

Performance Analysis of Mixed MIMO RF/FSO DF Relaying Based on Globally Coupled Low Density Parity Check (GC-LDPC) Codes

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Abstract— In this work, we analyze the performance of the use of error correcting codes in particular the LDPC codes with global coupling (GC-LDPC) in a double-hop relay system composed of links with multiple inputs and multiple outputs at radio frequency / free space optics (MIMO-RF/FSO). A multi-antenna listener listens to the information by decoding the signals received from the source node. In addition, to decode the signals we use two-phase local-global decoding. To eliminate interference in the first hop we use the interference alignment technique (IA) we also assume that the source-relay link undergoes Rayleigh fading, and that the relay-destination link is affected by the degradations of the channel optics, including path loss, atmospheric turbulence, and pointing errors. Using DF relay technology, mixed MIMO-RF/FSO systems combine the advantages of RF and FSO communication technologies. The use of mixed MIMO-RF/FSO cooperative transmission systems can improve network reliability and transmission. Results demonstrate improved performance of MIMO-RF/FSO DF cooperative relay system based on GC-LDPC codes with multiple antennas compared to MIMO-RF/FSO systems without the use of GC-LDPC codes, but also to systems SISO (Single-Input Single-Output) RF-FSO DF proposed in the existing literature.

Keywords— Free Space Optics (FSO), Multiple Input Multiple Output (MIMO), atmospheric turbulence, Bit Error Rate (BER), Pointing errors, Radio frequency (RF), globally coupled low density parity check codes (GC-LDPC), Gamma-Gamma Fading, Rayleigh fading .

I. INTRODUCTION

Radio frequency (RF) communication systems have advantages like low power with good operating range and besides these here the line of sight (LOS) is not mandatory for communication. However, the problem is a lack of licensed spectrum with insufficient and also expensive data throughput. The ever increasing demand for bandwidth given the advent of innovative services which are having high bandwidth constraints has forced the search for alternative solutions to ensure the transport of information. Advances in fiber research have increased its performance and made it stand out from copper cables. These performances now make fiber the leading medium in terms

of capacity and also in terms of range if we were limited to terrestrial transmission. In addition to their high bandwidth, optical free space communications (FSO) have many other advantages over radio frequencies (RF). Some of these benefits are: they are license-free spectrum communications, quick and easy to deploy, safer and less demanding in terms of power consumption, mass requirements and electromagnetic interference isolation. For these reasons, FSO has been implemented in many applications such as: radio astronomy, remote sensing, last mile access, back-haul for cellular networks, and many others [1], [2]. Because of these distinctive features of SFO communication, much research has been carried out recently in this area; see [1], [2] and references therein. A major challenge in FSO communications is rain, fog, dust, snow, turbulence and misalignment [3]. Nevertheless, an effective method to overcome this challenge is to use the RF/FSO combination relay networks. In these networks, the (sources) transmit their information to a base transceiver station (relay) by RF link in the first hop, while in the second hop this relay transmits the information to the backbone network (destination) by FSO connection. Another advantage of this mixed relay scheme is that it saves economic resources. This is achieved by avoiding unnecessary expensive fiber optic implementations, for example in suburbs and city centers, and simultaneously conserving the RF spectrum while supporting high information rates using FSO transmission, so mixed RF/FSO relay networks have received a great deal of research attention.

On the other hand, the cooperative relay has received a lot of attention due to its ability to reduce power, extend coverage and improve throughput. Thus, it is interesting and promising to use these advantages for the security of the physical layer. More precisely, In I GUEYE et al [4] proposed two cooperative schemes of decoding and transmitting (DF) based error correcting codes particularly the LDPC codes, namely the case I, which involves choosing parallel relays, the sending node transmits the data to the receiving node and to a relay node which in turn transmits the data to the destination node. This form of transmission acts as a distributed antenna network and is

considered a cooperative approach in diversity; Case II, Multi-hop relay is for extending the range of a transmission with limited transmission range. In this approach, the signal passes from one relay node to another in series. Their results show that, compared to the traditional mode of transmission, their cooperative FSO systems not only attenuate fading induced by atmospheric turbulence but also protect information.

To improve network reliability and improve coverage, it is important to use relays in both RF and FSO networks. Mixed systems relaying RF-FSO have been discussed extensively in the literature: In the literature there has been increasing interest in how FSOs and RF links can be used in a double-hop configuration to support the link. uplink [5] and downlink transmissions [6]. In [7] the authors consider a mixed RF-FSO system with double-hop AF relaying in which a partial relay selection scheme was used to select the best relay. They have also considered the RF channels to be the Rayleigh distribution while the FSO channel is assumed to be Gamma-Gamma distribution. In [8], a mixed RF-FSO based DF system is considered with a single multiple input-output (SIMO) RF source-relay links and a single-mono-input-output (SISO) FSO relay to destination link. In [9], the authors analyzed the performance of an FSO/RF-based hybrid switching transmission in a DH scenario with a combination selection (SC). The symbol error rate (SER) also was studied for mixed Rician shaded / GG fixed gain AF without pointing error in [10]. A relay system similar to that in [10] has been studied in terms of cutoff probability in [11], but for mixed Rayleigh/Mulaga (M) fading with pointing error. The authors [12] provided a state of the art in which they discussed the different types of cooperative systems in wireless optical communication in indoor, terrestrial, space and underwater environments.

