An LTE implementation of a Novel Strategy for the Gaussian Half-Duplex Relay Channel

R. Thomas *, M. Cardone*, R. Knopp*, D. Tuninetti† and B.T. Maharaj ‡
*Eurecom, Campus SophiaTech, 450 Route des Chappes, 06410 Biot Email: {thomas, cardone, knopp}@eurecom.fr
†University of Illinois at Chicago, Chicago, IL 60607, USA, Email: danielat@uic.edu
† Laboratoire de Signaux et Systèmes (L2S, UMR8506) CNRS-CentraleSupelec-Université Paris Sud, France
‡University of Pretoria, Private Bag X20 Hatfield 0028, Pretoria, South Africa, Email: sunil.maharaj@up.ac.za

***Abstract*—This paper presents a practical implementation of a novel three-message transmission strategy for the Gaussian half-duplex relay channel based on Turbo code superposition encoding and interference-aware successive interference cancellation. The impact of finite block-length and discrete input constellations on the Block Error Rate (BLER) performance is evaluated through extensive simulations on an LTE simulation test bench and compared to the theoretical performance of asymptotically large block-length Gaussian codes. For the practically relevant BLER value of 10^{-2} and by varying the direct source-destination link strength, the maximum spectral efficiency gap between theory and the presented implementation is found to be of 0.458 bits/dim when the strength of the source-destination and relay-destination links is the same and of 0.681 bits/dim when the relay-destination link is 5 dB stronger than the source-destination link. These values indicate that practical implementations of high-performing HD relay techniques for future Heterogeneous Network deployments are within reach. A comparison with a baseline strategy without direct source-destination transmission, as currently proposed in the LTE standard for relay scenarios, shows superior performances of the proposed scheme. In particular, the rate gain is of a factor of 2 when the strength of the source-destination and relay-destination links is the same and of a factor of 1.2 when the relay-destination link is 5 dB stronger than the source-destination link, thereby highlighting the critical importance of physical-layer cooperation in broadband wireless systems.**

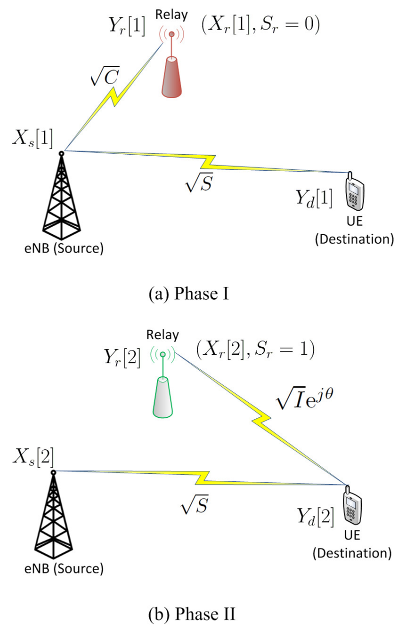

Fig. 1. Two-phase relay system model.

I. Introduction

The benefits of cooperative communications, as a means to enable single-antenna terminals to cooperatively operate with efficiency and diversity gains usually reserved to multi-antenna systems, have been extensively studied [1]. The different cooperative communication techniques and relay strategies available in the literature are largely based on the seminal information theoretic work by Cover and Gamal [2]. These advances have led to studies of practical relay architectures by 3GPP for inclusion in the LTE Release 9 standard [3], [4].

In this paper we provide a practical LTE-based implementation of the novel three-message relay strategy proposed in [5] for the fully connected Gaussian Half-Duplex Relay Channel (HD-RC) that is known to be to within a constant gap of the cut-set upper bound on the capacity of the network. The proposed two-phase scheme, see Fig. 1, employs superposition encoding at the source, Successive Interference Cancellation (SIC) both at the relay and at the destination, and Decode-and-Forward (DF) at the relay. During the first phase, the source sends a superposition of two independent messages w_0 and w_1; the relay decodes both messages while the destination only decodes w_1. During the second phase, the source sends a message w_2 directly to the destination while the relay sends the message w_0 to the destination; the destination first combines the received signals from both phases to decode w_0 and finally decodes w_2. In [5] the overall achievable rate was evaluated assuming (point-to-point capacity achieving) Gaussian codes, which results in no-error propagation among the different stages of the SIC.

