DOUBLE RELAY COMMUNICATION PROTOCOL WITH POWER CONTROL FOR ACHIEVING FAIRNESS IN CELLULAR SYSTEMS

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ABSTRACT

The growing demand for wireless connectivity has turned bandwidth into a scarce resource that has to be carefully managed and fairly distributed to users. However, the variability of the wireless channel can severely degrade the service received by each user. The Double Relay Communication Protocol (DRCP) [1] is a transmission scheme that addresses these problems by exploiting spatial diversity to enhance the fairness of the system without requiring any additional infrastructure (i.e relay nodes or a backhaul connection). Although DRCP has originally been proposed to work without channel state information at the transmitter (CSIT), in this paper we study how the performance of DRCP can be further improved through power control when CSIT is available. Our approach provides the highest fairness and the largest minimum spectral efficiency for most conditions compared to other studied baseline approaches.

Index Terms— Power control, fairness, relaying.

1. INTRODUCTION

The growing demand for wireless connectivity has turned bandwidth into a scarce resource that needs to be carefully managed and fairly distributed to users. Achieving fairness is especially critical in cellular systems, where the service that each user receives can be severely degraded by the variability of the wireless channel [2].

Fairness can be improved by introducing spatial degrees of freedom through the use of relays, which can average out the channel variability over different signal paths without the need for a backhaul connection [3, 4]. To further exploit the benefits of multiple-relay systems, physical-layer network coding (PNC) has been widely used to efficiently coordinate their transmissions. First proposed in [5], PNC exploits the linear superposition of wireless signals to increase the network throughput. However, much of the available literature on relaying-PNC focuses on achieving higher data rates for the particular case of the two-way relay channel (TWRC) [6, 7] by proposing different ways to encode the transmitted signals [8–13]. Moreover, the few papers on power control of relaying-PNC schemes are also limited to the TWRC case [14–17]. Nevertheless, all of the previous approaches require additional infrastructure (i.e. relay nodes), while none of them can guarantee fairness. Furthermore, they all consider only a limited number of nodes.

An attractive solution to tackle these issues has been proposed in [1]. Inspired by PNC, the Double Relay Communication Protocol (DRCP) exploits spatial diversity to achieve fairness without requiring a backhaul connection. Differently from other relaying-PNC configurations, DRCP does not need additional infrastructure as it uses base stations as relays, while it can also be extended to a larger system size. Additionally, the use of the relaying capabilities of base stations in order to improve the fairness of the system is a unique feature of DRCP.

DRCP has been shown to achieve fairness without any channel state information at the transmitter (CSIT). However, when this information is available, the fairness of DRCP can be further improved by controlling the transmit power at each base station. Following this rationale, in this paper we propose a power control mechanism for DRCP that achieves the highest fairness and the largest minimum spectral efficiency for most transmit power values compared to other baseline

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approaches. We prove that the optimal solution has at least one transmit power equal to the maximum power and we also propose a low complexity algorithm that computes these optimal transmit powers.

2. SYSTEM MODEL

Consider a system with 2 base stations, each of which has data to be delivered to a specific user. We denote as s_l the symbol from the l-th base station (BSl) to be delivered to the l-th user (Ul). We assume that the base stations and the users are half-duplex (i.e. they cannot transmit and receive simultaneously) and that no backhaul link exists between the base stations.[1] This last condition excludes the use of transmission schemes that require coordinated base stations, e.g. space-time block codes like Alamouti codes. We also assume that each base station can overhear the transmission of the other base station.

Let us define $P_l^{(t)}$ as the transmit power of BSl in time-slot t. We also define $\gamma_{lm}^{(t)} = \frac{\sigma_s^2}{\sigma_n^2} P_l^{(t)} |h_{lm}|^2$ and $\xi_{lm}^{(t)} = \frac{\sigma_s^2}{\sigma_n^2} P_l^{(t)} |g_{lm}|^2$, where h_{lm} is the channel gain from BSl to Um and g_{lm} is the channel gain from BSl to BSm.[2] The parameter $\sigma_s^2 = \mathbb{E}\{|s_1|^2\} = \mathbb{E}\{|s_2|^2\}$, and σ_n^2 is the noise power at the receiver, assumed equal for both users and base stations. Finally, $S_{\mathrm{U}l}$ represents the spectral efficiency of Ul. In order to have a rigorous assessment of the fairness, these metrics are defined:

1. $S_{\min} = \min\{S_{\mathrm{U1}}, S_{\mathrm{U2}}\}$ is the *minimum spectral efficiency*, which is the spectral efficiency of the user with the worst conditions.
2. $S_{\mathrm{mean}} = \frac{1}{2} S_{\mathrm{U1}} + \frac{1}{2} S_{\mathrm{U2}}$ is the *average spectral efficiency*, which is the average spectral efficiency of both users.
3. Fairness $\mathcal{F} = \frac{S_{\min}}{S_{\mathrm{mean}}}$, which is defined here as the ratio of $S_{\min}$ to S_{mean}.

$S_{\min}$ is commonly used as a metric to assess the max-min fairness of a system. However, a high $S_{\min}$ might not correspond to a high S_{mean}. Also, a high $\mathcal{F}$ does not imply a high $S_{\min}$ or S_{mean}. Hence, we believe that all $\mathcal{F}$, $S_{\min}$, and S_{mean} provide a better insight to assess the system performance.

2.1. Baseline Approaches

1. *TDMA*: In a basic time division multiple access (TDMA) approach, the communication is done in turns, i.e. first BS1 transmits s_1 to U1 while BS2 is inactive, and then BS2 transmits s_2 to U2 while BS1 is inactive, hence requiring 2 time-slots. The spectral efficiency per time-slot of TDMA for user Ul can be directly computed as [18]

$$S_{\mathrm{U}l}^{\mathrm{TDMA}} = \frac{1}{2} \log_2 \left(1 + \gamma_{ll}^{(l)}\right) \tag{1}$$

for $l = 1, 2$. It can be seen that the spectral efficiency of the two users in equation (1) can be quite different, which shows that this is not a fair approach.

2. *Diversity (DIV)*: By using the overhearing capabilities of the system to share the transmitted symbols between base stations we can increase the spatial diversity and, hence, the fairness. For instance, BS1 transmits s_1 to both U1 and BS2 in time-slot 1, then BS2 transmits s_2 to both U2 and BS1 in time-slot 2. Then, in time-slot 3 BS1 transmits s_2 and in time-slot 4 BS2 transmits s_1. The spectral efficiency per time-slot of DIV for user Ul (using maximal ratio combining) is

$$S_{\mathrm{U}l}^{\mathrm{DIV}} = \frac{1}{4} \log_2 \left(1 + \gamma_{ll}^{(t_1)} + \frac{\gamma_{ml}^{(t_2)}}{\frac{\gamma_{ml}^{(t_2)}}{\xi_{lm}^{(t_1)}} + 1}\right) \tag{2}$$

for $l = 1, 2$, $l \neq m$ and if $l = 1$ then $t_1 = 1$ and $t_2 = 4$ and if $l = 2$ then $t_1 = 2$ and $t_2 = 3$. Equation (2) shows that DIV can achieve fairness from the transmission of both base stations at the cost of increasing the number of time-slots.

3. *Interference (INTF)*: It consists in both base stations transmitting simultaneously regardless of the interference that they cause to the other user. The spectral efficiency per time-slot of INTF for user Ul can be directly computed as

$$S_{\mathrm{U}l}^{\mathrm{INTF}} = \log_2 \left(1 + \frac{\gamma_{ll}^{(1)}}{1 + \gamma_{ml}^{(1)}}\right) \tag{3}$$

for $l = 1, 2$ and $l \neq m$, which shows that this is not a fair approach as it only benefits one user. In contrast to TDMA and DIV which use maximum transmit power to maximize the spectral efficiency, INTF can maximize $S_{\min}^{\mathrm{INTF}}$ through geometric programming [19]. We refer to this power control version of INTF as INTF-PC.