In particular, an analysis of failure performance has been presented in [13] for mixed MIMO-RF/FSO DF relay systems with Cognitive Radio Scenarios sublayer taking into account Space-Time Block Orthogonal Coding (OSTBC) and transmitting antenna selection (TAS). In [14], the performance of a double-hop multi-user RF/FSO DF relay was analyzed using the V-BLAST strategy, and assuming that the IMDD channel passed out by GG with a pointing error. Alternatively, the work of [15] studied the performances of the DF relay for a faded RF/GG faded FSO $\eta - \mu$ mixed with pointing errors. In [16] where the performance of the DF relay has been analyzed for mixed Nakagami-m/M fading with pointing errors and considering HD and IMDD in a unified manner, in which the best known capacity results for the FSO channel IMDD [17] were used.

Motivated by the applications of RF/FSO, MIMO RF-FSO systems and taking into account the limitations of the existing literature, we study the performance of cooperative RF/FSO and MIMO RF/FSO systems assisted by DF relay based on error correcting codes particularly the globally linked LDPC codes (GC-LDPC). The main contribution of this article is to propose a cooperative MIMO RF/FSO scheme assisted by a DF relay based on error correcting codes including globally coupled LDPC codes (GC-LDPC). We focus on the use of cooperative systems and error correcting codes particularly quasi-cyclic LDPC codes with the combination of two-phase local-global decoding at the

relay level. We also used PPM to modulate the data, we assume that FSO links follow the Gamma-Gamma distribution, while MIMO-RF links follow Rayleigh fading. We will also compare the use of GC-LDPC in mixed MIMO-RF/FSO communication versus SC-LDPC and QC-LDPC codes.

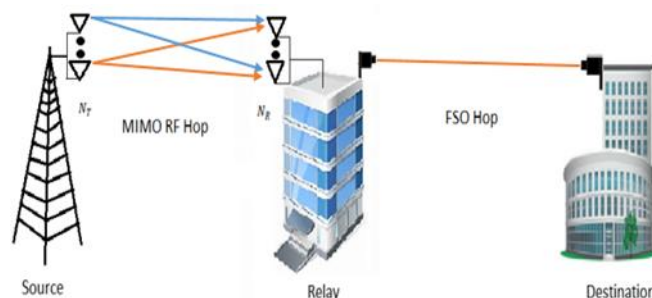


Figure 1. Schematic diagram of a mixed MIMO-RF / FSO DF cooperative relay network.

The rest of the article is organized as follows. Section II, the preliminaries, the system model and the study model are introduced. The two-phase local-global decoding procedure is presented in section III. Analysis of the simulation results is provided in IV. Finally, conclusions are drawn in section V.

II. MODEL SYSTEM AND CHANNEL MODEL

A. System Model

1) Ratings

In the following, we use letters, such as H , to denote a single parity matrix. We use B is the base matrix.

2) Les codes GC-LDPC

The globally coupled low density parity check codes (GC-LDPC) were first introduced in 2016 [18]. A GC-LDPC code is made up of several LDPC codes that are smaller blocks. The highly structural code construction facilitates efficient implementation while maintaining compelling error correction capabilities of large block length codes. A GC-LDPC code is an LDPC code made up of several LDPC codes of shorter block length, called local codes. The H_{GC} parity check matrix can have the format:

$$H_{GC} = \begin{bmatrix} H_{local}^{(1)} & 0 & \cdots & 0 \\ 0 & H_{local}^{(2)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & H_{local}^{(t)} \\ & & & H_{global} \end{bmatrix} \quad (1)$$

The t sub-matrices $H_{local}^{(1)}, H_{local}^{(2)}, \dots$ and $H_{local}^{(t)}$, placed along the main diagonal in the upper part of H_{GC} correspond to t local cascading codes. The H_{global} at the bottom forms a global connection part and connects these local codes so that the local decoders can work together. The global connection part provides high connectivity between the virtual networks, so that each virtual network is able to acquire more information from other virtual networks. It is

stated in [18] that connectivity is an important characteristic for iterative decoders to converge faster. It is perceived that the t -subgraphs of the local codes are disjoint, which implies that the local codes can be decoded simultaneously.

Algebraic GC-LDPC code construction methods have been introduced in [18] - [19]. These codes are QC-LDPC codes and the base matrices may have the format:

$$\mathbf{B}_{GC} = \begin{bmatrix} \mathbf{B}_{local}^{(1)} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_{local}^{(2)} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{B}_{local}^{(S)} \\ & & & \mathbf{B}_{global} \end{bmatrix} \quad (2)$$

The first GC-LDPC code proposed in [18] was constructed by a Latin square with the superposition technique [20]. By defining a matrix $\mathbf{B}_0$ on a prime field $GF(q)$,

$$\mathbf{B}_0 = \begin{bmatrix} \alpha^0 - 1 & \alpha - 1 & \alpha^2 - 1 & \cdots & \alpha^{q-2} - 1 \\ \alpha^{q-2} - 1 & \alpha^0 - 1 & \alpha - 1 & \cdots & \alpha^{q-3} - 1 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \alpha - 1 & \alpha^2 - 1 & \cdots & \alpha^{q-1} - 1 & \alpha^0 - 1 \end{bmatrix} \quad (3)$$

where α is a primitive element of $GF(q)$ [21], a subset of $\mathbf{B}_0$ is selected to form the base matrix $\mathbf{B}_{GC}$ in (2) and the CPM size is $q - 1$. To construct a GC-LDPC code of t local codes, it is necessary that t divides $q - 1$. Assuming that $q - 1 = ts$, $\mathbf{B}_0$ can be represented by an array $t \times t$ of sub-matrices $s \times s$, which is

$$\mathbf{B}_0 = \begin{bmatrix} \mathbf{W}_{0,0} & \mathbf{W}_{0,1} & \cdots & \mathbf{W}_{0,t-1} \\ \mathbf{W}_{1,0} & \mathbf{W}_{1,1} & \cdots & \mathbf{W}_{1,t-1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{W}_{t-1,0} & \mathbf{W}_{t-1,1} & \cdots & \mathbf{W}_{t-1,t-1} \end{bmatrix} \quad (4)$$