In this work we bridge theory and practice; by providing a practical implementation of the scheme of [5], we aim to shed light on the effect of finite block-code lengths and of discrete input constellations. Our implementation uses the channel coding libraries from OpenAirInterface (OAI) [6], an open-source software and hardware wireless communication experimentation platform developed in accordance with the evolving 3GPP LTE standard. The main contribution of this work is two-fold: (i) we show that, for the practically relevant Block Error Rate (BLER) value of 10^{-2} and by varying the direct source-destination link strength, the maximum spectral efficiency gap between theory and the presented implementation is of 0.458 bits/dim when the strength of the source-destination and relay-destination links is the same and of 0.681 bits/dim when the relay-destination link is 5 dB stronger than the source-destination link. These values indicate that low-implementation complexity and high-throughput HD relay schemes, either for Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD), are within practical reach for near-future high-spectral efficiency Heterogeneous Network (HetNet) deployments; (ii) we compare the rate performance of our scheme with a baseline strategy, where the link between the source and the destination is absent, i.e., there is no physical cooperation between the source and the relay to convey information to the destination. Simulations show that our scheme outperforms (in terms of achievable rate) the baseline one by a factor of 2 when the source-destination and relay-destination links are of the same strength and of a factor of 1.2 when the relay-destination link is 5 dB stronger than the source-destination link. This implies that enabling physical-layer cooperation among nodes is of critical importance in today's and future wireless networks.

Before going to the technical description of our system, we put our work in context. Wireless relay networks have long been conceptualized to cooperatively form virtual antenna arrays to improve spatial diversity and serve as a medium for multi-hop communications. However, the implementation of relay strategies in 3G and 4G cellular standards have been limited to layers 2 and 3 with only rudimentary relay functions, as a wireless repeater with Amplify-and-Forward (AF) capabilities, at the physical layer [7], [8]. In [9], a software-defined radio framework, using pre-existing software libraries for channel codes, was proposed for the scalar two-user Gaussian broadcast channel to show rate improvements from the use of SIC with respect to Time Division Multiplexing (TDM). The BLER performance of practical codes, such as multiple Turbo codes [10], Reed-Solomon [11] and convolutional codes [12], has been investigated in order to show diversity gains in HD relay networks. In [12], the performances of different relay schemes using convolutional and LTE Turbo codes were presented and shown to have low-latency. In [13], a physical layer network coding scheme for a two-message HD relay scenario was presented, which was limited to uncoded BPSK with hard-decision decoding. A two-layered demodulation strategy was proposed in [14] to improve the DF BLER performance of an asymmetric relay channel link using soft-combining of the Log-Likelihood Ratios (LLRs) during the broadcast and relaying phases. We highlight that in [12] and [13] the direct source-destination link is absent and, as a result, there is no physical cooperation between the source and the relay. Our main contribution is to show that, by exploiting physical cooperation, higher spectral efficiency gains can be achieved. Another novel feature of the proposed HD relaying scheme is the interference-aware SIC receiver, which decodes the desired signal in the presence of an interfering signal drawn from a discrete constellation.

The rest of the paper is organized as follows. Section II introduces the system model and overviews the scheme proposed in [5]. Section III presents the simulation test bench. Section IV evaluates the BLER performance of the proposed scheme and compares the achieved spectral efficiency with the theoretical one from [5] and with a baseline scheme that does not allow for direct link source-destination transmission. Section V concludes the paper.

II. System Model

We consider a system with three single-antenna nodes: the eNB (source), the relay, and the UE (destination). The channel input/output relationship is

$$\begin{aligned} Y_r &= \sqrt{C} X_s \ (1 - S_r) + Z_r \in \mathbb{C}, \\ Y_d &= \sqrt{S} X_s + e^{j\theta} \sqrt{I} X_r \ S_r + Z_d \in \mathbb{C}, \end{aligned}$$

where the channel parameters (S, C, I, θ) are fixed and known to all nodes (full Channel State Information (CSI)), the inputs are subject to unitary power constraints, S_r is the switch random binary variable which indicates the state of the relay, i.e., when $S_r = 0$ the relay is listening to the channel while when $S_r = 1$ the relay is transmitting, and the noises form independent white Gaussian noise processes with zero-mean and unit-variance [1]. We remark here that the results presented in this paper can be straightforwardly extended to multi-antenna nodes, as supported by the LTE standard [4]. We focus here on $C \geq I \geq S$ (a more general setting is currently under investigation). This assumption, as we will see later, implies that the relay is able to successfully decode whatever the destination decodes. We study a scheme with four codebooks to transmit three messages. The codes are

$$\begin{aligned} \mathcal{C}_{a1} &= \{X_{a1}^{N_1}(w) : w \in [1 : M_0]\}, \\ \mathcal{C}_{a2} &= \{X_{a2}^{N_2}(w) : w \in [1 : M_0]\}, \\ \mathcal{C}_{b} &= \{X_{b}^{N_1}(w) : w \in [1 : M_1]\}, \\ \mathcal{C}_{c} &= \{X_{c}^{N_2}(w) : w \in [1 : M_2]\}, \end{aligned}$$

by which we aim to achieve a rate of $\frac{\log_2(M_0 M_1 M_2)}{N_1 + N_2}$ bits/sec/Hz. In this work, we focus on the case $N_1 = N_2 = N$, i.e., equal resource allocation during the two phases.

