Low-complexity Multiple-relay Strategies for Improving Uplink Coverage in 4G Wireless Networks

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***Abstract*—In this work we present low-complexity coded-modulation strategies for distributed relaying in 4G wireless networks. The primary goal of these strategies is to improve coverage on the uplink while retaining high spectral efficiency through multiuser spatial-multiplexing using two or more relays between the users and the base station. We contrast layer 2 techniques based on full decoding at relay stations and simple compression-based (quantization) techniques with QAM alphabets. Mutual-information and error-exponent analysis clearly show the benefits of distributed quantization both in the high and medium spectral efficiency regions. We further present these results in the context of evolving LTE-Advanced standardization activities, primarily by suggesting adaptations to standardized coding and retransmission mechanisms for a multiple-relay system.** [1]

I. Introduction

In this paper, we examine a general version of the Gaussian parallel relay networks (PRNs), firstly proposed and studied in [1], [2], with phase fading. The general PRN with phase fading consists of multiple source and relay nodes, and a single destination node where source nodes want to communicate with the destination node with the assistance of intermediate relay stations (RSs). For the links between the RSs and the destination node we consider a particular channel model: orthogonal error-free limited-capacity backhaul (i.e., microwave links or fiber-optic connection between the RSs and the destination).

The PRN studied in this paper can find *applications* in cellular networks for UL communications, in long-range sensor networks, and in rapidly deployable infrastructure networks for military or civil applications.

For 4G cellular systems, the use of Coordinated Multi-Point (CoMP) transmission (or reception) is a promising tool for increasing system spectral efficiency and reliability by both alleviating inter-cell interference effect via joint processing of eNbs' received signals at a remote central unit (RCU) for UL communications and providing spatial diversity [3]. Moreover, allowing joint processing would lead to reduction in required transmit power at MSs. In most of the evaluations done so far for CoMP, it is assumed that the eNbs are connected to a RCU via a reliable and infinite capacity backhaul link, which however is an unrealistic assumption especially when system load is high. Hence, in this paper, we consider a more realistic system model where the eNbs (in our setup relays) are connected to the final destination via limited-capacity links.

The considered PRN model can also find applications in long-range sensor networks where RSs could be satellites with deep-space link to earth stations. Moreover, rapidly deployable infrastructure networks (military or civil applications) would also be target application of the PRN studied in this paper. In rapidly deployable infrastructure networks, some nomadic RSs, which are placed in different geographic locations, are connected to a RCU via reliable but finite-capacity links, and provide coverage for user equipments (UEs) on the geography.

A. Contributions

The contributions of this paper are

- We derived a new outer bound for a multi-source generalization of the PRN studied by Schien [2], and then analyzed the performance of different relaying strategies, such as Decode-and-Forward (DF), Block Quantization and Random Binning (BQRB) and Quantize-and-forward (QF) relaying, in terms of achievable rates and random coding error exponents (EEs). In the literature most of the information theoretic analysis done for relay channels are based on Gaussian codebook and Gaussian mapping assumption at the source and the relay, respectively. Since these assumptions impose more complexity on the system and the processing capabilities of RSs highly affect system performance, in this paper we investigate whether it is possible to have good performance (for both achievable rates and error exponents) by using simple and cheap RSs with limited backhaul connections to the destination. In particular, motivated by the observations given in [4], [5], we propose a *simple* and *practical* relaying scheme consisting of finite constellation alphabets (i.e., M-QAM) at sources and symbol-by-symbol uniform scalar quantization (uSQ) at the RSs, and show that it is possible to exploit the *structure* of source codewords by

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using non-Gaussian mapping at the RSs. Through numerical simulations we observe that from low to medium SNR, with sufficient backhaul capacities in order to be able to convey decoded bits reliably to the destination, the achievable sum-rate by using the proposed relaying scheme outperforms that of DF relaying where Gaussian codebooks are used at the sources. Moreover, we observe that with increasing modulation alphabet size this rate gain becomes more.

- Through numerical analysis we show that the random coding EEs corresponding to the proposed relaying scheme can be better than that of DF and BQRB relaying schemes when the right constellation size is selected by each source and the backhaul capacity is sufficient.
- Finally, inspired by performance improvements with the proposed relaying scheme, we construct an LTE based testbench using the OpenAir Interface platform, see [6] for detailed description of the platform, and assess the throughput and block error rate (BLER) performances of the proposed and DF relaying schemes, which are shown to be inline with the theoretical results.