Subsequently, the basic BGC matrix is obtained by the following steps:

- 1) Select $m_{local}^{(1)}$ rows in $\mathbf{W}_{0,0}$ and these row indexes form a set of row indexes $\mathcal{I}^{(1)} = \{i_1, i_2, \dots, i_{m_{local}^{(1)}}\}$
- 2) Select the columns $n_{local}^{(1)}$ in the sub-matrix obtained in 1) and the column indexes form a set of column indexes $\mathcal{J}^{(1)} = \{j_1, j_2, \dots, j_{n_{local}^{(1)}}\}$. The result is glocal (1) in (2) and its size is $m_{local}^{(1)} \times n_{local}^{(1)}$.
- 3) Repeat 1) and 2) to differentiate $\mathcal{I}^{(t')}, \mathcal{J}^{(t')}$ for $\mathbf{B}_{local}^{(1)}$ and $t' = 2, 3, \dots, t$.
- 4) The unselected rows of $\mathbf{W}_{0,0}$ form a complementary set $\mathcal{I}^c = \{0, 1, \dots, s - 1\} \setminus \{\mathcal{I}^{(1)} \cup \mathcal{I}^{(2)} \cup \dots \cup \mathcal{I}^{(t)}\}$
- 5) Select the m_{global} indices in $\mathcal{I}^c$ to form a set of global

row indices $\mathcal{I}_{local} = \{i'_1, i'_2, \dots, i'_{m_{global}}\} \in \mathcal{I}^c$. The $\mathbf{B}_{global}$ submatrix can be obtained by $[\mathbf{W}_{0,0}(i, j_2) \mathbf{W}_{0,1}(i, j_2) \dots \mathbf{W}_{0,t-1}(i, j_t)]$. Where $\mathbf{W}_{m,n}(i, j)$ denotes the (i, j) -th entry of $\mathbf{W}_{m,n}$; $i \in \mathcal{I}_{global}$, $j_1 \in \mathcal{J}^{(1)}, j_2 \in \mathcal{J}^{(2)}, \dots, \text{et } j_t \in \mathcal{J}^{(t)}$. Note that the $\mathbf{B}_{global}$ submatrix has m_{global} rows and $\sum_{t'=1}^t n_{local}^{(t')}$ columns.

The construction of the GC-LDPC codes is not limited to the approach mentioned above. $\mathbf{B}_0$ can have other forms [18].

3) Study model

Consider a mixed MIMO-RF / FSO DF cooperative relay network. -Relais is better than that of the Source-Destination channel ($SNRS-R > SNRS-D$) in which the source is equipped with several N_T antennas communicate with the destination via a node an intermediate relay in the presence of a receiver equipped with several N_R antennas as shown in Fig. 1. The communication channel between the source node and the relay node is a Rayleigh fading MIMO RF link, with the source and relay nodes equipped respectively with transmit N_T and receive N_R antennas. Unlike the AF protocol [22], [23], the relay first decodes the symbols transmitted during the first phase using the error correcting codes particularly the GC-LDPC codes and retransmits them to the destination via an FSO link in the next phase. To allow point-to-point FSO communication, the relay and the destination are assumed to be equipped with a single photo-opening transmitter and a single photo-detector, respectively.

B. Channel model

1) THE MIMO RF HOP

The communication process begins with the transmission of the symbol vector $\mathbf{X}_{SR}^{(k)} \in \mathbb{R}^{N_s \times 1}$ where $k = \{1, 2, \dots, N\}$ denotes the k^{th} transmission vector in a frame of length N and $\mathbb{R}^{N_s \times 1}$ is a column vector of real numbers with N_s rows. The signal received at R at k^{th} instant of time, $\mathbf{Y}_{SR}^{(k)} \in \mathbb{C}^{N_r \times 1}$, where $\mathbb{C}^{N_r \times 1}$ is a column vector of complex numbers with N_r rows, is given as

$$\mathbf{Y}_{SR}^{(k)} = \sqrt{\frac{P_S^{(k)}}{N_s}} \mathbf{h}_{SR}^{(k)} \mathbf{x}_{SR}^{(k)} + \mathbf{n}_{SR}^{(k)} \quad (5)$$

Where $\mathbf{x}_{SR}^{(k)}$ is the signal encoded with GC-LDPC codes, modulated with PPM modulation and then transmitted from the source, $P_S^{(k)}$ is the transmit power of the source and $\mathbf{n}_{SR}^{(k)}$ is the additive white Gaussian noise of the channel (AWGN) S-R where $\sigma_{SR}^2 = N_{01}$ is a one-sided power spectral density which is added at the relay level and $\mathbf{h}_{SR}^{(k)}$ represents the parameters of the channel between the source and the relay. The instantaneous SNR at the relay will be:

$$\gamma_{SR} = \frac{P_S^{(k)} |\mathbf{h}_{SR}^{(k)}|^2}{\sigma_{SR}^2}$$

where P_S is the average power of $\mathbf{X}_{SR}^{(k)}$ and σ_{SR}^2 is the noise power in the S-R link. The S-R link is modeled by the

Rayleigh distribution and is used for a small-scale fading signal under no line-of-sight (NLOS) conditions. The PDF of γ_{SR} is given by:

$$f_{\gamma_{SR}}(\gamma_{SR}) = \frac{1}{\gamma_{SR}} \exp\left(-\frac{\gamma_{SR}}{\gamma_{SR}}\right) \quad (6)$$

In this first hop interference elimination is possible by projecting the total received signal, using an interference elimination combination matrix, onto the desired signal subspace (zero forcing interference). Interference Alignment (IA) technique is used in MIMO RF hopping to eliminate interference, and therefore this associated with GC-LDPC codes results in improving the multiplexing gain in this hopping, and consequently the Overall system performance is improved. The design of the IA precoding matrix and the reception interference elimination matrix is performed using an orthogonalized minimum leakage (OR-ML) algorithm.