2.2. Double Relay Communication Protocol (DRCP)

In the first time-slot, BS1 transmits s_1 to U1, U2, and BS2. In the second time-slot, BS2 transmits s_2 to U1, U2, and BS1. In the third time-slot, each base station acts as a relay to transmit simultaneously the received symbol (s_2 for BS1 and s_1 for BS2) to U1 and U2. Assuming a channel coherence time larger than 3 time-slots, the received signals for user Ul are:

$$\begin{aligned} y_{\mathrm{U}l}^{(1)} &= \sqrt{P_1^{(1)}} h_{1l} s_1 + n_{\mathrm{U}l}^{(1)} \\ y_{\mathrm{U}l}^{(2)} &= \sqrt{P_2^{(2)}} h_{2l} s_2 + n_{\mathrm{U}l}^{(2)} \\ y_{\mathrm{U}l}^{(3)} &= \sqrt{P_1^{(3)}} h_{1l} z_{21} + \sqrt{P_2^{(3)}} h_{2l} z_{12} + n_{\mathrm{U}l}^{(3)}, \end{aligned} \tag{4}$$

[1] In femtocells deployed by end-users, a direct link to other BSs might be difficult to implement or mainly used for low-rate control information.

[2] The channel gains between base stations are assumed higher than the channel gains between base stations and users since base stations are usually equipped with more powerful receivers (i.e. with greater sensitivity and smaller noise figure) and they often count with line-of-sight (LOS) between them.

for $l = 1,2$ and $l \neq m$, where $z_{lm} = s_l + \frac{n_{\mathrm{BS}m}^{(l)}}{\sqrt{P_l^{(l)}} g_{lm}}$, $y_{\mathrm{U}l}^{(t)}$ is the received signal for Ul in time-slot t, and $n_{\mathrm{U}l}^{(t)}$ is the AWGN noise for Ul in time-slot t. The spectral efficiency per time-slot for Ul can then be expressed as $S_{\mathrm{U}l}^{\mathrm{DRCP}} = \frac{1}{3}\log_2\left(1 + \mathrm{SNR}_{\mathrm{U}l}^{\mathrm{DRCP}}\right)$, where using the results from [1], we can calculate the signal-to-noise ratio (SNR) as[3]

$$\mathrm{SNR}_{\mathrm{U}l}^{\mathrm{DRCP}} = \gamma_{ll}^{(l)} + \frac{\gamma_{ml}^{(3)}}{\frac{\gamma_{ll}^{(3)}}{\gamma_{ml}^{(m)}+1} + \frac{\gamma_{ll}^{(3)}}{\xi_{ml}^{(m)}} + \frac{\gamma_{ml}^{(3)}}{\xi_{lm}^{(l)}} + 1}. \qquad (5)$$

In [1], maximum transmit power was assumed in all time-slots such that $P_1^{(1)} = P_1^{(3)} = P_1^{\max}$ and $P_2^{(2)} = P_2^{(3)} = P_2^{\max}$, providing fairness when no CSIT is available. However, additional gains can be achieved with CSIT by controlling the transmit powers as shown in the next section.

3. DRCP WITH POWER CONTROL

In this section, we start by maximizing $S_{\min}^{\mathrm{DRCP}}$ in Section 3.1 and we then derive a low complexity algorithm in Section 3.2.

3.1. Maximization of $S_{\min}^{\mathrm{DRCP}}$

The maximization of $S_{\min}^{\mathrm{DRCP}}$ can be expressed as

$$\begin{aligned} \underset{P_1^{(t)}, P_2^{(t)}\ \forall t}{\text{maximize}} \quad & S_{\min}^{\mathrm{DRCP}} = \min\{S_{\mathrm{U1}}^{\mathrm{DRCP}}, S_{\mathrm{U2}}^{\mathrm{DRCP}}\} \\ \text{s.t.} \quad & 0 \le P_1^{(t)} \le P_1^{\max}\ \forall t = \{1,3\} \\ & 0 \le P_2^{(t)} \le P_2^{\max}\ \forall t = \{2,3\}. \end{aligned} \qquad (6)$$

This problem can be transformed as in [19,20] by introducing an auxiliary variable v

$$\begin{aligned} \underset{P_1^{(t)}, P_2^{(t)}\ \forall t}{\text{maximize}} \quad & v \\ \text{s.t.} \quad & 1 + \mathrm{SNR}_{\mathrm{U1}}^{\mathrm{DRCP}} \ge v \\ & 1 + \mathrm{SNR}_{\mathrm{U2}}^{\mathrm{DRCP}} \ge v \\ & 0 \le P_1^{(t)} \le P_1^{\max}\ \forall t = \{1,3\} \\ & 0 \le P_2^{(t)} \le P_2^{\max}\ \forall t = \{2,3\}. \end{aligned} \qquad (7)$$