II. Channel Model

We study the PRN model shown in Fig. 1 where a set of $\mathcal{T} = \{1, 2, \ldots, T\}$ sources want to communicate with a destination with the assistance of a set $\mathcal{K} = \{1, 2, \ldots, K\}$ of RSs. For the following we will assume $T = K = 2$ for better demonstration. We assume neither direct link between the sources and the destination nor among the RSs. All the channels are modeled as time-invariant, memoryless additive white Gaussian noise (AWGN) channels with constant gain (which may correspond to path-loss between each transmitter and receiver) and ergodic phase fading. Each source encodes its message $w_t \in [1, 2^{nR_t}]$, where R_t is the transmission rate of the t-th source, into the codeword $x_t^n(w_t)$, $t = 1, 2$. All source channel inputs are independent of each other.

The received signals at both RSs are given, in vector form, as follows

$$\begin{aligned}\mathbf{y}_R = \begin{bmatrix} y_{R_1} \\ y_{R_2} \end{bmatrix} &= \begin{bmatrix} |h_{11}|e^{j\Phi_{11}} & |h_{12}|e^{j\Phi_{12}} \\ |h_{21}|e^{j\Phi_{21}} & |h_{22}|e^{j\Phi_{22}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \\ &= \mathbf{H}\mathbf{x} + \mathbf{z} \\ &= \mathbf{h}_1 x_1 + \mathbf{h}_2 x_2 + \mathbf{z} = \begin{bmatrix} \mathbf{g}_1^T \\ \mathbf{g}_2^T \end{bmatrix} \mathbf{x} + \mathbf{z} \end{aligned} \tag{1}$$

where $\mathbf{H} = [\mathbf{h}_1 \ \ \mathbf{h}_2] = [\mathbf{g}_1 \ \ \mathbf{g}_2]^T$, $\mathbf{x} = [x_1 \ \ x_2]^T$ and $\mathbf{z} = [z_1 \ z_2]^T$. Here x_k is the transmitted signal from the k-th source and y_{R_k} is the received signal at the k-th RS, where $|h_{kt}| \in \mathbb{R}^+$, $\forall k, t \in \{1, 2\}$, is the fixed channel gain from the t-th source to the k-th RS, $z_k \sim \mathcal{CN}(0, \sigma^2)$ is circularly symmetric complex AWGN at the k-th RS. The Φ_{kt}, $\forall\{k, t\}$ denote the set of random phases induced by the channels from the t-th source to the k-th RS. Note that we assume ergodic phase fading where each of Φ_{kt} and Φ_{Dk} is a random variable distributed uniformly over $[-\pi; \pi]$. Random phases are perfectly known to the relevant receivers and unknown to the transmitters. Each source has an average power constraint,

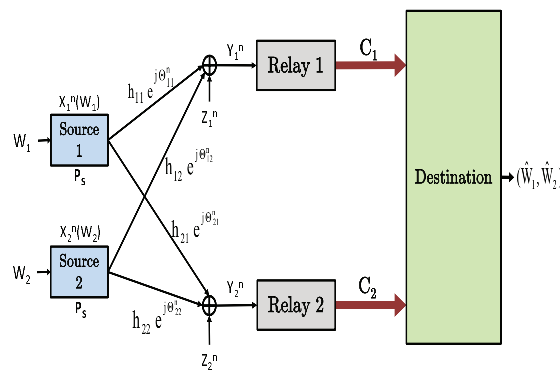

Fig. 1. A two-source, two-relay PRN setup with limited capacity backhaul links.

i.e., $\mathbb{E}[|x_t(w_t)|^2] = P_s$, $\forall w_t \in [1, 2^{nR_t}]$, $t = 1, 2$. The k-th RS transmits x_{R_k} based on the previously received signals (causal encoding) [7].

For the access channel from the RSs to the destination, we consider lossless orthogonal links with finite capacity between each RS and the destination. Let C_k[bits/transmission], $k = 1, 2$, be the link capacity between the k-th RS and the destination.

III. Achievable Rates Analysis

A. Gaussian Signaling at the Sources and the Relays

In this subsection, we briefly give the outer bound and achievable rates corresponding to different relaying strategies for the AWGN PRN with phase fading under the assumptions of Gaussian signaling at the sources and Gaussian mapping at the relays. Though with these assumptions it is easier to analyze system performance for various relaying schemes, it is not obvious whether these assumptions are the best one can make. Hence, in the following section we will also look at non-Gaussian settings and investigate the performances of different relaying schemes.

