Power-Efficient Opportunistic Amplify-and-Forward Single-Relay Aided Multi-User SC-FDMA Uplink

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***Abstract*—[1] In this contribution we exploit the benefits of combining the diversity gains arising from cooperation, multiple propagation paths and from the opportunistic scheduling of multiple users, for the sake of supporting a power-efficient single-relay assisted single-carrier frequency-division multiple-access uplink, where each relay supports a single user communicating over dispersive channels subject to large-scale fading. Based on the proposed joint frequency-domain equalisation and diversity combining aided receiver relying on the minimum mean-square error criterion, two different relay selection schemes designed for single-user and multi-user scenarios are investigated, which employ imperfect power control. Our results show that at a bit error ratio of 10^{-4}, the proposed receiver is capable of saving 2dB power by achieving a higher cooperative diversity gain than the conventional receiver. Moreover, an approximately 6.8dB and 8dB transmit power reduction are attainable by invoking the proposed selective diversity oriented single-user and multi-user relay selection schemes, respectively. Most importantly, a power-efficiency improvement is gleaned from our multi-user relay selection scheme, which avoids the effects of deep shadowing and provides 9.7dB power reduction compared to the non-cooperation scenario.**

I. Introduction

Cooperative communication [1] systems have attracted the attention of both academia and industry in recent years, since they are capable of achieving a diversity gain in *large-scale fading* environments by sharing the resources of the cooperating user terminals. This allows us to jointly exploity the benefits of both *time-* and *frequency-diversity* for the sake of mitigating the deleterious effects of wireless propagation and/or for increasing the attainable system throughput [2], [3]. Recently, the family of *cooperative diversity* oriented *Multiple-Access* (MA) techniques has been invoked in order to design the *uplink* of advanced cooperative cellular networks [4]–[6]. Furthermore, the cooperative concepts have been extended to broadband systems by designing techniques for mitigating the effects of *frequency-selective fading* with the aid of *Multi-Carrier* (MC) techniques associated with appropriate *source/relay power sharing* [7], [8]. From a *Multi-User* (MU) network point of view, the cooperative link sharing from the *source Mobile Terminals* (MT) to the *Base Station* (BS) can be determined by choosing the single or multiple *relays* from a cluster of idle MTs. Therefore, *Opportunistic Relaying* (OR) is capable of exploiting the benefits of what we refer to as *multi-user diversity* owning from appropriate *relay selection* [9]–[12].

The *Single-Carrier Frequency-Domain Multiple-Access* (SC-FDMA) technique [13], [14] was adopted for the uplink of the *3-rd Generation Partnership Project*'s (3GPP) *Long Term Evolutio*n (LTE) standard [15]. SC-FDMA was shown to be capable of avoiding the *Multi-User Interference* (MUI) imposed by the *cooperative sources* and *relays* upon the uplink receiver of the BS, while maintaining a low *Peak-to-Average Power Ratio* (PAPR). The *subband-based Frequency-Domain* (FD) *Amplify-and-Forward* (AF) *single-relay* assisted SC-FDMA uplink scheme was proposed in [16] for both *Single-Dedicated-Relaying* (SDR) with each dedicated relay aiding a single user and for *Single-Shared-Relaying* (SSR) with a single shared relay aiding all the active users. By inheriting the features of the SC-FDMA system invoking a *Discrete Fourier Transform* (DFT) spread *Orthogonal Frequency-Division Multiplexin*g (OFDM) [17] style transmitter, this FD-AF scheme carries out so-called *subband remapping* [16] at the relay in order to remove the effects of both noise and interference inflicted by other relays without changing the frequency band of the signals transmitted from the source MT. However, since the *Minimum Mean-Square Error* (MMSE) assisted FDE operates in the *direct* and *relaying branches* individually, followed by a *Time-Domain* (TD) *Equal-Gain Combiner* (EGC) [18], the systems obtain only a limited *cooperative diversity gain*. Since *power control* never performs perfectly in realistic wireless uplink transmissions, the source/relay power sharing of both the source MT and the relay imposes a time-varying level of *Power Control Error* (PCE) [19].

