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Abstract—In this paper we exploit the benefits of the diversity gains arising from a cluster of opportunistic relays (OR) and from the independently fading subcarriers of multiple users. Our goal is to improve the energy-efficiency of the OR assisted single-carrier frequency-division multiple-access (SC-FDMA) uplink using amplify-and-forward (AF), where the direct transmission (DT) link is unavailable. By assuming that the pilot aided channel quality information (CQI) of all the users may be exchanged amongst the cooperating relays, we propose two joint dynamic resource allocation (DRA) schemes based on the so-called ‘first-hop quality awareness’. Our results demonstrate that compared to the DT benchmark, the proposed joint DRA schemes are capable of achieving a power reduction of 10dB for a single-antenna base station (BS) receiver, albeit for a multi-antenna BS the power-reduction remains more modest.

I. INTRODUCTION

Relay-assisted wireless communications have been explored for the sake of improving the attainable spectral-efficiency or energy-efficiency of classic direct transmissions (DT). Naturally, the availability of inactive mobiles as candidate relays has the potential of mitigating the effects of fading. The activation of multiple relays results in cooperative diversity, and when dynamically reassigning the relays based on their location and/or channel quality, we arrive at the concept of opportunistic relaying (OR) [1].

Furthermore, orthogonal frequency-division multiplexing (OFDM) style broadband systems, such as single-carrier frequency-division multiple-access (SC-FDMA) scheme and orthogonal FDMA (OFDMA), conveniently facilitate near-instantaneous adaptive subband/subcarrier allocation and multiuser (MU) scheduling, depending on the channel state information (CSI) of the subbands/subcarriers [2], when communicating over frequency-selective fading channels. Clearly, directly adopting the conventional OR concept of [1] to OFDM based systems at the OFDM-symbol level is not feasible to exploit the different channel conditions of the different subcarriers or of the different relays. Since relay-assisted single-user (SU) OFDM transmissions are subjected to two-hop fading channels, dynamically rearranging the subcarriers at multiple relays may offer some additional diversity gains by appropriately pairing the subcarriers of the two hops [3].

Although both the dynamic relay selection (DRS) [4]–[6] and dynamic subband/subcarrier allocation (DSA) techniques [2] are capable of providing a power gain, conventional dynamic resource allocation (DRA) aided OR may be incapable of exploiting both. The main reason is that the two hops of the relay channel limit the capacity to that of the lower-capacity link of the two hops. In the context of OR assisted SC-FDMA systems, the relays limit the attainable MU performance, depending on the quality of the first-hop. The consideration of the received signal at multiple relays is capable of further improving the performance of DRA aided OR systems.

In this paper, we propose joint DRA strategies designed for the OR assisted SC-FDMA uplink, where the ORs invokes the subband-based AF protocol [7] and the DT link is unavailable. We assume that the multiple relays are capable of exchanging the pilot aided channel quality information (CQI) of all the users, facilitating the cooperation at the relays in order to carry out joint DRA. Two types of first-hop quality aware joint DRA algorithms are investigated, depending on, whether the S-R or the R-D channel quality dominates the attainable performance, when the system invokes either single or multiple antennas at the BS receiver. Additionally, the BS’s receiver of uncoded system employs the so-called multi-stage minimum mean-square error (MS-MMSE) criterion based frequency-domain decision-feedback equaliser (FD-DFE) relying on the principles of successive interference cancellation (SIC) [8], [9].

