An Efficient Network Coding Scheme with Symbol Combining: Performance Evaluation, Optimization and Comparisons

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***Abstract*—In this paper we investigate the performance advantages achieved by the use of the Symbol Combining (SC) approach in Random Linear Network Coding (RLNC) scheme for broadcast communications over lossy channels. In particular, the focus is on a modified RLNC scheme that makes use of repeated transmissions of each data symbol belonging to the same coded packet in order to implement the SC approach at the receiving ends. By considering as objective metrics the mean number of transmissions and energy consumption for each coded packet, two optimization procedures are proposed and compared in the paper. We considered a broadcast network model where an access point has to broadcast coded packets to a set of receiving nodes. In addition to that, the analysis presented in the paper is extended to broadcast communications in butterfly topology networks. For all the considered scenarios, the better behavior of the symbol combined RLNC scheme results clearly evident in comparison with the basic RLNC, without requiring additional implementation complexity at each receiving ends.**

***Index Terms*—Network Coding, Lossy Wireless Networks, Delay and Energy Optimization.**

I. Introduction

Network Coding (NC) principle [1] is receiving a great attention as an effective way of improving capacity of both wired and wireless networks, also including sensor [2] and vehicular [3] networks. Actually, the Random Linear Network Coding (RLNC) [4] approach represents the simplest and the most efficient way to implement the NC communication principle. A specific feature of RLNC is to allow, at *some* transit nodes, the algebraic combination of data packets (*encoding*) belonging to independent incoming flows.

It has been proved in [5] that RLNC achieves the *min-cut* flow in broadcast scenarios and allows to improve network capacity in the case of lossy links [6]. However, in this case independently from the error control protocol in use, higher packet error rates increase the delivery delay and introduce a severe degradation of the overall network performance. To counteract this drawback, several approaches have been proposed in the literature, including in particular the integration of the RLNC with Automatic Repeat-reQuest (ARQ) [4] or even Hybrid ARQ (HARQ) schemes [7]–[9]. Among novel proposals, Chiti *et al.* [10] outlines a power adaptation performed on a link basis, in order to increase the communication reliability. In particular this approach can be considered as an ideal realization of the well known Chase combining principle [11] widely adopted in the case of ARQ systems.

This paper deals with the performance evaluation and optimization of a novel RLNC scheme suitable for *burst* communications over lossy links, named Symbol Duration Increased-NC (SDI-NC), in which the Symbol Combining (SC) principle [11] is adopted. The idea underlying the SDI-NC scheme consists of transmitting packets where the symbol duration is increased by a fixed (and integer) factor.

Suitable optimization procedures have been proposed in the paper for SDI-NC scheme by focusing first of all on a broadcast network model. Numerical results are also provided to demonstrate the better behavior of the SDI-NC scheme with respect to the classical RLNC alternative. Finally, the paper considers the extension toward a butterfly topology network [4]. Also in this case the SDI-NC scheme outperforms the classical RLNC.

The remaining part of the paper is organized as follows: Sec. II provides a quick overview about the RLNC and related works. Sec. III describes the SDI-NC principle on a link-to-link basis by considering an AWGN and a slow fading regime; two optimization methods are proposed in this Section. Sec. IV generalizes the proposed scheme to the widely considered case of a butterfly network model. Besides Sec. V presents an extensive performance comparison among the classic RLNC and the proposed SDI-NC schemes. Finally, in Sec. VI conclusions are drawn.

II. Background and Related Works

A. Random Linear Network Coding Communication Strategy for Block Communications

Let $\mathbf{E} = \{\mathbf{e_1}, \mathbf{e_2}, \ldots, \mathbf{e_N}\}$ be a message composed of N packets (in the rest of the paper we will refer to it as "generation length"), each formed by J elements (belonging to a finite field and L/J bits long), where L is the packet length (in bits). Note that $\mathbf{E}$ can be alternatively modeled as a $J \times N$ matrix ($\mathbf{M_E}$) where the i-th column is defined by the i-th packet, $i = 1, \ldots, N$, will be transmitted. In this paper we will refer to the RLNC, where coded packets are generated by a linear combination of the original ones. The j-th coded packet $\hat{\mathbf{e}}_\mathbf{j}$ can be computed as follows:

$$\hat{\mathbf{e}}_\mathbf{j} = \mathbf{M_E} \cdot \mathbf{c_j} \ , \quad (1)$$

where $\mathbf{c_j} = [c_{1,j}, c_{2,j} \ldots, c_{N,j}]^T$ is an N-dimensional column vector (called "coding vector"), whose elements are randomly

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chosen. Finally, $\mathbf{c_j}$ and $\mathbf{e_j}$ (for all $j = 1, 2, \ldots, N$) belongs to a large enough finite field $\mathcal{G}_q$ of size q [12]. According to this, a transmitting node can compute $K = N + G$ coded packets where G represents the introduced redundancy. Parameter G is directly related to three parameters [13], [14]: q, N and the packet delivery probability.

From the main theorem of NC [12] and the basic properties of the RLNC [15], we have that a receiving node needs to collect at least N linearly independent coded packets to successfully recover the message $\mathbf{E}$.

Since coding vectors are randomly chosen, the probability that two coded packets are linearly dependent is nonzero. Hence, the transmitter node usually needs to broadcast K coded packets in order to assure a successfully decoding of a generation [16].

In order to recover the transmitted message, each receiver needs to know the coding vector associated to a given coded packet. So that, the nominal size of each coded packet has to be increased no more than $N \log_2(q)$ bits [17]. By considering the fact that usually coding vectors are quite sparse, several approaches have been proposed [17], [18] to reduce such kind of overhead. However, this particular aspect is out of the scope of this paper. Hence, we assumed that the coding vectors are known at the receiving ends.