For lossless orthogonal limited-capacity backhaul links between the RSs and the destination, we have the following outer bound:

Corollary 1. *An outer bound for the T-source K-relay PRN where each RS has lossless links to the destination with a capacity constraint $C_k, \forall k \in \mathcal{K}$, is given by, for $\mathcal{M} \subseteq \mathcal{T}$,*

$$\sum_{i \in \mathcal{M}} R_i \leq \max_{p(\mathbf{x}, \mathbf{x}_R)} \min_{\mathcal{R} \subseteq \mathcal{K}} \left\{ I(X_{(\mathcal{M})}; Y_{R_{(\mathcal{R})}} | X_{(\mathcal{M}^c)}) + \sum_{k \in \mathcal{R}^c} C_k \right\}. \tag{2}$$

Proof: See [8] for the detailed proof. Note also that this outer bound is the generalization of Schein's cross-cut outer bound [2]. Due to space limitation we skip the expressions for AWGN PRN with phase fading. Again, see [8] for the detailed derivations. ■

Now consider the DF relaying where each RS tries to decode all source messages and forwards them to the destination. In the second hop, each RS sends different portions of the decoded signals to destination via limited capacity backhaul links. Then, we have the following achievable rate region for the DF relaying.

Corollary 2. *The achievable rate region of T-source, K-relay discrete memoryless PRN with full DF relaying strategy is given by*

$$\begin{aligned}\sum_{t\in\mathcal{M}} R_t &\leq \min_{k=1,\ldots,K} \left\{ I(X_{(\mathcal{M})}; Y_{R_k} \mid X_{(\mathcal{M}^c)}) \right\}, \mathcal{M} \subseteq \mathcal{T} \\ \sum_{t=1}^{T} R_t &\leq \sum_{t=1}^{T} C_t.\end{aligned} \tag{3}$$

The following theorem corresponds to the BQRB relaying for the phase fading PRNs with capacity-constraint backhaul links from the relays to the destination node, see Fig. 1.

Theorem 3. *For the T-source K-relay Gaussian PRN with phase fading memoryless channel $f(y_{R_1},\ldots,y_{R_K}|x_1,\ldots,x_T)$ and backhaul link capacity constraint C_k between the k-th RS and the destination, choose any p.d.f. $f(x_1,\ldots,x_T)=\prod_{t=1}^{T} f(x_t)$ and any pair of conditional densities $f(v_k|y_{R_k})$, $\forall k\in\mathcal{K}$. We can reliably achieve the rates R_t, $\forall t\in\mathcal{T}$, satisfying*

$$\sum_{t\in\mathcal{M}} R_t \leq I(X_{(\mathcal{M})}; V_{(\mathcal{K})} \mid X_{(\mathcal{M}^c)}), \quad \mathcal{M}\subseteq\mathcal{T} \tag{4}$$

provided

$$I(Y_{R_{(\mathcal{S})}}; V_{(\mathcal{S})}|V_{(\mathcal{S}^c)}) \leq \sum_{k\in\mathcal{S}} C_k, \tag{5}$$

for all $\mathcal{S}\subseteq\mathcal{K}$ with respect to the joint p.d.f.

$$\prod_{t=1}^{T} f(x_t) \prod_{k=1}^{K} f(y_{R_k}|x_1,\ldots,x_T)\, f(v_k|y_{R_k}). \tag{6}$$

Proof: See [8] for the detailed proof. ■

Compared to the achievable rate region for the BQRB relaying, the only difference for the QF relaying is on the rate constraints given in (5). Regarding these, for the QF relaying we have the same achievable rate expressions as in BQRB relaying with the following constraints

$$I(V_k; Y_{R_k}) \leq C_k, \quad \forall k\in\mathcal{K}. \tag{7}$$

B. Non-Gaussian Signaling at the Sources and the Relays

Up to this point, we considered different relaying strategies assuming Gaussian signaling at the source nodes and Gaussian mapping at the relay nodes. However, it is not obvious whether these assumptions are optimal for the underlying PRN. Following the remarks in [4], [5], in this subsection we consider finite-alphabet signaling (e.g., M-QAM) at the sources and non-Gaussian mapping (e.g., uniform scalar quantization (uSQ)) at the RSs. We believe that with these practical assumptions one might have some intuitions on how to have better spectral efficiency and to come close to the limits of the network by using simple and practical schemes.

For the BQRB relaying scheme studied in the previous section, the relays perform the compression operation over received signal vectors of size n, i.e. the VQ, which relies on long block length assumption $n\to\infty$. However, since the relays are preferred to be as simple as possible, the BQRB relaying scheme presented above is unfavorable. Hence, here we look at a *simpler* and more *practical* quantization technique at the relays which relies on symbol-by-symbol quantization, namely uniform Scalar Quantization (uSQ).