II. SYSTEM MODEL

A. Scope and Assumptions

Fig. 1 illustrates the topology of the OR assisted system model. The OR assisted SC-FDMA system considered supports the $K$ uplink users of the set $K$ referred to as the
source MTs of a traffic cell. The idle terminals located in each other’s vicinity are members of the set \( \mathcal{J} \), which may act as a cluster of the relays. We assume that, these relays of a cluster are located midway between the source MT and the destination BS, hence they are assumed to experience an identical pass-loss of \( G_{SR} = G_{BD} = 0.5^{-4} \). On one hand, each source MT, such as the \( k \)-th user’s, is dynamically assigned to a single selected relay of say \( j_k \), i.e. we have \( \bigcap_{k \in \mathcal{K}} \mathcal{J}_k = \emptyset \), \( \forall j_k \in \mathcal{J}_k \), where \( \mathcal{J}_k \) represents the best relay set of user \( k \). On the other hand, each relay is capable of forwarding up to \( K \) users’ signals at a time, so that the \( j \)-th relay may serve the specific users hosed by the paired set \( \mathcal{K}_j \). We note that no relays are involved in the data transmission process, when the set of eligible relays is empty, i.e. we have \( \mathcal{K}_j = \emptyset \). Therefore, we define all the selected relays in the set \( \mathcal{J} \), \( \forall j \in \mathcal{J} \), according to \( \mathcal{J} = \bigcup_{k \in \mathcal{K}} \mathcal{J}_k \), \( \mathcal{J} \subseteq \mathcal{J} \), s.t.: \( \mathcal{K}_j \neq \emptyset \).

### B. Transmitted Signal

According to [10], in the so-called discrete Fourier transform (DFT) spread OFDMA transmitter [11], the symbol vector is transformed by an \( N \)-point DFT from the TD to the FD, yielding \( \mathbf{x}_k^{\mathcal{S}} = \mathbf{F}_N \mathbf{x}_k^{\mathcal{S}} \), where \( \mathbf{F}_N \) denormalised the normalised \( N \)-point fast Fourier transform (FFT) matrix. The \( k \)-th user’s resultant symbols are then mapped to the most appropriate \( N \) subbands selected from the entire set of \( U = (M \times N) \) subbands with the aid of the matrix \( \mathbf{P}_k^s \) at the source MT. We refer to this operation as subband mapping. Additionally, the resultant \( U \)-element FD symbol vector is transformed to the TD by the \( U \)-point IDFT operation, which is similar to the action of the OFDM transmitter [12]. Hence, the \( U \)-symbol baseband-equivalent discrete-time signal \( \mathbf{s}_k^{\mathcal{S}} \) transmitted by the \( k \)-th source MT before inserting the cyclic-prefix (CP) may be expressed as [5], [6]

\[
\mathbf{s}_k^{\mathcal{S}} = \sqrt{\frac{P}{N}} \mathbf{F}_U^H \mathbf{P}_k^s \mathbf{F}_N \mathbf{x}_k^{\mathcal{S}},
\]

(1)

where the superscript \(^1\) refers to the TD signal. We assume that the source and relay share the unity transmit power equally, i.e. we have \( I_k^u = P_k^u = 0.5 \), while \( \mathbf{F}_U^H \) denotes the normalised \( U \)-point inverted fast Fourier transform (IFFT) matrix [10].

Additionally, the channel coded SC-FDMA transmitter adopted the bit-interleaved coded modulation (BICM) [13] structure of Figure 2. Specifically, at the \( k \)-th source MT, the \( N_0 \)-length binary source data stream \( b_k^n \) is initialized by an outer channel code, such as a recursive systematic convolutional (RSC) code or a turbo code, having a coding rate of \( R_c \). Then the outer encoded bit stream \( c_k^n \) of Figure 2 is interleaved by a \( N_0 \)-length random bit-wise interleaver \( \pi_S \) and its output bit stream \( b_k^n = [(b_k_0^n)^T, (b_k_1^n)^T, \cdots, (b_k_((N_0-1))^T)^T \) is fed into the \( 2^Q \)-ary quadrature amplitude modulation (QAM) mapper transmitting \( Q \) bits per symbol, where we have \( N_c = N_c \). Hence we partition the \( N_c \)-length bit sequence \( b_k^n \) of Figure 2 into \( N_c \) segments \( b_k_{n,n} \), each having a length of \( Q \) for \( n_s = 0, 1, \cdots, N_c-1 \). Moreover, the \( N_c \)-length modulated symbol sequence of Figure 2 is then converted to \( N_c \) symbol vectors \( \mathbf{x}_k^{\mathcal{S}}[n_s] \), \( \forall n_s = 0, 1, \cdots, N_c-1 \), in which each vector \( \mathbf{x}_k^{\mathcal{S}}[n_s] \) is constituted by a SC-FDMA symbol, which contains \( N \) consecutive modulated symbol elements \( x_{k,n}^{\mathcal{S}} \) in the TD, \( (n = 0, 1, \cdots, N-1) \).