Phase I. During this phase the relay is listening, i.e., $S_r = 0$, and the transmitted signals are

$$\begin{aligned} X_s^N[1] &= \sqrt{1-\delta} X_b^N(w_1) + \sqrt{\delta} X_{a1}^N(w_0), \\ X_r^N[1] &= 0^N, \end{aligned}$$

where $\delta \in [0, 1]$ is a scaling parameter that allows for superposition, and the received signals are

$$\begin{aligned} Y_d^N[1] &= \sqrt{S(1-\delta)} X_b^N(w_1) + \sqrt{S\delta} X_{a1}^N(w_0) + Z_d^N[1], \\ Y_r^N[1] &= \sqrt{C(1-\delta)} X_b^N(w_1) + \sqrt{C\delta} X_{a1}^N(w_0) + Z_r^N[1]. \end{aligned}$$

[1]The model is without loss of generality because non-unitary power constraints or noise variances can be incorporated into the channel gains, and because of full CSI we can assume that a node compensates for the phase of one of its channel gains.

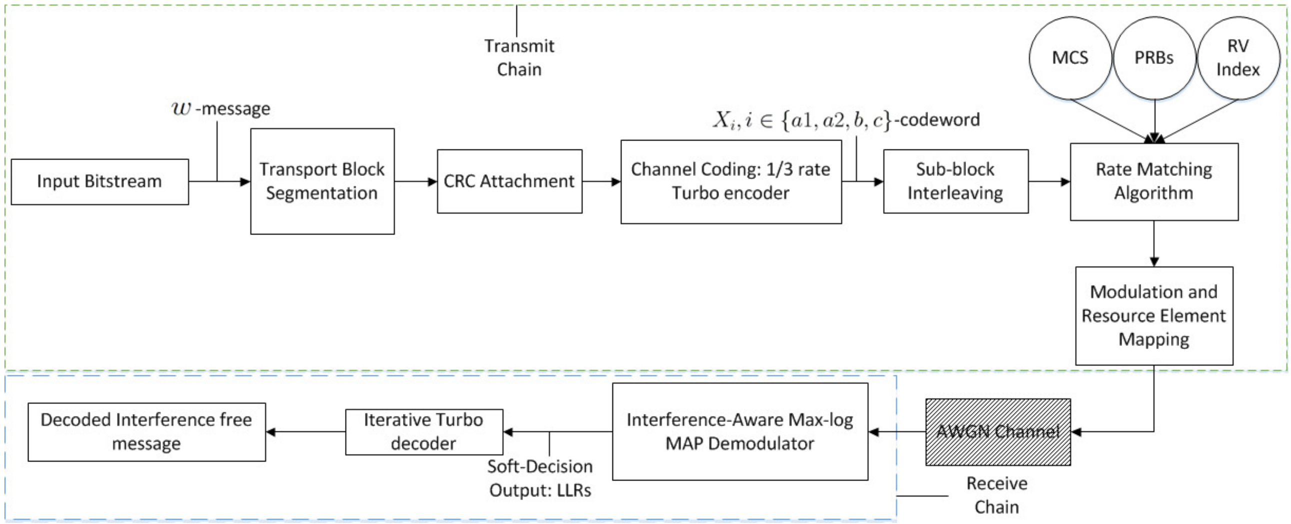

Fig. 2. Overall simulation block diagram.

We let $\delta = \frac{1}{1+S}$ as in [5], which was shown to be optimal to within a constant gap universally over all channel gains. The relay first decodes w_1 from $Y_r^N[1]$ and outputs the estimate $\widehat{w}_1^{(r)} \in [1 : M_1]$. The relay then decodes w_0 from $Y_r^N[1] - \sqrt{C(1-\delta)}X_b^N(\widehat{w}_1^{(r)})$ and outputs the estimate $\widehat{w}_0^{(r)} \in [1 : M_0]$. The destination decodes w_1 from $Y_d^N[1]$ and outputs the estimate $\widehat{w}_1^{(d)} \in [1 : M_1]$.

