A Quantize-and-Forward Scheme for Future Wireless Relay Networks

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***Abstract*—The orthogonal multiple-access relay channel with two sources is considered. The goal of this paper is to show the applicability and effectiveness of a previously introduced quantize-and-forward scheme to a more realistic channel and system model, including orthogonal frequency division multiple access and multipath fading channels. Simulation results are provided to demonstrate the gain of quantize-and-forward relayed communication as opposed to the point-to-point links without the relay.**

I. Introduction

Homogeneous user quality of service (QoS) over the coverage area of a base station is a major challenge in future wireless systems. To that end, relay nodes (RNs) shall be included in the LTE standard 3GPP release 10 [1] as an effective means to provide coverage extension and enhanced QoS to cell-edge users at reasonable cost. Those relay nodes are envisioned to be decode-and-forward (DF) type relays appearing to user equipment (UE) as a subcell independent from the enhanced node B (eNB) cell. Such a relay requires error-free decoding of the source message(s) at the relay. In contrast, an efficient quantize-and-forward (QF) scheme without the need for decoding at the relay would reduce the computational burden on the relay, reduce the delay incurred by the relay operations, and consequently reduce the maximum round-trip delay. Furthermore, relaxing the requirement for the relay to decode reliably may be beneficial in situations where the signal received at the RN is not strong enough.

In this paper, we focus on the multiple-access relay channel (MARC) with orthogonal receiver components displayed in Fig. 1, where two sources transmit independent information to a common destination via a single relay. In related work, DF strategies for the MARC using low-density parity-check codes [2] and distributed turbo codes [3] were investigated based on the assumption that the relay node decodes the source message perfectly. A scheme for the MARC with analog forwarding [4] achieves notable gains in fixed additive white Gaussian noise (AWGN) channels. In more recent work [5], the authors compute two-dimensional quantizers for symbol-by-symbol quantization of the received values at the relay with Rayleigh block fading channels. There, the quantizer design problem is

This work was carried out while Joerg Widmer was with DOCOMO Communications Laboratories Europe GmbH.

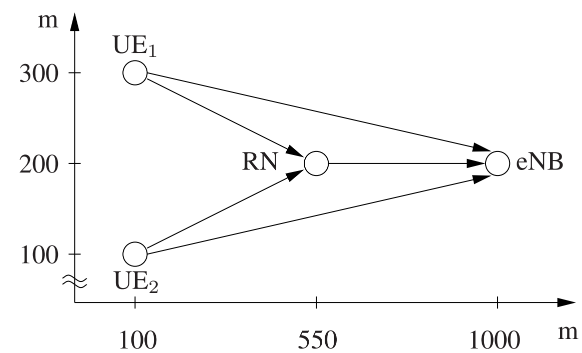

Fig. 1. The multiple-access relay channel.

based on an optimization problem known as the information bottleneck method [6]. No soft decoding is required at the relay to achieve second order diversity using a scheme in which a suitable quantizer at the relay is picked from a fixed set according to the channel quality of the incoming links at the relay node.

Our goal is to demonstrate the applicability and efficiency of the QF scheme in [5] for the MARC with frequency-selective channels and LTE-like modulation. To that end, we employ orthogonal frequency division multiple access (OFDMA) at the sources and the relay, and model the multipath channel according to the WINNER II channel model [7]. The results of our simulations demonstrate the benefit of quantize-and-forward relaying over point-to-point links for such a scenario.

Throughout this paper, random variables appear as upper case letters, while their realizations are printed in lower case letters.

II. System Model

An illustration of the system at hand is shown in Fig. 2. Further details will be provided in the following subsections.

A. Sources

The two UEs are assumed to generate independent and equiprobable blocks of bits of length k, $\boldsymbol{B}_i \in \{0,1\}^k$, $i \in \{1,2\}$, which are encoded to a block of code bits $\boldsymbol{X}_i \in \{0,1\}^n$ of length n (code rate k/n) and modulated according to [8], [9] to obtain the block of symbols $\boldsymbol{S}_i \in$

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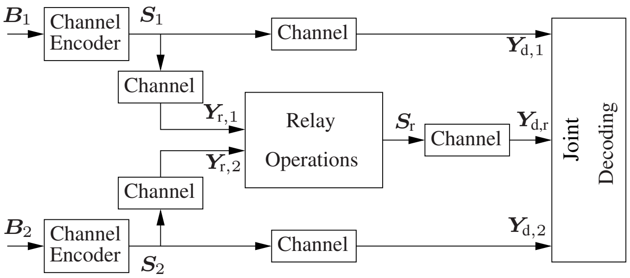

Fig. 2. System model.

