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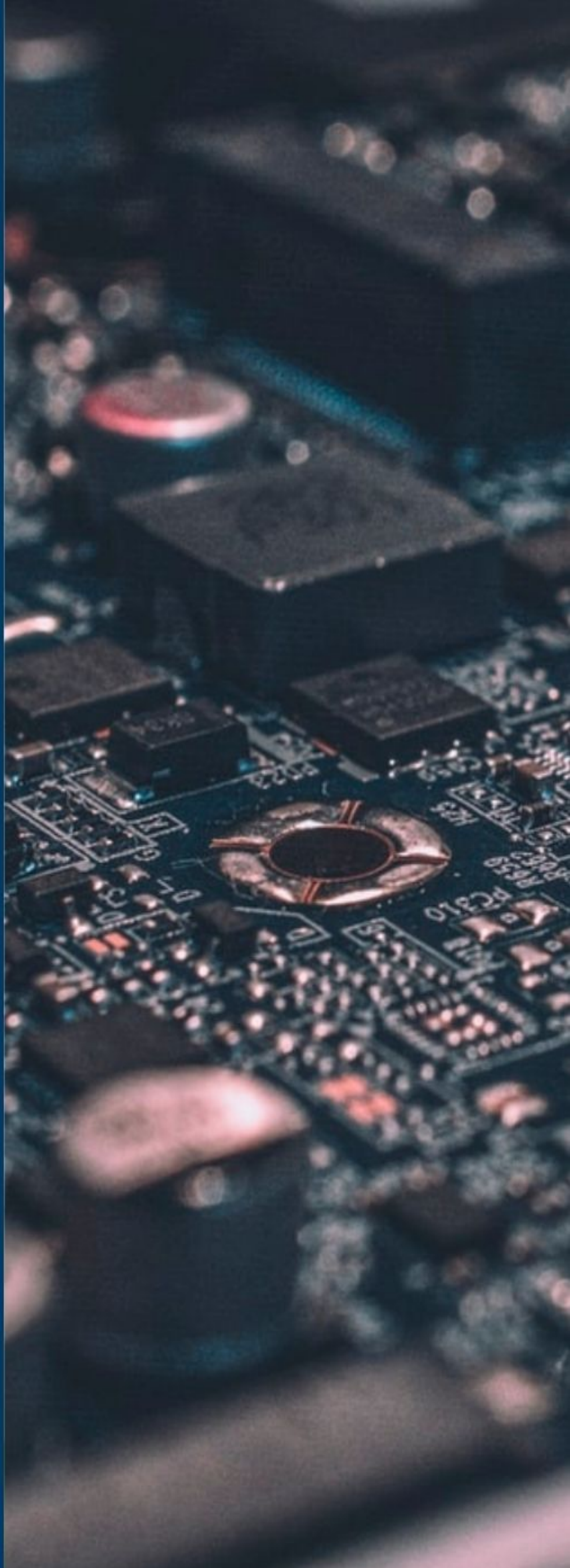

Dynamic optimized cooperation in multi-source multi-relay wireless networks with random linear network coding

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The authors present a strategy that improves the reliability of data transmission from multiple sources towards a destination *D* via multiple relays over wireless channels. After the broadcast phase, the destination selects the best cooperative direct link sources with the highest instantaneous signal-to-noise ratio γ, then generates and sends the random linear network coding coefficient matrix to the relays. After receiving the random linear network coding–coded symbols (packets) from the relays, *D* completes the reception and decoding of all source nodes packets. Monte Carlo simulations are conducted with Galois field (GF) (q) symbols ($q = 2, 4$ and 8) and the results are compared with the scenario of static cooperative direct links. An important decrease of symbol error rate (SER) is achieved. Furthermore, the efficiency of this approach is confirmed for the whole range of possible values of path loss exponent on direct links, that is, all types of environment between source nodes and destination *D*.