Let us now consider the transmitted signals of the relays. We assume that the transmitter of the SC-FDMA relay is identical to that of the source MT. Before inserting the CP at the \( j \)-th relay of the set \( \mathcal{J} \), the \( U \)-element TD transmitted signal \( \mathbf{s}_j^{\mathcal{R},t} \) containing the \( k_j \in \mathcal{K}_j \) source users’ data may be expressed as

\[
\mathbf{s}_j^{\mathcal{R},t} = \sum_{k \in \mathcal{K}} \rho_{k,j} \mathbf{s}_k^{\mathcal{S}} = \sum_{k_j \in \mathcal{K}_j} \mathbf{s}_{k_j}^{\mathcal{S}},
\]

(2)

where \( \rho_{k,j} \) is the S-R pairing factor of the \( k \)-th source and the \( j \)-th relay defined as follows: \( \rho_{k,j} = 1 \) if \( k = k_j, \ j = j \); otherwise \( \rho_{k,j} = 0 \). Hence, from the set of \( J \) relays, only the relays \( j \) selected for the set \( \mathcal{J} \) forward the source data of user \( k_j \) in the set \( \mathcal{K}_j \), while the remaining candidate relays are not allowed to transmit.

### C. Localised Subband Mapping invoking Subband Allocation

In the context of the SC-FDMA system considered, the so-called localised subband mapping mode [11] allows each user’s SC-FDMA symbols to be mapped to \( N \) consecutive subbands in the entire set of \( U \) subbands, as detailed below. When the CSI of each user’s signal is available at the transmitter (CSIT), the DSA allows the localised subbands to be allocated dynamically on a group-by-group basis based on some criterion, depending on the CQI of different users. To elaborate a little further, the subband allocation philosophy of our system is based on the localised subband mapping defined as \( \mathcal{P}^{(k)}_{m,(u,n)} = 1 \) if \( u = mN + n \), otherwise \( \mathcal{P}^{(k)}_{m,(u,n)} = 0 \), for \( m = 0, 1, \cdots, M-1 \), \( n = 0, 1, \cdots, N-1 \) and \( u = 0, 1, \cdots, U-1 \), where \( \mathcal{P}^{(k)}_{m,(u,n)} \) is the \( (u,n) \)-th entry of \( \mathbf{P}_k^s \) and \( m \in M \) refers to the index of the individual spectral blocks. Each block consists \( N \) consecutive subbands in the so-called subband group defined for resource allocation. Additionally, we define the static subband allocation (SSA) regime as having \( m = k \), which is the conventional localised subband mapping scheme adopted in both our source MT’s transmitter and in the relay’s receiver. Furthermore, \( m \neq k \) refers to the DSA supported by our relay’s transmitter and the BS’s receiver. We will detail the DSA in Section III.

### III. Dynamic Resource Allocation of Opportunistic Relay

In the OR channels we considered, both the spatial- and spectral-domain resources offered by multiple relays may be explored for the sake of power reduction. In order to achieving a selection diversity gain, the DRS allows each user to benefit from exploring \( J \) different S-R channels and \( J \) R-D channels. The corresponding complex-valued fading envelope may be
deemed to be independent and identically distributed (i.i.d) for each of these links of the resultant virtual MIMO scheme. Furthermore, the DSA beneficially rearranges the MU’s signals for transmission over the most appropriate subband groups for second-hop relaying. Additionally, experiencing frequency-selective fading in the DRA assisted OR scheme may provide an additional MU diversity gain for the system.

