Abstract—We consider relay selection technique in a cooperative cellular network where user terminals act as mobile relays to help the communications between base station (BS) and mobile station (MS). A novel relay selection scheme, called Joint Uplink and Downlink Relay Selection (JUDRS), is proposed in this paper. Specifically, we generalize JUDRS in two key aspects: (i) relay is selected jointly for uplink and downlink, so that the relay selection overhead can be reduced, and (ii) we consider to minimize the weighted total energy consumption of MS, relay and BS by taking into account channel quality and traffic load condition of uplink and downlink. Information theoretic analysis of the diversity-multiplexing tradeoff demonstrates that the proposed scheme achieves full spatial diversity in the quantity of cooperating terminals in this network. And numerical results are provided to further confirm a significant energy efficiency gain of the proposed algorithm comparing to the previous best worse channel selection and best harmonic mean selection algorithms.

Index Terms—relay selection, cooperative networks, energy-efficient, asymmetric traffic, weighted energy consumption.

I. INTRODUCTION

Cooperative relaying is a promising technology that can not only increase the overall throughput and energy efficiency, but also enable the system to guarantee the quality of service (QoS) desired by the various media classes for the next-generation wireless communications [1].

However, the relay nodes consume system resources and energy, hence limiting the transmission rate and energy efficiency. As a result, various relay selection schemes have been introduced in previous works. Nosratinia and Hunter [2] demonstrate that relay selection techniques can capture maximum diversity in the number of cooperating nodes, while each node only knows its own receive channel state. Madan et al. [3] consider selecting relays by minimizing the total power consumption. Tannious et al. [4] propose an ITRS protocol, which employs hybrid-ARQ with packet combining at the destination and includes a limited-feedback handshake for relay selection, achieving the multiple-input single-output (MISO) diversity-multiplexing tradeoff (DMT) bound. Bletsas et al. [5] propose a decentralized, opportunistic relaying scheme to select the best relay based on instantaneous end-to-end channel conditions, which also achieves the MISO DMT bounds.

The above-mentioned works all focus on single direction transmission, from source to destination. However, in most cellular networks, the uplink and downlink may be in deep fading at the same time. In this scenario, relay is needed for both uplink and downlink, and the same relay can be adopted if the channel reciprocity exists. Base station (BS) and mobile station (MS) can act interchangeably as source and destination, with the relay offering help for both two communications (see Fig. 1). In this paper, we consider to select the best relay for uplink and downlink jointly in one selection, which significantly reduce the relay selection overhead.

Meanwhile, the traffic load of uplink and downlink have been changing to be asymmetric to support new multimedia communication services. For example, the downlink traffic load may be larger than that in the uplink when MS downloads some files from BS. In this scenario, since the relay transmits signal to MS more often than to BS, the MS-relay channel and BS-relay channel may have different priority on relay
selection. Motivated by this, we take into account the traffic load condition of uplink and downlink during the selection of relay.

This paper is organized as follows. In the next section, we present the system model. In Section IV we describe the JUDRS protocol. Diversity-multiplexing tradeoff performance of the proposed scheme is analyzed in Section V and numerical results of energy-efficiency of JUDRS are discussed in Section VI. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

We consider a half-duplex dual-hop communication scenario in a fading environment with one MS, one BS and a set $S = \{1, 2, \ldots, N\}$ of $N$ decode-and-forward (DF) relays, depicted in Fig. 1. During the first hop, the source transmits its information to the relays and destination, while in the second phase, one relay (assume that each time, at most one relay is used) decodes and forwards the received signal using the same modulation and coding scheme (MCS). The destination receiver combines the messages it receives from the source and relay using optimal diversity combining. In cooperative cellular networks, MS and BS act interchangeably as source and destination, in the UL and DL transmission, with relay offering help for both the UL and DL communications.