Introduction: Recent advances in wireless networks exploit the concepts of cooperative communications (CC) [1, 2] and network coding (NC) [3–5] to enhance wireless systems' performance by increasing system throughput, diversity order, spectral efficiency and robustness in particular when CC and NC are jointy used [6–8]. In multi-source multi-relay and one destination wireless networks [9], the contribution of direct links between source nodes and the destination are not negligible. The right choice of cooperative direct links is crucial for achieving optimal system performance by reducing error probability and system energy and increasing diversity order [10]. The authors in [11] derived closed forms of outage probability and diversity gain of NCC-based multi-source multi-relay wireless networks where they proposed and applied a generalized relay selection (RS) method. They showed that the full diversity gain is only achieved in the scenario where the number of arbitrarily selected relays is greater or equal to N (number of sources) with N highest signal-to-noise ratio (SNR) relays. A new smart decode-and-forward (DF) RS scheme was proposed in [12] which considers the source–destination links outage status. Relays use linear NC with coefficients from a generator matrix of maximum distance separable (MDS) code. The proposed scheme outperforms the conventional min–max RS scheme. In [13], the authors showed how the introduction of multiple-input multiple-output (MIMO) strategy can improve the performance of NCC systems. They introduced a new RS strategy which utilizes only the local channel state information (CSI), thus allowing to reduce the signaling overhead. By equipping the relays and destination with multiple antennas, they proved the superiority of their proposed scheme in improving the performance of MIMO–NCC systems over the min–max traditional RS criterion scheme. RS [14, 15] is the main goal of almost all the previously mentioned works. We assume the relays as fixed network nodes along with the destination (base station, BS). Relay nodes are capable of performing random linear network coding (RLNC) [16–18] on their received signals with the assistance of destination D which has computational capabilities to execute the optimization process. This later relies on the mobility of source nodes (mobile users) to dynamically select the best cooperative ones in every transmission round.

System model: In order to highlight the main features and improvements offered by our proposed strategy, we use a multi-source multi-relay and single destination wireless system as illustrated in Figure 1. The N_S source nodes (mobile users) S_i $(i = 1, 2, \ldots, N_S)$ are communicating with the destination D or BS via N_R relays R_j $(j = 1, 2, \ldots, N_R)$ with the assumption $N_R \leq N_S$. All source nodes are inside the coverage area of the BS, that is, have direct links with the destination. Assumptions on the distances $d_{S_iR_j}$ (from source node S_i to relay node R_j), d_{S_iD} (from source node S_i to destination D) and d_{R_jD} (from relay node R_j to destination D) are as follows:

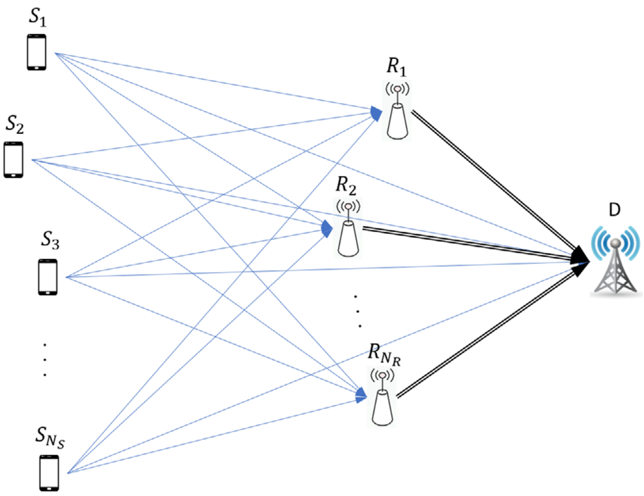

Fig. 1 *Considered system: multisource multirelay wireless network*

$$d_{S_iR_j} < d_{S_iD} \text{ and } d_{R_jD} < d_{S_iD}.$$

We assume all nodes equipped with a single antenna and relays work in half-duplex mode. Transmissions are performed in non-overlapping time slots in time division multiple access (TDMA) scheme. The destination and the relays are fixed while the source nodes are mobile. Direct links $S_i \rightarrow D$ are further weakened by the path loss due to their longer distances. Our proposed approach relies on this particular fading and the fact that source nodes are moving mobile users, hence, distances d_{S_iD} are permanently changing. According to the number of source nodes N_S, the number of relays N_R being constant, two scenarios are possible. The first one, when $N_R = N_S$, does not make use of cooperation but still requires the reception of all source nodes signals at destination D in the broadcast phase. The second scenario that is most optimized by our approach is when $N_R < N_S$ since it exploits the cooperation of the remaining $N_S - N_R$ direct links to destination. The N_R relays apply RLNC in $GF(q)$, where $q = 2^b$ and b denotes the number of bits per symbol (packet), on the N_S packets received in both scenarios.

Transmitted symbols are elements of finite fields $GF(q)$ $(q = 2, 4, 8, \ldots)$ and are modulated using q-ary PSK. Receiving nodes have perfect CSI of all their links that are subject to the Nakagami-m fading model. The transmission round of all N_S symbols lasts $N_S + N_R + 1$ time slots and is divided into three stages, namely, the broadcast phase, the optimization phase and the relaying phase.

Broadcast phase: The broadcast phase lasts N_S time slots where each source node S_i $(i = 1, 2, \ldots, N_S)$ modulates, using q-ary PSK, its symbol m_{S_i} into x_{S_i} and broadcasts the latter to destination D and all N_R relays. The received signal at each relay R_j $(j = 1, 2, \ldots, N_R)$ from each source node S_i $(i = 1, 2, \ldots, N_S)$ is given by

$$y_{S_iR_j} = \sqrt{E_{S_i}} x_{S_i} h_{S_iR_j} + n_{S_iR_j}, \quad (1)$$

where E_{S_i} is the average symbol energy of source S_i, $h_{S_iR_j}$ is the Nakagami-m channel fading coefficient on link $S_i \rightarrow R_j$ and $n_{S_iR_j}$ is the complex additive white Gaussian noise (AWGN) at the input of R_j. The AWGN component $n_{S_iR_j}$ is independent identically distributed (i.i.d.) random variable (RV) with zero mean and variance $\sigma^2_{S_iR_j}$, that is, $n_{S_iR_j} \sim \mathcal{CN}(0, \sigma^2_{S_iR_j})$. Upon reception, the relay applies the following equalization operation

$$\begin{aligned} \hat{x}_{S_iR_j} &= y_{S_iR_j} h^*_{S_iR_j} \\ &= \left(\sqrt{E_{S_i}} x_{S_i} h_{S_iR_j} + n_{S_iR_j}\right) h^*_{S_iR_j}, \end{aligned} \quad (2)$$

where $h^*_{S_iR_j}$ is the complex conjugate of $h_{S_iR_j}$. Then, by applying q-PSK demodulation on $\hat{x}_{S_iR_j}$, we obtain $\hat{m}_{S_iR_j}$ the estimate of m_{S_i} at relay R_j.

The key to our optimization process is to account for the effect of distance and path loss of cooperative direct links $S_i \rightarrow D$ ($i = 1, 2, \ldots, N_S$). Therefore, the received signal at D from S_i in the broadcast phase has the form

$$\begin{aligned} y_{S_iD} &= \sqrt{E_{S_i}} x_{S_i} \sqrt{PL_{S_iD}} h_{S_iD} + n_{S_iD} \\ &= \sqrt{E_{S_i}} x_{S_i} \tilde{h}_{S_iD} + n_{S_iD}, \end{aligned} \quad (3)$$

where $\tilde{h}_{S_iD} = \sqrt{PL_{S_iD}} h_{S_iD}$ represents the actual channel fading coefficient of link $S_i \rightarrow D$ and PL_{S_iD} represents its path loss which is evaluated using the simplified model commonly used for system design [19]

$$PL_{S_iD} = K \left(\frac{d_0}{d_{S_iD}} \right)^{\alpha}, \quad (4)$$

where K is a unitless constant depending on the antenna characteristics and average channel attenuation, d_0 is a reference distance and α is the path loss exponent. Parameters K and d_0 are usually adjusted to approximate either an analytical or empirical model. Path loss exponent α ranges from 2 to 6 depending on the carrier frequency, type of environment and obstructions. For urban areas, α is approximately equal to 3. Upon reception of the N_S signals, destination D first applies the following optimization processing.