At the receiver side each coded packet (linearly independent with the already received ones) and its corresponding coding vector (locally retrieved), defines a column of the $\mathbf{M_{\hat{E}}}$ and $\mathbf{C}$ matrices (of dimensions $J \times N$ and $N \times N$), respectively [12]. When the number of linearly independent coded packets is equal to N, the original message can be computed as follows:

$$\mathbf{M_E} = \mathbf{M_{\hat{E}}} \cdot \mathbf{C}^{-1} \ . \tag{2}$$

B. Related Works

The multimedia broadcasting (or multicasting) over a 4G networks will be in the near future a key commercial service [19]. Usually, users belonging to the same broadcast group are spread over a wide area and suffer of different propagation conditions. In such an environment, suitable techniques to preserve data integrity without loosing the throughput performance and power constraints in transmission are needed in order to guarantee a suitable quality of all the services provided to all the users. As an example, Kim *et al.* [20] proposed an optimized version of the well known Hybrid ARQ (HARQ) strategy adopting the classical SC principle. However, in this case we have to face with a severe limitation represented by the fact that every single packet needs to be acknowledged to the transmitting node.

This drawback can be overcome by resorting to the RLNC. In particular, Eryilmaz *et al.* [21] have proposed an interesting investigation of the application of the RLNC to ensure the data integrity in broadcast communications. In particular, the paper describes a strategy to counteract channel erasures by an optimized scheduling scheme and derives theoretical bounds under the assumption of a communication channel modeled as an ON/OFF Markov chain. After that, Ghaderi *et al.* proved in [6] that the RLNC can be efficiently used to replace classical ARQ schemes as error control strategy.

Finally, in [22], [23] it was proposed an optimized NC scheme with the aim of minimize the packet losses at the receiving nodes. However, the NC-based principle is adopted limited to packets that have been received with errors by (at least) a receiving node, consequently this strategy cannot fully exploit all the NC benefits highlighted in [6].

III. Symbol Combining Network Coding Principle

This Section deals with the investigation of performance improvements achieved by the use of the SC principle in RLNC communications over lossy channels. The original formulation of the SC principle foresees a bit-by-bit combination of *all* the received copies of the same data packet (also including those received with errors) transmitted at different epochs in order to individually implement a soft detection at each receiving ends [24]. It was demonstrated in several papers [10], [24] that this approach can increase the throughput, lower the delivery delay and, the buffer occupancy.

Unfortunately, in the case of the RLNC scheme (where each coded packet is generated independently of all the previous ones and transmitted at different time epochs) the basic SC approach [11] cannot be directly applied. However, this drawback can be overcome by resorting to the alternative formulation of the SC principle proposed in [24]. In this case, instead of proactively transmitting m copies of the same packet (to perform a bit-by-bit SC), a single packet where the duration of each symbol is increased by a factor m (i.e., the SDI factor), is transmitted. It was demonstrated in [24] that a significant implementation complexity reduction is achieved without losing performance with respect to an ideal implementation of the basic SC approach [11].

As a consequence, this paper deals with the performance evaluation of the RLNC scheme using the SC principle (namely, the SDI-NC scheme) according to [24]. Being the performance of the SDI-NC scheme dependent on parameter m, a suitable optimization analysis is also proposed in the paper in order to further enhance its advantages with respect to the classic RLNC alternative.

In particular, the performance optimization analysis has been carried out by focusing on a suitable *objective function* in terms of mean delivery delay (defined as the mean time needed to achieve the error free reception of K coded packets at all the receiving nodes) and the associated mean energy consumption. We start our analysis by focusing on the *broadcast network model* shown in Fig. 1, where a source, namely the access point (AP), broadcasts packets to a set of $\{R_i\}$ nodes (where $i = 1, \ldots, M$) over M lossy independent channels. Whenever R_i collects K coded packets without errors (i.e., whenever it collects N linearly independent coded packets), it transmits to the AP an acknowledgement[1] (ACK). Hence, the AP, in turn, is enabled to start the transmission of a new generation whenever it has got an ACK message from all the network nodes.

[1]Without loss of generality we assumed that the transmission of ACKs occurs instantaneously and through a fully reliable communication channel.

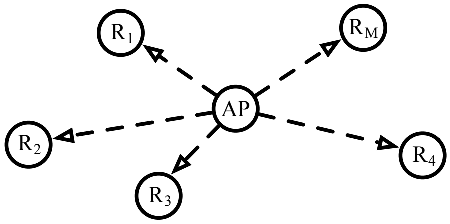


Fig. 1: Broadcast network model.

Moreover, we assumed that the burst of K coded packets are sent through an AWGN channel by means of a Quadrature Phase-Shift Keying (QPSK) modulation[2] [25].

Let L be the size of a coded packet (in bits), under the assumption of an ideal error detecting code, the Packet Error Probability (PER) characterizing the reception at the R_i side can be defined as follows:

$$P_{B,i}(m) = 1 - \Big[1 - P_{e,i}(m)\Big]^L , \tag{3}$$

where $P_{e,i}(m)$ represents the bit error probability at the R_i node. In particular, from [24], [25], $P_{e,i}(m)$ can be expressed as follows:

$$P_{e,i}(m) = \mathbf{Q}\Big(\sqrt{m\,\gamma_i}\Big) \quad \text{i=1, \ldots,M} , \tag{4}$$

with:

- γ_i: the ratio between the energy associated to each transmitted symbol and the one side AWGN spectral density (at the i-th receiver side); here after named as Signal-to-Noise Ratio (SNR) for the i-th link;
- $\mathbf{Q}(x)$: the well known Q function [25].

Note that in deriving (4) we have assumed that the channel interference contribution can be considered negligible (also taking into account the possibility of resorting to appropriate countermeasures [26]). The extension of our analysis to the case where this assumption does not apply is out of the scope of the present paper. However, limited to the case of an overall channel interference contribution modeled as an equivalent independent Gaussian noise, (4) is still valid if we define γ_i as the Signal-to-Interference-plus-Noise Ratio (SINR) at the i-th receiver side.