The channels from MS to relays and from relays to BS are frequency non-selective channels that undergo independent Rayleigh fading. Thus, the channel gains from MS to relays, denoted by $|h_i|^2$, and from relays to BS, denoted by $|g_i|^2$, are independent and exponentially distributed random variables with parameter $\lambda_{M,i}$ and $\lambda_{B,i}$, respectively, where $i = 1, \ldots, N$. The mean channel gains depend on shadowing and the distance between corresponding nodes, thus we get,

$$\frac{1}{\lambda_{i,j}} = \left(\frac{G_T G_R e}{4\pi d_0}\right)^2 \cdot \left(\frac{d_0}{d_{i,j}}\right)^p \cdot \psi_{i,j},$$

where $\mu$ is the carrier wavelength, $G_T$ and $G_R$ are the transmitter and receiver antenna gain respectively, $d_0$ is a reference distance for the antenna far field, $p$ is the path loss exponent, and $d_{i,j}$ and $\psi_{i,j}$ are the distance and shadow fading between corresponding nodes. We assume that the UL and DL of each link are reciprocal. This condition is fulfilled in TDD systems where round-trip duplex time is much shorter than coherence time of the channel.

At all nodes, the additive white Gaussian noise has a power spectral density of $N_0$. All transmissions in the system have a bandwidth of $B$ Hz. Assuming that the maximum power MS, relays and BS can supply are identical, which is $P_0$ joules per second. Thus the SNR at each receiver is $\rho|h_{i,j}|^2$, where $\rho := \frac{P_0}{N_0B}$ is the general SNR without fading.

In addition to SNR, we assume the transmission schemes are further parameterized by the MS-BS spectral efficiency $R$ bit/s/Hz attempted by the transmitting terminals [1]. As the transmission through relay needs two transmission phases, the spectral efficiency of each phase may be no less than $2R$ to get an end-to-end $R$ bit/s/Hz spectral efficiency. Fixing $R$ simplifies the design of the relays as they do not need to remodulate their transmission using a different signal constellation [3].

A. Asymmetric Traffic Model

To model the asymmetric traffic condition in the system, we introduce a traffic asymmetry factor $\zeta$, which gives the ratio of the traffic load $L_{UL}$ in the uplink to the total traffic load $L_{total}$. $L_{total}$ is the sum of uplink traffic load $L_{UL}$ and the downlink traffic load $L_{DL}$. The traffic load $L_{total}$, $L_{UL}$ and $L_{DL}$ are defined as the number of generated bits in a communication. Hence, the $L_{UL}$ and $L_{DL}$ can be obtained by $\zeta$ and $L_{total}$. In cellular systems, $\zeta$ can be obtained from upper layer at BS before relay selection.

B. Weighted Total Energy Consumption Model of Cooperation

In the scope of energy efficiency estimation methodologies, a measure usually taken for the comparison of radio transmission technologies is the energy consumption per bit [6]. However a comparison of the sheer energy consumption of the transmission schemes in cooperative networks is not suitable, because certainly MS, relay and BS have different power consumption challenges. Thus, we use the weighted total energy consumption of MS, relay and BS in the two-way communication, and allocate different weights to MS, relay and BS, denoted by $\omega_M$, $\omega_R$ and $\omega_B$, respectively. The weights $\omega_M$, $\omega_R$ and $\omega_B$ are defined based on criteria of priority level on power consumption of MS, relay and BS. They can be set arbitrary values according to different condition. An example can be $\omega_M = \omega_R = 1$ and $\omega_B = 0$. In this case, we give equal weight to MS and relay, and the energy consumption of BS is ignored. This is reasonable in user cooperative cellular networks, as MS and relay are all powered by batteries while BS is always powered by a fixed line [7].

We model only the energy required for radio transmission and not the energy consumed for receiving. This is reasonable as the radio transmission is the dominant component of energy consumption for long range transmissions [8]. Thus, the weighted total energy consumption of the cooperative communication per information bit can be expressed as

$$E_{coop} = \frac{1}{2RB} \left[ \zeta(\omega_M \cdot P_{UL}^{UL} + \omega_R \cdot P_{UL}^{UL}) + (1 - \zeta)(\omega_R \cdot P_{DL}^{DL} + \omega_B \cdot P_{DL}^{DL}) \right].$$

III. JOINT UPLINK AND DOWNLINK RELAY SELECTION

This section presents a relay selection protocol for a multi-relay network, called Joint Uplink and Downlink Relay Selection (JUDRS). We proceed JUDRS as follows.