Since the $N$ subbands of each user are grouped together within a resource block for relaying, we use the average S-R channel attenuation of the $N$ subbands of the $k$-th user’s signal received by the $j$-th relay for quantifying the corresponding channel quality, which may be expressed as

$$g_{SR,j}^k = \frac{1}{N} \sum_{n=0}^{N-1} |h_{SR,j,n}^k|^2.$$  

(3)

We also assume that the BS invokes $N_f$ receiver antennas, where the sum of channel attenuations averaged over multiple antennas may be considered as a relevant quality metric for the overall channel effects. The average attenuation of the $m$-th group of $N$ subbands in the channel spanning from the $j$-th relay to the BS is given by

$$g_{RD,j,m}^k = \frac{1}{N} \sum_{u=0}^{N-1} \sum_{n=0}^{N-1} |h_{RD,j,n}^u|^2.$$  

(4)

A. Static/Dynamic Subband Allocation Combined with Dynamic Relay Selection

Each user’s RB occupies a subband group in the FD and a time slot in the TD. When the relay allocates the same subbands for forwarding the $k$-th user’s signal as the one that was used for receiving over the S-R link, we referred to this scenario as static subband allocation (SSA). By assuming that the localised subband mapping regime is adopted for S-R transmissions, the $m$-th subband group may be allocated to the $k$-th user’s signal, when we have $m = k$, which is transmitted by the specific relay having the index of $j_m$ in the context of OR. We refer to this scenario as SSA for OR and describe it in detail below:

- **Second-Hop DRS:** Apart from random relay selection (RRS), the DRS philosophy may be invoked, which provides the maximum R-D gain of $g_{RD,j,m}^k$ amongst all the $m$-th subband groups of the other relays, i.e. we have

$$j_m = \arg\max_{j \in J} \{g_{RD,j,m}^k\}$$  

s. t. : $m = k, m \in \mathcal{M}, k \in K.$  

(5)

- Additionally, the initial set of desired relays is empty, i.e. we have $\mathcal{J} = \emptyset$. Then at the $m$-th subband group, for $m \in \mathcal{M}$, $m = 0,1,\ldots, M-1$, we update the set $\mathcal{J}$ by incorporating the relay having the index $j_m$, which is formulated as $\mathcal{J} = \mathcal{J} \cup \{j_m\}$. On the other hand, the original DSA concept invoked for a single-relay system may attain a diversity gain in the FD. In parallel, the conventional combination of DSA and DRS allows the multiple users’ received signals to be adaptively transmitted in the most appropriate subband groups at dynamically selected relays, by taking into account the $(M \times J)$ possible subband groups of the $J$ relays. Therefore, we now detail the procedure as follows:

- **Second-Hop DSA:** After we carry out the above-mentioned DRS procedure, we then initialise the ordered set of desired subband groups $\mathcal{M}$ to be empty, i.e. we have $\mathcal{M} = \emptyset$. The $i$-th desired subband group $\tilde{m}_i$ in set $\mathcal{M}$ having the highest R-D channel gain can be obtained by maximising the R-D channel gain $g_{RD,j,m}$ among all the $M$ groups from the relays in set $\mathcal{J}$. Hence, we arrive at

$$\tilde{m}_i = \arg\max_{m \in \mathcal{M}} \{g_{RD,j,m}^k\}, \quad \mathcal{M} = \mathcal{M} \cup \{\tilde{m}_i\}.$$  

(6)

- In order to guarantee for all users to be fairly treated and supported, the Therefore, the $i$-th user’s assignment of subband group $\tilde{m}_i$ and relay $j_{\tilde{m}_i}$, are randomly assigned to each user within each time slot.

B. First-Hop-Quality-Aware Joint Dynamic Resource Allocation

Although the conventional DRA achieves a diversity gain with the aid of beneficial subband allocation and relay selection, the grade-of-freedom associated with beneficially allocating MU’s signals across the entire set of $(M \times J)$ subband groups of the $J$ relays has not been fully exploited. The MU’s signals received and forwarded by the AF relays may result in error-propagation at the BS, due to the first-hop transmissions in terms of the S-R CQI. This phenomenon motivates us to design and investigate the first-hop-quality-aware joint DRA schemes conceived for OR assisted SC-FDMA. We assume that the CSI$s$ of the $K$ S-R links and of the $(M \times J \times N_t)$ R-D links are estimated perfectly at each relay’s receiver. We also assume that these cooperating relays are capable of exchanging their pilot CQI.