Ghaderi *et al.* [6] showed that the random variable V_i representing the number of coded packets that the AP has to broadcast, to ensure the correct reception of K packets by R_i, has a negative binomial distribution. In particular for $x \geq K$, the probability mass function $f_{V_i}(x;K)$ of V_i (for $i = 1, 2, \ldots, M$) can be defined as:

$$f_{V_i}(x;K) = \binom{x-1}{K-1}\Big[1 - P_{B,i}(m)\Big]^K P_{B,i}^{x-K}(m) . \tag{5}$$

with $f_{V_i}(x;K)$ equal to zero if $x < K$.

For this reason the number of coded packets transmitted by the AP to allow an error free reception of K coded packets to all the M receiving nodes (i.e., to allow the recovery of a generation), can be defined as: $W = \max_{i=1,\ldots,M}\Big\{V_i\Big\}$.

Hence, the probability mass function of W results to be [27]:

$$f_W(x;K) = \text{Prob}\Big\{W \leq x\Big\} - \text{Prob}\Big\{W \leq x-1\Big\} = \\ = \prod_{r=1}^{M}\left[\sum_{i=K}^{x} f_{V_r}(i;K)\right] - \prod_{r=1}^{M}\left[\sum_{i=K}^{x-1} f_{V_r}(i;K)\right], \tag{6}$$

where $\text{Prob}\Big\{W \leq x\Big\}$ is the probability that the value of W is equal to or less than x (for $x = 1, 2, \ldots, \infty$).

According to (6), the average value of W can be defined as follows:

$$\Upsilon(m;K) = \sum_{i=K}^{\infty} i\, f_W(i;K) . \tag{7}$$

The goal of the optimization is to find the value of m (m_o) minimizing the mean delivery delay and mean energy consumption needed to successfully recover a generation. Hence, m_o can be derived by solving the optimization problem (oSDI-NC)[3]:

$$\text{(oSDI-NC)} \qquad \text{minimize} \quad \Upsilon(m;K) \tag{8}$$

$$\text{subject to} \quad m \in \mathbb{N} . \tag{9}$$

Recalling again (6) and (7), we can note that the (oSDI-NC) problem is nonlinear. Moreover, due to the constraint (9) it is also an integer optimization problem. For these reasons, it is quite hard to solve the (oSDI-NC) problem in a closed form, therefore, we have resorted to a suitable numerical approach[4]. In order to relax the computational complexity of the problem, we propose here a suboptimal optimization method. The accuracy of the proposed suboptimal approach will be validated by comparing the achieved performance with those obtained by the (oSDI-NC) alternative. We start our analysis by defining the mean Link-to-Link (L2L) delivery delay for the node R_i (i.e., the mean time needed by the i-th node to collect K error free coded packets) as:

$$\hat{\delta}_i(m;K) = \frac{m\,K\,L\,T_b}{1 - P_{B,i}(m)} , \tag{10}$$

where T_b denotes the time duration of a bit when m is equal to one. From (10), it follows that the mean time needed to correctly receive a coded packet (normalized to the nominal coded packet duration $L\,T_b$) is:

$$\delta_i(m) = \frac{m}{1 - P_{B,i}(m)} . \tag{11}$$

From (11) it is straightforward to note that the mean communication throughput (*normalized* to $L\,T_b$) can be derived as the inverse of the $\delta_i(m)$ function.

Being the energy consumption at the AP side of special interest in several applications, we assume here as performance metric also the L2L mean energy $\epsilon_i(m)$ needed to successfully

[2] Note that the derived results are quite general and they can be easily extended to different modulation schemes and communication channel models.

[3] In the rest of this paper with the symbol $\mathbb{N}$ we will refer to the set of non-null integer numbers.

[4] In particular, we have resorted here to the NOMAD solver [28].

deliver a coded packet, normalized with respect to $L\,E_b$ (i.e., the energy associated to the transmission of a coded packet composed of L bits each of duration T_b). In particular, we have:

$$\epsilon_i(m) = \frac{m}{1 - P_{B,i}(m)} \ . \tag{12}$$

It is important to note also that, the normalized L2L mean delay and mean energy consumption needed to achieve an error free reception of a coded packet in the case of the classical RLNC scheme, are defined by (11) and (12), respectively, by setting m equal to one.

Moreover, from (11) and (12) it is easy to note that $\delta_i(m) = \epsilon_i(m)$ (for $i = 1, \ldots, M$). Hence, we can simplify our analysis by defining as objective function, the function $\Gamma_i(m) : \mathbb{N} \longrightarrow \mathbb{R}^+$ given by[5]:

$$\Gamma_i(m) \doteq \delta_i(m) \ = \ \epsilon_i(m) \ = \ = \frac{m}{1 - P_{B,i}(m)} \ = \ \frac{m}{\left[1 - P_{e,i}(m)\right]^L} \ . \tag{13}$$

In particular, form (13) we can easily note that minimizing $\Gamma_i(m)$ means to minimize, at the same time, the mean L2L delay and overall L2L energy consumption. Therefore, for the sake of simplicity, in the rest of this paper we simply consider the minimization of the function $\Gamma_i(\cdot)$ without explicitly referring to functions $\delta_i(m)$ and $\epsilon_i(m)$.

From (4), (13) it can be proved that $\Gamma_i(m)$ is monotonically decreasing (for $i, j = 1, \ldots, M$ and $i \neq j$):

$$\Gamma_i(m) \geq \Gamma_j(m) \quad \text{iff} \quad \gamma_i \leq \gamma_j \ . \tag{14}$$

As a result, we can refer to a min-max approach as suboptimal realization of the optimization criterion. As a consequence, we introduce the (sSDI-NC) problem defined as:

$$\text{(sSDI-NC)} \qquad \min \max_{i=1,2,\ldots,M} \quad \Gamma_i(m) \tag{15}$$
$$\text{subject to} \quad m \in \mathbb{N} \ . \tag{16}$$

The accuracy of the (sSDI-NC) model will be validated later (see Sec. V) by comparing it with the (oSDI-NC) approach.

In order to demonstrate that the (sSDI-NC) can be solved with affordable computing efforts, we will verify that the (sSDI-NC) problem is convex.

