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Virtual Antenna Based Combining for Hybrid AF/DF Relaying Scheme over Multi-Antenna Broadband Channels

Houda Chafnaji, Tarik Ait-Idir, Halim Yanikomeroglu, and Samir Saoudi

Abstract—This paper focuses on turbo packet combining for hybrid AF/DF multi-relay systems operating over multiple-input-multiple-output (MIMO) broadband channels. We consider *virtual antenna* based combining strategy that has been widely studied for the point-to-point hybrid ARQ. However, the extension of this combining strategy to hybrid AF/DF cooperative communications is not straightforward. In this paper, we revisit this combining strategy. First, we build an appropriate system model to mask the cooperation. Then, we extend the turbo packet combiner inspired by *virtual antenna* concept to cooperative communications. Finally, block error rate (BLER) are investigated to demonstrate the gain offered by the studied turbo packet combiner.

Index Terms—Cooperative relaying, multiple-antenna systems, turbo equalization, packet combining.

I. INTRODUCTION

The presence of diversity in wireless networks is a key requirement to combat channel fading and to enable communication at high spectral efficiencies. Point-to-point hybrid automatic repeat request (ARQ) is a popular mechanism that has been introduced to exploit temporal diversity. This mechanism has been studied for many years and is still receiving considerable attention [1], [2]. However, it suffers from temporal diversity limitations especially in slow fading environments. To mitigate this problem, the authors in [3] have proposed cooperative relaying transmissions that exploit the broadcast nature of the wireless channel and add spatial diversity by incorporating relays in the network. In this cooperative transmissions, the relays play the role of packet re-transmitters instead of the source, thereby creating an independent channel to increase the diversity order. Cooperative relaying presents a good alternative to classical point-to-point hybrid ARQ in slow fading environments and is becoming an area of wide interest for many researchers (see for instance [4] and [5]).

Several interesting relaying schemes have been proposed, among which are two basic modes: amplify-and-forward (AF), and decode-and-forward (DF). The AF scheme represents the simplest way that a relay may cooperate with the source and the destination. The AF relay simply amplifies the received signal and forwards it towards the destination. On the other hands, in the DF scheme, the relay first decodes the signal received from the source, re-encodes and retransmits it to the destination. This approach suffers from error propagation when the relay transmits an erroneously decoded data block [5], [6]. Selective DF, where the relay only transmits when it

can reliably decode the data packet, has been introduced as an efficient method to reduce error propagation [7]. In this paper, we focus on hybrid AF/DF scheme where the better scheme between AF and DF is selected depending on the channel condition of the source-to-relay link [8].

To improve spatial diversity of a relaying system, signals received over the source-destination and the relay-destination links are combined at the receiver side. In [9], the authors have introduced a maximum ratio combining (MRC)-aided strategy for AF scheme. The proposed combiner in [9] has been designed for systems where the source broadcasts the data packet to both the relay and the destination during the first time slot, and both the source and the relay re-send the packet to the destination during the relaying time slot. Block equalization has been proposed in [10] for cooperative systems where the broadcast nature of the channel is not considered, i.e., the source sends to the relay during the first time slot, and both the source and the relay send to the destination in the relaying time slot. As a generalization of ARQ mechanisms, a transmission protocol called protocol II has been proposed in [11]. In this protocol, the source broadcasts the data packet to both the relay and the destination during the first time slot, while during the second time slot only the relay sends the packet to the destination. To the best of the authors knowledge, previous works proposed under the framework of protocol II didn't present a real study of packet combining and simply suggest the use of one of combining techniques widely studied in the classical point-to-point hybrid ARQ [5], [12]. However, the extension of this combining strategies, especially *virtual antenna* concept based combining, to cooperative communications is not straightforward and this is what this paper aims to show.

In this paper, we consider a broadband multi-relay-assisted system using hybrid AF/DF scheme. Our main contribution is to build an appropriate system model to mask the cooperation and simplify the application of *virtual antenna* concept based combining. The proposed communication model is of a great use for hybrid AF/DF cooperative systems where the different relays selected to assist the data packet transmission between the source and the destination do not necessarily use the same relaying schemes. In the case of DF relaying, masking the cooperation is very simple as the relayed packet can be viewed, at the destination side, as a direct retransmission from the source through a different channel. However, in AF scheme, transmissions over relaying links suffer from

colored noise as well as correlation between source-to-relay and relay-to-destination multi-path channels. To mask this cooperation problems, we perform whitening using Cholesky decomposition and derive an equivalent source-to-relay-to-destination channel.