$\{-1,+1\}^n$. These modulated symbols are then mapped to blocks of symbols $\boldsymbol{S}_{i,j} \in \{-1,+1\}^{n_{\text{sub}}}$, $n_{\text{sub}} = \lceil n/N_{\text{sub}} \rceil$, per subcarrier $j \in \{1,\ldots,N_{\text{sub}}\}$ for OFDM transmission. Here, we assume transmission over an OFDMA system with N_{sub} subcarriers. Note that since the primary purpose of our study is to demonstrate the benefit from QF relaying, we deliberately chose to not employ DFT-Spread OFDMA for the sake of simplicity, although DFT-Spread OFDMA is the multiplexing scheme for the uplink of an LTE system. However, the channel code is the LTE turbo code using the LTE interleaver [9], and we use binary phase shift keying (BPSK) at the sources for the sake of simplicity.

B. Channel Model

After transmission from the two sources, the received signals at the relay and destination can be written as

$$\boldsymbol{Y}_{\text{r},i,j} = H_{\text{r},i,j}\boldsymbol{S}_{i,j} + \boldsymbol{N}_{\text{r},i,j}, \tag{1}$$

$$\boldsymbol{Y}_{\text{d},i,j} = H_{\text{d},i,j}\boldsymbol{S}_{i,j} + \boldsymbol{N}_{\text{d},i,j}, \tag{2}$$

with the frequency responses $H_{\text{r},i,j} \in \mathbb{C}$ and $H_{\text{d},i,j} \in \mathbb{C}$ for the channels between the UEs and the relay and between the UEs and the destination, respectively, as well as the additive white Gaussian noise terms $\boldsymbol{N}_{\text{r},i,j} \in \mathbb{C}^{n_{\text{sub}}}$ and $\boldsymbol{N}_{\text{d},i,j} \in \mathbb{C}^{n_{\text{sub}}}$ at the relay and destination, respectively, where each entry in the noise vectors has variance P_n. Further, the vectors $\boldsymbol{Y}_{\text{r},i}$ and $\boldsymbol{Y}_{\text{d},i}$ in Fig. 2 represent the received information over all subcarriers at the relay and the destination pertaining to one codeword $\boldsymbol{X}_i$.

Finally, the relay transmits symbols $\boldsymbol{S}_{\text{r},j} \in \mathbb{S}_{\text{r}}^{n_{\text{sub}}}$ over the channel between the relay and the destination with the frequency response $H_{\text{d,r},j} \in \mathbb{C}$, i.e.,

$$\boldsymbol{Y}_{\text{d,r},j} = H_{\text{d,r},j}\boldsymbol{S}_{\text{r},j} + \boldsymbol{N}_{\text{d,r},j}, \tag{3}$$

where $\boldsymbol{N}_{\text{d,r},j} \in \mathbb{C}^{n_{\text{sub}}}$ denotes the additive white Gaussian noise term for the link between relay and destination. The modulation alphabet $\mathbb{S}_{\text{r}}$ employed at the relay is 16-QAM. Similarly to above, the vector $\boldsymbol{Y}_{\text{d,r}}$ in Fig. 2 represents the received information over all subcarriers at the destination belonging to one codeword transmitted from the relay. Note that all channel frequency responses are generated according to the WINNER II channel model [7], [10]; furthermore, we assume perfect channel state information (CSI) at all receivers, which employ a minimum-mean squared error (MMSE) equalizer as defined in the standard.

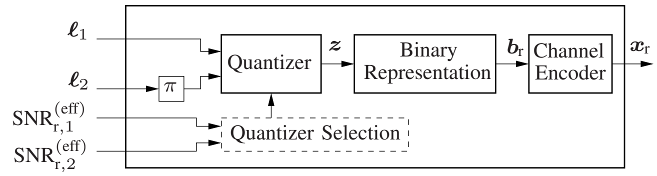

Fig. 3. Relay operations.

