TDMA COOPERATION USING SPATIAL REUSE OF THE RELAY SLOT WITH INTERFERING POWER DISTRIBUTION INFORMATION

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ABSTRACT[1]

Cooperative transmission has emerged as an effective tool to combat fading by improving the diversity gain. Although this technique can be viewed as a "virtual" MIMO system, when implemented under orthogonal access it does not allow multiplexing gains. In this work we have studied a possible application of the cooperative transmission in a TDMA centralized cellular system in the downlink. In order to reduce the inefficiency, we have considered the spatial reuse of one relay slot by simultaneous active relays in the cell. To this end we have modeled the interfering power received by each destination in the relay link. It is shown that cooperative transmission with amplify and forward strategy is able to provide significant throughput gains for user-relaying over the direct transmission under TDMA.

1. INTRODUCTION

Wireless communications have provided an important development of personal communications because they are offered in any place and at any time. However, they face channel propagation problems that need to be solved, mainly the time-varying fading, shadowing effects and interference. In the last years the space and polarization diversity obtained by using multiple antennas at the transmitters and receivers [1],[2], MIMO (Multiple Input Multiple Output) systems, has received much attention from the research community. Basically, MIMO systems offer two possible gains, multiplexing gain (an increase of the total mutual information), and diversity gain (it improves the robustness of the communication to undesirable channel fading effects) [3]. Recently, an old space diversity technique has been reconsidered again: the relay channel. This technique is based on using the antennas of multiple terminals to combat the fading [4][5]. Moreover, in [6], [7], a new extension of the relay channel is proposed, named cooperative diversity. Basically, the cooperating users create a "virtual" array through distributed transmissions, thus the system can also be seen as "virtual" MIMO system. A new element comes up in the communication between a source and destination, which is the relay terminal. The role played by it maybe dummy (it amplifies and forwards the received signal, AF) or smart (it decodes, re-encode and forwards the received signal to the destination, DF) [7].

Due to practical consideration in the design of RF equipment, orthogonal channels for the reception and retransmission from the relay are usually assumed, for example the Time Division Multiple Access (TDMA). Additionally, this consideration allows us to apply the cooperative transmission to the downlink (DL) to enhance high speed packet services in cellular networks.

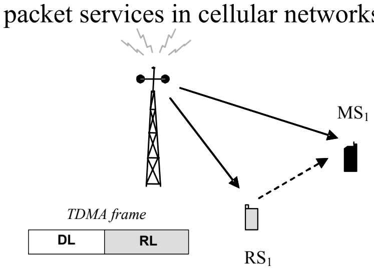

Figure 1.- Single user cooperative transmission. Solid line: transmissions in the DL. Dashed line: transmissions in the RL.

Figure 1 presents the single user cooperative transmission using a TDMA frame. The base station (BS) is the only source of the system and transmits a signal in the DL slot. This signal is received by the destination, a mobile station (MS), and its associated relay station (RS). Note that we assume that during some period of time there is an idle terminal helping the MS in the decoding of the signal transmitted by the BS (*user-relaying*). Likewise, the RS retransmits the received data to the destination in the relay link (RL) slot using the AF or the DF protocol. Destination receives data from two nodes in two separate time slots, so synchronization between the transmitting nodes is not required like in the uplink cooperative case. This scheme is able to provide diversity gains, though at the expenses of an increased utilization of the radio resources [7].

The consideration of multiple terminals reusing the relay link can help to combat the increased utilization of radio resources. In [8] it is proposed a convenient reuse of the relay channel for a system based on uplink transmissions using OFDM (orthogonal frequency division multiplexing) and algorithms for the power allocation based on the game theory. Figure 2 shows the main guidelines of this method applied to the downlink TDMA system. It assumes that one

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time slot is devoted for transmissions from the source to each destination and its associated relay (solid lines in Figure 2). Afterwards, the RL slot, is used for all the simultaneous transmissions from the RSs to its associated MSs. With this solution, N_u users are using N_u+1 slots and therefore the system exhibits a reuse factor of $\Pi = N_u/(N_u+1)$. In case of the single user cooperation (N_u=1) the reuse factor is Π=0,5.