Step 1: MS broadcasts a RTS1 packet to the relays and BS using a fixed transmission power $P_0$. Each relay hears the RTS1 packet and estimates the gain of the channel between MS and itself, denoted by $|h_i|^2$. Depending on the channel...
states, only a subset $\Gamma$ of the $N$ relays can be chosen as candidate relays, defined by

$$\Gamma \triangleq \{ i \in S : P_0 \cdot |h_i|^2 \geq N_0 B(2^{2R} - 1) = th_1 \}.$$  

In (3), the relay is assumed to be helpful to the transmission from MS to BS only if $P_0 \cdot |h_i|^2 \geq th_1$. We use $t$ to denote the size of $\Gamma$. BS also measures the channel gain of the direct link, which is denoted as $|h_{\text{direct}}|^2$.

**Step2:** The $t$ relays in $\Gamma$ send RTS2 packets to the BS along with the channel quality indicator (CQI) using power $P_0$.

**Step3:** BS estimates the channel gain of the direct link $h_{\text{direct}}$, along with the relay $i$, $i \in \Gamma$. The relay can be helpful to the transmission between MS and BS only if

$$P_0 \cdot |g_i|^2 \geq N_0 B(2^{2R} - 1) \cdot (1 - \frac{|h_{\text{direct}}|^2}{|h_i|^2}) \triangleq th_2.$$  

The relays satisfy (4) form the candidate relay set $\Sigma$.

**Step4:** BS selects the best relay from $\Sigma$ under the following criteria, and broadcasts the index of the best relay along with the transmitting power allocated to MS and the relay in UL and DL transmissions. In order to minimize the total energy consumption, we optimize the transmitting power of all transmitters in both UL and DL to the minimum required for successful transmission at an end-to-end data rate $R$, which are:

$$P_M^{UL} = \frac{th_1}{|h_i|^2}, \quad P_B^{DL} = \frac{th_1}{|h_i|^2}, \quad P_R^{DL} = \frac{th_3}{|h_i|^2},$$

where $th_3 = N_0 B(2^{2R} - 1) \cdot (1 - \frac{|h_{\text{direct}}|^2}{|g_i|^2})$. Substituting (5) into (2), the weighted total energy consumption of MS, relay and BS per information bit can be expressed as,

$$E_{\text{coop}} = \frac{N_0(2^{2R} - 1)}{2R} \cdot \left(\frac{\zeta \cdot \omega_M + (1 - \zeta) \cdot \omega_R}{|h_i|^2} + \frac{\zeta \cdot \omega_B + (1 - \zeta) \cdot \omega_B}{|g_i|^2} - \frac{\omega_R \cdot |h_{\text{direct}}|^2}{|h_i|g_i|^2}\right).$$

Note that MS can also communicate with BS directly without the help of any relay if the channel gain of the direct link is strong enough. Thus, we calculate the weighted energy consumption per bit required for direct transmission between MS and BS for successful transmission at data rate $R$,

$$E_{\text{direct}} = \frac{\zeta \cdot \omega_M \cdot P_M^{UL} + (1 - \zeta) \cdot \omega_B \cdot P_B^{DL}}{R} = \frac{N_0(2^{2R} - 1) \cdot \zeta \cdot \omega_M + (1 - \zeta) \cdot \omega_B}{R \cdot |h_{\text{direct}}|^2}.$$  

In this paper, we select the relay which minimizes the weighted total energy consumption of communication as best relay, which can be expressed as,

$$i^* = \arg\min_{i \in \Sigma} \{ E_{\text{coop}} \}. \quad (8)$$

BS compares the $E_{i^*}^{\text{coop}}$ with $E_{\text{direct}}$, and choose the one with the minimum weighted energy consumption. If $E_{\text{direct}} \leq E_{i^*}^{\text{coop}}$, no relay is selected as the direct transmission is more energy-efficient than the transmission via any relay.

**Step5:** MS and BS communicate with each other in uplink and downlink via the selected relay. If the direct link is selected, MS and BS communicate directly with each other.

