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

E. Benamira,1 F. Merazka,1,2* and G. K. Kurt2

1LISIC Lab., Telecommunications Department, University of Science and Technology Houari Boumediene, El Alia, Algeria
2Electronics and Communication Engineering, Istanbul Technical University, Ayazaga Campus, Maslak, Turkey
*Email: fmerazka@usthb.dz

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, 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 jointly 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 diversity 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 times the 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 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 Ns source nodes (mobile users) Si (i = 1, 2, …, Ns) are communicating with the destination D or BS via Nk relays Rj (j = 1, 2, …, Nk) with the assumption Nk ≤ NS. All source nodes are inside the coverage area of the BS, that is, have direct links with the destination. Assumptions on the distances dSRj (from source node Si to relay node Rj), dSD (from source node Si to destination D) and dRjD (from relay node Rj to destination D) are as follows:

\[ d_{SRj} < d_{SD} \text{ and } d_{RjD} < d_{SD}. \]

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 Si → D are further weakened by the path loss due to their larger distances. Our proposed approach relies on this particular fading and the fact that source nodes are moving mobile users, hence, distances dSRj are permanently changing. According to the number of source nodes NS, the number of relays Nk being constant, two scenarios are possible. The first one, when Nk = NSk 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 NSk < NSk since it exploits the cooperation of the remaining NSk − NSk direct links to destination. The Nk relays apply RLNC in GF(q), where q = 2 and b denotes the number of bits per symbol (packet), on the N2 packets received in both scenarios. Transmitted symbols are elements of finite fields GF(q) (q = 2, 4, 8, …) 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 Ns symbols lasts NSk + Nk + 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 NSk time slots where each source node Si (i = 1, 2, …, NSk) modulates, using q-ary PSK, its symbol ms to xSi and broadcasts the latter to destination D and all Nk relays. The received signal at each relay Rj (j = 1, 2, …, Nk) from each source node Si (i = 1, 2, …, NSk) is given by

\[ y_{ISRj} = \sqrt{E_{s}} x_{Si} h_{SRj} + n_{ISRj}, \tag{1} \]

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

\[ x_{ISRj} = y_{ISRj} h_{ISRj}^\ast = \left( \sqrt{E_{s}} x_{Si} h_{ISRj}^\ast + n_{ISRj} \right) h_{ISRj}^\ast, \tag{2} \]
where $h^*_{s,r}$ is the complex conjugate of $h_{s,r}$. Then, by applying $q$-PSK demodulation on $\hat{s}_{s,r}$, we obtain $\hat{m}_{s,r}$, the estimate of $m_{s,r}$ 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

$$y_{s,D} = \sqrt{E_s} x_s \sqrt{P_{s,i}} h_{s,D} + n_{s,D}$$

(3)

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

$$PL_{s,D} = K \left( \frac{d_0}{d_{s,D}} \right)^\alpha$$

(4)

where $K$ is a unitless constant depending on the antenna characteristics and average channel attenuation, $d_0$ is a reference distance and $\alpha$ is the path loss exponent. Parameters $K$ and $d_0$ are usually adjusted to approximate either an analytical or empirical model. Path loss exponent $\alpha$ ranges from 2 to 6 depending on the carrier frequency, type of environment and obstructions. For urban areas, $\alpha$ 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 coefficients matrix, without decoding of 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, with those highest instantaneous SNR ($y_{s,D}$). Since $y_{s,D} = \frac{\hat{h}_{s,D}}{\sigma_s}$ and assuming all transmitting nodes have the same average symbol energy, the selection criterion is reduced to the highest values of $\hat{h}_{s,D}$. Indices of the selected cooperative source nodes are denoted $I_k$ ($k = 1, 2, \ldots, N_S - N_R$) and derived as follows:

$$I_k = \arg\max \{ |\hat{h}_{s,D}|^2, |\hat{h}_{s,D}^2|, \ldots, |\hat{h}_{s,D}^N_S| \},$$

(5)

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

$$\hat{x}_{s,D} = y_{s,D} \hat{h}_{s,D}^*$$

(6)

for $k = 1, 2, \ldots, N_S - N_R$. Then, each $\hat{x}_{s,D}$ is demapped into $\hat{m}_{s,D}$ 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 $\hat{A}$ by injecting columns of ones ‘1’ at the indices $I_1, I_2, \ldots, I_{N_S-N_R}$.