Optimization phase: After N_S time slots, the BS (destination D) compares N_S with N_R. If $N_S = N_R$, D generates the full-rank $N_R \times N_R$ RLNC coeffidients matrix, without decoding any of the received signals, and broadcasts it to the relays. However, if $N_S > N_R$, then destination D first selects the $N_S - N_R$ 'best' direct links for cooperation, that is, those with highest instantaneous SNR (γ_{S_iD}). Since $\gamma_{S_iD} = \frac{E_{S_i}|\tilde{h}_{S_iD}|^2}{\sigma^2_{S_iD}}$ and assuming all transmitting nodes have the same average symbol energy, the selection criterion is reduced to the highest values of $|\tilde{h}_{S_iD}|^2$. Indices of the selected cooperative source nodes are denoted I_k ($k = 1, 2, \ldots, N_S - N_R$) and derived as follows:

$$I_1 = \text{argmax}\{|\tilde{h}_{S_1D}|^2, |\tilde{h}_{S_2D}|^2, \ldots, |\tilde{h}_{S_{N_S}D}|^2\}, \quad (5)$$

then $|\tilde{h}_{S_{I_1}D}|^2$ is replaced by 0 in (5) to find I_2 and so on until we find $I_{N_S - N_R}$. Only signals $y_{S_{I_k}D}$ ($k = 1, 2, \ldots, N_S - N_R$) are decoded at destination as follows:

$$\begin{aligned} \hat{x}_{S_{I_k}D} &= y_{S_{I_k}D} \tilde{h}^*_{S_{I_k}D} \\ &= \left(\sqrt{E_{S_{I_k}}} x_{S_{I_k}} \tilde{h}_{S_{I_k}D} + n_{S_{I_k}D}) \right) \tilde{h}^*_{S_{I_k}D} \end{aligned} \quad (6)$$

for $k = 1, 2, \ldots, N_S - N_R$. Then, each $\hat{x}_{S_{I_k}D}$ is demapped into $\hat{m}_{S_{I_k}D}$ using q-PSK demodulation for use in the next relaying phase. Afterward, destination D generates the $N_R \times N_R$ full-rank RLNC matrix A with elements in $GF(q)$

$$A = \begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1N_R} \\ a_{21} & a_{22} & \ldots & a_{2N_R} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N_R1} & a_{N_R2} & \ldots & a_{N_RN_R} \end{pmatrix}$$

and then A is being augmented to $N_R \times N_S$ matrix denoted $\tilde{A}$ by injecting columns of ones '1' at the indices $I_1, I_2, \ldots, I_{N_S - N_R}$.

For instance, if $q = 8$, $N_S = 6$, $N_R = 4$, the selected cooperative sources are S_2 and S_4, that is, $I_1 = 2$ and $I_2 = 4$ and the generated full-rank 4×4 RLNC matrix in $GF(8)$ is

$$A = \begin{pmatrix} 5 & 5 & 7 & 6 \\ 6 & 1 & 2 & 2 \\ 2 & 0 & 4 & 4 \\ 5 & 3 & 1 & 5 \end{pmatrix},$$

then

$$\tilde{A} = \begin{pmatrix} 5 & 1 & 5 & 1 & 7 & 6 \\ 6 & 1 & 1 & 1 & 2 & 2 \\ 2 & 1 & 0 & 1 & 4 & 4 \\ 5 & 1 & 3 & 1 & 1 & 5 \end{pmatrix}$$

is the augmented 4×6 matrix that is sent to the relays.