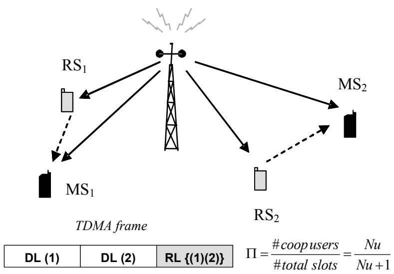

Figure 2.- DL cooperative transmission scheme for 2 users.

The contribution of this paper is the study of the cellular reuse of the relay link with unknown fast changing interference patterns experienced at the MS. This effect is typically found in best effort traffic situations. Alternatively [8][9] consider distributed power control algorithms suitable for QoS preservation. In this work we have modeled the interfering power distribution received at each MS in the RL slot. Therefore we assume the knowledge of the interfering power distribution information by the source. The objective is to show how reusing the relay slot can improve the single cooperative transmission by considering the interference generated as the only source of outage, thus assuming non-delayed BS-MS and BS-RS channel knowledge when selecting the transmission rate. In a nutshell, we will adjust the data rate in the cooperative transmission given the interference in the relay channel as the only source of an outage event. Moreover, it will be shown that significant gains can be provided without assuming any centralized scheduling or power allocation policy to control the total interference on the relay slot. This will be analyzed for the AF case, while the evaluation for DF is deferred to [12].

3. COOPERATIVE SCENARIO

In this work we have assumed a Poisson distribution of the terminals, MSs and RSs. In that case if the Poisson distribution has a parameter λ (the average number of terminals per unit area), the probability of finding *k* terminals in a region R with area A is given by,

$$P[k\ in\ R] = \frac{(\lambda A)^k}{k!}\exp(-\lambda A) \qquad (1)$$

There is only one source, the BS, equipped with M=2 antennas, which transmits Gaussian codewords. The destination, MS and the RS only have N=1 and R=1 antenna, respectively. The destination uses a simple receiver without any multi-user detection capability. As cooperative strategy we have considered the AF mode, [7]. Additionally, in our scenario it is assumed that each MS is able to select the nearest idle terminal (candidate to become a RS) as its associated RS. In that case and taking into account the distribution of the terminals, the distance between each RS-MS, r_2, becomes a random variable modeled by a Rayleigh distribution with parameter λ. Its pdf is given by,

$$f_{r_2}(r_2) = 2\pi\lambda r_2 \exp\left(-\pi\lambda r_2^2\right). \qquad (2)$$

Assuming that all terminals have the same probability of transmitting in the relay link slot (p_t), the set of the active terminals also presents a Poisson distribution with the following density $\lambda_{active}=\lambda p_t$. Moreover, we have fixed that those active RSs should obtain the same signal to noise ratio (SNR) in the relay link (without interference and only due to the path-loss in the relay link), achievable for example by a low rate feedback channel between each MS and its RS. Therefore, the transmitted power in each RS is given by,

$$P_{TX} = \min\left(P_{MAX}, \frac{1}{K_2} N_0 SNR r_2^{\gamma}\right) \quad SNR = K_2 \frac{P_{TX}}{(r_2)^{\gamma} N_0} \qquad (3)$$

with P_{MAX} the maximum power allowed at the RS, N_0 the noise density power, K_2 might consider the effect of shadowing and r_2 the distance between each RS and its associated MS, a random variable given by (2). The power transmitted by each RS is variable due to r_2.

It is also implicitly assumed that the scheduler at the BS is serving packets randomly to all users within the cell without assigning any priority. This way, the interference patterns generated are homogeneous and completely random.

3. INTERFERENCE MODELING

The interfering power received by a MS due to an interfering RS is given by,

$$g(r_1) = K_1 \frac{P_{TX}}{(r_1)^{\gamma}} \qquad (4)$$

with P_{TX} the power transmitted by the interfering RS, r_1 the distance between the MS and some interfering RS, γ the propagation exponent and K_1 is a constant that can take into account the shadowing and fast fading effects. In case of assuming the variable power transmission level due to (3), the interference power received is given by,

$$g(r_1,r_2) = \begin{cases} \frac{K_1}{K_2} N_0 SNR \frac{r_2^{\gamma}}{r_1^{\gamma}} = C_1\left(\frac{r_2}{r_1}\right)^{\gamma} & r_2 \le \Delta = \left[\frac{K_2 P_{MAX}}{N_0 SNR}\right]^{\frac{1}{\gamma}} \\ K_1 \frac{P_{MAX}}{r_1^{\gamma}} = C_2\left(\frac{1}{r_1}\right)^{\gamma} & otherwise \end{cases} \qquad (5)$$