From (14), it can be proved that (sSDI-NC) is equivalent to the following optimization problem:

$$\text{(esSDI-NC)} \qquad \text{minimize} \quad \Gamma_h(m), \tag{17}$$
$$\text{where } h := \arg\min\{\gamma_i | i = 1, \ldots, M\}$$
$$\text{subject to} \quad m \in \mathbb{N} \ , \tag{18}$$

where we assumed that the h-th node experiences the worst propagation conditions among all the other ones.

Let $\hat{\Gamma}_i(\hat{m}) : \mathbb{R}^+/\{0\} \longrightarrow \mathbb{R}^+$ be the continuous extension of $\Gamma_i(m)$ (for $i = 1, \ldots, M$). In particular, it will be proved in the Appendix that the following proposition is valid.

Proposition 1: The function $\hat{\Gamma}_i(\hat{m})$, for $i = 1, \ldots, M$ is convex, continuously differentiable and admits a unique minimum in $\mathbb{R}^+/\{0\}$.

[5] In the rest of the paper with $\mathbb{R}^+$ symbol we will refer to the set of not negative real numbers.

The (esSDI-NC) problem can be solved by relaxing the constraint (18). Hence, we can restate the problem as:

$$\text{(reSDI-NC)} \qquad \text{minimize} \quad \hat{\Gamma}_h(m), \tag{19}$$
$$\text{where } h := \arg\min\{\gamma_i | i = 1, \ldots, M\}$$
$$\text{subject to} \quad m \in \mathbb{R}^+/\{0\} \ . \tag{20}$$

By Proposition 1 the solution of (reSDI-NC) problem is represented by the root ($\hat{r}$) of the equation:

$$\frac{d}{d\hat{m}}\Big(\hat{\Gamma}_h(\hat{m})\Big) = 0 \Leftrightarrow$$
$$\Leftrightarrow 1 - \mathbf{Q}\Big(\sqrt{\hat{m}\gamma_h}\Big) - L\sqrt{\frac{\gamma_h \hat{m}}{2\pi}} e^{-\frac{\hat{m}\gamma_h}{2}} = 0 \ . \tag{21}$$

Finally, if $\hat{r}$ exists, from Proposition 1, $\tilde{m}$ has to be selected between the values $\lfloor \hat{r} \rfloor$ and $\lceil \hat{r} \rceil$, by choosing the one that minimizes the objective function (15).

It is important to note that the proposed optimization is quite general and it can be extended to cases of different channel propagation conditions (among the AP and the M nodes). The only requirement is that the AP has to know the propagation conditions experienced by each node. It can be achieved by means of periodic messages holding Channel Quality Indicator (CQI) information as foreseen in the standard of the most recent broadband wireless communication networks [29], [30].

In order to validate this statement, in the rest of this Section we will address the case of *slow* fading regime. In performing our analysis, we assume that the propagation conditions are constant for all the nodes during the transmission of a coded packet (regardless to the m value)[6] and independent for each transmitted coded packets. Hence, it follows that $P_{B,i}(m)$ can be defined as [25]:

$$P_{B,i}(m) = 1 - \frac{1}{\overline{\gamma}_i} \int_0^\infty \Big[1 - P_{e,i}(m, \gamma_i)\Big]^L e^{-\frac{1}{\overline{\gamma}_i}\gamma_i} \ d\gamma_i \ , \tag{22}$$

where $\gamma_i = |\alpha_i|^2 \frac{2\,E_b}{N_{0,i}}$. The parameter $|\alpha_i|$ is the channel attenuation (usually assumed Rayleigh distributed [25]), $N_{0,i}$ is the one side AWGN spectral density (at the i-th receiver side) and, $\overline{\gamma}_i$ is the mean SNR per symbol[7] (characterizing R_i).

Also in this case the (oSDI-NC) optimization problem cannot be solved with affordable computing efforts. As an alternative, the parameter m can be optimized by resorting to the (sSDI-NC) model. The validity of Proposition 1, in the case of fading channels, is proved in the Appendix. Hence, we have that:

- the (sSDI-NC) optimization problem can be equivalently rewritten as the (esSDI-NC) one;
- the solution ($\hat{r}$) of the (rsSDI-NC) problem can be derived

[6] This occurs, for example, whenever data transmissions are organized on a frame-basis (as in LTE [29] or WiMAX [30] systems).

[7] Note that in the case of Gaussian interference modeling, γ_i and $\overline{\gamma}_i$ can be defined as the resulting SINR values.

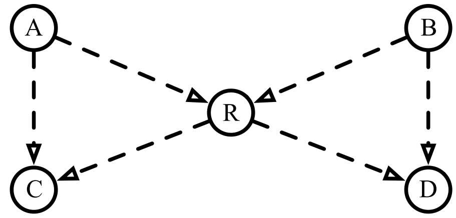


Fig. 2: *Butterfly* network model.

by solving the following equation

$$\frac{d}{d\,\hat{m}}\left(\hat{\Lambda}(\hat{m})\right) = 0 \Leftrightarrow$$
$$\Leftrightarrow \int_0^{\infty}\left[1 - Q(\sqrt{\hat{m}\,\gamma_i})\right]^L e^{-\frac{1}{\overline{\gamma}_i}\gamma_i} d\gamma_i +$$
$$-\frac{L\sqrt{\hat{m}}}{2\sqrt{2\pi}}\int_0^{\infty}\sqrt{\gamma_i}\left[1 - Q(\sqrt{\hat{m}\,\gamma_i})\right]^{L-1}\cdot$$
$$\cdot\, e^{-\frac{2+\hat{m}\overline{\gamma}_i}{2\overline{\gamma}_i}\gamma_i} d\gamma_i = 0\ ; \tag{23}$$

- from Proposition 1, the solution ($\tilde{m}$) of (sSDI-NC) can be selected between $\lfloor \hat{r} \rfloor$ and $\lceil \hat{r} \rceil$, by choosing the one that minimizes the objective function (15) .