1) Joint DRA Approach-1: The first joint DRA approach, denoted as JDRA-1, optimises the conventional DRA scheme by allocating the RBs having the highest channel gain for the R-D links to the appropriate users, which are stored in an ordered user set at each relay in terms of their first-hop CQI. We assume that each relay stores and labels a sorted CQI set of the $M \times J \times N_t$.

To elaborate a little further, we describe the associated procedures step by step as follows:

- **Second-Hop DRS and DSA:** Initially, we adopt the second-hop DSA combined with DRS as detailed in Subsection III-A.

- **First-Hop Consideration:** Furthermore, by maximising $g_{SR,j,k}^s$ for the $j$-th relay among all users, we obtain the $i$-th ordered user index ($i = 0, 1, \ldots, K-1$) as the $i$-th element in the set $\hat{K}_j$ at the $j$-th relay, which is given by

$$\hat{k}_{i,j} = \arg\max_{k \in K} \{g_{SR,j,k}^s\}, \quad \hat{K}_j = \hat{K}_j \cup \{\hat{k}_{i,j}\}.$$  

(7)

- **User Assignment:** Finally, we assign the RB at subband group $\hat{m}_i$ of relay $j_{\hat{m}_i}$ to the $i$-th user $\hat{k}_{i,j_{\hat{m}_i}}$. 

2) Joint DRA Approach-2: The best first-hop channel quality may be determined form either the user’s or the relay’s perspective. This distinction leads to the definition of our joint DRA Approach-2, denoted as JDRA-2. More specifically, rather than finding the best link of a specific user to a relay in Approach-2, we find the specific user, which can be supported by a specific relay with the best possible channel quality. The relay selection and user assignment of Approach-2 are based on the first-hop quality, while those of Approach-1 are dependent on the second-hop quality. By contrast, both joint DRA schemes allocate the subband groups based on the second-hop channel gains. Let us now highlight the associated scheme in more detail below.

- First-Hop DRS: By maximising the S-R channel gain $g_{k,j}^{SR}$ over all relays in the set $\mathcal{J}$ for the $k$-th user, the best relays and the corresponding channel gains can be stored in the sets $\mathcal{J}$ and $G_{SR}$, which are formulated as:

$$
\mathcal{J} = \arg \max_{j \in J} \{ g_{k,j}^{SR} \},
$$

$$
G_{SR} = G_{SR}^{j} \cup \{ g_{k,j}^{SR} \}. 
$$

- First-Hop Consideration: Furthermore, we have the ordered user set $K$ based on the first-hop channel gains in the set $G_{SR}$ at the best relays in $\mathcal{J}$. Specifically, we obtain the $i$-th element in $\mathcal{K}_i$ ($i = 0, 1, \ldots, K - 1$), by seeking the maximum S-R channel gain $g_{\hat{k},j}^{SR}$ among the channels spanning between all the $K$ users and the specific relays in the set $\mathcal{J}$, which is expressed as:

$$
\hat{k}_i = \arg \max_{k \in K, j \in J} \{ g_{k,j}^{SR} \}. 
$$

Second-Hop DSA: After that, the $i$-th user’s signal is transmitted to the best relay $j_{\hat{k}}$ to the $k_{\hat{k}}$-th user’s signal for transmission from this relay to the BS.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, the performance achieved by the various resource allocation schemes relying on AF aided OR assisted SC-FDMA is characterised. We assume that both the S-R and S-D channels experience frequency-selective Rayleigh fading and benefit from perfect power-control, which eliminates the effects of shadowing. The knowledge of the S-D channel is unavailable. The normalised pathloss of the S-R and S-D links are given by $G_{SR} = G_{RD} = 0.5^{-4}$.

Fig. 3 depicts the performance of the AF aided OR assisted SC-FDMA uplink system of Fig. 1 upon varying the resource allocation schemes compared to its DT benchmark, for $N_r = 1$ and 8 at the BS. Gray mapped 4-QAM and no channel coding is used. The system employ the MS-MMSE FD-DFE (SIC) aided receiver, which was originally applied for MU detection in both CDMA and SDMA systems [8]. The SIC-ordering is based on quantifying the reliabilities of the detected symbols relying on the maximum a-posteriori probability criterion, rather than simply using the SINR.