Therefore, we propose a *Joint Frequency-Domain Equalisation and Combining* (JFDEC) scheme, which provides a joint optimal FDE and *diversity combiner* solution based on the MMSE criterion applied at the BS of the above-mentioned cooperative SC-FDMA arrangement. The *Single-User* and *Multi-User Relay Selection* (SU-/MU-RS) schemes based on the proposed JFDEC solution are investigated in the context of the SDR topology in a large-scale fading scenario, where the effects of *imperfect power control*[2] are also quantified. Our results show that the proposed JFDEC approach outperforms the original FDE-EGC solution of [16] as a benefit of the increased cooperative diversity gain, which retained even in the absence of *multi-path diversity*. Additionally, when encountering a realistic propagation *path-loss* and *shadowing*, a significant *relaying gain* and *multi-user diversity gain* are attainable by the proposed SU-RS and MU-RS schemes, respectively, in terms of the required *Signal-to-Interference-plus-Noise Ratio* (SINR).

II. Relay Assisted SC-FDMA System Model

A. Transmitted Signal of Source MT

The relay-assisted SC-FDMA system considered supports K uplink users referred to as the source MTs in a cell. There are also idle terminals, which can be chosen as the relays. The U-symbol baseband equivalent discrete-time signal transmitted by the k-th source MT before inserting the *cyclic-prefix* (CP) can be expressed as [16].

$$\boldsymbol{s}_{S,k}^{(t)} = \sqrt{P_{St,k}}\boldsymbol{\mathcal{F}}_U^H\boldsymbol{\mathcal{P}}_k\boldsymbol{\mathcal{F}}_N\boldsymbol{x}_k^{(t)}, \tag{1}$$

where the superscript $^{(t)}$ refers to the TD signal, $\boldsymbol{\mathcal{F}}_U$ and $\boldsymbol{\mathcal{F}}_N$ denote the normalised U-point and N-point *Fast Fourier Transform* (FFT) matrices, respectively, $\boldsymbol{\mathcal{P}}_k$ represents the mapping of the k-th user's symbols to the appropriate subband, which may be termed as *subband*

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[2]Power control errors are imposed on the MT's transmit power due to feedback delay and estimation error at the BS.

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mapping, while $\boldsymbol{x}_k^{(t)}$ denotes the N-symbol original information packet of the k-th user. Finally, $P_{St,k}$ is the source MT's transmitted power determined by the power allocation and subjected to a power control error as it will be discussed in Subsection II-B.

B. Channel Modelling and Assumptions

For the sake of simplicity, we assume that the source MTs, relays and BS are all located in a line, and the relays roam between the source and *destination*. Let us assume that the length of the S-D link is the reference distance in the propagation model having a *path-loss exponent* η [18]. Then, the *instantaneous path-loss* values of the *relay channels*, denoted by G_{SR} and G_{RD}, respectively, become the corresponding relaying gains, which incorporate the effects of the *average path-loss* combined with shadowing. Specifically, the average path-losses of the S-R and R-D links are denoted by $\delta_{SR}^{-\eta}$ and $\delta_{RD}^{-\eta}$, respectively, where $\delta_{SR} + \delta_{RD} = 1$, and δ_{SR} and δ_{RD} are the distance normalised by the S-D distance. The shadowing component is characterised by the *log-normal* distribution associated with a *zero mean* and a *standard deviation* of σ_ξ, i.e. we have $\xi(dB) \sim \mathcal{N}(0, \sigma_\xi^2)$. Therefore, we can write $G_{SR} = \xi_{SR}\delta_{SR}^{-\eta}$, $G_{RD} = \xi_{RD}\delta_{RD}^{-\eta}$, while the shadowing effect at the S-D link is denoted by ξ_{SD}.

Note that in a *small-scale* scenario, we assume that the systems are experiencing *frequency-selective fading* associated with L paths, and that *perfect Channel State Information* (CSI) is available for both the relays and BS, including the path-loss, shadowing and *fast fading*.

Furthermore, in order to guarantee a fair comparison between the *cooperative* and *non-cooperative* systems, the total signal power P_t of each user is normalised to *unity*. Specifically, the source and relay MT's transmit power assigned to the k-th user are quantified as $P_{St,k} = \epsilon_{S,k}\alpha_{S,k}P_t$ and $P_{Rt,k} = \epsilon_{R,k}\alpha_{R,k}P_t$, respectively. The imperfect power control effects imposed on the transmitted power of the MTs can be evaluated by modelling it using the classic log-normal distributed power control error having a standard deviation of σ_ϵ in dB, i.e. $\epsilon(dB) \sim \mathcal{N}(0, \sigma_\epsilon^2)$ [19]. Additionally, we quantify the *power sharing* of the source and relay as $\alpha_{S,k} + \alpha_{R,k} = 1$.