The design of the b^{th} user precoding matrix V_b and of the interference suppression matrix U_b associated with its corresponding b^{th} relay is carried out by adapting the orthogonalized minimum leak algorithm (OR-ML). In this algorithm, the interference I_b at each b^{th} relay is minimized in the forward direction, where the interference is written:

$$I_b = T_r(U_b^H Q_b U_b) \quad (7)$$

Where Q_b is the interference covariance matrix for this b^{th} BTS (relay), and it is modeled as

$$Q_b = \sum_{g=1, g \neq b}^G \frac{P_g}{d} h_{bg} V_g V_g^H h_{bg}^H \quad (8)$$

To minimize the interferences in this direction, U_b is composed of the eigenvectors associated with the smallest eigenvalues of Q_b . In the opposite direction, the interference $\tilde{I}_i$ for the user k^{th} is minimized where

$$\tilde{I}_i = T_r(\tilde{U}_i^H \tilde{Q}_i \tilde{U}_i) \quad (9)$$

and the inverse interference covariance matrix is

$$\tilde{Q}_i = \sum_{b=1, b \neq i}^B \frac{P_b}{d} \tilde{h}_{ib} \tilde{V}_b \tilde{V}_b^H \tilde{h}_{ib}^H \quad (10)$$

where $\tilde{h}_{ib} = h_{bi}^H$; $\tilde{V}_b = U_b$ et $\tilde{U}_i = V_i$

To minimize the interferences in the opposite direction, $\tilde{U}_i$ (ie V_i) is composed of the eigenvectors associated with the smallest eigenvalues of $\tilde{Q}_i$.

Algorithm 1 Orthogonalized Minimum Leakage (OR-ML) Algorithm

1: **Start** with arbitrary N_t precoding matrices N_t with $V_i^H V_i = I_{d \times d} \quad \forall i \in \{1, \dots, M\}$.
2: **Repeat**
3: **Calculate** the interference covariance matrices $Q_b \quad \forall b \in \{1, \dots, M\}$ according to (9).
4: **Compute** the interference suppression vector U_b^* for the i^{th} data stream at b^{th} BTS (relay) where $U_b^* = v_i[Q_b] \quad \forall b \in \{1, \dots, M\}$, where $v_i[Q_b]$ is the eigenvector of the i^{th} smallest eigenvalue of Q_b .
5: **Combine** the interference suppression vectors U_b^* to form the interference suppression matrix $U_b \quad \forall b \in \{1, \dots, M\}$.
6: **Reverse** the direction and set the reverse precoding matrix as the interference suppression matrix $\tilde{V}_b = U_b \quad \forall b \in \{1, \dots, M\}$.
7: **Calculate** the reverse interference covariance matrices

$\tilde{Q}_b \quad \forall b \in \{1, \dots, M\}$ according to (11).

8: **Compute** the reverse interference suppression vector $\tilde{U}_i^*$ for the i^{th} data stream at i^{th} user where $\tilde{U}_i^* = v_i[\tilde{Q}_i] \quad \forall i \in \{1, \dots, M\}$.
9: **Combine** the interference suppression vectors U to form the reverse interference suppression matrix $\tilde{U}_i \quad \forall i \in \{1, \dots, M\}$.
10: **Reverse** the direction and set the precoding matrix as the reverse interference suppression matrix $V_i = \tilde{U}_i \quad \forall i \in \{1, \dots, M\}$.
11: **Until** a pre-defined number of iterations.
12: **Output** $U_b \quad \forall b \in \{1, \dots, M\}$ and $V_i \quad \forall i \in \{1, \dots, M\}$.

2) THE FSO HOP

After receiving the signal, the relay (BTS) transmits a decoded version of it to the destination in the second phase of transmission. Since the relay has knowledge of the source-relay channel, the received signals are combined using a combiner and the decision is made by choosing the best received signal.

At the relay after converting the signal from the MIMO-RF link into an electrical signal, the latter will be demodulated using BPSK demodulation and then decoded using two-phase local-global decoding. The decoding principle will be described in the following section.

After these decoding operations, the relay estimates the vectors of the resulting symbols and the latter is then amplified by a factor g_1^k . The amplified signal is then re-encoded using GC-LDPC codes, modulated by a PPM modulator. This electrical signal is converted into optical and transmitted to the 2nd time slot by the relay towards the destination. This optical channel for the FSO link between the relay and the destination at k^{th} instant can be modeled as $H_{RD}^k = H_l H_a H_p$, where H_l represents the path loss [24], H_a represents the atmospheric turbulence induced fading modeled at using the Gamma-Gamma distribution, and H_p represents the fading of the misalignment (pointing errors).

Thus, the signal received at the destination for the case of IMDD can be, expressed by:

$$y_{RD}^{(k)} = \sqrt{P_R^{(k)}} \eta H_{RD}^{(k)} w_{RD}^{(k)} + n_{RD}^{(k)} \quad (11)$$

where $w_{RD}^{(k)}$ is the signal retransmitted from the relay. $P_R^{(k)}$ is the transmission power of the relay. H is the optical-electrical conversion coefficient. $n_{RD}^{(k)}$ denotes the additive noise at the receiver which consists of thermal noise, dark noise and background radiation. This signal will be demoded with a PPM demodulator and then decoded with a GC-LDPC decoder to give the estimated information.