IV. Application to the Butterfly Network Topology

This Section proposes a generalization of the results provided in Sec. III to the case of the *butterfly* network model (shown in Fig. 2). Even if the network sketched is clearly a theoretical model, it is useful to inspect the performance of the SDI-NC approach in a multi-hop like network [4] thank to the coding sub-three decomposition theory [4].

We considered independent sources A and B transmitting independent informative messages. Each message is N packets long (message $\mathbf{a}$ for the node A and message $\mathbf{b}$ for the node B) and is directed to three different destinations C, D and R. Moreover, the node R acts also as a relay for nodes C and D. The node A transmits coded packets obtained from the message $\mathbf{a}$ to node R and C. The node B performs the same operation on the message directed to the nodes R and D. For the sake of simplicity, we assume that:

- all the transmitting nodes access the medium at not overlapped time instant in a contention free fashion;
- coding/decoding operations are performed by consenting the same finite field $\mathcal{G}_q$. Hence, the same number (K) of coded packets (each L bits long) are needed (for each information flow) to ensure a successful decoding at all the receiving ends.

Whenever the relay node R has recovered $\mathbf{a}$ and $\mathbf{b}$, it can start the transmission of coded packets $\hat{\mathbf{r}}_\mathbf{i}$ (L bits long) obtained as follows:

$$\hat{\mathbf{r}}_i = \mathbf{M_r}\cdot\mathbf{c_i}\ , \tag{24}$$

where $\mathbf{c_i}$ is the i-th N-ary coding vector. $\mathbf{M_r}$ is a $P \times N$ matrix where the q-th column is defined as $\mathbf{a}_q \otimes \mathbf{b}_q$ (i.e., the q-th coded packet of $\mathbf{a}$ and $\mathbf{b}$ are XORed bit-by-bit). Moreover, $\mathbf{M_r}$ defines the original message $\mathbf{r} = \{\mathbf{r_1}, \ldots, \mathbf{r_N}\}$ transmitted by the node R.

In the butterfly network under consideration, each destination node (C or D), receives two coded packets, one from a source node (A or B) and the other one from the relay node R. The decoding process operated by node C (or D) can be summarized as follows:

1) to recover message $\mathbf{a}$ ($\mathbf{b}$) by decoding the packets received from node A (B) (see Eq. (2);
2) to recover message $\mathbf{b}$ ($\mathbf{a}$) by decoding the packet received from node R. In particular the q-th plain packet of the message $\mathbf{b}$ ($\mathbf{a}$) is given by $\mathbf{r}_q \otimes \mathbf{a}_q$ ($\mathbf{r}_q \otimes \mathbf{b}_q$).

In order to apply the optimization criterion presented in Sec. III the butterfly network has to be split into three broadcast networks:

- $\widehat{ACR}$, subnetwork A, where A is the AP for C and R;
- $\widehat{BRD}$, subnetwork B, in this case B is AP for R and D;
- $\widehat{RCD}$, subnetwork R, in this case R is the AP for C and D.

Finally, we can note that R is both a receiver for A and B but it is also an AP for the $\widehat{RCD}$ broadcast network.

We assume here that each node can receive coded packets coming from just a transmitter at time. In particular, a receiver can start to receive a new message only when it has successfully decoded (and acknowledged[8]) the previous one.

It is important to note that the SDI-NC scheme can be optimized by the (oSDI-NC) or (sSDI-NC) model. Hence, we can find the optimal m value, i.e., m_X (where $X \in \{A, B, R\}$), for each broadcast subnetwork. In order to compare the performance of the SDI-NC scheme with that of the classical RLNC one, we consider as metric the mean End-to-End (E2E) delivery delay (normalized to KLT_b). Let $\widetilde{\delta}$ be the mean time required by C and D to successfully recover an informative packet belonging to $\mathbf{a}$ and $\mathbf{b}$, the mean normalized E2E delivery delay results to be:

$$\widetilde{\delta} = \overline{\delta}(m_A) + \overline{\delta}(m_B) + \overline{\delta}(m_R)\ , \tag{25}$$

where m_A, m_B and m_R are the optimized m values for the subnetworks A, B, R, respectively, derived according to the (oSDI-NC) or (sSDI-NC) optimization criteria. The parameter $\overline{\delta}(m_X)$ is the overall mean delay (normalized to $L\,T_b$) needed by all the receiving nodes in the subnetwork X, (with $X \in \{A, B, R\}$), to successfully recover a coded packet. Note that (25), with $m_X = 1$ (for $X \in \{A, B, R\}$), defines the mean normalized E2E delivery delay (for a coded packet) in the case of classical RLNC scheme.

V. Numerical Results

This Section deals with the performance evaluation of the optimized SDI-NC scheme in the case of a broadcast and a butterfly network, respectively. In particular, we focus on the cases of an AWGN and a slow fading regime. In addition to this, comparisons with the (oSDI-NC) optimization criterion

[8]Without any loss of generality we assumed also in this case that acknowledgement messages are transmitted on a fully reliable channel.

TABLE I: Probability of nonsingularity for $N = K$ in the case of $N = 10$.

q	2^4	2^5	2^6	2^7	2^8
p_{ns}	0.934	0.968	0.984	0.992	0.996

are also provided to validate the effectiveness of the (sSDI-NC) approach. Results are provided in terms of normalized mean delivery delay and, consequently, in terms of normalized throughput (see Sec. III).

A. Broadcast Network Scenario

In order to compare the (oSDI-NC) and (sSDI-NC) optimization models, the performance of the resulting optimized SDI-NC schemes has been evaluated by resorting to computer simulations. In particular we considered the following network scenarios:

I number of network nodes M equal to 30 and non equal propagation conditions among the AP and the M nodes. In particular, the maximum SNR (AWGN case) and mean SNR (slow fading case) unbalance among nodes has be set to 10 dB. Without loss of generality, we have assumed that node R_M experiences the most favorable propagation conditions while node R_1 the worst ones[9]. The SNR (AWGN case) and mean SNR values (slow fading case) for the remaining nodes has be taken uniformly spaced in the [5, 15] dB and [0, 10] dB intervals, respectively (i.e., the SNR unbalance between any couple of nodes is kept constant).