Since $S_{\min}^{\mathrm{DRCP}}$ is an increasing function of $P_1^{(1)}$ and $P_2^{(2)}$, equation (6) can be maximized with full transmit power in time-slots 1 and 2 ($P_1^{(1)} = P_1^{\max}$ and $P_2^{(2)} = P_2^{\max}$). Hence, for the following we assume maximum transmit power in the first two time-slots. Concerning $P_1^{(3)}$ and $P_2^{(3)}$, we can notice that maximizing any of them increases the spectral efficiency of one user, but decreases the spectral efficiency of the other user. The optimal transmit powers can be found using the following lemma.

Lemma 1: The DRCP transmit power values $P_1^{(3)}$ and $P_2^{(3)}$ for maximizing $S_{\min}^{\mathrm{DRCP}}$ have at least one power value equal to the maximum transmit power.

Proof. The optimal power combination $\mathbf{P}^* = \{P_1^{(3)*}, P_2^{(3)*}\}$ that maximizes $S_{\min}^{\mathrm{DRCP}}$ lies in the feasible space $\Omega^2 = \{\mathbf{P} | 0 \le P_1^{(3)} \le P_1^{\max}, 0 \le P_2^{(3)} \le P_2^{\max}\}$. Since Ω^2 is closed and bounded and $S_{\min}^{\mathrm{DRCP}}$: $\Omega^2 \to \mathbb{R}$ is continuous, it has a solution [21]. For $\beta > 1$ and $\mathbf{P} \in \Omega^2$:

$$\begin{aligned} & S_{\min}^{\mathrm{DRCP}}(P_1^{(3)}, P_2^{(3)}) < S_{\min}^{\mathrm{DRCP}}(\beta P_1^{(3)}, \beta P_2^{(3)}) = \\ & = \min\left\{ \log_2\left(1 + \beta\gamma_{11}^{(1)} + \frac{\gamma_{21}^{(3)}}{\frac{\gamma_{11}^{(3)}}{\beta\gamma_{21}^{(2)}+1} + \frac{\gamma_{11}^{(3)}}{\beta\xi_{21}^{(2)}} + \frac{\gamma_{21}^{(3)}}{\beta\xi_{12}^{(1)}} + \frac{1}{\beta}}\right), \right. \\ & \left. \log_2\left(1 + \beta\gamma_{22}^{(2)} + \frac{\gamma_{12}^{(3)}}{\frac{\gamma_{22}^{(3)}}{\beta\gamma_{12}^{(1)}+1} + \frac{\gamma_{22}^{(3)}}{\beta\xi_{12}^{(1)}} + \frac{\gamma_{12}^{(3)}}{\beta\xi_{21}^{(2)}} + \frac{1}{\beta}}\right) \right\}. \end{aligned} \qquad (8)$$

We can thus increase $S_{\min}^{\mathrm{DRCP}}$ by increasing β until one transmit power hits the boundary $P_1^{\max}$ or $P_2^{\max}$. $\square$

This means that the solution of equation (6) is always found on the boundary of the space containing all the possible power combinations $\{P_1^{(3)}, P_2^{(3)}\}$. This can be seen in Fig. 1 for given channel gains, which shows the surface of $S_{\min}^{\mathrm{DRCP}}$ formed by all the possible power combinations within the range $0 \le P_1^{\max} \le 1$ and $0 \le P_2^{\max} \le 1$. We refer to this power control version of DRPC as DRCP-PC.

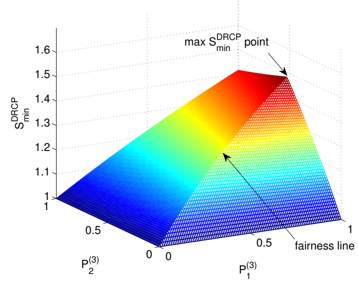

Fig. 1. $S_{\min}^{\mathrm{DRCP}}$ surface with $|h_{11}|^2 = |h_{22}|^2 = |h_{12}|^2 = 1$, $|h_{21}|^2 = 2$, $|g_{12}|^2 = |g_{21}|^2 = 40$dB, and $P_1^{\max} = P_2^{\max} = 1$.