The corresponding PDF of the optical channel is given as

$$f_{H_{RD}^{(k)}}(h) = \frac{\alpha \beta \xi^2}{A_0 H_l \Gamma(\alpha) \Gamma(\beta)} G_{1,0}^{2,0} \left(\frac{\alpha \beta h}{A_0 H_l} \middle| \xi^2 - 1, \alpha - 1, \beta - 1 \right) \quad (12)$$

Where H_l is the loss on the path, A_0 is the fraction of the power collected at $r = 0$, r being the radial displacement due to pointing errors.

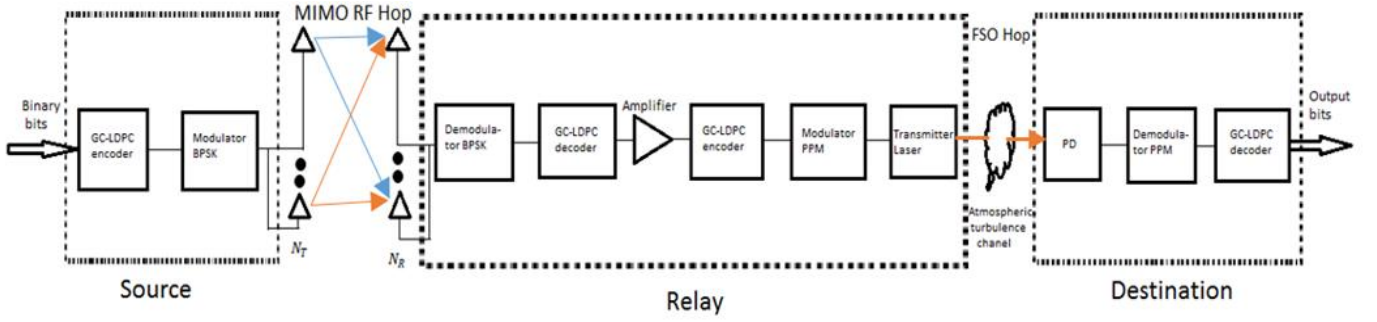


Figure 2. Functional diagram of GC-LDPC coded MIMO-RF/FSO communication system

The quantity ξ is defined as $\xi = \frac{\omega_e}{2\sigma_s}$, where ω_e is the equivalent beamwidth radius and σ_s is the standard deviation of the pointing error displacement at the receiver.

Moreover, $G_{p,q}^{m,n} \left(x \middle| \begin{smallmatrix} a_1, \dots, a_p \\ b_1, \dots, b_q \end{smallmatrix} \right)$ is the Meijer function G , α and β are the parameters of large and small scale scintillation, respectively which depend on the Rytov variance $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$, where k , C_n^2 and L denote the wave optical number, refractive index structure constant and bond distance respectively.

For a coherent optical receiver with heterodyne detection [26] at the destination, the instantaneous SNR of the relay link is given:

$$\gamma_{RD}^{(k)} = \frac{\Re A}{q \Delta f} H_{RD}^{(k)} \quad (13)$$

Where $\Re$ is the reactivity of the photodetector, A is the area of the photodetector, q is the electronic charge, and Δf denotes the bandwidth equivalent to the noise of the receiver. On the other hand, the instantaneous SNR of the destination-relay FSO link with intensity modulation/direct detection (IM/DD) is given as:

$$\gamma_{RD}^{(k)} = \frac{(F \Re \zeta)^2}{2 \Delta f (q \Re A I_b + 2 k_b T_b F_n / R_L)} (H_{RD}^{(k)})^2 \quad (14)$$

Where I_b is the background light irradiance, k_b is Boltzmann's constant, T_b is the temperature in Kelvin, ζ is a factor used to avoid over-modulation, F_n represents a thermal noise improvement factor due to noise from the amplifier and R_L is the load resistance.

The CDF of $\gamma_{RD}^{(k)}$ is given by:

$$f_{\gamma_{RD}^{(k)}}(x) = \Theta_1 G_{\theta+1, 3\theta+1}^{3\theta, 1} \left(\frac{\Theta_2}{\mu_\theta} x \middle| \begin{smallmatrix} 1, \Theta_3 \\ \Theta_4, 0 \end{smallmatrix} \right) \quad (15)$$

Where θ defines the type of detection technique used at the destination, ie $\theta = 1$ represents heterodyne detection and $\theta = 2$ represents IM / DD, and μ_θ is the average electrical SNR [26]. In addition, the different sizes are defined

$$\Theta_1 = \frac{\theta^{\alpha+\beta-2} \xi^2}{(2\pi)^{\theta-2} \Gamma(\alpha) \Gamma(\beta)}, \quad \Theta_2 = \frac{(\alpha\beta)^\theta}{\theta^{2\theta}}, \quad \Theta_3 = \frac{\xi^2+1}{\theta}, \dots, \frac{\xi^2+\theta}{\theta}$$

includes θ terms,

$$\Theta_4 = \frac{\xi^2}{\theta}, \dots, \frac{\xi^2+\theta-1}{\theta}, \frac{\alpha}{\theta}, \dots, \frac{\alpha+\theta-1}{\theta}, \frac{\beta}{\theta}, \dots, \frac{\beta+\theta-1}{\theta}$$

and includes 30 terms

The destination receives the signal $\gamma_{RD}^{(k)}$ from the FSO link. This signal will be decoded with a GC-LDPC decoder then demoded with a PPM demodulator.