II number of receiving nodes $M \in [2, 32]$ interval with equal (and fixed) propagation conditions for all nodes (i.e., $\gamma_i = 9$ dB and $\overline{\gamma}_i = 5$ dB in an AWGN and slow fading regime, respectively).

Moreover, regardless to the chosen scenario, we assumed that all the coding operations are performed within a finite field large enough so that two coded packets can be considered linearly independent with a high probability [31]. In particular, Table I shows the probability (p_{ns}) that a node has received $N = 10$ over $K = N$ linearly independent coded packets (without considering the channel effects) [13] (i.e., the probability of nonsingularity). In particular whenever the coding vectors are uniformly selected over a finite field with a dimension greater than or equal to 2^8, the probability that two coding vectors are linearly dependent is less than $4 \cdot 10^{-3}$. Hence, we have assumed here $N \cong K$ and a generation length equal to 10 packets (i.e, $N = 10$).

Fig 3 shows the normalized mean delivery delay (for the case of two different packet lengths, AWGN regime, scenario I, optimized m values derived by the (oSDI-NC) and (sSDI-NC) criteria) as a function of the mean SNR value among users ($\overline{\gamma}$) defined as:

$$\overline{\gamma} = \frac{1}{M} \sum_{i=1}^{M} \gamma_i \ . \tag{26}$$

[9]It corresponds to the R_h in the (esSDI-NC) problem formulation

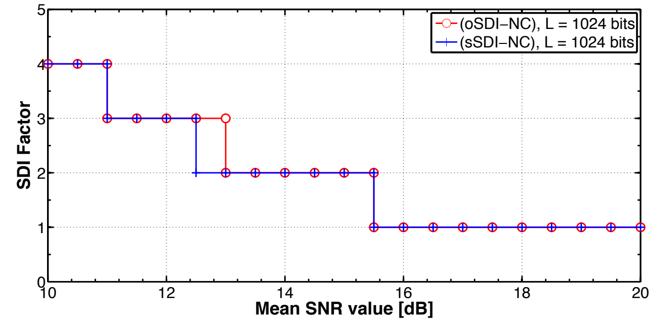


Fig. 3: Optimal SDI factors as function of the mean SNR among users (AWGN regime and scenario I).

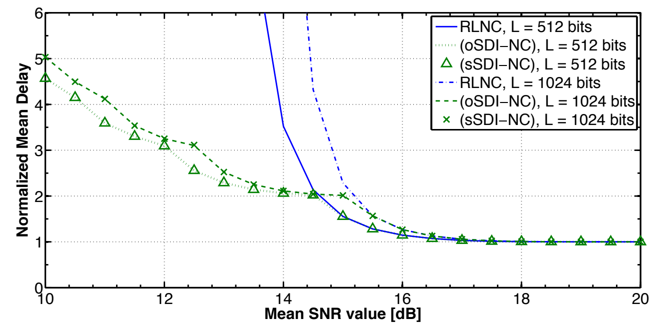


Fig. 4: Normalized mean delivery delay as function of the mean SNR among users (AWGN regime and scenario I).

In this Figure we can note that the same optimum m values (m_o) have been obtained for both the considered optimization criteria (only a slightly difference can be noted for $\overline{\gamma} \in [12.2, 12.4]$ dB).

Fig 4 compares the performance of the SDI-NC scheme (optimized according to the (oSDI-NC) and (sSDI-NC) criteria), respectively, to that of the classical RLNC scheme. This figure highlights a same behavior for the (oSDI-NC) and (sSDI-NC) criteria. Moreover, we can also note that the optimized SDI-NC clearly outperforms the classical RLNC scheme for mean SNR values less than 15 dB.

We would like to point out that in Fig. 4 the performance of (oSDI-NC) and (sSDI-NC) models is the same for $L = 512$ bits. On the other hand, in the case of $L = 1024$ bits, the (sSDI-NC) strategy is characterized by a normalized mean delivery delay that is, at most, 0.4 % greater than that characterizing the (oSDI-NC) approach.

Likewise, Fig. 5 compares the normalized mean delivery delay for informative packet as a function of the number of receiving nodes in an AWGN regime in the case of the II scenario. Here again, we can note the same behavior already described for the (oSDI-NC) and (sSDI-NC) criteria.

Finally, in Fig. 6-8 the performance of the proposed scheme is inspected in a slow fading regime. Numerical results are shown in figures as function of the parameter $\tilde{\gamma}$, defined as

$$\tilde{\gamma} = \frac{1}{M} \sum_{i=1}^{M} \overline{\gamma}_i \ , \tag{27}$$

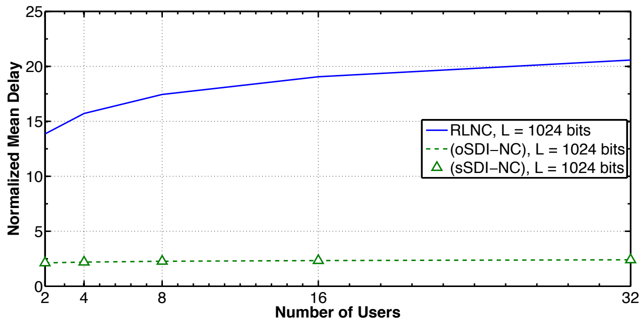


Fig. 5: Normalized mean delivery delay as function of number of receiving nodes in AWGN regime (scenario II).

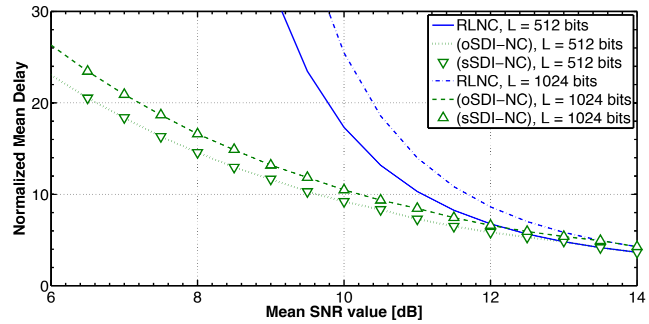


Fig. 7: Normalized mean delivery delay as function of mean SNR among users (slow fading regime and scenario I).