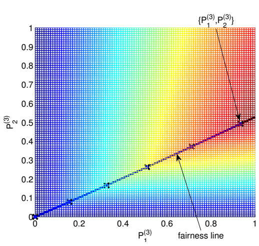

Fig. 2. Upper view of Fig. 1. The point $\{P_1^{(3)}, P_2^{(3)}\}$ corresponds to a given value of v.

3.2. Low complexity algorithm for $S_{\min}^{\mathrm{DRCP}}$ maximization

It is noticed that the $S_{\min}^{\mathrm{DRCP}}$ surface forms a line that reaches the maximum $S_{\min}^{\mathrm{DRCP}}$ point as seen in Fig. 1. We denote it as

[3] Notice that these equations extend the results of [1] by assuming possible transmission errors in the link between BS1 and BS2.

the *fairness line* and it is used to find the maximum $S_{\min}^{\mathrm{DRCP}}$ point in a low complexity fashion. For this purpose, we reformulate the first two constraints of problem (7) as:

$$(v-1-\gamma_{ll}^{\max})\left(1+\frac{\gamma_{ll}^{(3)}}{\gamma_{ml}^{\max}+1}+\frac{\gamma_{ll}^{(3)}}{\xi_{ml}^{(m)}}+\frac{\gamma_{ml}^{(3)}}{\xi_{lm}^{(l)}}\right)-\gamma_{ml}^{(3)}=0 \tag{9}$$

for $l=1,2$ and $l\neq m$, where the super script "max" refers to the maximum transmit power used in time-slots 1 and 2 ($P_1^{(1)}=P_1^{\max}$ and $P_2^{(2)}=P_2^{\max}$). By setting both constraints as an equality while increasing v, we aim to find the boundary point of $S_{\min}^{\mathrm{DRCP}}$.

From (9), we can see that the first equation ($l=1$) is a linear function of $\gamma_{11}^{(3)}$ and $\gamma_{21}^{(3)}$, hence a linear function of $P_1^{(3)}$ and $P_2^{(3)}$, while the second equation ($l=2$) is a linear function of $\gamma_{22}^{(3)}$ and $\gamma_{12}^{(3)}$, hence also a linear function of $P_2^{(3)}$ and $P_1^{(3)}$. By substitution, we can obtain both $P_1^{(3)}$ and $P_2^{(3)}$ *only* as a function of v (and not as a function of each other):

$$P_l^{(3)}=\frac{|h_{ml}|^2A_{lm}+|h_{mm}|^2B_{lm}}{|h_{12}|^2|h_{21}|^2A_{12}A_{21}-|h_{11}|^2|h_{22}|^2B_{12}B_{21}} \tag{10}$$

for $l=1,2$ and $l\neq m$, where $A_{mn}=\frac{1}{v-1-\gamma_{mm}^{\max}}-\frac{1}{\xi_{mn}^{(m)}}$ and $B_{mn}=\frac{1}{\gamma_{mn}^{\max}+1}+\frac{1}{\xi_{mn}^{(m)}}$. This results in a fairness line located in the plane formed by $P_1^{(3)}$ and $P_2^{(3)}$. Then, by tuning the value of v, we can obtain different values of $P_1^{(3)}$ and $P_2^{(3)}$ until one of them reaches the boundary value $P_1^{\max}$ or $P_2^{\max}$ as can be seen in Fig. 2. The granularity on the increasing steps of v determines the accuracy of the optimal solution.

The advantage of this approach is that the search of the $S_{\min}^{\mathrm{DRCP}}$ point is uni-dimensional. However, the fairness line might lie outside the boundaries of the space containing the possible transmit powers. Following Lemma 1, this means that the optimum power combination is one maximum transmit power and the other zero, such that $\{P_1^{(3)}=P_1^{\max}, P_2^{(3)}=0\}$ if $\mathrm{SNR}_{\mathrm{U1}}^{\mathrm{DRCP}}>\mathrm{SNR}_{\mathrm{U2}}^{\mathrm{DRCP}}$ and $\{P_1^{(3)}=0, P_2^{(3)}=P_2^{\max}\}$ if $\mathrm{SNR}_{\mathrm{U2}}^{\mathrm{DRCP}}>\mathrm{SNR}_{\mathrm{U1}}^{\mathrm{DRCP}}$.