III. THE LOCAL-GLOBAL DECODING PROCEDURE IN TWO PHASES

To take advantage of the locally disjoint and globally coupled parity check matrix structure, the decoding can be organized in a two-phase local-global hierarchical fashion. The local phase and the global phase are associated with the local codes and the global connection part, respectively. In the local decoding phase, all local codes are decoded independently. Several iterations of local decoding are performed and the updating of the message is confined between the local VNs and the local CNs . Information from other local nodes can only be obtained by global decoding. The decoding switches between the local phase and the global phase until the convergence conditions are met. The concept of two-phase local-global decoding was first mentioned in [23] with various use cases. Two-phase decoding is very flexible in controlling the decoding flow by configuring the number of iterations of the local and global phases. In some latency sensitive applications, decoding may be completed as soon as all local code parity check equations are satisfied. Figure 3 illustrates a possible two-phase decoding procedure. I_L and I_G are the number of iterations of local decoding and global decoding, respectively. I is the iteration number of the complete decoding. The predefined maximum number of decoding iterations for the local and global phases is T_L and T_G respectively. In layer decoding, this two-phase decoding stream can be achieved by forcing the control nodes to be updated in different iterations of decoding. A maximum of $itr \times (T_L + T_G)$ iterations can be performed. For each $T_L + T_G$ iteration, only local control nodes are updated in the first T_L iterations, and global control nodes are updated only in subsequent T_G iterations. In addition, if the bit error rate is not uniform among these local codes, local codes corresponding to lower raw bit error rates will converge faster and may help other local codes to converge by the information exchanged in the global phase.

The two-phase local-global decoding mentioned above can be simplified in a direct-acting approach. Similar to the two-level decoding introduced in [27], all local decoders first perform independent decoding.

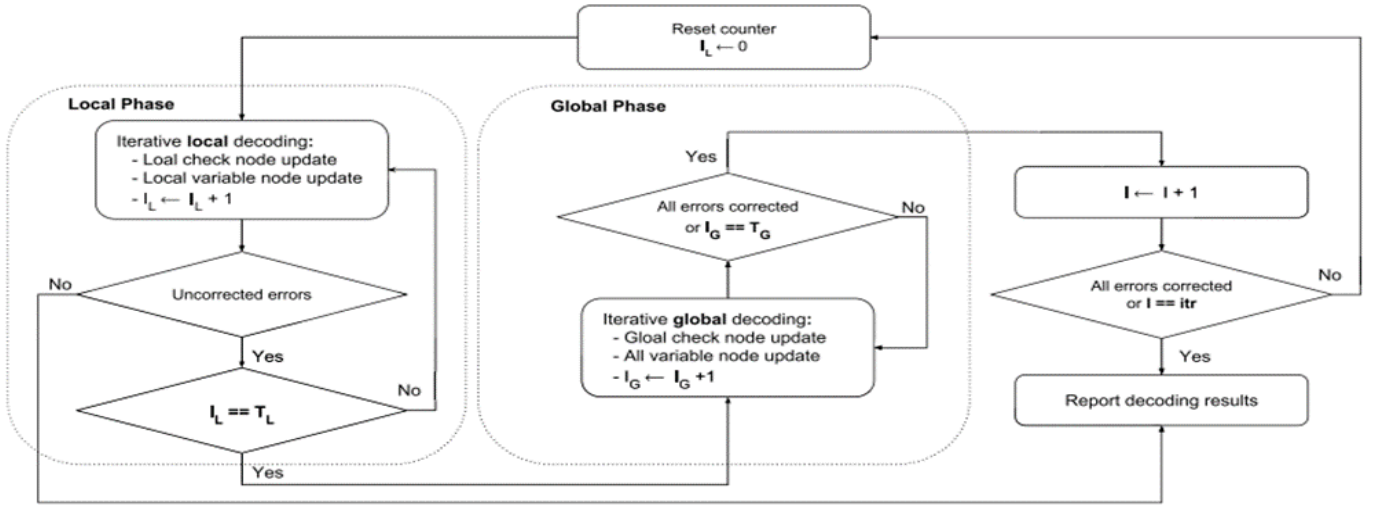


Figure 3. Local / global two-phase decoding flow

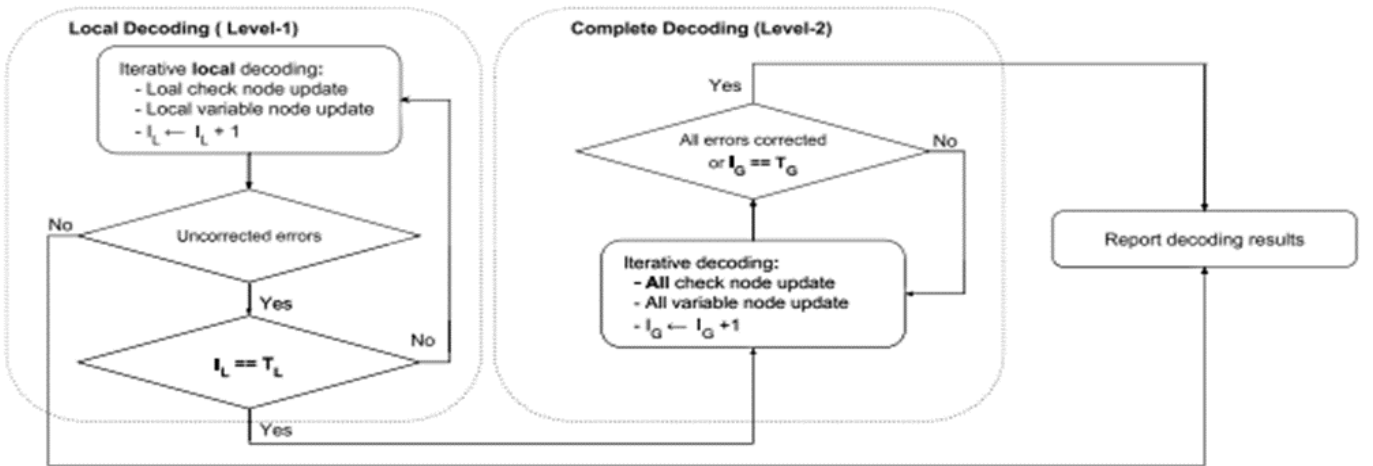


Figure 4. Two-level decoding flow.