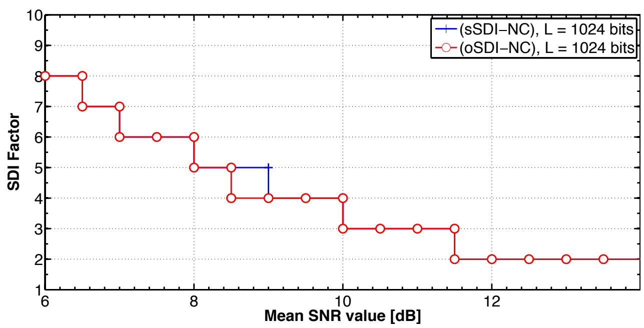


Fig. 6: Optimal SDI factors as function of mean SNR among users given by (27) in slow fading regime and scenario I .

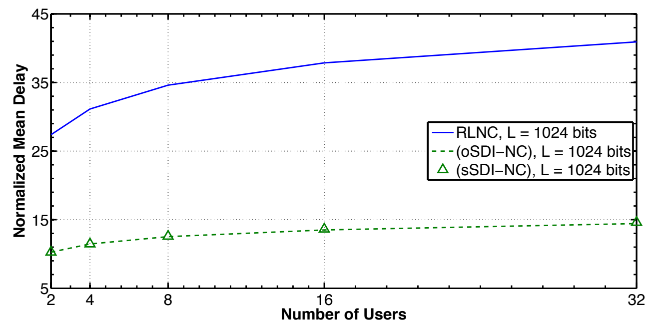


Fig. 8: Normalized mean delivery delay as function of number of receiving nodes under slow fading regime (scenario II).

and as function of the number of receiving nodes. The same considerations provided in the discussion of the numerical results presented in Figs. 3-5 are here again valid: (i) the optimized SDI-NC scheme outperforms the classical RLNC and, (ii) the (oSDI-NC) performance is very close to the (sSDI-NC) one.

Also in this case we would like to point out that in Fig. 7 the performance of (sSDI-NC) and (oSDI-NC) models is the same. The only exception is represented by the case of $L = 1024$ bits where the (sSDI-NC) approach is characterized by a normalized mean delivery delay that increases no more than 0.34 % (if compared to the same metric that we would have by using the (oSDI-NC) strategy).

B. Butterfly Network Scenario

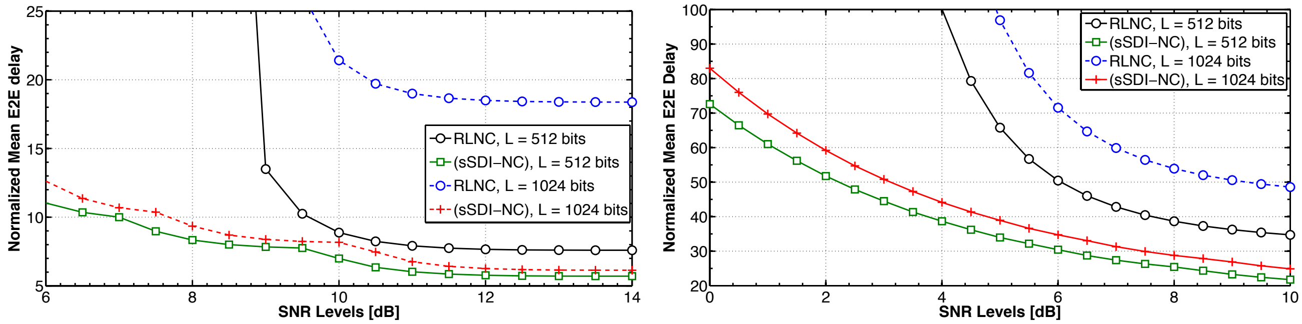
In this case we considered a butterfly network scenario (shown in Fig. 2) where:

- γ_i values at the end points of links A-C and A-R are equal to 9 dB in AWGN regime and, $\overline{\gamma}_i$ values are equal to 5 dB in the case of a slow fading regime;
- γ_i values at the end points of links B-D and B-R are equal to 10 dB and, $\overline{\gamma}_i$ values are equal to 6 dB in the case of a slow fading regime;
- SNR values at the end points of R-C and R-D links are equal and takes values within $[5, 15]$ dB (likewise, for the case of a slow fading regime, the mean SNR values at the end points of the same links have been considered equal and with values in $[0, 10]$ dB);
- communications relying on the SDI-NC approach are characterized by a generation length of 10 packets with $K \cong N$;
- the packet length has been set to 512 or 1024 bits.

Numerical results (under AWGN and a slow fading regime), obtained by resorting to computer simulations, are given in Fig. 9. This figure shows the normalized mean E2E delivery delay for informative packet as function of the (mean) SNR values associated to the receiving nodes of the $\overbrace{RCD}$ network. Fig. 9 clearly points out that, regardless to the chosen optimization and channel model, the SDI-NC scheme outperforms the classical RLNC scheme.

VI. Conclusions

This paper has proposed a novel RLNC scheme where the use of the SC approach is accomplished by increasing the symbol duration of a suitable factor m. It was discussed in the paper that this solution avoids any increase in the implementation complexity at the receiving ends with respect to the classical RLNC implementation. Being the performance of the proposed NC scheme (in terms of mean delivery delay and mean energy consumption for the completion of an informative message) dependent on m, two alternative optimization methods have been proposed and compared by focusing on different network topologies under AWGN and slow fading channel propagation conditions. The results presented in the paper clearly show that the SDI-NC scheme proposed: (i) can be easily integrated within an existing RLNC implementation,



(a) AWGN regime (b) Slow fading regime

Fig. 9: Mean normalized E2E delivery delay as a function of the SNR (or mean SNR) values at the C and D sides.