Phase II. During this phase the relay is transmitting, i.e., $S_r = 1$, and the transmitted signals are

$$X_s^N[2] = X_c^N(w_2), \quad X_r^N[2] = X_{a2}^N\left(\widehat{w}_0^{(r)}\right),$$

where X_{a2}^N is a different redundancy version of X_{a1}^N transmitted by the source in Phase I. The received signals are

$$Y_d^N[2] = \sqrt{S}X_c^N(w_2) + e^{j\theta}\sqrt{I}X_{a2}^N\left(\widehat{w}_0^{(r)}\right) + Z_d^N[2],$$
$$Y_r^N[2] = Z_r^N[2].$$

The destination forms the aggregate received signal

$$Y_d^{2N} := \begin{bmatrix} Y_d^N[1] - \sqrt{S(1-\delta)}X_b^N\left(\widehat{w}_1^{(d)}\right) \\ Y_d^N[2] \end{bmatrix}$$
$$\overset{\substack{\widehat{w}_0^{(r)} = w_0 \\ \widehat{w}_1^{(d)} = w_1}}{=} \begin{bmatrix} \sqrt{S\delta}X_{a1}^N(w_0) + Z_d^N[1] \\ e^{j\theta}\sqrt{I}X_{a2}^N(w_0) + \left(\sqrt{S}X_c^N(w_2) + Z_d^N[2]\right) \end{bmatrix}.$$

The destination first decodes w_0 from Y_d^{2N} by assuming that all decoding operations in Phase I were successful and outputs the estimate $\widehat{w}_0^{(d)} \in [1 : M_0]$. We assume that a perfect error detection mechanism, such as the Cyclic Redundancy Check (CRC), is employed at the decoders. The destination finally decodes w_2 from $Y_d^N[2] - e^{j\theta}\sqrt{I}X_{a2}^N\left(\widehat{w}_0^{(d)}\right)$ and outputs the estimate $\widehat{w}_2^{(d)} \in [1 : M_2]$.

Error analysis. Since we assume $C \geq I \geq S$, we focus now on the error analysis at the destination, by assuming that all the decoding operations at the relay in Phase I were successful. Since we are exploiting SIC in the decoding operation, we need to understand the performance of codes $\mathcal{C}_{a1}$, $\mathcal{C}_{a2}$ and $\mathcal{C}_b$ in non-Gaussian noise ($\mathcal{C}_b$ in the first decoding step in Phase I and $\mathcal{C}_{a1}$, $\mathcal{C}_{a2}$ in the first decoding step in Phase II) and the performance of code $\mathcal{C}_c$ in Gaussian noise (second decoding operation in Phase II when no error propagation). In the decoding stages where a message is treated as noise, we develop a decoder that specially accounts for the fact that the overall noise is non-Gaussian. We will consider different choices for the codebooks $(\mathcal{C}_{a1}, \mathcal{C}_{a2}, \mathcal{C}_b, \mathcal{C}_c)$; for each choice, we make sure that in all the decoding stages we have a BLER below a given threshold (here set to 10^{-2} in order to have a probability of successful decoding of 0.99).

III. Simulation Design

We developed a simulation testbed using the OAI (a platform for wireless communication experimentation) software libraries in order to evaluate the performance of the aforementioned scheme with practical codes (see Fig. 2). The data messages are transported in units known as Transport Blocks (TBs) to convey the messages w_0, w_1 and w_2. The TB Size (TBS) depends on the choice of the Modulation and Coding Scheme (MCS), which describes the modulation order and the coding rate of a particular transmission.

1) TB Processing. The TBs undergo a series of processing stages prior to modulation before the codeword can be mapped onto the Resource Elements (REs) in the Physical DL-SCH (PDSCH). Error detection at the receiver is enabled by appending 24 CRC bits to the TB. The subsequent bit sequence is then fed into the $1/3$ rate Turbo encoder.

2) Channel Coding. The channel coding scheme comprises of a 1/3 rate Turbo encoder, which follows the structure of a parallel concatenated convolutional code with two 8-state constituent encoders, and one Turbo code internal interleaver [15]. A single set of systematic bits and two sets of parity bits are produced at the output of the encoder.

3) Rate Matching. The rate matching component ensures, through puncturing or repetition of the bits, that the output