Relaying phase: Each relay R_j ($j = 1, 2, \ldots, N_R$) has N_S decoded symbols $\hat{m}_{S_iR_j}$ from the broadcast phase and the augmented $N_R \times N_S$ RLNC coefficients matrix $\tilde{A}$ from the optimization phase. Each relay index j is equal to the number of its corresponding row of coefficients in matrix $\tilde{A}$. That is, each relay R_j derives its network coded symbol equal to the linear combination of $\tilde{a}_{jk}$ ($k = 1, 2, \ldots, N_S$) and $\hat{m}_{S_iR_j}$ ($i = 1, 2, \ldots, N_S$). Then, the N_R RLNC-coded symbols are given by

$$m_{R_j} = \tilde{a}_{j1} \hat{m}_{S_1R_j} \oplus \tilde{a}_{j2} \hat{m}_{S_2R_j} \oplus \ldots \oplus \tilde{a}_{jN_S} \hat{m}_{S_{N_S}R_j} \quad (7)$$

for $j = 1, 2, \ldots, N_R$.

The symbol $\oplus$ designates the bitwise exclusive OR (XOR) operator in $GF(q)$ and hence the resulting symbols m_{R_j} are elements of $GF(q)$ as well. After mapping them into x_{R_j} ($j = 1, 2, \ldots, N_R$) with q-ary PSK modulation, they are transmitted in N_R time slots to destination D. In each time slot $N_S + 1 + j$ ($j = 1, 2, \ldots, N_R$), D receives one RLNC signal given by

$$y_{R_jD} = \sqrt{E_{R_j}} x_{R_j} h_{R_jD} + n_{R_jD.} \quad (8)$$

After equalization into $\hat{x}_{R_j}$ followed by demodulation into $\hat{m}_{R_j}$, destination D applies XOR between each $\hat{m}_{R_j}$ and all the previously selected cooperative symbols (in optimization phase), that is, for $j = 1, 2, \ldots, N_R$:

$$\tilde{m}_{R_j} = \hat{m}_{R_j} \oplus \hat{m}_{S_{I_1}D} \oplus \hat{m}_{S_{I_2}D} \oplus \ldots \oplus \hat{m}_{S_{I_{N_S - N_R}}D}$$

that can be expressed by

$$\begin{pmatrix} \tilde{m}_{R_1} \\ \tilde{m}_{R_2} \\ \vdots \\ \tilde{m}_{R_{N_R}} \end{pmatrix} = \begin{pmatrix} \hat{m}_{R_1} \\ \hat{m}_{R_2} \\ \vdots \\ \hat{m}_{R_{N_R}} \end{pmatrix} \oplus \hat{m}_{S_{I_1}D} \oplus \hat{m}_{S_{I_2}D} \oplus \ldots \oplus \hat{m}_{S_{I_{N_S - N_R}}D.} \quad (9)$$

Procedure of expression (9) serves to eliminate all the cooperative direct link symbols from the combinations (i.e. RLNC network coded symbols) $\hat{m}_{R_j}$. The last step is to recover the remaining N_R source nodes symbols by solving, using Gaussian elimination in $GF(q)$, the following system of linear equations

$$\begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1N_R} \\ a_{21} & a_{22} & \ldots & a_{2N_R} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N_R1} & a_{N_R2} & \ldots & a_{N_RN_R} \end{pmatrix} \times \begin{pmatrix} \hat{m}_{S_1} \\ \hat{m}_{S_2} \\ \vdots \\ \hat{m}_{S_{N_R}} \end{pmatrix} = \begin{pmatrix} \tilde{m}_{R_1} \\ \tilde{m}_{R_2} \\ \vdots \\ \tilde{m}_{R_{N_R}} \end{pmatrix}, \quad (10)$$

