^r - 2\}.$$

If we denote $F^* = \mathrm{GF}\,(2^r) \setminus \{0\}$, then

$$\mathrm{GF}\,(2^{rs}) \setminus \{0\} = F^* \cup \alpha F^* \cup \alpha^2 F^* \cup \cdots \cup \alpha^{t-1} F^*.$$

But, then the vector

$$v = (v_0\, v_1\, \cdots\, v_{t-1}) \in \mathrm{GF}\ (2^{rs})^{mt\beta}$$

where $v_i = (\alpha^i a_1\, \alpha^i a_2\, \cdots\, \alpha^i a_n)$, for each i, $0 \le i \le t-1$, has the property that the sums of at most two adjacent elements within the byte of size β give each of the nonzero elements of GF$\,(2^{rs})$ exactly once. Viewing the columns as binary vectors of dimension rs we obtain the following result.

Theorem 2: If there exists a perfect $(m\beta,\, m\beta - r)$ 2-burst-correcting code with bytes of size β, then there exists a perfect $(mt\beta,\, mt\beta - rs)$ 2-burst-correcting code with bytes of size β, where $t = (2^{sr} - 1)/(2^r - 1)$, for any $s > 1$.

Combining Theorem 2 with the perfect $(2^{r-1},\, 2^{r-1} - r)$ 2-burst-correcting codes, $r \ge 5$, obtained in Section II and the perfect $(9, 5)$ 2-burst-correcting code with bytes of size 3 obtained in this section we have the following.

Corollary 2: There exists a perfect $(n,\, n - \rho)$ 2-burst-correcting code with bytes of size 2^{r-1}, $r \ge 5$, for each redundancy ρ, $\rho \equiv 0\,(\mathrm{mod}\, r)$.

Corollary 3: There exists a perfect $(n,\, n - \rho)$ 2-burst-correcting code with bytes of size 3, for each redundancy ρ, $\rho \equiv 0\,(\mathrm{mod}\, 4)$.

Finally, we want to remark that the construction given and Theorem 2 apply also for perfect b-burst-correcting code with $b > 2$. For example, it can be applied when the length of the burst is the same as the length of the byte (see [6]).

IV. Conclusion

We gave a construction for perfect $(2^{r-1},\, 2^{r-1} - r)$ 2-burst-correcting code for each $r \ge 5$. We also gave a construction for a perfect 2-burst-correcting codes for byte-oriented memories. The construction yields codes which are organized in bytes of length 2^{r-1}, $r \ge 5$, for each redundancy ρ, $\rho \equiv 0\,(\mathrm{mod}\, r)$. The construction also yields perfect 2-burst-correcting codes with bytes of size 3 for each redundancy ρ divisible by 4.

The bound given in (3) does not exclude the existence of perfect b-burst-correcting codes for each $b \ge 2$, and each redundancy r, $r \ge 2b$, as implied by (1). We conjecture that for $r = 2b$ no such code exists, but it is an intriguing question whether such codes for $r > 2b$ and $b > 2$ exist.

Another interesting question is whether there exist perfect 2-burst-correcting codes for nonbinary alphabets. Two problems should be solved in this context. The first is to find some seed codes and the second is to give a recursive construction for such codes. We note that the recursive construction given in Section II does not work for nonbinary alphabets.

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