C. Relay Models

In order to separate multiple users in the FD and hence to avoid the MUI, each source MT is assigned a *single relay* by the BS according to the opportunistic relaying mechanism to be detailed in our forthcoming discourse in Section IV. We assume that the cooperation is *half-duplex time-division* based, hence during the *first time-slot* (TS_1) all the K source MTs *broadcast* their messages represented by $\boldsymbol{s}_{S,k}, (k = 0, 1, \cdots, K-1)$, which are received by both the relays and the BS via the *Source-to-Relay* (S-R) and *Source-to-Destination* (S-D) links, respectively. During the *second time-slot* (TS_2) which is the *cooperation-phase*, the relays only forward the signals from the dedicated source MT to the BS via the *Relay-to-Destination* (R-D) links, implying that a total of K relays are required. The signal received by the k'-th relay as well as by the BS during TS_1 and TS_2, respectively, are expressed by the U-length vectors of

$$\boldsymbol{r}_{SR,k'}^{(t)} = \sqrt{G_{SR}} \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{SR,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{R,k}^{(t)}, \tag{2}$$

$$\boldsymbol{r}_{RD}^{(t)} = \sqrt{G_{RD}} \sum_{k'=0}^{K-1} \tilde{\boldsymbol{H}}_{RD,k'}^{(t)} \boldsymbol{s}_{R,k'}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}, \tag{3}$$

where $\tilde{\boldsymbol{H}}_{SR,k}^{(t)}$ and $\tilde{\boldsymbol{H}}_{RD,k'}^{(t)}$ host the $(U \times U)$ TD channel coefficient matrices of the S-R and R-D links for the k-th and k'-th source MT's signals, respectively, while $\tilde{\boldsymbol{n}}_{R,k}^{(t)}$ and $\tilde{\boldsymbol{n}}_{D1}^{(t)}$ represent the U-length *complex-valued Additive White Gaussian Noise* (AWGN) vectors having a zero mean and a variance of σ_N^2 at each element, i.e. we have $\mathcal{CN}(0, \sigma_N^2)$ at both the k-th *relay* and the BS, respectively.

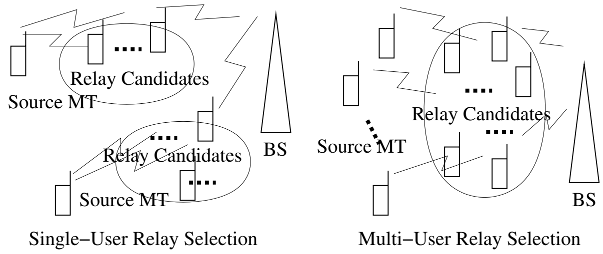

Fig. 1. Opportunistic Single-Relay aided SC-FDMA Uplink

By invoking the so-called *subband based* FD-AF scheme of [16], the relay's received TD signals are firstly transformed to the FD by the U-point DFT operation and then demapped to the apporpriate N subbands by $\boldsymbol{\mathcal{P}}_k^T$ which we refer to as *subband demapping* [13]. Each user's resultant signal is multipled by the $(N \times N)$-element diagonal matrix $\boldsymbol{\beta}_k^{(f)}$, where the n-th element is the specific *gain factor* of the n-th subband, yielding [16]

$$\beta_{kn}^{(f)} = \sqrt{P_{Rt,k}/[P_{St,k}G_{SR}|h_{SR,kn}^{(f)}|^2 + \sigma_N^2]}. \tag{4}$$

Then the relay's signal coorresponding to the k-th user is mapped to the subband corresponding to the k-th source MT. After that, the U-point IDFT operation is invoked to transform the signal to the FD, before it is transmitted to the BS. We refer to the joint subband mapping and demapping procedure as the subband remapping operation. Therefore, the relay's reception is free from interference, since neither the source MT nor the relay inflict interference during relaying. As an additional benefit, the noise in the other users' subband is also removed by the above-mentioned subband demapping process.