The remainder of the paper is organized as follows: In Section II, we introduce the relay system model and derive the unified communication model for DF and AF relaying schemes. In Section III, we introduce the multi-slot block communication model together with *virtual antenna* based turbo combining scheme. Performance evaluation is provided in Section IV. Finally, the paper is concluded in Section V. Throughout the paper we use the following notation: $(\cdot)^H$ and $(\cdot)^T$ are the the transpose conjugate and transpose of the argument, respectively. $\text{diag}\{\mathbf{x}\}$ and $\text{diag}\{\mathbf{X}_1, \dots, \mathbf{X}_m\}$ denote the diagonal matrix and the block diagonal matrix constructed from $\mathbf{x} \in \mathbb{C}^n$ and from $\mathbf{X}_1, \dots, \mathbf{X}_m \in \mathbb{C}^{n_1 \times n_2}$, respectively. For $\mathbf{x} \in \mathbb{C}^{TN}$, \mathbf{x}_f denotes the discrete Fourier transform (DFT) of \mathbf{x} , i.e. $\mathbf{x}_f = \mathbf{U}_{T,N}\mathbf{x}$, with $\mathbf{U}_{T,N} = \mathbf{U}_T \otimes \mathbf{I}_N$, where \otimes denotes the Kronecker product, \mathbf{U}_T is a unitary $T \times T$ matrix whose (m, n) th element is $(\mathbf{U}_T)_{m,n} = \frac{1}{\sqrt{T}}e^{-j(2\pi mn/T)}$, $j = \sqrt{-1}$, and \mathbf{I}_N is the $N \times N$ identity matrix.

II. RELAY SYSTEM MODEL

A. Multi-Relay Transmission Scheme

We consider a multi-relay-assisted wireless communication system, where the M_S antenna source terminal denoted as S transmits information blocks to the M_D antenna destination terminal denoted as D with the assistance of $K - 1$ dedicated hybrid AF/DF relays denoted as $R_2, \dots, R_k, \dots, R_K$. Each relay R_k is equipped with M_{R_k} transmit and receive antennas. In this paper, the multi-relay-assisted system is assumed to be heterogeneous which means that the $K - 1$ selected relays ¹don't necessarily use the same type of relaying schemes. We consider a relaying system using K time slots for sending one information block from the source to the destination to guarantee orthogonal transmissions. During the first time slot, the source broadcasts the data packet to the $K - 1$ relays and the destination. During the following time slots, each relay participates in the packet retransmission during the allocated time slot and keeps silent during the other time slots. The block diagram of the considered system is depicted in Fig. 1.

The source-relay ($S \rightarrow R_k$), source-destination ($S \rightarrow D$), and relay-destination ($R_k \rightarrow D$) links are assumed to be frequency selective fading. The channel matrices corresponding to the $A \rightarrow B$ link are $\mathbf{H}_0^{(AB)}, \dots, \mathbf{H}_{L_{AB}-1}^{(AB)} \in \mathbb{C}^{M_B \times M_A}$ with $A \in \{S, R_k\}$, and $B \in \{R_k, D\}$ and L_{AB} denotes the number of symbol-spaced taps. Their entries are zero-mean circularly symmetric complex Gaussian random variables. To prevent inter-block interference and allow the use of frequency domain processing at the receiver side, cyclic prefix (CP)-aided transmission is assumed for all links. The average

¹The selection of the best candidate node to participate in the packet retransmissions and the best relaying scheme, AF or DF, can be performed using one of relay selection algorithms proposed in the literature [13], [14], [15]. Relay selection is beyond the scope of this paper.

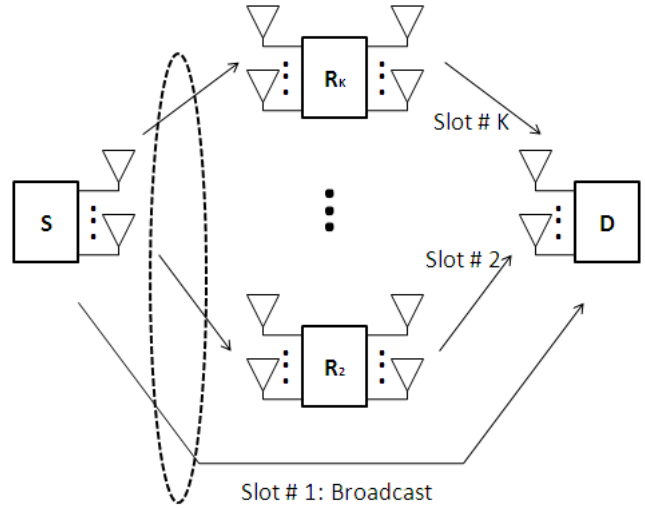


Figure 1. Block diagram of the considered multi-relay assisted systems.

received energies of the different links are E_{SR_k} , E_{SD} and E_{R_kD} , and take into account the path-loss and shadowing effects of each link. We assume no transmit channel state information (CSI) is available at the source and the relays and suppose perfect receive CSI at the relays and the destination.

