Coding for Resistive Random-Access Memory Channels

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***Abstract*—We propose channel coding techniques to mitigate both the sneak-path interference and the channel noise for resistive random-access memory (ReRAM) channels. The main challenge is that the sneak-path interference within one memory array is data-dependent. We propose an across-array coding scheme, which assigns a codeword to multiple independent memory arrays. Since the coded bits from different arrays experience independent channels, a "diversity" gain can be obtained during decoding, and when the codeword is adequately distributed, the code performs as that over an independent and identically distributed (i.i.d.) channel without data-dependency. We also present a real-time channel estimation scheme and a data shaping technique to improve the decoding performance.**

I. Introduction

Resistive random-access memory (ReRAM) is an emerging non-volatile memory technology that stores data via memristors. The memristor cells are arranged in a crossbar structure, which offers a huge density advantage. A fundamental drawback of the ReRAM crossbar array is the existence of the sneak paths, which are undesirable paths in parallel to the selected cell for reading. Works [1]–[3] tackled the sneak-path problem by using information and communication theoretical frameworks. Y. Ben-Hur [2] and Zehui *et al.* [3] considered ReRAM systems with imperfect cell selectors which fail with a certain probability. They proposed a probabilistic sneak-path model and developed the corresponding data detection schemes. However, no error correction code (ECC) was employed in previous research works. A main challenge for the ECC design is that the sneak-path interference within one crossbar array is data-dependent and hence the conventional error correction coding scheme will be inadequate.

In this paper, we propose an across-array coding scheme for ReRAM channel which spreads a codeword to multiple independent memory arrays. Since the coded bits from different arrays experience independent channels, a "diversity" gain is acquired during decoding, and when the codeword is adequately distributed, the code performs as that over an independent and identically distributed (i.i.d.) channel without data-dependency. We also present a real-time channel estimation scheme together with an elementary signal estimator (ESE) to obtain the instant channel status, as well as the soft information of the channel coded bits for decoding. A data shaping technique is further adopted to improve the decoding performance.

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II. ReRAM Channel Model

Consider an $m \times n$ crossbar memory array. The memristor that lies at the intersection of row i and column j denotes memory cell (i, j). Each array is able to store an $m \times n$ binary data matrix $\boldsymbol{X} = [x_{i,j}]_{m\times n}$, where bit $x_{i,j} \in \{0, 1\}$ is stored in memory cell $(i, j), i \in \{1, ..., m\}, j \in \{1, ..., n\}$. The two resistance states of a memristor, High-Resistance State (HRS) R_0 and Low-Resistance State (LRS) R_1, represent the two logical values 0 and 1 of a bit. During read, the data bit can be detected by measuring the resistance value of the corresponding cell. However, due to the existence of the sneak-path interference and channel noise, the memory reading becomes unreliable [2], [3]. We define a sneak-path event indicator $e_{i,j}$ for cell (i, j) to be a Boolean variable with the value $e_{i,j} = 1$ if the cell (i, j) is affected by sneak paths, otherwise, $e_{i,j} = 0$.

An *ReRAM channel* with input data $\boldsymbol{X} \in \{0,1\}^{m\times n}$ and readback signal $\boldsymbol{Y} \in \mathcal{R}^{m\times n}$ is specified as:

$$y_{i,j} = \begin{cases} (\frac{1}{R_0} + \frac{e_{i,j}}{R_s})^{-1} + \eta_{i,j} & \text{if } x_{i,j} = 0, \text{ with Prob. } 1-q \\ R_1 + \eta_{i,j} & \text{if } x_{i,j} = 1, \text{ with Prob. } q \end{cases} \quad (1)$$

where R_s is the parasitic resistance value brought by sneak paths. Here $\eta_{i,j} \sim \mathcal{N}(0, \sigma^2), i = 1, ..., m, j = 1, ..., n$ is an additive white Gaussian noise (AWGN) with 0 mean and variance σ^2. Note that $\frac{e_{i,j}}{R_s}$ is an interference term when input data bit $x_{i,j} = 0$, and the sneak-path event indicators $e_{i,j}, i \in \{1, ..., m\}, j \in \{1, ..., n\}$ are correlated and depend on the whole input data pattern of the array. The details of the sneak path definition and the ReRAM channel model can be found in [2], [3] and the full version of this paper [4].

Our objective is to recover the stored data array $\boldsymbol{X}$ based on the channel readback signal array $\boldsymbol{Y}$ in the presence of sneak-path interference $[e_{i,j}]_{m\times n}$ and Gaussian noise $[\eta_{i,j}]_{m\times n}$. The main challenge for the ECC design is that the sneak-path interference of the ReRAM channel is data-pattern-dependent, while conventional ECCs can only correct i.i.d. errors. To describe the instant channel status of a memory array, we define a *sneak-path rate* $\epsilon = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} e_{i,j}}{mn(1-q)}$, which is the fraction of cells with sneak paths. A higher sneak-path rate indicates a worse channel, and vice versa.

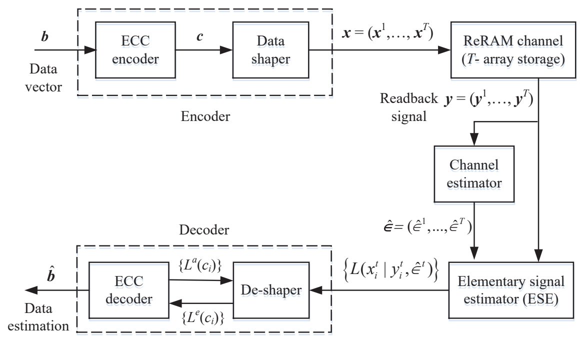

Fig. 1. Proposed coded system for ReRAM.