where a_{ij} ($i, j = 1, 2, \ldots, N_R$) are elements of the $N_R \times N_R$ full-rank (invertible) RLNC matrix A generated randomly at D in the optimization phase. The vector of elements $\hat{m}_{S_j}$ ($j = 1, 2, \ldots, N_R$) solutions of (10) represents the set of the estimate values of the remaining source nodes symbols (those that were not decoded at destination D in the optimization phase). Finally, the set of all the N_S source nodes messages in the initial order is obtained by injecting the cooperative links messages $\hat{m}_{I_kD}$ at the corresponding indices I_k ($k = 1, 2, \ldots, N_S - N_R$) into the set $\hat{m}_{S_j}$ ($j = 1, 2, \ldots, N_R$).

Performance evaluation: In this section, the performance of our proposed optimization strategy is analysed by simulation and comparison with the scenario where the cooperative source nodes are fixed and numerical results are provided.

The performance metrics used are symbol error rate (SER) versus SNR for a fixed value of path loss exponent α and SER versus α for fixed values of SNR.

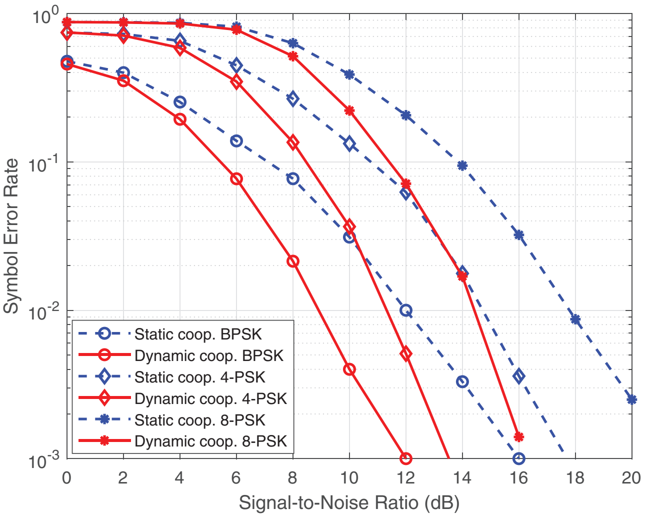

Fig. 2 *SER reduction of our proposed strategy for symbols in* $GF(2)$, $GF(4)$ *and* $GF(8)$. *Nakagami-m shape factor* $m = 2$ *and path loss exponent* $\alpha = 3$, $N_S = 3$ *and* $N_R = 2$

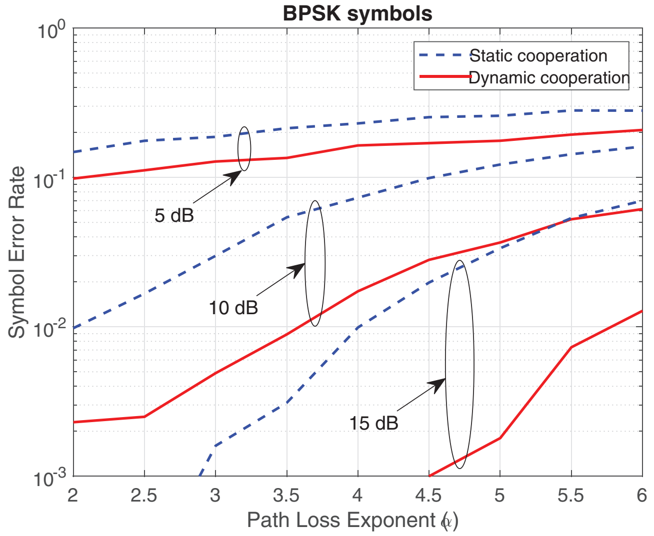

Fig. 3 *Comparison of SER vs.* α *for BPSK symbols and SNR = 5 dB, 10 dB and 15 dB between our proposed dynamic cooperation and fixed cooperation scenarios*