III. Signal Detection

A. Representation of Received Signal at the BS

After removing the CP, the U-point DFT of the TD signal to the FD and subband demapping at the BS receiver, the FD signals of the k-th user received via the *direct branch* during TS_1 and that via the *relay branch* during TS_2 can be expressed by the N-symbol vectors of $\boldsymbol{y}_{SD,k'}^{(f)} = \sqrt{P_{St,k'}\xi_{SD}}\boldsymbol{H}_{SD,k'}^{(f)}\boldsymbol{x}_{k'}^{(f)} + \boldsymbol{n}_{D0}^{(f)}$ and $\boldsymbol{y}_{RD,k'}^{(f)} = \sqrt{P_{St,k'}G_{RD}G_{SR}}\boldsymbol{H}_{RD,k'}^{(f)}\boldsymbol{\beta}_{k'}^{(f)}\boldsymbol{H}_{SR,k'}^{(f)}\boldsymbol{x}_{k'}^{(f)} + \bar{\boldsymbol{n}}_{D1}^{(f)}$, respectively, where $\boldsymbol{H}_{SD,k'}^{(f)}$, $\boldsymbol{H}_{SR,k'}^{(f)}$ and $\boldsymbol{H}_{RD,k'}^{(f)}$ are the $(N \times N)$-element equivalent diagonal FD channel matrices at the S-D, S-R and R-D links, respectively. Furthermore, $\boldsymbol{n}_{D0}^{(f)}$ and $\bar{\boldsymbol{n}}_{D1}^{(f)}$ represent the noise vectors having a length of N and represented by $\mathcal{CN}(0, \sigma_N^2)$, which are imposed at the BS during the two time-slots, respectively. We amalgamate the above two equations into a $2N$-length joint observation vector as

$$\boldsymbol{y}_{D,k'}^{(f)} = \sqrt{P_{St,k'}}\boldsymbol{H}_{D,k'}^{(f)}\boldsymbol{x}_{k'}^{(f)} + \boldsymbol{n}_D^{(f)}, \tag{5}$$

where the $(2N \times N)$-element joint equivalent FD channel matrix is given by $\boldsymbol{H}_{D,k'}^{(f)} = \left[(\boldsymbol{H}_{D0,k'}^{(f)})^T, (\boldsymbol{H}_{D1,k'}^{(f)})^T\right]^T$. Additionally, we formulate the n-th element of the diagonal matrices $\boldsymbol{H}_{D0,k'}^{(f)}$ and $\boldsymbol{H}_{D1,k'}^{(f)}$ as $h_{D0,k'n}^{(f)} = \sqrt{\xi_{SD}}h_{SD,k'n}^{(f)}$ and $h_{D1,k'n}^{(f)} = \beta_{k'n}^{(f)}\sqrt{G_{RD}G_{SR}}h_{RD,k'n}^{(f)}h_{SR,k'n}^{(f)}$. Similarly, the total received noise of the k'-th user at the BS includes the noise contribution imposed by the k'-th relay after the above-mentioned subband remapping operation plus that added at the BS during the two time slots, which is expressed by a $2N$-length vector as $\boldsymbol{n}_D^{(f)} = \left[(\boldsymbol{n}_{D0}^{(f)})^T, (\bar{\boldsymbol{n}}_{D1}^{(f)})^T\right]^T$, where the power of the noise components $\boldsymbol{n}_{D0}^{(f)}$ and $\bar{\boldsymbol{n}}_{D1}^{(f)}$ in the n-th subband can be expressed as $\mathcal{N}_{D0,n} = \sigma_N^2$ and $\mathcal{N}_{D1,n} = \sigma_N^2(\beta_{k'n}^{(f)})^2 G_{RD}|h_{RD,k'n}^{(f)}|^2 + \sigma_N^2$, respectively.

B. MMSE assisted Joint Frequency-Domain Equalisation and Combining

It can be readily shown based on Eq. (5) that the *optimum* MMSE solution is given by

$$\boldsymbol{W}_{D,k'} = \boldsymbol{R}_{yD,k'}^{-1}\boldsymbol{R}_{yxD,k'}, \tag{6}$$

where the *auto-correlation* matrix of $\boldsymbol{y}_{D,k'}^{(f)}$ is given by $\boldsymbol{R}_{yD,k'} = P_{St,k'}\boldsymbol{H}_{D,k'}^{(f)}(\boldsymbol{H}_{D,k'}^{(f)})^H + \boldsymbol{R}_{nD}$ with $\boldsymbol{R}_{nD}$ denoting the diagonal *covariance* matrix of $\boldsymbol{n}_D^{(f)}$, which is constituted by two $(N\times N)$-element diagonal matrices given by $\boldsymbol{R}_{nD0} = \sigma_N^2\boldsymbol{I}_N$ and $\boldsymbol{R}_{nD1} = \sigma_N^2[G_{RD}\boldsymbol{H}_{RD,k'}^{(f)}\boldsymbol{\beta}_{k'}^{(f)}(\boldsymbol{\beta}_{k'}^{(f)})^H(\boldsymbol{H}_{RD,k'}^{(f)})^H + \boldsymbol{I}_N]$. In Eq. (6), $\boldsymbol{R}_{yxD,k'}$ is the matrix of *cross-correlation* between $\boldsymbol{y}_{D,k'}^{(f)}$ and $\boldsymbol{x}_{S,k'}^{(f)}$, which can be expressed as $\boldsymbol{R}_{yxD,k'} = P_{St,k'}\boldsymbol{H}_{D,k'}^{(f)}$.