It is only when one of the local decoders fails to correct the errors that the decoding is switched to the second level: a full decoding based on H_{GC} . Figure 4 illustrates the two-level decoding flow. The maximum iterations allowed for these local decodings are T_L and $T_L = 3, 6, 10$ are compared. Then the decoder performs decoding based on the full parity check matrix H_{GC} , which is called second level or level 2 decoding. The maximum number of iterations for level 2 decoding, T_G , is 10 in our simulation. The two-level decoding strategy, the number of iterations required is very close to the upper limit T_L , the maximum local decoding iterations allowed. This implies that the decoding ends in 1 or 2 iterations after entering the level 2 decoding. For two-phase decoding, Each iteration includes at most $T_L = 3$ and $T_G = 2$ local and global iterations. The converged iterations around 2 imply that the global connection part in H_{GC} can effectively provide secondary information for local decoders. Most of the time, decoding can be done with in 4 times after the global message exchange.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we present numerical examples to demonstrate the exact analytical expressions and use of GC-LDPC codes in mixed RF/FSO, MIMO-RF/FSO communication and also to illustrate the impact of various system parameters and channel on the performance of our system. In addition, this section checks the comparison results between GC-LDPC codes and other codes like SC-LDPC and QC-LDPC in mixed MIMO-RF/FSO communication.

The systems described above have been simulated on Matlab to explain the different parameters of the system considered. All the parameters of the FSO link used here are defined as follows: distance $L = 1\text{km}$, the wavelength $\lambda_{FSO} = 785\text{nm}$, the refractive structure parameter $C_n^2 = 1.2 \times 10^{-13}\text{m}^{-\frac{2}{3}}$, the loss on the path as a function of the distance in clear weather $I_l = 0.9/\text{km}$, the fraction of the optical power collected $A_0 = 1$, the average power of the LOS component $\Omega = 1.3265$, the mean power of the total scattering components $b_0 = 0.1079$, the quantity of scattering power coupled to the LOS component $\rho_0 = 0.596$, and the scintillation parameters $\alpha = 2.296$ and $\beta = 2$.

Figure 5 is the BER versus the SNR graph, when two cooperation schemes are used. As can be seen, the performance of the end-to-end system improves when using error correcting codes including GC-LDPC codes. In addition, to show the impact of using GC-LDPC codes we compared it with other LDPC codes such as QC-LDPC and SC LDPC codes. Figure 6 shows the comparison between the use of GC-LDPC codes with the codes mentioned above. All of these codes have been applied in mixed RF-FSO transmission. As can be seen, the BER decreases with the use of GC-LDPC codes and this results in better performance in mixed RF-FSO transmission. It can be seen that RF/FSO transmission using

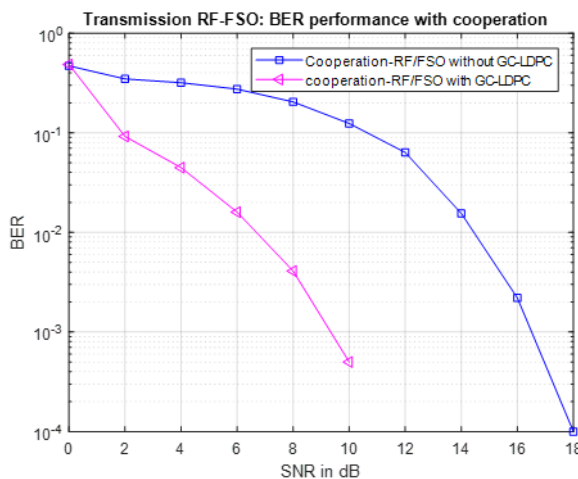


Figure 5. Performances of a mixed RF / FSO DF cooperative system for transmission based on GC-LDPC codes.

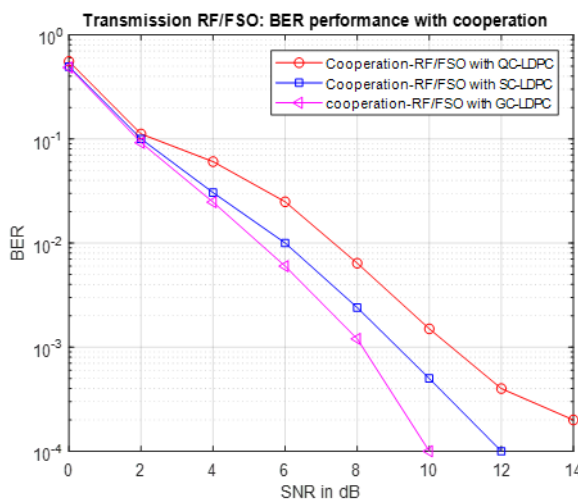


Figure 6. BER graph versus average SNR for a mixed RF / FSO DF link based on GC-LDPC codes compared with other codes.

error correcting codes including GC-LDPC codes have better performance compared to mixed RF/FSO transmission using SC-LDPC and QC-LDPC. As we can see from the figure above, GC-LDPC code provides higher encoding gain. The performance improves as the length of the coupling increases.

Figure 7 shows the graph of the analytical BER, simulated against the mean SNR to show the impact of DF MIMO-RF/FSO cooperative systems using GC-LDPC codes for conditions of severe atmospheric turbulence. Figure 8 shows the BER versus mean SNR graph to assess the

influences of atmospheric turbulence parameters σ_{RD}^2 the robustness of the GC-LDPC codes for conditions of strong and moderate atmospheric turbulence as well as for conditions of weak atmospheric turbulence.