**IV. DIVERSITY-MULTIPLEXING TRADEOFF OF JUDRS**

This section analyzes the diversity-multiplexing tradeoff (DMT) performance of the proposed relay selection scheme. We use the definition given in [9]. A channel is said to achieve multiplexing gain $r$ and diversity gain $d$ if there exists a sequence of codes $C(\rho)$ operating at SNR $\rho$ with rate $R(\rho)$ and resulting outage probability $P_{out}(\rho)$ such that

$$\lim_{\rho \to \infty} \frac{R(\rho)}{\log(\rho)} = r, \quad \lim_{\rho \to \infty} \frac{\log P_{out}(\rho)}{\log(\rho)} = -d.$$  

In the following developments, we say $f(\rho)$ is exponentially equal to $\rho^v$, denoted by $f(\rho) = \rho^v$, if

$$\lim_{\rho \to \infty} \frac{\log f(\rho)}{\log(\rho)} = v.$$  

We can define $\triangleq$ in a similar fashion.

The main DMT result for JUDRS scheme is given in the following theorem, where we denote $(\cdot)^+ = \max\{\cdot, 0\}$.

**Theorem 1:** The JUDRS scheme achieves the following diversity-multiplexing tradeoff:

$$d_{\text{JUDRS}}(r) = (N + 1) \left(1 - \frac{2N + 1}{N + 1}\right)^+. \quad (11)$$
The outage probability of the JUDRS scheme can be expressed as,
\[
P_{\text{out}} = \zeta \cdot P_{\text{out}}^{UL} + (1 - \zeta) \cdot P_{\text{out}}^{DL}. \tag{12}
\]

For the uplink transmission, during the broadcast phase, the mutual information across the MS-BS channel is:
\[
I_D = \log(1 + \rho |h_{\text{direct}}|^2). \tag{13}
\]

If a retransmission occurs, the combination of the two transmission forms an equivalent channel between the MS and BS, whose mutual information is:
\[
I_{2-hop} = \frac{1}{2} \log \left( 1 + \rho(|h_{\text{direct}}|^2 + |g_i|^2) \right), \tag{14}
\]

where \(i^*\) denotes the index of the selected relay. Using the law of total probability, the outage probability of uplink transmission can be expressed as:
\[
P_{\text{out}}^{UL} = \sum_{t=1}^{N} Pr\{I_D < R, I_{2-hop} < R|\Gamma = t\} \cdot Pr\{\Gamma = t\}
+ Pr\{\Gamma = 0\} \cdot Pr\{I_D < R\}
= \left[ \sum_{t=1}^{N} Pr\{I_{2-hop} < R|I_D < R, |\Gamma = t\} \cdot Pr\{\Gamma = t\} \right.
\]
\[
+ Pr\{\Gamma = 0\} \cdot Pr\{I_D < R\}. \tag{15}
\]

The probability that exact \(t\) nodes know the message is given by (3):
\[
Pr\{\Gamma = t\} = \binom{N}{t} \prod_{i \in \Gamma} \exp \left( -\lambda_{M,i} \frac{g_2 - 1}{\rho} \right)
\cdot \prod_{i \notin \Gamma} \left[ 1 - \exp \left( -\lambda_{M,i} \frac{g_2 - 1}{\rho} \right) \right]. \tag{16}
\]

The probability that the direct link is in outage is given by,
\[
Pr\{I_D \leq R\} = Pr\{1 + |h_{\text{direct}}|^2 \leq r \log \rho\}
\leq \rho^{r-1}. \tag{17}
\]

And the condition probability that the 2-hop channel is in outage can be calculated as,
\[
Pr\{I_{2-hop} < R|I_D < R, |\Gamma = t\}
= Pr\{\frac{1}{2} \log(1 + \rho(|h_{\text{direct}}|^2 + |\max_{i \in \Gamma} |g_i|^2)|) \leq r \log \rho
\]
\[
\leq \rho^{2r-1} - \rho^{r-1}, \Gamma \}
\leq Pr\{\max_{i \in \Gamma} |g_i|^2 \leq \rho^{2r-1} |h_{\text{direct}}|^2 \leq \rho^{r-1}, \Gamma \}
\leq Pr\{\max_{i \in \Gamma} |g_i|^2 \leq \rho^{2r-1} \}
\leq \rho^{(2r-1)} \tag{18}
\]

Here (a) follows from Lemma 2 in [5].