It is worth noting that $\boldsymbol{R}_{yD,k'}$ is an $(2N\times 2N)$-element non-diagonal matrix. Hence, the complexity of inverting $\boldsymbol{R}_{yD,k'}$ might be high. In order to implement the low complexity *single-tap* FDE and *diversity combining* jointly, the *matrix inversion lemma* of [13] can be invoked, yielding the $(2N\times N)$-element *optimum weight* matrix of the MMSE aided JFDEC scheme formulated as:

$$\boldsymbol{W}_{D,k'} = P_{St,k'}\boldsymbol{R}_{nD}^{-1}\boldsymbol{H}_{D,k'}^{(f)}[P_{St,k'}(\boldsymbol{H}_{D,k'}^{(f)})^H\boldsymbol{R}_{nD}^{-1}\boldsymbol{H}_{D,k'}^{(f)} + \boldsymbol{I}_N]^{-1}. \tag{7}$$

Consequently, it can be shown that the n-th and $(n+N)$-th element of $\boldsymbol{W}_{D,k'}$ can be expressed by

$$w_{D,k'n} = \frac{h_{D0,k'n}^{(f)}\omega_{k'n}}{\sigma_N^2}, \quad w_{D,k'(n+N)} = \frac{h_{D1,k'n}^{(f)}\omega_{k'n}}{\mathcal{N}_{D1,n}}, \tag{8}$$

where $\omega_{k'n} = \left(\frac{|h_{D0,k'n}^{(f)}|^2}{\sigma_N^2} + \frac{|h_{D1,k'n}^{(f)}|^2}{\mathcal{N}_{D1,n}} + P_{St,k'}^{-1}\right)^{-1}$. Correspondingly, the decision variable vector for $\boldsymbol{x}_{k'}^{(f)}$ is given by $\hat{\boldsymbol{y}}_{D,k'}^{(f)} = \boldsymbol{W}_{D,k'}^H\boldsymbol{y}_{D,k'}^{(f)}$.

It will be shown that, applying the weight matrix $\boldsymbol{W}_{D,k'}$ is capable of joint carrying out single-tap FDE and diversity combining of the direct and relay branches. Specifically, the coefficients $h_{D0,k'n}^{(f)}$ and $h_{D1,k'n}^{(f)}$ defined in Eq. (8) are used for single-tap FDE, while $\omega_{k'n}/\sigma_N^2$ and $\omega_{k'n}/\mathcal{N}_{D1,n}$ are employed for diversity combining in conjunction with *noise whitening* of the two branches, respectively.

Additionally, due to the averaging effects of the N-point IDFT operation, all the resultant TD symbols within the vector have the same MMSE value e that can be calculated as the average of the FD MMSE values over N subbands, yielding the MMSE of the JFDEC solution as

$$e_{k'} = \frac{P_{St,k'}}{N}\sum_{n=0}^{N-1}\left[\gamma_{SD,k'n} + \left(\frac{1}{\gamma_{SR,k'n}} + \frac{1}{\gamma_{RD,k'n}}\right)^{-1} + 1\right]^{-1}, \tag{9}$$

where the received SNRs of the direct and relaying branches in the n-th subband are expressed as

$$\gamma_{SD,k'n} = \frac{\xi_{SD}|h_{SD,k'n}^{(f)}|^2}{\sigma_N^2/P_{St,k'}}, \quad \gamma_{SR,k'n} = \frac{G_{SR}|h_{SR,k'n}^{(f)}|^2}{\sigma_N^2/P_{St,k'}}, \tag{10}$$

$$\gamma_{RD,k'n} = \frac{P_{Rt,k'}G_{RD}G_{SR}|h_{RD,k'n}^{(f)}|^2|h_{SR,k'n}^{(f)}|^2}{\sigma_N^2(G_{SR}|h_{SR,k'n}^{(f)}|^2 + \sigma_N^2/P_{St,k'})}. \tag{11}$$

Consequently, the k'-th user's overall received SINR at the output of the JFDEC scheme can be expressed as

$$\gamma_{k'} = \left\{\frac{1}{N}\sum_{n=0}^{N-1}\left[\begin{array}{c}1+\gamma_{SD,k'n}+\\ \left(\gamma_{SR,k'n}^{-1}+\gamma_{RD,k'n}^{-1}\right)^{-1}\end{array}\right]^{-1}\right\}^{-1} - 1, \tag{12}$$

when using the relationship between SINR and MMSE as a general feature of the MMSE criterion [13].