At each RS we assume two independent uSQs each quantizes the in-phase (or quadrature) part of the received signal into $L_k^R = 2^{\frac{C_k}{2}}$ (or $L_k^I = 2^{\frac{C_k}{2}}$) transition levels. With this selection of transition levels, it is guaranteed that entropy of the output of the quantizer will be less than equal to the quantization rate constraint. Given the transmitted signals at the sources, the detailed calculation of the probability of the quantizer outputs can be found in [8].

IV. Random Coding Error Exponent Analysis

The random coding error exponent (EE) [9] gives insights about how to achieve a certain level of reliability in communication at a rate below the channel capacity. The basic and thorough EE analysis for single antenna point-to-point communications is done by Gallager in [9]. Later on in [10], Gallager also analyzed the EEs of multiple access channels (MACs). We will follow the basic definitions and procedures given in [10].

For a given MAC, let $P_{e,sys}(n,R_1,R_2)$ denote the smallest average probability of system error of any length-n block-code and rates R_1, R_2 for source 1 and source 2, respectively. Then, the random coding EE for a MAC is defined as

$$E_{sys}(R_1,R_2) \triangleq \lim_{n\to\infty} -\frac{\log_2 P_{e,sys}(n,R_1,R_2)}{n}. \tag{8}$$

In [10], Gallager derived an upper bound on the average probability of system error for an input distribution $f(x_1,x_2)=f(x_1)f(x_2)$ using *joint* ML decoding rule at the receiver as follows

$$P_{e,sys}(n,R_1,R_2) \leq 3\cdot 2^{-n\,(E_r(R_1,R_2,f(x_1,x_2)))} \tag{9}$$

where

$$\begin{aligned}&E_r(R_1,R_2,f(x_1,x_2)) \\ &\qquad = \min_{1\leq i\leq 3}\max_{0\leq\rho\leq 1}\left[E_{0i}(\rho,f(x_1,x_2)) - \rho R_i\right].\end{aligned} \tag{10}$$

is the random coding error exponent with $R_3 = R_1 + R_2$. The expressions $E_{0i}(\rho,f(x_1,x_2))$, for $i=1,2,3$, are defined in [10].

1) DF relaying with Gaussian Inputs: For the DF, we assume Gaussian codebooks at the sources and maximum-likelihood (ML) decoding at the RSs where each passes its own decision and a corresponding *reliability function* (which is a scalar variable equal to the logarithm of the Euclidean distance between the received signal and the detected signal) to the destination. We note that for the DF the destination is not required to have channel side information (CSI). We assume that the backhaul link capacities are at least equal to the sources' transmission sum-rate, R_1+R_2. Hence, the backhaul links do not create a bottleneck for system performance.

Upon receiving the detected signals and the reliability information, the destination makes its decision by comparing the reliability information: it decides on the codeword which has the *minimum* reliability information (Euclidean distance). Hence, if the codeword detected at one of the RS is wrong and its corresponding reliability information is smaller, then the ultimate detection will be wrong even if the other RS has made a correct detection (but with greater reliability information).

In order to simplify the relay processing, we assume that wireless medium is shared by the sources in an *orthogonal* fashion, i.e., time-division (TD) MAC, with $\alpha_1 n$ duration for source 1 and $\alpha_2 n$ duration for source 2, where $\alpha_1 + \alpha_2 = 1$. During the access of each source, both RSs perform the same steps as in the single-source PRN case [11]. We have the following error exponent for the DF relaying case.

Theorem 4. *With symmetric channel assumption from each source to the RSs, e.g.,* $h_i = h_{1i} = h_{2i}$*, for* $i = 1, 2$*, and time-division medium access protocol, the following EE corresponds to the proposed DF relaying scheme*

$$\begin{aligned} &E_{DF}(R_1, R_2) \\ &= \max_{\alpha_1+\alpha_2=1} \min \{\alpha_1 E_{DF,1}(R_1, \alpha_1), \alpha_2 E_{DF,2}(R_2, \alpha_2)\} \end{aligned} \tag{11}$$

where

$$E_{DF,i}(R_i, \alpha_i) = \min \{2\, E_{r,i}(R_i, \alpha_i),\ E_{r,i}(R_i, \alpha_i) + T(\Gamma_i(\alpha_i))\} \tag{12}$$

and $\Gamma_i(\alpha_i) = \frac{h_i^2 P_s}{\alpha_i \sigma^2}$*,* $T(\Gamma) = \frac{\log_2(e)}{2} - \frac{\log_2(e)(1+2\Gamma)^2}{1+(1+2\Gamma)^4}$*, and* $P_{ML,i} = 2^{-\alpha_i n E_{r,i}(R_i, \alpha_i)}$ *being the standard ML error probability at each RS.*