Specifically, when a simple single-stage MMSE receiver is invoked, the FD-DFE receiver degenerates to the classic single-tap MMSE frequency-domain linear equaliser (FD-LE) and its performance is characterised in Fig. 3(a), while the performance of the MS-MMSE FD-DFE (SIC) scheme is characterised in Fig. 3(b). When the number of dispersive paths is $L = 4$, the system suffers from residual ISI, which cannot be entirely eliminated by a classic FD-LE receiver. By observing Fig. 3(b) and 3(a), we infer that the proposed MS-MMSE FD-DFE enhances the OR system’s performance by up to 5dB at the BER of $10^{-4}$ compared to the conventional MMSE FD-LE.

Furthermore, when the MU system operates at full user load, i.e. we have $K = M$, the DRS-SSA achieves the same performance as the DRS-DSA arrangement combined with DRS. By invoking a single-antenna BS receiver, the DRS-SSA and DRS-DSA schemes attain a prover gain of about 2.5dB over the RRS benchmark at a BER of $10^{-4}$, while both of our proposed joint DRA schemes perform similarly and attain an approximately 2.5dB additional power gain compared to the DRS-SSA and DRS-DSA scheme.

By contrast, in the multiple-antenna BS invoked in our system offers receive diversity gains while the achievable selection diversity gain of using $J$ R-D channels is reduced when summing an increased number of $N_r$ independent channel attenuations. As a result, the conventional DRS-SSA and DRS-DSA schemes have more-or-less the same performance as the RRS-SSA, which implies that the gain gleaned from selection diversity over R-D channels cannot be simply attained in the multiple-antenna scenario. However, the proposed joint DRA methods are capable of achieving an additional gain by rearranging the resources at the ORs by appropriately exploiting the S-R link quality. Importantly, by invoking the joint DRA-2, the first-hop quality becomes the dominant factor in determining the achievable performance benefits of exchanging CQI between the cooperating relays. At a BER of $10^{-4}$, we note that JDRA-2 and JDRA-1 attain gains of 1-4dB and 3dB compared to their conventional counterparts, respectively.

Additionally, Fig. 4 characterises the AF aided OR assisted system using a half-rate RSC coded Set-Partition (SP) mapped 4-QAM [13]. The system employs a classic MMSE FD-LE with the aid of channel decoding, where ’0-iteration’ refers to the classic non-iterative receiver in Figure 4. Note that, in the BICM SC-FDMA system using $N_r = 8$, JDRA-2 scheme offers an additional 3dB gain over JDRA-1 approach and also saves up to 2dB transmit power compared to the DT benchmark.

Finally, Fig. 5(a) and Fig. 5(b) characterise the impact of the number of source users $K$ and that of the number of candidate relays $J$ involved in the various resource allocation schemes on the achievable BER performance of AF aided OR assisted uncoded systems, respectively. Since the design of JDRA-1 was further developed from the DRS-DSA by invoking user ordering based on their first-hop quality, its SU
BER performance of Fig. 5(a) remains the same as that of DRS-DSA, but its BER performance was better than that of DRS-DSA, when the MU system operated at its full user load. In contrast to JDRA-1, the JDRA-2 scheme guarantees that the best relay is assigned to each user before DSA, hence providing a better performance than the conventional schemes, when increasing $J$.

V. CONCLUSIONS

In this contribution we have proposed two novel joint DRA schemes for the OR assisted SC-FDMA uplink. The MS-MMSE FD-DFE (SIC) receiver enhances the OR assisted SC-FDMA uplink. The MS-MMSE FD-DFE (SIC) receiver invokes the classic MMSE FD-LE and a RSC decoder.

REFERENCES


SC-FDMA AF OR ($N_r=1$, $N=12$, $M=6$, $L=4$)

(a) Effects of the number of source users $K$ at $E_b/N_0 = 3\text{dB}$

(b) Effects of the number of candidate relays $J$ at $E_b/N_0 = 12\text{dB}$

Fig. 5. BER performance of the AF aided OR assisted uncoded SC-FDMA uplink upon varying the various resource allocation schemes, where the single-antenna BS’s receiver invokes the MS-MMSE FD-DFE.