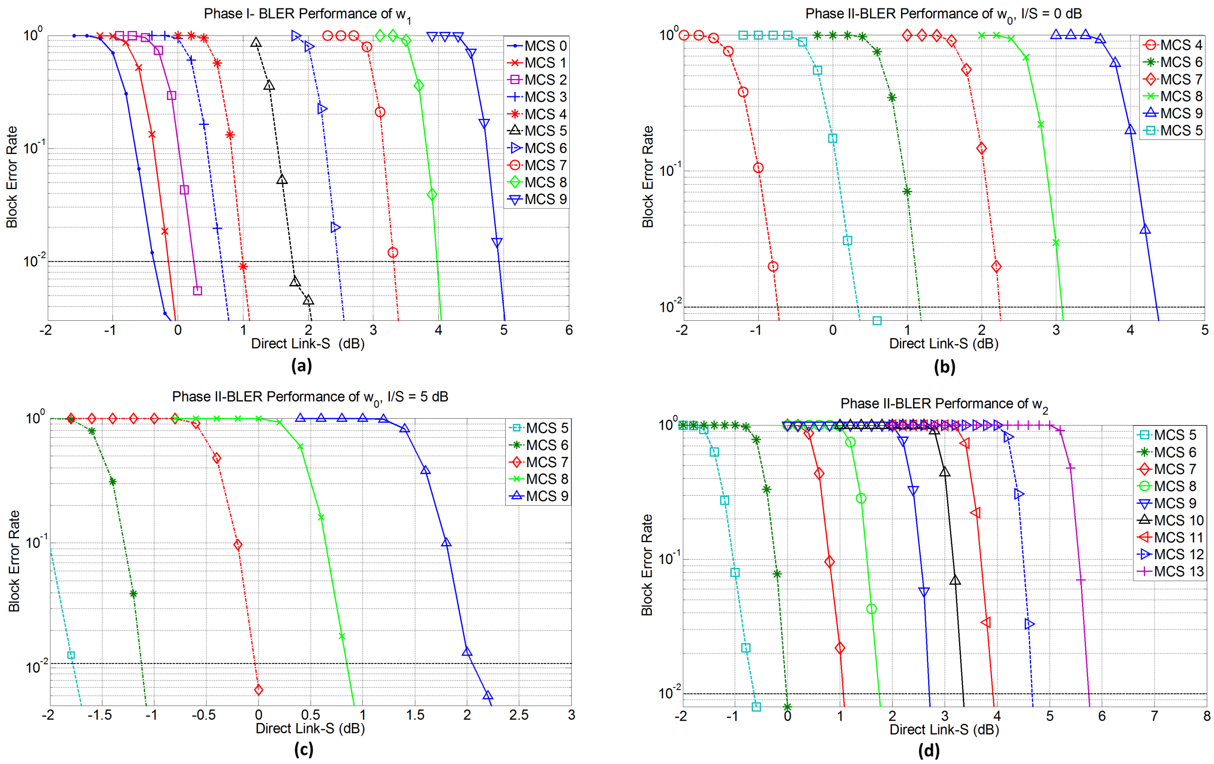

Fig. 3. BLER performances of w_0, w_1 and w_2 versus different strengths of direct source-destination link.

TABLE I

MCS RELAY MAPPING FOR EACH DECODING OPERATION WITH $I/S = 0$ dB.

Phase I - X_b			**Phase II** - (X_{a1}, X_{a2})		**Phase II** - X_c		**Theoretical**	**Practical**	**Theoretical BS**	**Practical BS**
MCS	S [dB]	TBS [bits]	MCS	TBS [bits]	MCS	TBS [bits]	Rate [bits/dim]	Rate [bits/dim]	Rate [bits/dim]	Rate [bits/dim]
0	-0.370	680	4	1800	5	2216	1.222	0.764	0.607	0.351
1	-0.145	904	4	1800	6	2600	1.265	0.862	0.629	0.413
2	0.242	1096	5	2216	6	2600	1.326	0.961	0.669	0.413
3	0.665	1416	5	2216	7	3112	1.425	1.100	0.714	0.494
4	0.992	1800	6	2600	7	3112	1.494	1.220	0.750	0.494
5	1.7588	2216	6	2600	8	3496	1.661	1.350	0.838	0.555
6	2.4535	2600	7	3112	9	4008	1.820	1.580	0.922	0.636
7	3.3115	3112	8	3496	10	4392	2.028	1.790	1.033	0.697
8	3.9743	3496	9	4008	11	4968	2.195	2.030	1.122	0.789
9	4.930	4008	9	4008	12	5736	2.446	2.240	1.254	0.910

TABLE II

MCS RELAY MAPPING FOR EACH DECODING OPERATION WITH $I/S = 5$ dB.

Phase I - X_b			**Phase II** - (X_{a1}, X_{a2})		**Phase II** - X_c		**Theoretical**	**Practical**	**Theoretical BS**	**Practical BS**
MCS	S [dB]	TBS [bits]	MCS	TBS [bits]	MCS	TBS [bits]	Rate [bits/dim]	Rate [bits/dim]	Rate [bits/dim]	Rate [bits/dim]
0	-0.370	680	7	3112	5	2216	1.605	0.98	1.125	0.788
1	-0.145	904	7	3112	6	2600	1.653	1.08	1.157	0.910
2	0.242	1096	7	3112	6	2600	1.737	1.11	1.211	0.910
3	0.665	1416	8	3496	7	3112	1.832	1.30	1.273	1.025
4	0.992	1800	8	3496	7	3112	1.907	1.37	1.321	1.025
5	1.7588	2216	9	4008	8	3496	2.088	1.58	1.435	1.147
6	2.4535	2600	9	4008	9	4008	2.261	1.73	1.541	1.228
7	3.3115	3112	9	4008	10	4392	2.482	1.87	1.676	1.267
8	3.9743	3496	9	4008	11	4968	2.658	2.03	1.780	1.451
9	4.930	4008	9	4008	12	5736	2.921	2.24	1.933	1.573