First, the source encodes its data blocks using a space-time bit interleaved coded modulation (ST-BICM) encoder. In fact, a data block is coded using a ρ -rate encoder, interleaved with the aid of a semi-random interleaver, then symbol mapped to a constellation \mathcal{S} , and spatial multiplexing over M_S transmit antennas. The rate of this space-time code is therefore $R = \rho M_S \log_2(|\mathcal{S}|)$. Moreover, to have independent transmitted symbols, we assume the presence of sufficiently deep interleaver. The resulting symbol vector is given by,

$$\mathbf{s} \triangleq [\mathbf{s}_0^T, \dots, \mathbf{s}_{T-1}^T]^T \in \mathcal{S}^{M_S T}, \quad (1)$$

where $\mathbf{s}_i \triangleq [s_{1,i}, \dots, s_{t,i}, \dots, s_{M_S,i}]^T \in \mathcal{S}^{M_S}$ is the symbol vector at channel use ² $i = 0, \dots, T - 1$. During the first time slot, the source inserts a CP symbol word of length $T_{CP}^{(1)} \geq \max_{k=2, \dots, K} (L_{SR_k}, L_{SD})$, then broadcasts the resulting symbol frame. After CP deletion, the baseband $M_D \times 1$ signal vector obtained at the destination side is given by,

$$\mathbf{y}_i^{(1)} = \sqrt{E_{SD}} \sum_{l=0}^{L_{SD}-1} \mathbf{H}_l^{(1)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(1)}, \quad (2)$$

where $\mathbf{n}_i^{(1)} \sim \mathcal{N}(\mathbf{0}_{M_D \times 1}, \sigma^2 \mathbf{I}_{M_D})$ is the thermal noise and $\mathbf{H}_l^{(1)} = \mathbf{H}_l^{(SD)}$. During the following $K - 1$ time slots, each relay participates in the packet retransmission using AF or DF relaying scheme depending on the channel condition of the source-to-relay link. In the remainder of this section, our main focus is to build an appropriate system model to mask

²Channel use i represents the order number of a symbol within the transmitted packet at the current time slot.

the cooperation and simplify the application of *virtual antenna* concept based combining.

B. Decode-and-Forward Relaying

In this paper, we consider selective DF to mitigate the error propagation problem. Under this scheme, each relay first decodes the received signal packet. If the decoding outcome is correct, the relay re-encodes the information using the same ST-BICM encoder as the source and retransmits the resulting symbol block during the allocated time slot. If the relay k decoding outcome is erroneous, the packet retransmission is not activated during time slot k . In this work, we assume that the number of DF relay antennas is equal to or greater than the number of source antennas, i.e., $M_{R_k} \geq M_S$, and the DF relay uses only M_S transmit antennas for packet relaying. This reduces the inter-symbol interferences and simplify the the application of *virtual antenna* combining at the destination side [7]. Therefore, if the data packet is correctly decoded at DF relay R_k , the resulting symbol vector at channel use $i = 0, \dots, T-1$ is given by (1). Before transmission, the relay inserts a CP symbol word of length $T_{CP}^{(k)} \geq L_{R_k D}$. Therefore, at time slot k , the received signal at the destination side is expressed as

$$\mathbf{y}_i^{(k)} = \sqrt{E_k} \sum_{l=0}^{L_k-1} \mathbf{H}_l^{(k)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(k)}. \quad (3)$$

where $E_k = E_{R_k D}$, $L_k = L_{R_k D}$, and $\mathbf{H}_l^{(k)} = \mathbf{H}_l^{(R_k D)} \in \mathbb{C}^{M_D \times M_S}$.