Proof: See the detailed proof in [11]. ∎

2) BQRB and relaying with Gaussian Inputs: For BQRB (and also for QF relaying) where Gaussian codebooks and Gaussian mappings are assumed at the sources and the relays, respectively, we assume all the sources access the wireless medium simultaneously, hence the system probability of error can be upper bounded as in MAC studied in [10] with modified channel matrices and noise assumptions. The detailed derivation of the corresponding error exponents for this relaying scheme can be found in [11], [12]. We skip the analysis due to the space limitation.

3) QF relaying with Non-Gaussian Signaling: As in BQRB relaying case, we assume all the sources access the wireless medium *simultaneously*. The i-th source transmits $(n, R_i), i = 1, 2,$ block code where each letter of each codeword is independently selected with probability assignment $p(x_i)$ and M-QAM constellation is used where 2^{nR_i} messages (alphabet size) are encoded over blocks of length n. The received signals at the RSs are simply quantized by using uSQ, where correlation information is discarded (no compression is done). We assume that each symbol $x_i = x_i^R + j x_i^I$ on the M-QAM constellation has equal probability $p(x_i) = 1/M$ ($p(x_i^R) = 1/\sqrt{M}, p(x_i^I) = 1/\sqrt{M}$) with $\mathbb{E}[(x_i^R)^2] = \mathbb{E}[(x_i^I)^2] = \frac{P_s}{2}$ and $\mathbb{E}[x_i^R x_k^I] = 0, \forall i, k \in \{1, 2\}$.

For a given source input signal vector $\mathbf{x} = [x_1, x_2]^T$, each RS performs uSQ and outputs the representation points (v_{k,l^R}^R and v_{k,l^I}^I) for both real and imaginary parts where $l^R = 2, 3, \ldots, L_k^R$ and $l^I = 2, 3, \ldots, L_k^I$ with L_k^R (L_k^I) being the number of quantization outputs for real (imaginary) part of the received signal at the k-th RS, $k = 1, 2$. The probability that the quantizer output is in the $\underline{l} = (l^R, l^I)$-th quantizing interval, i.e., $\underline{V}_k = (V_k^R, V_k^I) = \underline{v}_{k,\underline{l}} = (v_{k,l^R}^R, v_{k,l^I}^I)$, $k = 1, 2$, is given by [12, eq. (22)].

Theorem 5. *The destination performs ML decoding on the observations* v_1, v_2*, which are the representation points corresponding to the received signals at each RS. Then, we have the following EE for the QF relaying with uniform M-QAM at the sources and uSQ at the RSs*

$$E_{r,QF}(R_1, R_2) = \min_{1 \le i \le 3} \max_{0 \le \rho \le 1} [E_{0i}(\rho) - \rho R_i] \tag{13}$$

with $R_3 = R_1 + R_2$ *where* $E_{0i}(\rho)$*, for all* $i = 1, 2, 3$ *is defined as in the equations given in* (14) *and* (15) *where* $p(v_k^R | x_1, x_2)$ *and* $p(v_k^I | x_1, x_2)$*, for* $k = 1, 2$*, are given by [12, eq. (22)].*

Proof: See the detailed proof in [12]. ∎

A. Numerical Results

In this subsection, we compare the achievable rate and error exponent performances of the relaying strategies studied above forphase fading AWGN PRN model, consisting of $T = 2$ UEs and $K = 2$ RSs, where all the UEs have the same transmit power P_s. The link capacities from each RS to the destination are assumed to be the same, $C = C_1 = C_2$. In the following, we evaluate the performances of DF, BQRB and QF relaying strategies through numerical simulations. We take a sample channel matrix from UEs to RSs as

$$\mathbf{H} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & exp\{-j\pi/3\} \\ exp\{-j2\pi/3\} & 1 \end{bmatrix}. \tag{16}$$

1) Achievable Rates Analysis: In Fig. 2, we examine the outer bound on sum-rate and the achievable sum-rates corresponding to DF and QF with Gaussian codebooks at the UEs and Gaussian mapping at the RSs for backhaul capacity $C = 4$ [bits/transmission], and compare those ideal relaying strategies to the proposed relaying scheme wherein 4-QAM and 16-QAM alphabets are used at the UEs and uSQ at the RSs. For higher backhaul capacities, e.g., $C = 4$[bps/Hz], even though there are enough backhaul resources since the use of finite alphabet of cardinality 4 and 16 (4-QAM and 16-QAM), the achievable sum-rate with the proposed relaying is upper limited by 4[bps/Hz]. However, a more interesting behavior is in the low-SNR regime, $SNR = P_s/\sigma^2 \le 10[dB]$, where the DF sum-rate performance is worse than the proposed relaying scheme.