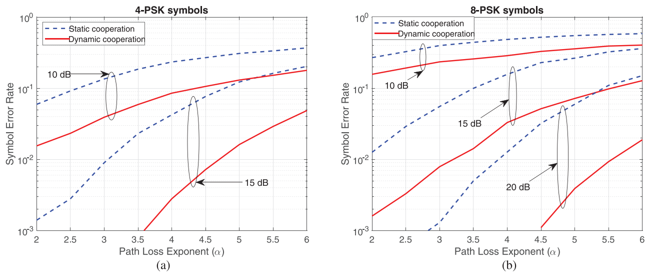

Fig. 4 *Comparison of SER vs.* α *between our proposed dynamic cooperation and fixed cooperation scenarios for (a) 4-PSK symbols and (b) 8-PSK symbols*

In our simulations, the network configuration is set as follows: Relay nodes are fixed at a distance of 5 km from the BS (destination D) and source nodes are mobile users moving between the relays and the maximum radio range of the BS set to 20 km, that is, 5 km $\leq d_{S_iD} \leq$ 20 km ($i = 1, 2, \ldots, N_S$). Hence, the path loss parameters K and d_0 are adjusted to fit this configuration as $K = 1$ and $d_0 = 5$ km. All transmitting nodes have the same average SNR per symbol (same average symbol energy). In every round ($N_S + N_R + 1$ time slots), a set of N_S GF(q) symbols, a set of $N_S \times N_R$ fading coefficients $h_{S_iR_j}$, a set of N_S fading coefficients h_{S_iD} and a set of N_R fading coefficients h_{R_jD} are randomly generated. With every coefficient h_{kl}, a corresponding AWGN component n_{kl} is randomly generated. Also, a set of N_S random distances d_{S_iD} ranging from 5 km to 20 km is generated each round. In our simulations, $N_S = 3$ and $N_R = 2$. All fading coefficients are Nakagami-*m* i.i.d. The results are averaged over 10 simulations with 1000 symbols in each simulation. The SER (or error probability) is evaluated for the transmission of one of the source nodes symbols that are recovered after Gaussian elimination at destination D (not a direct link to destination). Figure 2 shows how the proposed approach outperforms the fixed cooperative sources scenario in terms of SER versus SNR for orders of Galois field (GF) $q = 2, 4$ and 8. Nakagami-*m* shape factor is set to 2 and the path loss exponent equals 3. For transmission of binary phase shift keying (BPSK) symbols at an error rate of 10^{-3}, the SNR required in fixed cooperation scenario is $SNR = 16$ dB, while in dynamic optimized cooperation, we need only $SNR = 12$ dB which demonstrates that our approach allows to achieve a gain of 4 dB. Almost the same gain is produced in case of GF symbols of higher orders $q = 4$ and $q = 8$.

In Figure 3, we extend the results to the whole range of path loss exponent possible values to prove the superiority and outperformance of our strategy over the fixed cooperation scenario in reducing the symbol error probability in $GF(2)$. The gap of SER between our proposed dynamic optimized cooperation and fixed cooperation increases with SNR, that is, with the average symbol transmit energy, as we can see it clearly illustrated in Figure 4(a) for $GF(4)$ symbols and for all values of path loss exponent α. Figure 4(b) reenforces the validity of these results with $GF(8)$ symbols transmission.

Conclusion: We proposed and detailed a new strategy for optimizing the performance of NCC-based multi-source multi-relay wireless networks. We introduced a cooperative source nodes selection technique with fixed relay nodes equipped with RLNC computation capability. Numerical results obtained through Monte Carlo simulations show significant system performance enhancement in terms of SER in comparison with fixed cooperative source nodes scenario. Furthermore, the efficiency of this new approach is consolidated with results showing important SER decrease for the whole range of possible values of path loss exponent α. In addition, the proposed approach requires no retransmission because of the guaranteed resolution of the RLNC system of N_R linear equations since the destination ensures the full-rank matrix generation.

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