C. Amplify-and-Forward Relaying

In AF scheme, the relay amplifies and sends the block of received signals to the destination. At AF relay R_k , the $M_{R_k} \times 1$ received signal, after CP removal, is expressed as,

$$\mathbf{y}_i^{(SR_k)} = \sqrt{E_{SR_k}} \sum_{l=0}^{L_{SR_k}-1} \mathbf{H}_l^{(SR_k)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(SR_k)}, \quad (4)$$

where $\mathbf{n}_i^{(SR_k)} \sim \mathcal{N}(\mathbf{0}_{M_{R_k} \times 1}, \sigma^2 \mathbf{I}_{M_{R_k}})$ is the thermal noise at the relay R_k . The relay first normalizes received signals $\mathbf{y}_i^{(SR_k)}$ as,

$$\tilde{\mathbf{y}}_i^{(SR_k)} = \frac{1}{\sqrt{M_S E_{SR_k} + \sigma^2}} \mathbf{y}_i^{(SR_k)}, \quad (5)$$

then inserts a CP signal word of length $T_{CP}^{(k)} \geq L_{R_k D}$ and transmits the resulting signal packet to the destination during time slot k . At the destination side, after CP deletion, the $M_D \times 1$ received signal during time slot k can be expressed as in (6) where $\tilde{\mathbf{n}}_i^{(SR_k D)}$ is the effective zero-mean Gaussian noise given by,

$$\tilde{\mathbf{n}}_i^{(SR_k D)} = \sqrt{\frac{E_{R_k D}}{M_S E_{SR_k} + \sigma^2}} \sum_{l=0}^{L_{R_k D}-1} \mathbf{H}_l^{(R_k D)} \mathbf{n}_{(i-l) \bmod T}^{(SR_k)} + \mathbf{n}_i^{(R_k D)}. \quad (7)$$

To cover the cooperation and simplify the application of *virtual antenna* concept, we derive an equivalent multi-path channel corresponding to link $S \rightarrow R_k \rightarrow D$ and perform whitening using Cholesky decomposition. The equivalent multi-path Source-Relay-Destination channel has $L_{SR_k D} = L_{SR_k} + L_{R_k D} - 1$ symbol-spaced taps. The l th equivalent tap channel matrix is the discrete convolution of channels corresponding to $S \rightarrow R_k$ and $R_k \rightarrow D$ links and expressed as,

$$\mathbf{H}_l^{(SR_k D)} = \begin{cases} \sum_{n=\max(0, l-L_{SR_k D}+1)}^{\min(l, L_{R_k D}-1)} \mathbf{H}_n^{(R_k D)} \mathbf{H}_{l-n}^{(SR)}, & \text{if } L_{R_k D} \geq L_{SR_k} \\ \sum_{n=\max(0, l-L_{R_k D}+1)}^{\min(l, L_{SR_k}-1)} \mathbf{H}_l^{(R_k D)} \mathbf{H}_n^{(SR_k)}, & \text{otherwise.} \end{cases} \quad (8)$$

Using this equivalent channel, we can re-write the received signal in (6) as,

$$\mathbf{y}_i^{(R_k D)} = \sqrt{\frac{E_{R_k D} E_{SR_k}}{M_S E_{SR_k} + \sigma^2}} \sum_{l=0}^{L_{SR_k D}-1} \mathbf{H}_l^{(SR_k D)} \mathbf{s}_{(i-l) \bmod T} + \tilde{\mathbf{n}}_i^{(SR_k D)}. \quad (9)$$

Note that the effective noise at the destination is colored due to the convolution by the $R_k \rightarrow D$ channel. Its conditional covariance matrix, (i.e., conditioned upon $\mathbf{H}^{(R_k D)}$), is given by,

$$\Theta_{|\mathbf{H}^{(R_k D)}} = \sigma^2 \left(\mathbf{I}_{M_D} + \frac{E_{R_k D}}{M_S E_{SR_k} + \sigma^2} \sum_{l=0}^{L_{R_k D}-1} \mathbf{H}_l^{(R_k D)} \mathbf{H}_l^{(R_k D)H} \right). \quad (10)$$

We therefore proceed to a Cholesky decomposition aided whitening, i.e., $\Theta_{|\mathbf{H}^{(R_k D)}} = \sigma^2 \mathbf{L} \mathbf{L}^H$, where \mathbf{L} is a $M_D \times M_D$ lower triangular matrix. This yields signal vector,

$$\mathbf{y}_i^{(k)} = \mathbf{L}^{-1} \mathbf{y}_i^{(R_k D)}. \quad (11)$$

The received signal at the destination side can therefore be expressed as in (3) where

$$\begin{cases} \mathbf{H}_l^{(k)} &= \mathbf{L}^{-1} \mathbf{H}_l^{(SR_k D)}, \\ L_k &= L_{SR_k D}, \\ E_k &= \frac{E_{R_k D} E_{SR_k}}{M_S E_{SR_k} + \sigma^2}, \end{cases} \quad (12)$$

with $\mathbf{n}_i^{(k)} \sim \mathcal{N}(\mathbf{0}_{M_D \times 1}, \sigma^2 \mathbf{I}_{M_D})$ is the whitened effective noise at the destination side.