The effective signal-to-noise ratio (SNR) $\text{SNR}^{(\text{eff})}$ per subcarrier is defined as $\text{SNR}^{(\text{eff})} = p \cdot T_{\text{sym}}/(T_{\text{sym}} + T_{\text{cp}}) \cdot P_s/P_n$, where $P_s = 1$ is the power available for transmission on one subcarrier, P_n is the thermal noise power, $0 < p \ll 1$ is the path-loss coefficient provided by the channel model [7], and $T_{\text{sym}}/(T_{\text{sym}} + T_{\text{cp}})$ is the power-loss [11] due to the cyclic prefix.

C. Relay Operations

The relay is assumed to have a half-duplex constraint, i.e., it cannot transmit and receive simultaneously in the same frequency band. After demultiplexing, equalization, and soft demodulation, the relay has soft information $\boldsymbol{\ell}_i \in \mathbb{R}^n$, $i \in \{1,2\}$, about the coded bits $\boldsymbol{X}_i \in \{0,1\}^n$ at its disposal. Based on this soft information, the relay applies the operations as shown in the block diagram of Fig. 3. Instead of now invoking decoders to recover the source messages, the relay employs a two-dimensional quantizer to quantize the soft information obtained from the UEs. To that end, it first selects a suitable quantizer from a fixed set according to the quality of the soft information from each UE, quantizes $(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2)$ using that quantizer, and subsequently computes the binary representation $\boldsymbol{b}_{\text{r}}$ of $\boldsymbol{z}$, channel encodes, modulates, and transmits the resulting 16-QAM symbols $\boldsymbol{s}_{\text{r},j}$ to the destination. In Fig. 3, $\boldsymbol{x}_{\text{r}}$ denotes the coded quantized information which is then mapped to the 16-QAM symbols $\boldsymbol{s}_{\text{r},j}$. The design of each quantizer available to the relay is based on the statistics of the soft information $\boldsymbol{\ell}_1$ and $\boldsymbol{\ell}_2$ and will be described in Section III. We refer the reader to [5] for a detailed description of the remaining relay operations.

Note that for decoding, the destination needs to know the quantizer employed at the relay. The necessary signaling between the relay and the destination is assumed to be perfect, and we remark that the associated overhead depends on the size of the quantizer set at the relay.

D. Receiver at Destination

At the destination, the iterative decoder structure shown in Fig. 4 is employed. In addition to two turbo decoders for the symbols $\boldsymbol{y}_{\text{d},1} \in \mathbb{C}^n$ and $\boldsymbol{y}_{\text{d},2} \in \mathbb{C}^n$ received over the direct links, the decoder contains the relay check nodes coupling the component turbo decoders, which are further detailed in Fig. 5. The coupling of the component decoders at the destination is a result of the joint quantization at the relay. Essentially, if the information received via the relay is small, the decoder structure can be seen as two separate turbo decoders for $\boldsymbol{y}_{\text{d},1}$ and $\boldsymbol{y}_{\text{d},2}$, since very little information can pass the check

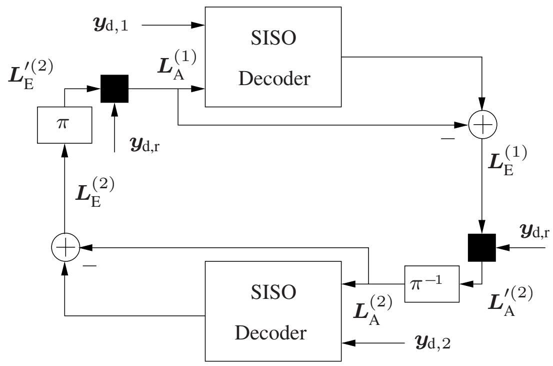

Fig. 4. Iterative decoder.