Substituting (16), (18) and (17) into (15), we can get the upper bound of overall uplink outage probability:
\[
P_{\text{out}}^{UL} \leq \rho^{r-1} \left( \sum_{i=1}^{N} \rho^{t(2r-1)} \rho^{(N-i)(2r-1)} + \rho^{N(2r-1)} \right). \tag{19}
\]

The same methodology can be applied to downlink transmission. Thus the DMT of the JUDRS scheme is given by
\[
d_{\text{JUDRS}}(r) = (N + 1) \left( 1 - \frac{2N + 1}{N + 1} r \right)^{\frac{1}{r}}. \tag{20}
\]

The DMT analysis corroborates the merits of the JUDRS scheme that it can achieve full spatial diversity in the number of the cooperating nodes, not just the number of decoding relays.

V. SIMULATION RESULTS

In this section, we present the performance results of the JUDRS protocol. For comparison, we also simulate the performance of some existing relay selection schemes. In [10], the best worse channel selection is introduced, in which the relay whose worse channel, \(\min\{|h_i|, |g_i|\}\), is the best is selected. In [5], the best harmonic mean selection is proposed, in which the relay selection function is chosen as the harmonic mean of the two channel’s magnitudes: \(|h_i|^{-2} + |g_i|^{-2})^{-1}\). The relay with the largest harmonic mean cooperates. We extend the best worse channel selection and the best harmonic harmonic mean selection to both uplink and downlink straightforward.

The parameters used in the simulation is shown in Table I, which are mainly taken from [6], where \(f_c\) is the frequency of the central carrier. Throughout the simulations, we use \(\omega_M = \omega_R = 1\) and \(\omega_B = 0\). The simulation results are shown in Fig. 3 and Fig. 4.

\begin{table}[h]
\centering
\caption{Simulation Parameters}
\begin{tabular}{ |c|c|c|c|c| }
\hline
Parameter & Symbol & Value & Parameter & Symbol & Value \\
\hline
Base station power & \(P_B\) & 24dBm & Center frequency & \(f_c\) & 180KHz \\
Radio frequency & \(B\) & 2.5GHz & Channel gain & \(G_{I-R}\) & 0 \\
Number of relays & \(N_0\) & -171dBm/Hz & Channel bandwidth & \(\beta\) & 2.5GHz \\
Number of decoding relays & \(\lambda\) & 3.76 & & & \\
\hline
\end{tabular}
\end{table}

In Fig. 3(a) and Fig. 3(b) the total transmission energy of MS and relay per bit is plotted as a function of the number of relays for two scenarios: a direct link between MS and BS exists (see Fig. 3(a) MS-BS distance of 450m) and a direct link does not exists (see Fig. 3(b) MS-BS distance of 1200m, \(|h_{\text{direct}}| \ll \min\{|h_i|, |g_i|\}\). These figures indicate that the proposed JUDRS scheme can save the total transmission energy efficiently than the best worse channel selection and the best harmonic selection in both cases with different traffic load conditions. It is also shown in the figures that the energy consumed for transmitting one bit decreases with the active relay number, which means that it is helpful to have a larger number of relays.
Fig. 3. Total transmission energy of MS and relay per bit in two topologies.

Fig. 4. The energy consumption of MS and relay per bit for different traffic conditions, with 8 active relays and MS-BS distance of 450m, $R = 3$ bit/s/Hz.

Fig. 4 also illustrates that the energy saving achieved by the proposed scheme grows with the decrease of the asymmetric traffic factor $\zeta$. It gives the advantage of the JUDRS scheme that it can adaptively adjust the transmit energy to the minimum according to the traffic condition in the system. As the uplink traffic load is always less than that of the downlink, we can always expect a larger energy-saving using the JUDRS scheme. Fig. 4 also indicates the energy-saving achieved by the JUDRS scheme mainly comes from the energy saving of the relay, especially when the uplink traffic load is less than the downlink traffic load.

VI. CONCLUSION

This paper presents an energy-efficient relaying scheme through selection of mobile relays. We propose Joint Uplink and Downlink Relay Selection (JUDRS) scheme, in which relay is selected jointly for uplink and downlink, and the weighted total energy consumption is minimized. Power allocation policies are also designed for communication nodes to improve the overall energy efficiency. The diversity-and-multiplexing tradeoff result demonstrates that the JUDRS scheme can achieve full spatial diversity in the number of cooperating terminals. Numerical results further confirm that the proposed scheme can improve the energy-efficiency of MS and relay compared with previous best harmonic mean selection and best worse channel selection.

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