III. VIRTUAL ANTENNA BASED TURBO PACKET COMBINING SCHEME

A. Multi-Slot Block Communication Model

Using the unified communication model (3), the received signals during the relaying time slots can be viewed as a direct retransmissions from the source. In fact, (3) is of a great importance as it allows us to apply the *virtual antenna*

$$\begin{aligned}
 \mathbf{y}_i^{(R_k D)} &= \sqrt{E_{R_k D}} \sum_{l=0}^{L_{R_k D}-1} \mathbf{H}_l^{(RD)} \tilde{\mathbf{y}}_{(i-l) \bmod T}^{(SR_k)} + \mathbf{n}_i^{(R_k D)}, \\
 &= \sqrt{\frac{E_{R_k D} E_{SR_k}}{M_S E_{SR_k} + \sigma^2}} \sum_{l=0}^{L_{RD}-1} \sum_{j=0}^{L_{SR}-1} \mathbf{H}_l^{(R_k D)} \mathbf{H}_j^{(SR_k)} \mathbf{s}_{(i-(j+l)) \bmod T} + \tilde{\mathbf{n}}_i^{(SR_k D)}.
 \end{aligned} \tag{6}$$

concept at the destination side, i.e., each relaying time slot can be viewed as an additional set of virtual receive antennas. Therefore, after K time slots, the system (source, $K-1$ relays, and destination) can be viewed as a point to point MIMO link with M_S transmit and $K M_D$ receive antennas. First, we introduce

$$\underline{\mathbf{y}}_i^{(K)} \triangleq \left[\mathbf{y}_i^{(1)\top}, \dots, \mathbf{y}_i^{(k)\top}, \dots, \mathbf{y}_i^{(K)\top} \right]^\top \in \mathbb{C}^{K M_D}, \tag{13}$$

where reception over multiple time slots is viewed as multiple antenna reception³. Then, we construct the $K M_D T \times 1$ block received signal vector $\underline{\mathbf{y}}^{(K)}$, as

$$\underline{\mathbf{y}}^{(K)} \triangleq \left[\underline{\mathbf{y}}_0^{(K)\top}, \dots, \underline{\mathbf{y}}_{T-1}^{(K)\top} \right]^\top \in \mathbb{C}^{K M_D T}. \tag{14}$$

The block communication model corresponding to the K -slot relay transmission scheme is given by,

$$\underline{\mathbf{y}}^{(K)} = \underline{\mathcal{H}}^{(K)} \mathbf{s} + \underline{\mathbf{n}}^{(K)}, \tag{15}$$

where

$$\underline{\mathbf{n}}^{(K)} = \left[\underline{\mathbf{n}}_0^{(K)\top}, \dots, \underline{\mathbf{n}}_{T-1}^{(K)\top} \right]^\top \in \mathbb{C}^{K M_D T} \tag{16}$$

denotes the thermal noise present in the K -slot equivalent MIMO system, with $\underline{\mathbf{n}}_i^{(K)} \triangleq \left[\mathbf{n}_i^{(1)\top}, \dots, \mathbf{n}_i^{(K)\top} \right]^\top \sim \mathcal{N}(\mathbf{0}_{K M_D \times 1}, \sigma^2 \mathbf{I}_{K M_D})$. $\underline{\mathcal{H}}^{(K)} \in \mathbb{C}^{K M_D T \times M_S T}$ is a block circulant matrix whose first $K M_D T \times M_S$ block column matrix is

$$\left[\underline{\mathbf{H}}_0^{(K)\top}, \dots, \underline{\mathbf{H}}_{L-1}^{(K)\top}, \mathbf{0}_{M_S \times (T-L) K M_D} \right]^\top \tag{17}$$

with $L = \max_{k=1, \dots, K} (L_k)$ and $\underline{\mathbf{H}}_l^{(K)} \triangleq \left[\sqrt{E_1} \mathbf{H}_l^{(1)\top}, \dots, \sqrt{E_K} \mathbf{H}_l^{(K)\top} \right]^\top \in \mathbb{C}^{K M_D \times M_S}$ correspond to the order and the l th tap of the virtual MIMO channel, respectively. Applying the discrete Fourier transform (DFT) to the K -slot block signal vector (15) yields the following frequency domain block communication model,

$$\underline{\mathbf{y}}_f^{(K)} = \underline{\mathbf{\Lambda}}^{(K)} \mathbf{s}_f + \underline{\mathbf{n}}_f^{(K)}, \tag{18}$$

where

$$\begin{cases} \underline{\mathbf{\Lambda}}^{(K)} \triangleq \text{diag} \left\{ \underline{\mathbf{\Lambda}}_0^{(K)}, \dots, \underline{\mathbf{\Lambda}}_{T-1}^{(K)} \right\} \in \mathbb{C}^{K M_D T \times M_S T}, \\ \underline{\mathbf{\Lambda}}_i^{(K)} = \sum_{l=0}^{L-1} \underline{\mathbf{H}}_l^{(K)} e^{-j(2\pi i l / T)} \in \mathbb{C}^{K M_D \times M_S}. \end{cases} \tag{19}$$