IV. Relay Selection Schemes

The opportunistic relaying allows a single relay to be selected from a cluster of $J(J>0)$ inactive MTs, the so-called *Relay Candidates* (RC), depending on which MT provides for the best *end-to-end* link between the source and destination [9]. The *Random Relay Selection* (RRS) philosopy allows the BS to appoint a relay randomly without any channel knowledge, but in this case a simultaneous relay path gain and multi-user diversity gain cannot be achieved. By contrast, the so-called *Distance-Dependent Relay Selection* (DD-RS) policy is based on the distance from the relay to the source MT or BS, hence the RCs which benefits from a high path gain may experience deep shadowing and fast fading. However, the *Channel-Dependent Relay Selection*(CD-RS) regime benefits from a certain *degree-of-freedom* in terms of selecting the cooperating MT, by monitoring the instantaneous channel conditions in a distributed scenario, including the associated path-loss, hadowing and *multi-path fading* effects. Therefore, our proposed SU- and MU-RS are both carried out with the objective of maximising the average received SINR of each user at the BS for both the direct and relaying branches. Additionally, we assume that the transmissions of the S-D, S-R and R-D links are orthogonal and hence do not impose an increased MUI.

A. Single-User Relay Selection

We firstly consider the so-called SU-RS scheme in which each source MT is associated with a cluster of J independent RCs. Therefore, SU-RS requires a total of $(K\times J)$ inactive MTs to support K source MTs. Let us briefly describe the selection procedure [9], [11] as follows.

Broadcast: The source MT broadcasts a *Request-To-Send* (RTS) packet with half transmit power received by the RCs and the BS.

Training: All RCs carry out FD-AF transmissions of the RTS message containing the CSIR and the SNR of all the n subbands of the S-R links formulated in Eq. (10), assuming that the *default* power is received by the BS.

Power allocation: The BS is assumed to be capable of estimating the CSIR and SNR of all the S-D and R-D links, which were formulated in Eq. (10) and (11). Either Equal Power Allocation (EPA) or Optimum Power Allocation [7], [10] can be activated by the BS. Here we only consider the EPA for simplicity, which is formulated as $\alpha_{S,j,k} = \alpha_{R,j,k} = 0.5$.

Selection: The BS calculates the overall SINR of the k-th user, when tentatively relying on any of the J RCs and selects the maximum SINR associated with the index of $j_k^{(opt)}$, as formulated by

$$j_k^{(opt)} = \arg\max_{j\in[0,J-1]}\{\gamma_{j,k}\}. \tag{13}$$

Feedback: A *Clear-To-Send* (CTS) packet is returned from the BS to the source MT, to the *desired relay* and to all the other $(J-1)$ unselected MTs, including the results of power allocation and relay selection.

Data transmission: When the above steps are completed, the source MT transmits the information signal using the specific power allocation and the *selected relay* starts the next FD-AF transmission using its allocated power.

B. Multi-User Relay Selection

However, when the total number of inactive MTs roaming within a cell is low, an insufficient number of RCs is available and hence we are limited to the SDR regime. In this subsection, we propose the so-called MU-RS scheme. In general, a cluster of K source MTs is assocated with a cluster of $J(J \geq K)$ RCs, but the system only requires a total of K relays. Although the main procedure of the MU-RS is similiar to that of the SU-RS, the selection steps are different, as elucidated below.

The system invokes an *optimal partner ordering* scheme by extending the *relay ordering* regime of [12] to both multiple source and relay MTs in order to optimise the cooperative partner selection. It calculates the overall SINR of all the K source MT's signal by tentatively assuming cooperation with all the J RCs, and chooses the RCs having the highest K SINR values provided by the relays corresponding to the particular source MTs. Specifically, at the i-th iteration, the desired relay's index $j_{k,i}^{(opt)}$ selected for assisting the k-th source MT is assumed to be the index i, which are compiled in *descending order*, yielding

$$j_{k,i}^{(opt)} = \arg \max_{j \in [0,J-1], k \in [0,K-1]} \{\gamma_{j,k}\}. \qquad (14)$$

Thus, upon removing the k-th source MT and the $j_{k,i}^{(opt)}$-th relay from the selected pools, the target relay of the $(k+1)$-st user can be allocated during the next iteration using Eq. (14).