2) Error Exponent Analysis: In Fig. 3, we plot the EEs corresponding to DF, BQRB and QF (with 4-QAM at the sources and uSQ at the RSs) relaying strategies with respect to sum-rate $R_{sum} = R_1 + R_2$ [bits/transmission] for fixed $\frac{P_s}{\sigma^2} = \{0\}$ [dB] where $R_1 = R_2 = R_{sum}/2$. We see that the proposed simple and practical relaying scheme has better EE than both DF and BQRB over all operating sum-rates.

$$E_{0i}(\rho) = -\log_2 \left[\sum_{v_1^R, v_2^R} \sum_{v_1^I, v_2^I} \sum_{\substack{x_j \\ j=\{1,2\}\setminus i}} \frac{1}{M} \left[\sum_{x_i} \frac{1}{M} \left[p(v_1^R|x_1,x_2)p(v_2^R|x_1,x_2)p(v_1^I|x_1,x_2)p(v_2^I|x_1,x_2) \right]^{\frac{1}{1+\rho}} \right]^{1+\rho} \right], \quad i = 1, 2, \tag{14}$$

$$E_{03}(\rho) = -\log_2 \left[\sum_{v_1^R, v_2^R} \sum_{v_1^I, v_2^I} \left[\sum_{x_1} \sum_{x_2} \frac{1}{M^2} \left[p(v_1^R|x_1,x_2)p(v_2^R|x_1,x_2)p(v_1^I|x_1,x_2)p(v_2^I|x_1,x_2) \right]^{\frac{1}{1+\rho}} \right]^{1+\rho} \right] \tag{15}$$

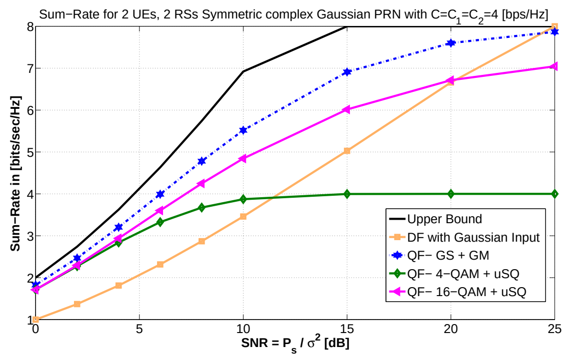

Fig. 2. 2 Sources, 2 Relays complex Gaussian PRN: Achievable rates versus $SNR = \frac{P_s}{\sigma^2}$ for 4-QAM and 16-QAM with $C = C_1 = C_2 = 4$[bits/transmission] and sample channel matrix (16).

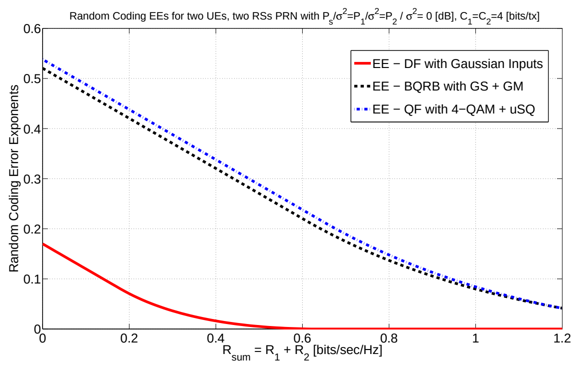

Fig. 3. Random coding EEs for 2-Source, 2-Relay PRN with $\frac{P_s}{\sigma^2} = \frac{P_1}{\sigma^2} = \frac{P_2}{\sigma^2} = 0$ [dB] and $C = C_1 = C_2 = 4$[bits/transmission].