³Note that in the case of selective DF, if the DF relay k decoding outcome is erroneous, the packet retransmission is not activated during time slot k . In this case, $\mathbf{y}_i^{(k)}$ is an empty vector.

B. Turbo Packet Combining Strategy

The decoding of the information frame is performed in iterative fashion through the exchange of soft information between the *virtual antenna based soft combiner* and the soft input soft output (SISO) decoder. The *soft combiner* performs packet combining jointly with frequency domain soft minimum mean square error (MMSE) equalization by considering each transmission as an additional set of virtual receive antennas. First, the *soft combiner* computes extrinsic log-likelihood ratio (LLR) about coded and interleaved bits using signals received during time slots $1, \dots, K$ and *a priori* information. Second, the generated soft output is deinterleaved and transferred to the SISO decoder that computes a *posteriori* LLR on useful bits and extrinsic information on coded bits.

At each turbo iteration, the *soft combiner* produces the MMSE estimate \mathbf{z}_f on \mathbf{s}_f with the aid of the block communication model (18) and *a priori* information fed back by the SISO decoder. The soft MMSE filter output \mathbf{z}_f can be expressed as,

$$\mathbf{z}_f = \underline{\Phi} \mathbf{y}_f^{(K)} - \underline{\Psi} \tilde{\mathbf{s}}_f, \tag{20}$$

where $\underline{\Phi} = \text{diag} \{ \underline{\Phi}_0, \dots, \underline{\Phi}_{T-1} \}$ and $\underline{\Psi} = \text{diag} \{ \underline{\Psi}_0, \dots, \underline{\Psi}_{T-1} \}$ are, respectively, the multi-relay joint forward and backward filters given by,

$$\begin{cases} \underline{\Phi}_i \triangleq \underline{\mathbf{\Lambda}}_i^{(K)H} \underline{\mathbf{B}}_i^{-1}, \\ \underline{\mathbf{B}}_i = \sigma^2 \mathbf{I}_{K M_D} + \underline{\mathbf{\Lambda}}_i^{(K)} \tilde{\underline{\mathbf{\Xi}}} \underline{\mathbf{\Lambda}}_i^{(K)H}, \end{cases} \tag{21}$$

$$\begin{cases} \underline{\Psi}_i \triangleq \underline{\Phi}_i \underline{\mathbf{\Lambda}}_i^{(K)} - \underline{\Upsilon}, \\ \underline{\Upsilon} = \frac{1}{T} \sum_{i=0}^{T-1} \underline{\Phi}_i \underline{\mathbf{\Lambda}}_i^{(K)}, \end{cases} \tag{22}$$

and $\tilde{\mathbf{s}}_f$ denotes the DFT of the conditional expectation, i.e., computed based on *a-priori* LLRs, of \mathbf{s} . In (21), $\tilde{\underline{\mathbf{\Xi}}}$ denotes the unconditional symbol covariance matrix. It is computed as the time average of conditional covariances $\underline{\mathbf{\Xi}}_i \triangleq \text{diag} \{ \sigma_{1,i}^2, \dots, \sigma_{M_S,i}^2 \}$ where $\sigma_{t,i}^2$ is the conditional variance of symbol $s_{t,i}$. The inverse DFT of \mathbf{z}_f is then computed, yielding thereby the time domain equalized vector,

$$\mathbf{z} = \mathbf{U}_{T, M_S}^H \mathbf{z}_f. \tag{23}$$

The MMSE estimate $z_{t,i}$ corresponding to antenna t and channel use i can simply be extracted from \mathbf{z} as $z_{t,i} = \mathbf{e}_{t,i}^H \mathbf{z}$, where $\mathbf{e}_{t,i}$ denotes the $(M_S i + t)$ th vector of the canonical basis. The extrinsic LLR values corresponding to coded and interleaved bits are then calculated, deinterleaved and fed back to the SISO decoder.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the proposed combining strategy in term of block error rate (BLER) and in term of throughput. Following [16], we define the throughput as $\eta = \frac{\mathbb{E}[\mathcal{R}]}{\mathbb{E}[\mathcal{K}]}$, where \mathcal{R} is a random variable (RV) that takes R when the packet is correctly received or zero when the packet is erroneous after K time slots. \mathcal{K} is a RV that denotes the number of time slots used for transmitting one data packet.