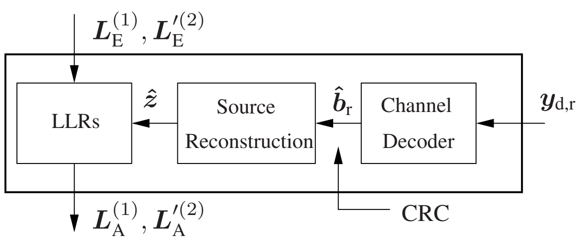

Fig. 5. Operations of the relay check node.

nodes. In contrast, if the information received from the relay is reliable, soft information is exchanged iteratively between the component decoders.

In order to avoid error propagation effects in the source reconstruction process in case of residual errors in $\hat{\boldsymbol{b}}_{\mathrm{r}}$, a cyclic redundancy check (CRC) in the bits $\boldsymbol{b}_{\mathrm{r}}$ sent by the relay is assumed; consequently, the information from the relay is discarded if $\hat{\boldsymbol{z}}$ cannot be reconstructed perfectly based on $\boldsymbol{y}_{\mathrm{d,r}}$. The processing rules yielding the soft values $\boldsymbol{L}_{\mathrm{A}}^{(1)}, \boldsymbol{L}_{\mathrm{A}}'^{(2)}$ from $\boldsymbol{L}_{\mathrm{E}}^{(1)}, \boldsymbol{L}_{\mathrm{E}}'^{(2)}$, and $\hat{\boldsymbol{z}}$ are as in [5].

III. Quantizer Design

Let $\boldsymbol{L}_1 \in \mathbb{R}^n$ and $\boldsymbol{L}_2 \in \mathbb{R}^n$ denote the block of soft information obtained at the relay pertaining to the codewords $\boldsymbol{X}_1 \in \{0,1\}^n$ and $\boldsymbol{X}_2 \in \{0,1\}^n$. Suppose that each element of $\boldsymbol{L}_i$ is a random variable L_i with probability density function $f(\ell_i)$, and suppose that each entry of $\boldsymbol{X}_i$ is a binary uniformly distributed random variable $X_i \in \{0,1\}$, where X_1 is independent of X_2. The random variable obtained by applying the quantization function $q : \mathbb{R} \times \mathbb{R} \to \mathcal{Z}$ to the pair (L_1, L_2) is $Z = q(L_1, L_2)$, where $Z \in \mathcal{Z} = \{0, 1, \ldots, J-1\}$. Since the quantizer is assumed invariant for the entire block of codebits, we can also write the quantization function q as a conditional probability mass function $p(z|\ell_1, \ell_2)$ taking on only the values zero and one; the mass function $p(z|\ell_1, \ell_2)$ can be obtained from q by

$$p(z|\ell_1,\ell_2) = \begin{cases} 1 & \text{if } q(\ell_1,\ell_2) = z \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

By averaging over realizations of the channel coefficients $H_{\mathrm{r},i,j}$ and $H_{\mathrm{d},i,j}$ of the channels between the UEs and the relay and the noise on the UE–relay links followed by histogram measurements, we obtain estimates $p(\ell_1)$ and $p(\ell_2)$ of the probability density functions $f(\ell_1)$ and $f(\ell_2)$ of the random variables L_1 and L_2. For a quantizer with J regions, we then formulate the quantizer design problem as a maximization over the mutual information $I(X_1; q(L_1, L_2)|X_2) + I(X_2; q(L_1, L_2)|X_1)$, with constraints ensuring that $p(z|\ell_1, \ell_2)$ is in the form of (4), i.e., that it is a valid probability mass function. More specifically, the optimization problem at hand is [5]

$$\begin{aligned} p^*(z|\ell_1,\ell_2) = \underset{p(z|\ell_1,\ell_2)}{\operatorname{argmax}} \;\; & I(X_1; Z|X_2) + I(X_2; Z|X_1) \\ \text{s.t. } & p(z|\ell_1,\ell_2) \in \{0,1\} \\ & \sum_{z\in\mathcal{Z}} p(z|\ell_1,\ell_2) = 1 \\ & |\mathcal{Z}| = J. \end{aligned} \tag{5}$$

Given the probability mass functions $p(\ell_1)$ and $p(\ell_2)$, we solve Problem (5) with an appropriately modified version of the information bottleneck iterative algorithm [5], [6]. Note that the quantizers used at the relay can be designed offline.