V. Simulation Results and Discussions

Initially, we consider a simple idealised systems subject to small-scale fading only, while the effects of path-loss, relay selection and power control are all ignored. Figs. 2 illustrates the *Bit Error Ratio* (BER) versus E_b/N_0 performance of the FD-AF relaying system relying on different receiver solutions for full-load single-relay aided multi-user uplink transmissions experiencing frequency-selective Rayleigh fading, upon varying the number of paths for $L = 1, 4, 8$ and for $U = 64$, $N = M = K = 8$. Compared to the FDE-EGC method, the proposed JFDEC scheme carries out the FDE and diversity combining with the aid of the optimised weights of Eq. (8) over each subband for both the direct and relaying branches jointly. Although the JFDEC scheme exhibits only a modest improvement, when communicating over a *single-path fading* channel associated with $L = 1$, it achieves slightly more significant improvements for $L = 4$ and 8. Quantitatively, our proposed scheme is capable of achieving an approtimatedly 4dB cooperative diversity gain at a BER of 10^{-4}, when experiencing multi-path fading associated with $L = 8$.

For the sake of fair comparsions, we assume that we have $K = 4$ source MT assisted by $J = 4$ and 16 RCs for SU-RS and MU-RS respectively. Upon varying the effects of shadowing and PCE for $\eta = 4$ at all links for transmission over Rayleigh fading channels in the presence of path-loss, Fig. 3 characterises the overall average BER versus E_b/N_0 performance of different relay selection aided FD-AF systems, respectively. Compared to RRS, both SU-RS and MU-RS provide a substantial multi-user diversity gain, which is about 4dB at a BER of 10^{-4}. Furthermore, the proposed MU-RS has the edge over the SU-RS, providing an additional multi-user diversity gain in excess of 2dB, which is a benefit of the relay selection procedure that avoids the effects of deep shadow fading, despite being subjected to imperfect power control associated with a variance of 2dB error.