bits from the Turbo encoder match the available physical resources using the MCS, the Redundancy Version (RV) index and the Physical Resource Blocks (PRBs). For the numerical evaluations, an equal bandwidth allocation is chosen between the two phases of the relay strategy, i.e., the number of PRBs allocated in the first (relay listening) and second (relay transmitting) phases is the same. The message w_0, transmitted by the source and the relay over the two phases, corresponds to two different RVs with equal resource allocations.

4) Modulation and REs Mapping. During this stage, complex-valued symbols are generated according to the chosen modulation scheme supported in LTE. However, in this study we only use QPSK as it is assumed that the channel quality between the relay and the destination is not much better than that of the source-destination link. Note that when the relay-destination link is significantly stronger than the source-destination link, a better performance/higher spectral efficiency may be attained with higher modulation schemes at the relay.

5) Demodulator. The demodulator comprises of a discrete constellation interference-aware receiver designed to be a low-complexity version of the max-log MAP detector. The main idea is to decouple the real and imaginary components through a simplified bit-metric using the Matched Filter (MF) output and thus reduce the search space by one complex dimension [16]. As a result, it is possible to decode the required codeword in the presence of an interfering codeword of the same (or different) modulation scheme. Thereafter, it is possible to strip out the decoded signal from the received signal and then decode the remaining signal (in an interference-free channel in case of no error propagation). The LLRs for both phases are computed as follows

$$\begin{aligned}\Lambda_1 = & \max_{\substack{\Re(x_D)=\frac{1}{\sqrt{2}} \\ \Im(x_D)=\frac{1}{\sqrt{2}}}} \Im(\bar{y}_a)\Re(x_D) + |\eta_0|\Re(x_I) + |\eta_1|\Im(x_I) \\ & - \max_{\substack{\Re(x_D)=\frac{1}{\sqrt{2}} \\ \Im(x_D)=\frac{1}{\sqrt{2}}}} \Im(\bar{y}_a)\Im(x_D) + |\eta_0|\Re(x_I) + |\eta_1|\Im(x_I) \\ & -\sqrt{2}\Re(\bar{y}_a),\end{aligned}$$

$$\begin{aligned}\Lambda_2 = & \max_{\substack{\Re(x_D)=\frac{1}{\sqrt{2}} \\ \Im(x_D)=\frac{1}{\sqrt{2}}}} \Re(\bar{y}_a)\Re(x_D) + |\eta_0|\Re(x_I) + |\eta_1|\Im(x_I) \\ & - \max_{\substack{\Re(x_D)=\frac{1}{\sqrt{2}} \\ \Im(x_D)=\frac{1}{\sqrt{2}}}} \Re(\bar{y}_a)\Re(x_D) + |\eta_0|\Re(x_I) + |\eta_1|\Im(x_I) \\ & -\sqrt{2}\Im(\bar{y}_a),\end{aligned}$$

where

$$\begin{aligned}\eta_0 &= \Re(\rho)\Re(x_D) + \Im(\rho)\Im(x_D) - \Re(\bar{y}_b), \\ \eta_1 &= \Re(\rho)\Im(x_D) - \Im(\rho)\Re(x_D) - \Im(\bar{y}_b),\end{aligned}$$

and where $\Re\{.\}$ and $\Im\{.\}$ are the real and imaginary components, respectively, x_D is the desired signal to be decoded while x_I represents the interfering signal, $\bar{y}_a$ and $\bar{y}_b$ are the MF outputs of the desired and interfering signals, respectively, and ρ is the correlation coefficient between the two signals x_D and x_I. Similar bit metrics can be derived for higher modulation schemes [16]. The generated LLRs are soft-combined in decoding w_0 at the destination at the end of Phase II.

IV. Performance Evaluation

In this section we numerically evaluate the performance of the proposed transmission strategy. The transmission bandwidth is 5 MHz (25 PRBs). For each of the decoding operations in Phases I and II, the BLER performances at the destination are evaluated for different values of S. For Phase I, the BLER performance of w_1 is shown in Fig. 3(a) for MCS values ranging in the interval $[0:9]$ (QPSK). For Phase II, the BLER performance of w_0 is shown in Figs. 3(b) and 3(c), by using the LLRs of the two phases. Two ratios of I/S are examined, namely 0 dB in Fig. 3(b) and 5 dB in Fig. 3(c). It is worth noting that in our model, the relay-destination link is assumed to be stronger than the source-destination link so that using the relay indeed boosts the rate performance with respect to direct transmission and, at the same time, motivates our choice of same (QPSK) modulation both at the source and at the relay. We remark here that, for larger I/S ratios, it could be advantageous to use a higher modulation scheme (such as 16 QAM) at the relay in order to fully exploit the higher quality of the relay-destination link. Finally, Fig. 3(d) shows the BLER performance of w_2 at the end of Phase II.