4. PERFORMANCE EVALUATION

In this section we compare the approaches analyzed in the previous sections in terms of fairness $\mathcal{F}$ and $S_{\min}$. We consider Rayleigh fading channel coefficients. In order to study non-symmetric conditions we assume: $\mathbb{E}\{|h_{12}|^2\}=\mathbb{E}\{|h_{22}|^2\}=1$ and $\mathbb{E}\{|h_{11}|^2\}=\mathbb{E}\{|h_{21}|^2\}=15$dB. Also, the channel gains between base stations are assumed to be higher: $\mathbb{E}\{|g_{12}|^2\}=\mathbb{E}\{|g_{21}|^2\}=40$dB, and $\sigma_{\mathrm{s}}^2=\sigma_{\mathrm{n}}^2=1$.

For simplicity, we fix the maximum transmit power of BS2 to 10dBW and we vary the maximum transmit power of BS1. For the non-optimized schemes TDMA, DIV, INTF, and DRCP, we assume maximum transmit power such that $P_1^{(t)}=P_1^{\max}$ and $P_2^{(t)}=P_2^{\max}=10$dBW $\forall t$. For DRCP-PC we use $P_1^{(1)}=P_1^{\max}$, $P_2^{(2)}=P_2^{\max}=10$dBW, while $P_1^{(3)}$ is chosen between 0 W and $P_1^{\max}$ and $P_2^{(3)}$ is chosen between 0 W and $P_2^{\max}=10$dBW following Lemma 1. The optimal power values of INTF-PC can be found through geometric programming [19] within the range 0 W and $P_1^{\max}$ for $P_1^{(1)}$ and between 0 W and $P_2^{\max}=10$dBW for $P_2^{(1)}$.

Our results show that DRCP-PC offers the highest fairness $\mathcal{F}$ for increasing values of $P_1^{\max}$ as seen in Fig. 3. A peak in INTF-PC and INTF can be seen when $P_1^{\max}$ equals $P_2^{\max}$ because both users receive a similar transmit power from each base station and hence fairness is improved. Nevertheless, the fairness of INTF, INTF-PC, and TDMA drastically decreases with $P_1^{\max}$ since only one of the users receives the benefit, confirming that these are not fair approaches.

DRCP-PC also achieves the largest $S_{\min}$ for increasing values of $P_1^{\max}$ as seen in Fig. 4. TDMA has a region where it presents the highest $S_{\min}$ due to the fact that both users have a similar spectral efficiency when $P_1^{\max}$ is similar to $P_2^{\max}$.

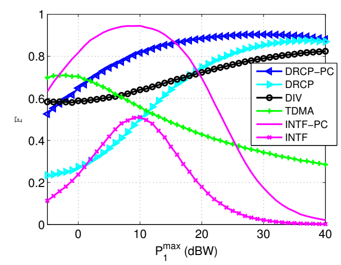

Fig. 3. Fairness $\mathcal{F}$ for $P_2^{\max}=10$dBW.

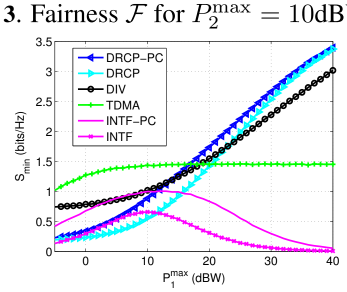

Fig. 4. Minimum spectral efficiency for $P_2^{\max}=10$dBW.

5. CONCLUSIONS

In this paper, we have proposed a power control mechanism that increases the fairness of DRCP when CSIT is available. We have proven that the optimal solution that maximizes the minimum spectral efficiency is to use maximum transmit power in the first two time-slots, and to use at least one transmit power equal to the maximum power in the third time-slot. Our results show that using power control allows DRCP to achieve the highest fairness and the largest minimum spectral efficiency for increasing values of transmit power compared to the studied approaches. Furthermore, a low complexity algorithm that computes the optimal transmit powers with a uni-dimensional search has also been proposed.

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