For instance, if $q = 8$, $N_R = 6$, $N_S = 4$, the selected cooperative sources are $S_1$ and $S_2$, that is, $I_1 = 2$ and $I_2 = 4$ and the generated full-rank $4 \times 4$ RLNC matrix $A$ in $GF(8)$ is

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

(7)

the augmented $4 \times 6$ matrix that is sent to the relays.

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

$$m_{r,j} = \hat{a}_{i,j} \hat{m}_{s,r} \oplus \hat{a}_{i,j} \hat{m}_{s,r} \oplus \ldots \oplus \hat{a}_{i,j} \hat{m}_{s,r}$$

(8)

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 $N_S + 1 + j = 1, \ldots, N_R$, $D$ receives one RLNC signal given by

$$y_{r,D} = \sqrt{E_r} x_{r,D} \hat{h}_{r,D} + n_{r,D}$$

(9)

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

$$\hat{m}_{r,j} = \hat{m}_{r,j} \oplus \hat{m}_{s,r} \oplus \hat{m}_{s,r} \oplus \ldots \oplus \hat{m}_{s,r}$$

(10)

which can be expressed by

$$\begin{pmatrix}
\hat{m}_{r,1} \\
\hat{m}_{r,2} \\
\vdots \\
\hat{m}_{r,N_R}
\end{pmatrix} = \begin{pmatrix}
\hat{m}_{s,1} \\
\hat{m}_{s,2} \\
\vdots \\
\hat{m}_{s,N_S}
\end{pmatrix} \oplus \begin{pmatrix}
\hat{m}_{s,1} \\
\hat{m}_{s,2} \\
\vdots \\
\hat{m}_{s,N_S}
\end{pmatrix} \oplus \ldots \oplus \begin{pmatrix}
\hat{m}_{s,1} \\
\hat{m}_{s,2} \\
\vdots \\
\hat{m}_{s,N_S}
\end{pmatrix}$$

(11)

Procedure of expression (11) 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 $N_S$ source nodes symbols by solving, using Gaussian elimination in $GF(q)$, the following system of linear equations

$$\begin{pmatrix}
a_{11} & a_{12} & \ldots & a_{1N_R} \\
\vdots & \vdots & \ddots & \vdots \\
a_{N_R1} & a_{N_R2} & \ldots & a_{N_RN_R}
\end{pmatrix} \times \begin{pmatrix}
\hat{m}_{s,1} \\
\hat{m}_{s,2} \\
\vdots \\
\hat{m}_{s,N_S}
\end{pmatrix} = \begin{pmatrix}
\hat{m}_{r,1} \\
\hat{m}_{r,2} \\
\vdots \\
\hat{m}_{r,N_R}
\end{pmatrix}$$

(12)

where $a_{ij} (i = 1, 2, \ldots, N_S)$ are elements of the $N_R \times N_S$ full-rank (invertible) RLNC matrix $A$ generated randomly at $D$ in the optimization phase. The vector of elements $\hat{m}_{s}$ ($j = 1, 2, \ldots, N_S$) solutions of (12) 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 $\hat{m}_{r,j}$ at the corresponding indices $I_k$ ($k = 1, 2, \ldots, N_S - N_R$) into the set $\hat{m}_{s}$ ($j = 1, 2, \ldots, N_S$).

**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 path loss exponent $\alpha$ and SER versus $\alpha$ for fixed values of SNR.
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 ≤ d_{i,j} ≤ 20 km (i = 1, 2, . . . , 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_R GF(q) symbols, a set of N_S × N_R fading coefficients h_{k,R}, a set of N_S fading coefficients h_{k,D} and a set of N_R fading coefficients h_{g,D} are randomly generated. With every coefficient h_{k,R}, a corresponding AWGN component n_{ij} is randomly generated. Also, a set of N_S random distances d_{i,D} 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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