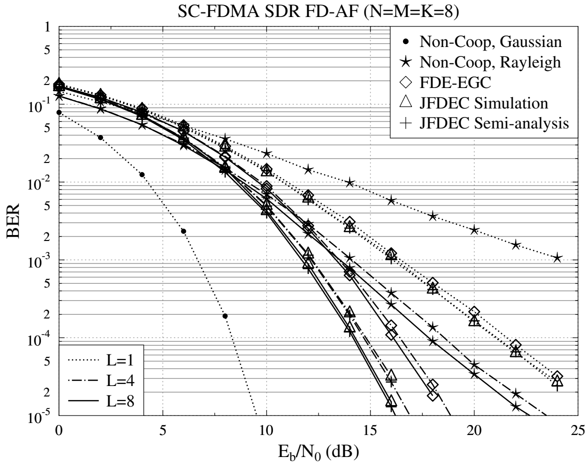

Fig. 2. BER Performance comparison of JFDEC and FDE-EGC

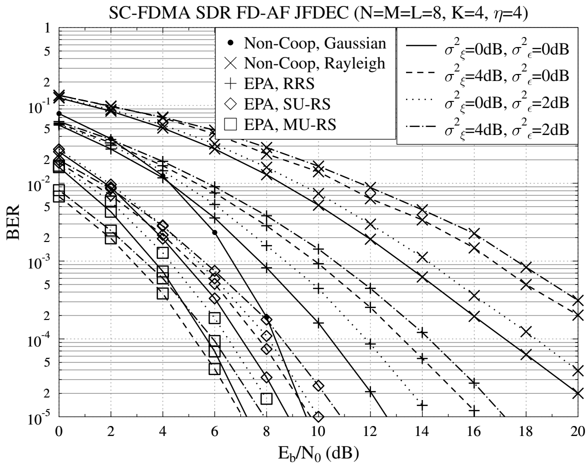

Fig. 3. BER performance of different relay selection schemes

We adopt the sum-rate of all user's data transmissions in order to represent the attainable system throughput. For the sake of quantifying the power-efficiency, when invoking different relay selection schemes, Fig. 4 illustrates the E_b/N_0 versus sum-rate performance, upon varying the standard deviation of shadowing and PCE for the SU-RS in conjunction with $J = 4$ and for the MU-RS using $J = 16$. Clearly, when aiming for a fixed target throughput of say 10 bits per transmission in the presence of shadowing compared to non-cooperation scenario, the multi-user diversity gain accruing from avoiding small-scale fading allows the MU-RS scheme to achieve a significant power reduction of 7.8dB, while the SU-RS attains a power saving of 6.8dB. Finally the RRS provides the lowest power gain by 4.8 only. Furthermore, observe in Fig. 4 that the throughput difference between the scenarios with and without shadowing implies that opportunistic scheduling constitutes a power-efficient design, when communicating over realistic shadow fading channels associated with $\sigma_\xi^2 = 4$dB, when compared to the non-cooperative benchmark. For instance, compared to the 5dB power reduction attained by RRS-aided cooperative transmissions of a sum-rate of 12 bits per transmission, the proposed SU-RS and MU-RS schemes are capable of saving 8dB and 9.7dB transmit power, respectively.

Fig. 5 depicts the attainable system throughput as a function of the

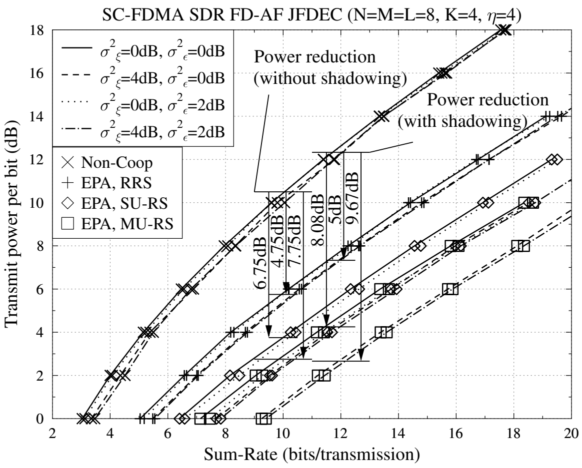

Fig. 4. Power reduction of different relay selection schemes

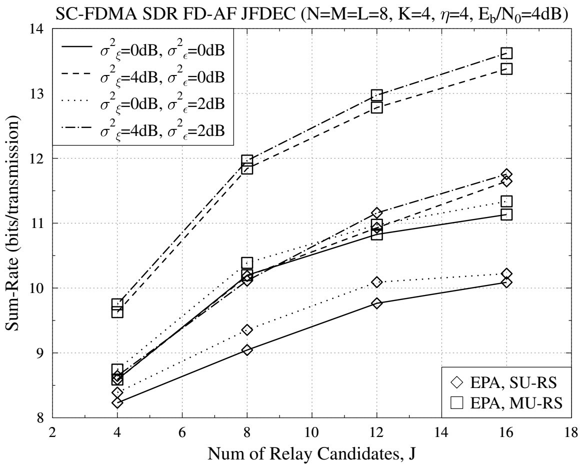

Fig. 5. Effect of varying the number of relay candidates

number of RCs, when the number of source MTs was fixed to $K = 4$ for $E_b/N_0 = 4$dB. Generally, the sum-rate curve emerges from its lower bound value, when the number of RCs and source MTs is equal, and improves upon increasing the number of RCs. Specifically, the MU-RS scheme is capable of substantially improving the throughput performance compared to the SU-RS approach, particularly when communicating over channels subject to shadow fading.

VI. Conclusions

In this paper we evaluated the performance benefits of the power-efficient opportunistic AF cooperation aided multi-user SC-FDMA uplink, which was designed to be free from any MUI at the relays, when communicating over frequency-selective fading channels in shadow fading scenarios. The channel-dependent single-user and multi-user relay selection schemes were investigated based on the proposed MMSE aided JFDEC solution in order to exploit the multi-user diversity combined with cooperative diversity for the SDR regime in the persence of both pass-loss and shadowing, while subjected to imperfect power control. Our results show that at a BER of 10^{-4}, the proposed receiver is capable of saving a 2dB higher power as a benefit of its higher cooperative diversity gain, than the conventional FDE receiver. Moreover, an approximately 6.8dB and 8dB transmit power reduction are attainable by invoking the proposed selective diversity aided single-user and multi-user relay selection schemes, respectively. Most importantly, a power-efficiency improvement is gleaned from our multi-user relay selection scheme, which avoids the effects of deep shadowing and provides a 9.7dB power reduction compared to the non-cooperation scenario.

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