(ii) it is characterized by the same implementation complexity of a system adopting the widely used SC principle and, (iii) can be successfully optimized by resorting to a convex heuristic approach. Moreover, it is also highlighted that by using the optimized SC-NC schemes we can achieve significant performance improvements with respect to the classical RLNC scheme. Finally, a computational complexity reduction can be reach without a significant loss in performance by using the proposed simplified (sSDI-NC) optimization criterion.

Appendix
Proof of the Lemma 1

This Appendix deals with the proof of Lemma 1, enunciated in Sec. III, in the case of AWGN and slow fading propagation conditions.

A. AWGN Regime

Proof: Towards this end, we rewrite (21), for $i = 1, \ldots, M$, as:

$$\frac{d}{d\hat{m}}\Big(\hat{\Gamma}_i(\hat{m})\Big) = \frac{1 - g_i(\hat{m}) - h_i(\hat{m})}{[1 - g_i(\hat{m})]^{L+1}} \,, \qquad (28)$$

where

$$g_i(\hat{m}) := \mathbf{Q}\Big(\sqrt{\hat{m}\gamma_i}\Big) \,, \qquad (29)$$

$$h_i(\hat{m}) := L\sqrt{\frac{\gamma_i \hat{m}}{2\pi}} e^{-\frac{\hat{m}\gamma_i}{2}} \,. \qquad (30)$$

Moreover, due to both $g_i(\hat{m})$ and $h_i(\hat{m})$ functions decrease, what follows holds:

$$\frac{d^2}{d\hat{m}^2}\Big(\hat{\Gamma}_i(\hat{m})\Big) \geq 0 \Leftrightarrow$$
$$\Leftrightarrow \Big[-\frac{d}{d\hat{m}}\Big(g_i(\hat{m})\Big) - \frac{d}{d\hat{m}}\Big(h_i(\hat{m})\Big)\Big]\Big[1 - g_i(\hat{m})\Big] +$$
$$-(L+1)\Big[1 - g_i(\hat{m}) - h_i(\hat{m})\Big]\frac{d}{d\hat{m}}\Big(g_i(\hat{m})\Big) \geq 0 \,. \qquad (31)$$

As a result, $\frac{d\hat{\Gamma}_i(\hat{m})}{d\hat{m}}$ increases with $\hat{m}$, for these reasons $\hat{\Gamma}_i(\hat{m})$ is convex in $\mathbb{R}^+/\{0\}$. In addition to that, for all practical operative conditions (namely for $L \geq 8$ bits and $\gamma_i \geq -1$ dB) the following relations hold:

$$\frac{d}{d\hat{m}}\Big(\hat{\Gamma}_i(\hat{m})\Big)\Big|_{\hat{m}=1} = \frac{1 - \mathbf{Q}\Big(\sqrt{\gamma_i}\Big) - L\sqrt{\frac{\gamma_i}{2\pi}}e^{-\frac{\gamma_i}{2}}}{[1 - \mathbf{Q}\left(\sqrt{\gamma_i}\right)]^{L+1}} < 0, \quad (32)$$

and

$$\lim_{\hat{m}\to\infty} \frac{d}{d\hat{m}}\Big(\hat{\Gamma}_i(\hat{m})\Big) > 0 \,. \qquad (33)$$

Thus, $\hat{\Gamma}_i(\hat{m})$ has an unique minimum $\hat{m}_o \geq 1$ [32]. ■

B. Slow Fading Regime

Proof: In the case of slow fading propagation conditions, let us consider the following definitions:

$$l_i(\hat{m}) \doteq \int_0^\infty \Big[1 - Q(\sqrt{\hat{m}\,\gamma_i})\Big]^L e^{-\frac{1}{\overline{\gamma}_i}\gamma_i} d\gamma_i \,, \qquad (34)$$

$$s_i(\hat{m}) \doteq \frac{L\sqrt{\hat{m}}}{2\sqrt{2\pi}} \int_0^\infty \sqrt{\gamma_i}\Big[1 - Q(\sqrt{\hat{m}\,\gamma_i})\Big]^{L-1} \cdot$$
$$\cdot\, e^{-\frac{2+\hat{m}\overline{\gamma}_i}{2\overline{\gamma}_i}\gamma_i} d\gamma_i \,. \qquad (35)$$

where $l_i(\hat{m}) : \mathbb{R}^+/\{0\} \longrightarrow \mathbb{R}^+$ and $s_i(\hat{m}) : \mathbb{R}^+/\{0\} \longrightarrow \mathbb{R}^+$ (for $i = 1, 2, \ldots, M$) are continuously differentiable in $\mathbb{R}^+/\{0\}$. The first-order derivative of

The first and the second-order derivative of $\hat{\Gamma}_i(\hat{m}) : \mathbb{R}^+/0 \longrightarrow \mathbb{R}^+$ are expressed by the following relations:

$$\frac{d}{d\,\hat{m}}\Big(\hat{\Lambda}_i\Big) = \overline{\gamma}_i \frac{l_i(\hat{m}) - s_i(\hat{m})}{l_i^2(\hat{m})} \,, \qquad (36)$$

and

$$\frac{d^2}{d\,\hat{m}^2}\Big(\hat{\Lambda}_i\Big) \geq 0 \Leftrightarrow$$
$$\Leftrightarrow 2\frac{d}{d\,\hat{m}}\Big(l_i(\hat{m})\Big)s_i(\hat{m}) +$$
$$-l_i(\hat{m})\Bigg[\frac{d}{d\,\hat{m}}\Big(l_i(\hat{m})\Big) - \frac{d}{d\,\hat{m}}\Big(s_i(\hat{m})\Big)\Bigg] \geq 0 \,. \qquad (37)$$

Since (37) is verified in any operative conditions (namely for $L \geq 8$ bits and $\overline{\gamma}_i \geq -1$ dB), we have that $\frac{d}{d\,\hat{m}}\Big(\hat{\Lambda}_i\Big)$ increases. For all these reasons the $\hat{\Lambda}_i(\hat{m})$ function is convex in $\mathbb{R}^+/\{0\}$ [33]. ■

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