The results in Fig. 3, Tables I ($I/S = 0$ dB) and II ($I/S = 5$ dB) were generated as follows. From Fig. 3(a) we considered a BLER $= 10^{-2}$ and, for each value of the MCS of X_b (first column of Tables I and II), we selected the corresponding value of S (second column of Tables I and II). Thereafter, for each value of the ratio I/S, we selected the MCS of (X_{a1}, X_{a2}) which, for each value of S (second column of Tables I and II), allowed to achieve a BLER $\leq 10^{-2}$. These MCS values are reported in the fourth column of Tables I and II. Similarly, we proceeded for selecting the MCS of X_c (sixth column of Tables I and II). The TBSs of each MCS (at the source and at the relay), based on the LTE standard [17], are also reported in Tables I and II. In order to compare the achieved spectral efficiency with the theoretical rate (eighth column of Tables I and II), we firstly computed the value of C (strength of the source-relay link), by reversing [5, eq.(42)] with $\gamma = 0.5$ (in order to account for the fact that the duration of the two phases is equal). Finally, we used the values of (S, I, C) and computed [5, eq.(37)]. The total rate R (ninth column of Tables I and II) was determined by using only the number of soft-bits (G-useful information bits), and ignoring the overhead bits, such as pilots used for channel estimation, as follows:

$$R = \frac{\text{TBS}(X_b) + \text{TBS}\left(X_{a1}, X_{a2}\right) + \text{TBS}(X_c)}{\left(\frac{\text{G}_1}{\text{Q}_{\text{mod1}}} + \frac{\text{G}_2}{\text{Q}_{\text{mod2}}}\right)}, \quad (1)$$

where G_1 is the number of soft-bits utilized to decode (X_b, X_{a1}) and G_2 to decode (X_{a2}, X_c), and where Q_{mod1} and Q_{mod2} are the corresponding modulation orders (here equal to 2 since we use QPSK both at the source and at the relay). Although not presented here for sake of space, it can be easily checked that the BLER performance of w_0 and w_1 at the relay is always less than 10^{-2}, implying that the relay capabilities are superior than those of the destination (since we are assuming $C \geq I \geq S$). Finally, for comparisons, we also considered a Baseline Scheme (BS) (last two columns of Tables I and II), which mimics relay models used in today's networks, where the UE does not have a direct connection with the eNB, i.e., the source-destination link is absent and the eNB can communicate with the UE only through the relay.

From Tables I and II, the maximum difference between the theoretical rate in [5, eq.(37)] and the achieved rate by the proposed scheme is of 0.458 bits/dim when $I/S = 0$ dB and of 0.681 bits/dim when $I/S = 5$ dB. The rate gap between theory and practice can be mostly attributed to two key factors: (i) the TBs used are of finite length (see Tables I and II), differently from the theoretical assumption of infinite block length and (ii) the channel inputs are drawn from a discrete constellation (QPSK), rather than from Gaussian codebooks as assumed in the theoretical analysis. Furthermore, the fact that the difference is higher when $I/S = 5$ dB than when $I/S = 0$ dB is due to the fact that when the ratio I/S increases it becomes more critical to choose higher MCS values for the relay in order to fully exploit the strength of the relay-destination link. We also remark that the difference between theoretical and practical rates might be decreased by tuning the parameters δ (superposition factor) and γ (fraction of time the relay listens to the channel) in the interval $[0, 1]$, instead of considering them as fixed values.

From Tables I and II, we also notice that the maximum difference between the practical and the BS rates is of 1.33 bits/dim (factor of 2) and of 0.667 bits/dim (factor of 1.2), respectively. The fact that the difference is higher when $I/S = 0$ dB than when $I/S = 5$ dB is due to the fact that when the ratio I/S is small, the presence of the source-destination link plays a significant role in the rate performance.