V. Throughput and Block Error Rate (BLER) Analysis via LTE Compliant Testbeds

In this section, we analyze overall BLER and throughput performances of the DF and the proposed relaying (which is based on symbol-by-symbol uSQ) schemes through EURECOM's long term evolution (LTE) compliant OpenAir Interface platform [6]. The OpenAir Interface platform consists of all the standard LTE transmitter (and receiver) blocks such as turbo encoder, scrambler, modulation mapper, resource element (RE) mapper and OFDM symbol generator as defined in the 3GPP LTE release 8 specifications [13]–[15]. The main parameters used in our testbeds are shown in Table I. For both testbeds we assume a PRN with one UE, 2 RSs and one eNb.

For our purposes we construct two testbeds: one for the evaluation DF relaying and the other for the proposed relaying scheme which are illustrated in Fig. 4 and Fig. 5, respectively. For the DF relaying (Layer-2 relaying) each RS decodes the transmitted messages and forwards them to the eNb through backhaul which is assumed to have enough capacity for forwarding, i.e., backhaul links are not bottleneck for the system performance. If both RSs can not decode the transmitted message, then a re-transmission request is done vie error-free feedback channel (if maximum number of re-transmission hasn't been reached.) Maximum number of retransmission is set to 4 for both testbeds. If the eNb cannot decode the source message at the last re-transmission then an error is declared.

For the proposed relaying (uSQ based) scheme, each RS calculates the log-likelihood ratio (LLR) of each transmitted bits and then quantizes them using uniform SQ (uSQ), and forwards the quantized bits to the eNb. At the eNb, the quantized bits from the two RSs are combined and passed to turbo decoder. As in DF relaying case if the eNb can not decode the source message at the last re-transmission then an error is declared.

Both BLER and throughput plots show that for both modulation and coding schemes (MCSs) the proposed relaying scheme with 2bit/LLR has 2dB gain over the DF relaying and 2.5dB gain over no relaying case. We also see that the performance improvement over no relaying case achieved by DF relaying is negligible. Hence, the analysis done in this section justifies the conclusions we have made in the previous sections.

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Bandwidth Allocated	5 MHz (25 RBs)
Maximum Transmission Bandwidth	4.5 MHz
Downlink Resource Blocks (RB)	25
Number of Subcarriers	512
Subcarrier Spacing	15 KHz
Sampling Frequency	7.68 MHz
MCS (modulation and coding scheme)	{4,8}
Number of OFDM symbols per slot	7 (normal Cyclic prefix)
Number of Transmit/Receiving Antennas	1/1
Maximum HARQ rounds	4

VI. Conclusions

We studied low-complexity coded-modulation strategies for distributed relaying with achievable rates and random coding error exponents being the main figures of merit for performance analysis. We compare layer 2 techniques based

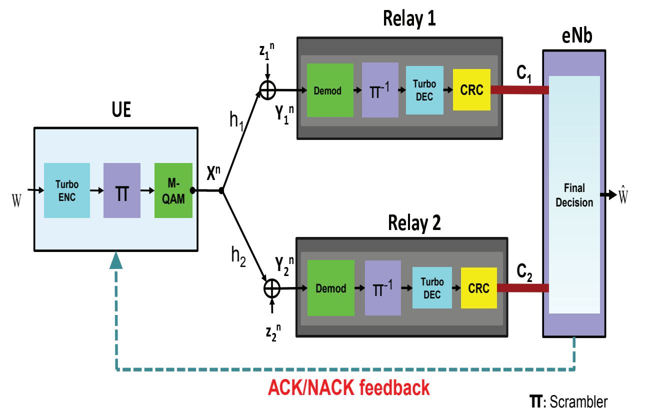

Fig. 4. Scheme 1: 1 Source, 2 Relays PRN with decoding based relaying schemes with turbo coding at the UE

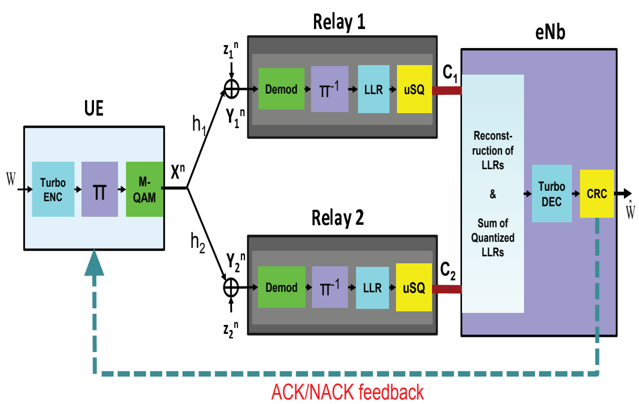

Fig. 5. Scheme 2: 1 Source, 2 Relays PRN with LLR generation and uSQ at the relays