IV. Simulations

The channel model employed for both the system with the relay and the point-to-point links assumes a suburban macro-cell (C1) environment according to the geometry in Fig. 1, a carrier frequency $f_c = 2\,\mathrm{GHz}$, and $10\,\mathrm{MHz}$ bandwidth. At a subcarrier-spacing of $15\,\mathrm{kHz}$, a total of 666 subcarriers is available in the system, so that one OFDM symbol lasts $T_{\mathrm{sym}} = 71.36\,\mu\mathrm{s}$ with a cyclic prefix of length $T_{\mathrm{cp}} = 4.69\,\mu\mathrm{s}$ [12]. The power $P_s = 1$ per subcarrier is assumed constant, and each block of bits has length $k = 992$.

To ensure a fair comparison, each UE gets $N_{\mathrm{sub}} = 333$ subcarriers in the reference point-to-point link and uses a code rate of $R = 1/3$, whereas in the system with the relay, both UEs and the relay each have $N_{\mathrm{sub}} = 222$ subcarriers. Using a code rate of $R = 1/2$ at the UEs and an appropriate code rate at the relay depending on the choice of the quantizer yields that the total emitted power in both systems is equal. The quantizers available at the relay have $J = 3$ quantization regions, and the set is of size 22, thereby inducing a signaling overhead of at most 5 bits.

Throughout, we assume that the source-destination and source-relay links are not line-of-sight (NLOS), while the relay-destination link is line-of-sight (LOS), which is a reasonable assumption given proper relay placement above rooftop. The associated SNR values in dB are related by $\mathrm{SNR}_{\mathrm{r},i}^{(\mathrm{eff})} = \mathrm{SNR}_{\mathrm{d},i}^{(\mathrm{eff})} + 10\log_{10}(p_{\mathrm{r},i}/p_{\mathrm{d},i})$ and $\mathrm{SNR}_{\mathrm{d,r}}^{(\mathrm{eff})} = \mathrm{SNR}_{\mathrm{d},i}^{(\mathrm{eff})} + 10\log_{10}(p_{\mathrm{d,r}}/p_{\mathrm{d},i})$; with the appropriate path-loss coefficients $p_{\mathrm{r},i}$, $p_{\mathrm{d},i}$, and $p_{\mathrm{d,r}}$ for our geometry [7] we have $10\log_{10}(p_{\mathrm{r},i}/p_{\mathrm{d},i}) = 10\,\mathrm{dB}$ and $10\log_{10}(p_{\mathrm{d,r}}/p_{\mathrm{d},i}) = 40\,\mathrm{dB}$.

The common frame-error-rate (CFER) of both systems is shown in Fig. 6. At a practically relevant CFER of 10^{-3}, the QF scheme outperforms the point-to-point link by approximately 7 dB.

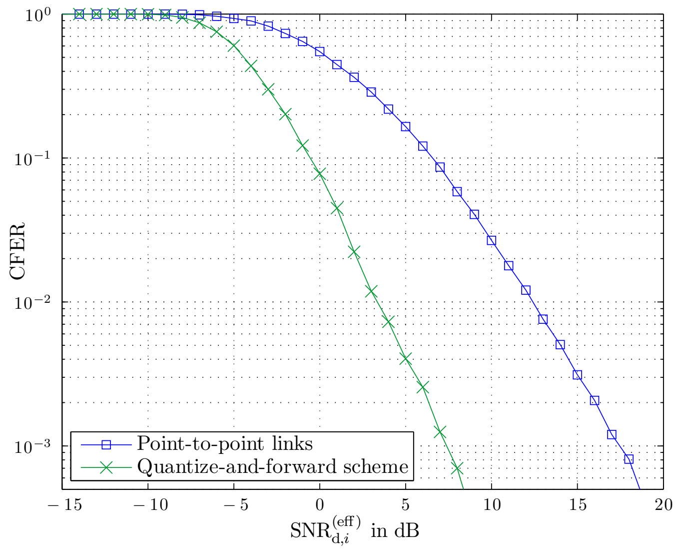

Fig. 6. CFER performance comparison.

V. Conclusions

We demonstrated the application of a QF scheme for the MARC providing a significant gain over point-to-point links, and emphasize that the relay does not have to decode the source messages to achieve that gain, thereby inducing low complexity and delay.

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