V. Conclusions

In this paper, we designed a practical transmission strategy for the Gaussian half-duplex relay channel by using codes as in the LTE standard and by running simulations on an LTE test bench. The scheme uses superposition encoding, decode-and-forward relaying and sequential interference cancellation in order to send three messages in two time slots from a source to a destination with the help of a relay (which forwards one of the three messages). Comparisons between the theoretical achievable rate with (point-to-point capacity achieving) Gaussian codes and the rate achieved in a practical scenario were provided for a BLER of 10^{-2}. In addition, a baseline scheme was also considered where the source-destination link is absent. The rate performance of this scheme, which mimics the one implemented in today's wireless networks, was shown to be inferior to that of the proposed scheme, implying that physical layer cooperation brings about throughput gains.
Future work will consider the employment of multiple antennas at the relay and destination, and the capability of decoding signals with higher modulation orders (16-QAM and 64-QAM) on the receiver side.

Acknowledgments

Eurecom's research is partially supported by its industrial partners: BMW Group Research & Technology, IABG, Monaco Telecom, Orange, SAP, SFR, ST Microelectronics, Swisscom and Symantec. The research carried out at Eurecom has also received funding from the EU Celtic+ Framework Program Project SHARING and from a 2014 Qualcomm Innovation Fellowship. This work was also financially supported by a scholarship from the National Research Foundation (NRF) of South Africa. The work of D. Tuninetti was partially funded by NSF under award number 1218635; the contents of this article are solely the responsibility of the author and do not necessarily represent the official views of the NSF.

References

[1] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.
[2] T. M. Cover and A. A. E. Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Info. Theory*, vol. 25, no. 5, pp. 572–584, Sept. 1979.
[3] Third Generation Partnership Project, "Relay architectures for E-UTRA (LTE-Advanced)(Release 9)," 3GPP, Tech. Rep. 3GPP TR 36.806 v2.0.0, Feb. 2010.
[4] Third Generation Partnership Project, "Further advancements for E-UTRA physical layer aspects(Release 9)," 3GPP, Tech. Rep. 3GPP TR 36.814 v9.0.0, Mar. 2010.
[5] M. Cardone, D. Tuninetti, R. Knopp, and U. Salim, "On the Gaussian Half-Duplex Relay Channel," *IEEE Trans. Info. Theor.*, vol. 60, no. 5, pp. 2542–2562, May 2014.
[6] F. Kaltenberger, "OpenAirInterface Project," Eurecom, Feb. 2014, https://twiki.eurecom.fr/twiki/bin/view/OpenAirInterface. Last accessed on 15 Oct. 2014.
[7] M. Iwamura, H. Takashi, and S. Nagata, "Relay technology in LTE-Advanced," *NTT Docomo Technical Journal*, vol. 12, no. 2, pp. 29–36, Sept. 2010.
[8] Z. Juan, P. Sartori, and B. Wei, "Performance Analysis of Layer 1 Relays," in *IEEE Intl. Conf. on Commun. Communication Workshop (ICC)*, Jun. 2009, pp. 1–6.
[9] S. Vanka, S. Srinivasa, Z. Gong, P. Vizi, K. Stamatiou, and M. Haenggi, "Superposition Coding Strategies: Design and Experimental Evaluation," *IEEE Trans. Wireless Commun.*, vol. 11, no. 7, pp. 2628–2639, July 2012.
[10] K. Ishibashi, K. Ishii, and H. Ochiai, "Dynamic Coded Cooperation Using Multiple Turbo Codes in Wireless Relay Networks," *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 197–207, Feb. 2011.
[11] L. Chen, "Opportunistic cooperative communications with reed-solomon convolutional concatenated codes," in *IEEE Intl. Conf. on Commun. Tech. (ICCT)*, Sept. 2011, pp. 22–26.
[12] G.J. Bradford and J.N. Laneman, "Low latency relaying schemes for next-generation cellular networks," in *IEEE Intl. Conf. on Commun. (ICC)*, Jun. 2012, pp. 4294–4299.
[13] H. Yang, W. Meng, B. Li, and G. Wang, "Physical layer implementation of network coding in two-way relay networks," in *IEEE Intl. Conf. on Commun. (ICC)*, Jun. 2012, pp. 671–675.
[14] Y. Meng, M. You, S. Zhao, and L. Zhang, "A Distributed Layered Modulation for Relay Downlink Cooperative Transmission," in *IEEE Intl. Symp. on Personal, indoor and mobile radio communications (PIMRC)*, Sept. 2010, pp. 1–5.
[15] Third Generation Partnership Project, "Multiplexing and channel coding (Release 11)," 3GPP, Tech. Rep. 3GPP TS 36.212 v11.3.0, Jun. 2013.
[16] R. Ghaffar and R. Knopp, "Spatial Interference Cancellation Algorithm," in *IEEE Wireless Commun. and Networking Conf.*, Apr. 2009, pp. 1–5.
[17] Third Generation Partnership Project, "Phyisical Layer Procedures (Release 11)," 3GPP, Tech. Rep. 3GPP TS 36.213 v11.3.0, Jun. 2013.