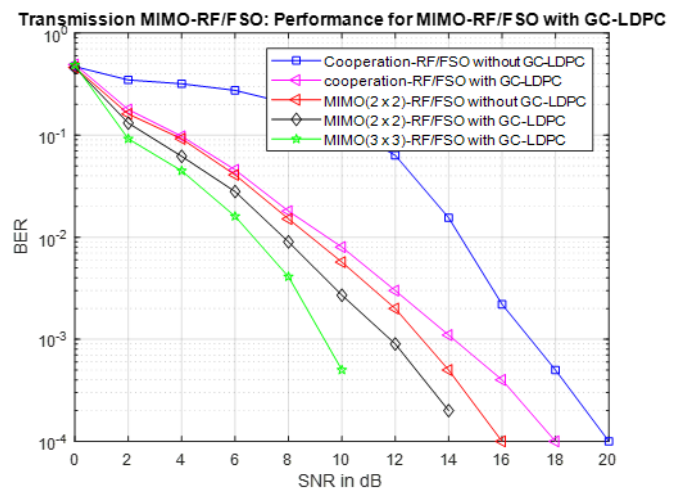


Figure 7. BER versus average SNR plot for a mixed MIMO-RF / FSO DF cooperative system for IM / DD detection with $\alpha = 2.296, \beta = 2, \rho_{RF} = 0.85, \rho_{FSO} = 0.5$ based GC-LDPC code.

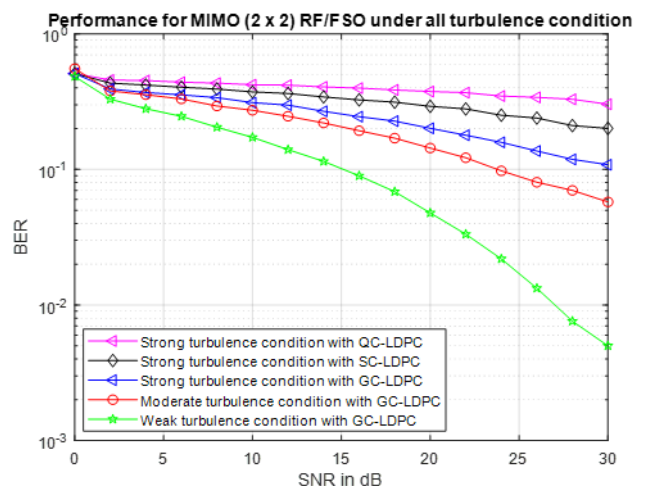


Figure 8. Performance of a mixed MIMO-RF / FSO DF cooperative system based GC-LDPC codes under all turbulence conditions for IM / DD detection with $\sigma_{RD}^2 = 1.5, \sigma_{RD}^2 = 1, \sigma_{RD}^2 = 0.7, \sigma_{RD}^2 = 0.1$.

Figure 7 shows that the cooperation is more advantageous in the case of a mixed RF/FSO DF cooperative system using the error correcting codes called GC-LDPC codes compared to an RF/FSO cooperative system without the use of GC-LDPC codes. Hence the importance of using error correcting codes. This figure also shows the advantage of using mixed DF MIMO-RF/FSO cooperative systems using GC-LDPC codes. It is clearly seen that the performance of MIMO-RF/FSO systems is better than that of end-to-end (RF/FSO) systems. In addition, one can also see the impact of the number of transmitting and receiving antennas on the performance of the MIMO-RF/FSO system. If we increase the number of antenna N_T (number of antenna on transmission) and the number of antenna N_R (number of antenna on reception) between the source node and the relay node (MIMO RF link) with the use of parameters ($\alpha = 2.296, \beta = 2, \rho_{FSO} = 0.5$) between the relay node and the destination (point-to-point FSO) the

performance of the mixed MIMO-RF/FSO DF system increases.

In figure 8 it can be clearly seen that smaller values σ_{RD}^2 , i.e. lower atmospheric turbulence, give better performance compared to schemes with higher values σ_{RD}^2 , i.e. stronger atmospheric turbulence. Here we obtained BER performance that is better for low turbulent environments compared to moderate and high turbulence environments. The graph shows that the performance of the system deteriorates as the force of the turbulence increases. In addition, we can also see on this graph the robustness of the GC-LDPC codes compared to other codes such as the SC-LDPC and QC-LDPC codes in environments of strong turbulence. It can be seen that the performance of MIMO-RF/FSO links is better overall when the channel is weakly turbulent with the use of GC-LDPC codes to protect information.

V. CONCLUSIONS

This paper investigated a mixed DF relay scheme (MIMO-RF/(FSO)) based on globally coupled low density parity check codes (GC-LDPC). MIMO-RF links were assumed to follow Rayleigh fading, while the link the FSO link was a point-to-point distributed Gamma-Gamma link, affected by path loss and pointing errors. In MIMO RF hopping, the IA technique was used to eliminate interference, and hence this leads to improve the gain of multiplexing in this hop, and as a result the overall performance of the system is improved. It has been shown that the use of error correcting codes name GC-LDPC codes allow to protect the information results in an improvement system performance. It is also shown that a MIMO-RF/FSO system using the GC-LDPC error correcting codes gives a substantial improvement in performance over a MIMO-RF/FSO system without them. codes correcting errors but also compared to an RF/FSO system using the other codes such as the codes SC-LDPC and QC-LDPC. This interesting result is due to the fact that error correcting codes play a very important role in communication systems. In our future research we are interested in the use of MIMO-RF/MIMO-FSO systems associated with error correcting codes and the use of MIMO FSO systems in advanced telecommunications i.e. the fifth generation. (5G).

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