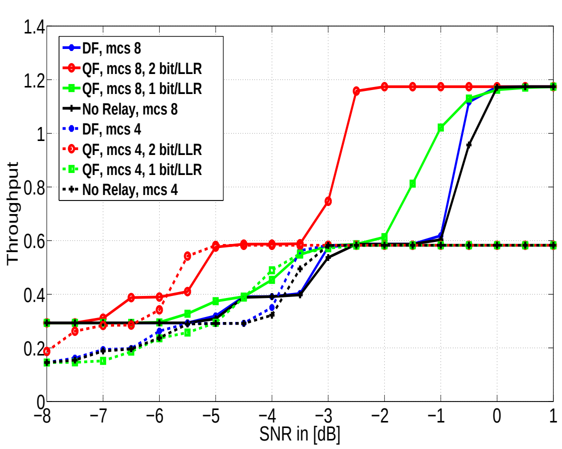

Fig. 6. Throughput vs SNR

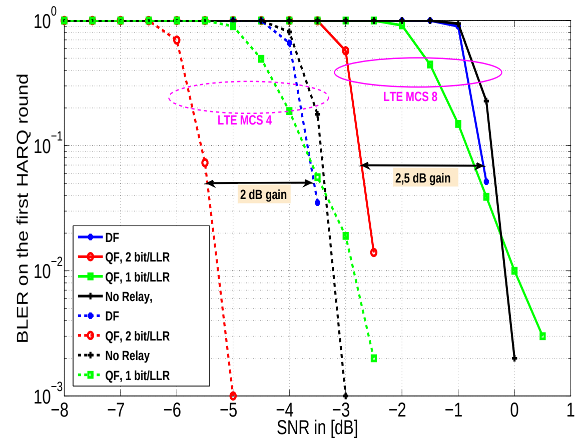

Fig. 7. BLER vs SNR

on full decoding at relay stations and simple compression-based (quantization) techniques with QAM alphabets and show through mutual-information and error-exponent analysis that distributed quantization is clearly beneficial both in the high and medium spectral efficiency regions.

References

[1] B. E. Schein and R. G. Gallager, "The gaussian parallel relay network," in *Proc. IEEE Int. Symp. on Information Theory*, Sorrento, Italy, June 2000, p. 22.

[2] B. E. Schein, "Distributed coordination in network information theory," *PhD. dissertation*, October 2001.

[3] S. S. (Shitz), O. Somekh, O. Simeone, A. Sanderovich, B. M. Zaidel, and H. V. Poor, "Cooperative multi-cell networks: impact of limited-capacity backhaul and inter-users links," in *in the Proc. of Joint Workshop on Coding and Communications*, Drnstein, Austria, October 2007.

[4] A. Sanderovich, S. S. (Shitz), Y. Steinberg, and G. Kramer, "Communication via decentralized processing," *IEEE Transactions on Information Theory*, vol. 54, p. 30083023, July 2008.

[5] R. Dabora and S. Servetto, "On the role of Estimate-and-Forward with time-sharing in cooperative communication," *IEEE Transactions on Information Theory*, October 2008.

[6] http://www.openairinterface.org/.

[7] T. M. Cover and A. A. E. Gamal, "Capacity theorems for the Relay Channel," *IEEE Transactions on Information Theory*, vol. 25, pp. 572–584, September 1979.

[8] E. Yılmaz, "Coding strategies for relay based networks," *Ph.D. dissertation, Mobile Communications Dept., EURECOM*, July 2010.

[9] R. G. Gallager, *Information theory and reliable communication*. John Wiley & Sons, 1968.

[10] ——, "A perspective on multi-access channels," *IEEE Transactions on Information Theory*, vol. 31, p. 124142, March 1985.

[11] E. Yılmaz, R. Knopp, and D. Gesbert, "Error exponents for backhaul-constrained parallel relay networks," in *Proc. IEEE Int. Symp. on Personal, Indoor and Mobile Radio Comm.*, Istanbul, Turkey, Sept. 2010.

[12] ——, "Error exponents for multi-source multi-relay parallel networks with limited backhaul capacity," in *Proc. IEEE Int. Conf. on Communication*, Kyoto, Japan, June 2011.

[13] *3GPP LTE*, Physical channels and modulation Std. 36.211, Rev. 8.5.0, Feb. 2009.

[14] *3GPP LTE*, Multiplexing and channel coding Std. 36.212, Rev. 8.5.0, Feb. 2009.

[15] *3GPP LTE*, Physical layer procedures Std. 36.213, Rev. 8.5.0, Feb. 2009.