For simulations, we consider a homogeneous case where the distances between the source and the destination l_{SD} , the source and the relay l_{SR} , and the relay and the destination l_{RD} are normalized in such a way that $l_{SD} = l_{SR} + l_{RD} = 1$. Both relays are located at the optimal distance to source and the destination, i.e., $l_{SR_2} = l_{SR_3} = 0.5$. We assume that all links have the same frequency-selective fading channel profile, i.e., $L = 3$ equal power paths with the same path loss exponent $\kappa = 3$. The link average energy is $E_{AB} = (l_{AB})^{-\kappa}$ with $A = S$ or R , and $B = R$ or D . The source and DF relays use the same ST-BICM scheme, where the encoder is a 16 state convolutional code with polynomial generators $(35, 23)_8$, the modulation scheme is quadrature phase shift keying (QPSK), and $M_S = M_{R_2} = M_{R_3}$. The length of the code frame is 2048 bits including tails, and the CP length is $T_{CP} = 3$. we consider a cooperative relaying system that uses up to two hybrid AF/DF relays to assist the transmission between the source and the destination. Moreover, we assume that the considered cooperative system is heterogeneous, i.e., one of the two selected relays uses selective DF relaying scheme while the other relay uses AF relaying scheme. To evaluate the performance gain provided by the proposed combining strategy, the conventional LLR-level packet combining⁴ is used as a reference. For SISO decoding, we use the max-log-MAP version of the MAP decoding algorithm [17]. The iterative MMSE receiver at the destination runs three turbo iterations and the SNR_{SD} appearing in all figures is the $S \rightarrow D$ link signal-to-noise ratio per useful bit per receive antenna. In all simulations, we consider the case of overloaded systems where the source node and relay nodes are equipped with more antennas than the destination node, i.e., $M_S > M_D$. This represents the case where, at low SNR, the destination can never correctly decode the first slot received signal.

First, we consider the case where the source node and relay nodes are equipped with two antennas, i.e., $M_S = M_{R_2} = M_{R_3} = 2$ while the destination node is equipped with only one receive antenna, i.e., $M_D = 1$. Figure 2 shows that the proposed combiner outperforms the conventional LLR-level combiner. At $K = 2$, if the selected node is the DF relay, the *virtual antenna* based combiner outperforms the LLR-level combiner by 3dB, at 10^{-2} BLER. This gap becomes more than 4dB, if the selected node is the AF relay. If the cooperative system makes use of the two relay nodes, i.e. $K = 3$, the *virtual antenna* concept based combining strategy offers a gain

⁴In LLR-level combining, turbo equalization is separately performed for each transmission, and right before SISO decoding, extrinsic LLRs are simply added together with those obtained at the last iteration of previous time slot.

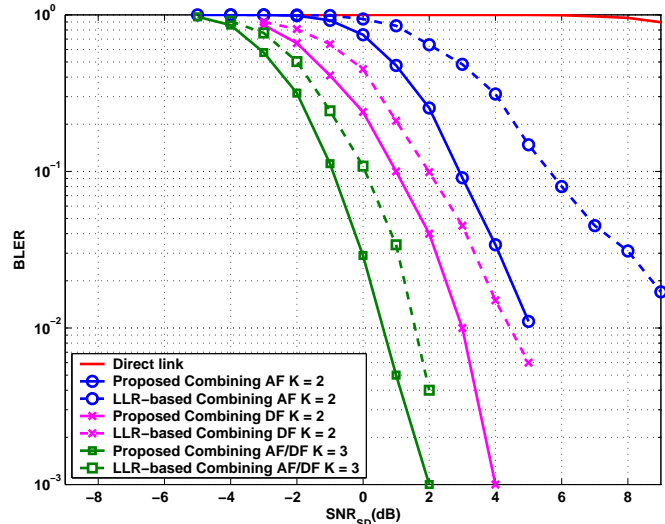


Figure 2. BLER performance for CC $(35, 23)_8$, QPSK, $M_S = M_R = 2$, $M_D = 1$, $L = 3$ equal energy paths, $l_{SR_2} = l_{SR_3} = 0.5$ and the path loss exponent $\kappa = 3$.

of 2dB over LLR-level combining strategy.