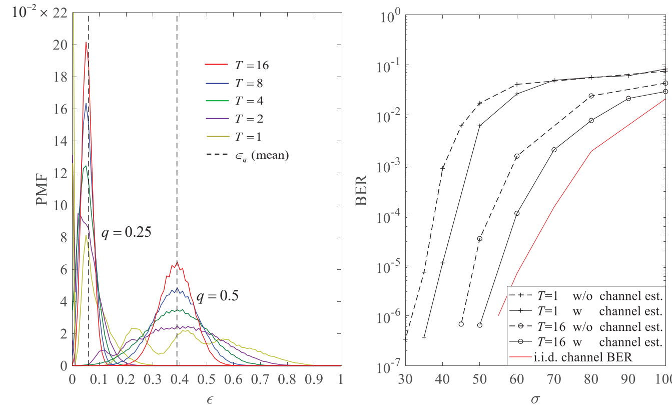

Fig. 2. Simulation results for $m \times n = 64 \times 64$, $R_1 = 100\ \Omega$, $R_0 = 1000\ \Omega$, $R_s = 250\ \Omega$, and selector failure probability 10^{-3}. Left: PMF of sneak-path rate with across-array coding $T = 1, 2, ..., 16$, $q = 0.25, 0.5$. Right: BER of IRA coded ReRAM channel with and without (w/o) channel estimation and $T = 1, 16$.

III. Coding Scheme

Since the ReRAM channel quality is sensitive to the input data pattern within each array, we propose an across-array coding scheme that assigns a codeword to T memory arrays. Since the codeword experiences T independent channels, when T is large, the overall channel quality will approach its average characteristic. We further found that the input data distribution (q) also affects the sneak-path rate as well as the ReRAM channel capacity [4]. Hence we adopt a data shaping technique to form the optimal input data distribution.

Our proposed coded system for ReRAM is shown in Fig. 1. The data vector $\boldsymbol{b}$ is encoded into $\boldsymbol{c}$ by an ECC encoder. The entries of $\boldsymbol{c}$ are uniformly distributed on $\{0, 1\}$. The data shaper reforms the data distribution into Bernoulli (q). The output codeword $\boldsymbol{x} = (\boldsymbol{x}^1, ..., \boldsymbol{x}^T)$ of length N is assigned to T memory arrays with $\boldsymbol{x}^t$ being assigned to the t-th memory array. Since each memory array is of size $m \times n$, mnT/N codewords can be stored by these T memory arrays, where mnT/N is assumed to be an integer. If the code rate is R, the storage efficiency is R bits/cell.

Each codeword is decoded independently based on the corresponding channel readback signal. Consider the decoding of the codeword $\boldsymbol{x}$ whose readback signals from the ReRAM channel is $\boldsymbol{y} = (\boldsymbol{y}^1, ..., \boldsymbol{y}^T)$. Since the channel varies from memory array to array, based on $\boldsymbol{y}$, a channel estimator first estimates the sneak-path rates $\hat{\boldsymbol{\epsilon}} = (\hat{\epsilon}^1, ..., \hat{\epsilon}^T)$ for the T memory arrays. Using the obtained $\hat{\boldsymbol{\epsilon}}$ and (1), an ESE calculates the soft estimation $\{L(x_i^t|y_i^t, \hat{\epsilon}^t)\}$, i.e., the log-likelihood ratio (LLR), for each coded bit x_i^t, which is then used as the decoder input. The decoder consists of a de-shaper and an ECC decoder, both of which use soft-in soft-out (SISO) processings and exchange the soft information iteratively to improve the performance of decoding. The details of the data shaper, channel estimator, ESE, and the data de-shaper can be found in the full version of this paper [4].

IV. Numerical Results

To illustrate the advantage of the across-array coding scheme, in Fig 2 (Left), we evaluate the probability mess function (PMF) of the sneak-path rate over one codeword that is stored in $T = 1, 2, 4, 8, 16$ memory arrays. We set the array size and the code length to be $N = m \times n = 64 \times 64$. Observe that as T increases, the spread of the PMF of the sneak-path rate gets smaller and concentrates closer to the mean value and the channel becomes more stable and approaches an average characteristic. The reason is that since the codeword is assigned to T independent memory arrays, the sneak-path rate is averaged over the T arrays. According to the law of large numbers, as $T \to \infty$, the sneak-path rate converges exactly to the mean value ϵ_q, and hence, we can design a code based on this mean value to guarantee error free decoding. We can also see that the mean value of the sneak-path rate ϵ_q is related to the input data distribution q, and hence, we can improve the channel condition by reforming the input data distribution. This is realized by the data shaper in our coded system.

In Fig. 2 (Right), we simulate the BER of irregular repeat-accumulate (IRA) coded ReRAM system with the across-array coding scheme of $T = 1, 16$. The code is designed for the channel with the average sneak path rate ϵ_q using density evolution method (data shaper with $q = 5/16$ is employed) [4]. Observe that the BER with across-array coding of $T = 16$ significantly outperforms that without across-array coding (i.e., $T = 1$) and is close to the BER of the i.i.d. channel (sneak-path interference is added in an i.i.d. way [4]). The performance improvement with increase of T can be considered as a "diversity" gain by assigning the codeword to multiple memory arrays. We also compared the BER between the IRA-coded ReRAM channel with and without channel estimation. Observe that by applying the channel estimation, the BER improvement is obvious for each comparison pair.

References

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