Now, we turn to the case where the source node and relay nodes are equipped with three antennas, i.e., $M_S = M_{R_2} = M_{R_3} = 3$. As the previous case, the destination node is still equipped with only one receive antenna, i.e., $M_D = 1$. For this configuration, the proposed scheme offers higher diversity order than LLR-level combining. In Figure 3, we observe that the LLR-level combining curves tend to saturate for high SNR_{SD} values, while *virtual antenna* based combiner has better steeper slopes of BLER curves at $K = 2$ and $K = 3$. This means that the proposed turbo combining has higher intersymbol interference (ISI) cancellation capability than LLR-level combining. This result is due to the fact that in *virtual antenna* based combining, each time slot is considered as a set of virtual M_D receive antennas. This allows the temporal diversity to be efficiently exploited. Moreover, for the proposed combiner, the two-relay system clearly outperforms the one-relay system, i.e the gap is more than 6dB.

In Figure 4, we compare the throughput performances of two-relay cooperative system and one-relay cooperative system. We consider an overloaded system where $M_S = M_{R_2} = M_{R_3} = 3$ and $M_D = 1$. Note that in the region of low SNR, the proposed combiner saturates around 1.5bit/s/Hz. This is due to the fact that the most of the packets received during the first time slot are erroneous. Moreover, we observe that, if the cooperative system makes use of the two relay nodes, i.e. $K = 3$, the *virtual antenna* concept based combining strategy offers a gain of more than 3dB at $\eta = 1$ bit/s/Hz.

V. CONCLUSION

In this paper, we investigated an efficient turbo packet combining strategy for hybrid AF/DF relay-assisted systems operating over MIMO broadband channels. We proposed

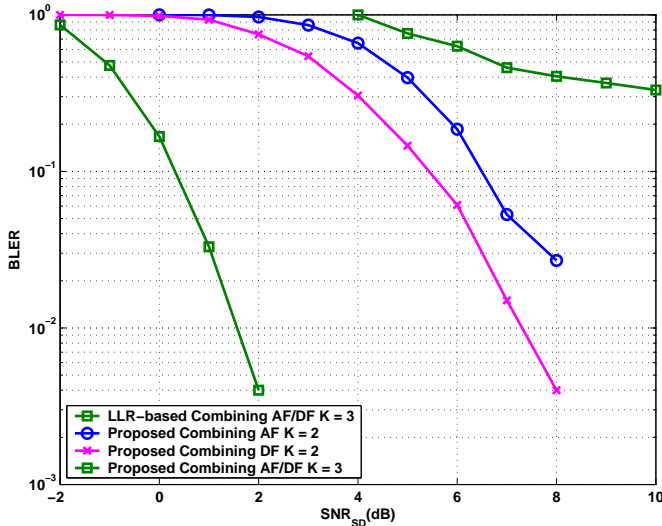


Figure 3. BLER performance for CC $(35, 23)_8$, QPSK, $M_S = M_R = 3$, $M_D = 1$, $L = 3$ equal energy paths, $l_{SR_2} = l_{SR_3} = 0.5$, and the path loss exponent $\kappa = 3$.

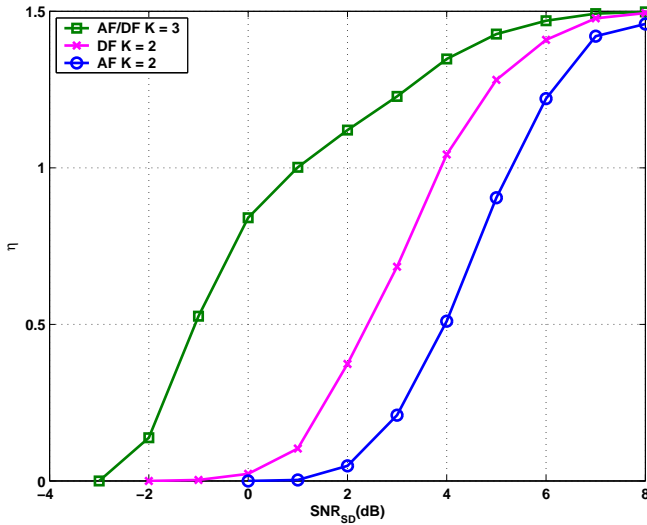


Figure 4. Throughput performance for CC $(35, 23)_8$, QPSK, $M_S = M_R = 3$, $M_D = 1$, $L = 3$ equal energy paths, $l_{SR_2} = l_{SR_3} = 0.5$, and the path loss exponent $\kappa = 3$. Spectrum efficiency=3bit/s/Hz.

an appropriate communication model in order to mask the cooperation and simplify the application of *virtual antenna* based combining. Using simulations, we demonstrated the gain offered by the studied turbo packet combiner.

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