In order to study the interference received by a MS we have followed the same procedure considered in [10] (but it assumes that terminals transmit at fixed power level). Let Y_a be the interference power received from those active RSs which are in D_a, a disk of radius *a*,

$$Y_a = \sum_{r_1 \le a} g(r_1, r_2) \qquad (6)$$

Afterwards, letting $a \to \infty$ then $Y_a = Y$, we will obtain the characteristic function of the total interference, Y. The characteristic function of Y_a may be evaluated as,

$$\begin{aligned}\phi_{Y_a}(\omega) &= \mathbf{E}\left(e^{i\omega Y_a}\right) = \mathbf{E}\left(\mathbf{E}\left(e^{i\omega Y_a} \mid k \ in\ D_a\right)\right) = \\ &= \sum_{k=0}^{\infty} \frac{\left(\lambda_{active}\pi a^2\right)^k}{k!} \exp\left(-\lambda_{active}\pi a^2\right) \mathbf{E}\left(e^{i\omega Y_a} \mid k \ in\ D_a\right)\end{aligned} \tag{7}$$

with λ_{active} the density of active relays in the RL. After some calculation we obtain the characteristic function of an α-stable variable [11]:

$$\phi_Y(\omega) = \exp\left(-K\cos(\alpha\pi/2)(\omega)^{\alpha}\left(1 - i\tan(\alpha\pi/2)\right)\right) \tag{8}$$

and K a constant given by,

$$K = \left(\left(\frac{N_0 SNR}{K_2}\right)^{\alpha} \frac{\left(1-\left(1+\pi\lambda\Delta^2\right)\Omega\right)}{\pi\lambda} + \Omega\left(P_{MAX}\right)^{\alpha}\right)\Upsilon, \tag{9}$$

$$\Upsilon = \Gamma(1-\alpha)\left(K_1\right)^{\alpha}\lambda_{active}\pi,\ \Omega = \exp\left(-\pi\lambda\Delta^2\right)$$

with $\alpha=2/\gamma$, $\Gamma(\cdot)$ the Gamma function and Δ given by (5). In case of $\gamma=4$ it is possible to obtain a closed-form expression for its cumulative density function (cdf),

$$F(y<x) = erfc\left(\frac{K}{2\sqrt{x}}\right) \tag{10}$$

4. CELLULAR THROUGHPUT

In order to study the benefits of the cooperative transmission with cellular reuse of the relay link we will study the Sum-Throughput (ST) obtained by (N_u+1) users in the direct transmission and by N_u users using cooperation, both using (N_u+1) TDMA slots. Note that cooperation needs of 1 slot for relaying. For comparison purposes we have assumed all served users with the same channel. The ST is given by,

$$Sum\_Thr_{DL} = \frac{1}{\left(N_u+1\right)T_{slot}} \sum_{j=1}^{N_u+1} R_j^{DL} T_{slot} = R^{DL}\ (bps/Hz) \tag{11}$$

with (N_u+1) the number of served users and T_{slot} the period of time devoted for one downlink slot. Assuming that SNR_0, SNR in the BS-MS link, defined in (12), is known at the transmitter, the selected rate at the downlink is,

$$R^{DL} = \log_2\left(1 + \frac{P_{BS}}{N_0 M L_0}\mathbf{h}_0\mathbf{h}_0^H\right) = \log_2\left(1 + SNR_0\right) \tag{12}$$

with P_{BS} the power transmitted by the BS, M the number of transmit antennas, L_0 the pathloss and $\mathbf{h}_0 \in \mathbb{C}^{1xM}$ the channel coefficients in the BS-MS link. In case of cooperative transmission we have to consider the effect of the unknown interfering power received during the relay slot, modeled in the previous section. Assuming all the N_u users exhibit the same cooperative link capacity, the ST is given by:

$$\begin{aligned}Sum\_Thr_{AF} &= \frac{1}{\left(N_u+1\right)T_{slot}} \sum_{j=1}^{N_u} R_j^{AF}\left(1 - P_{out}\left(R_j^{AF}\right)\right)T_{slot} = \\ &= \Pi R^{AF}\left(1 - P_{out}\left(R^{AF}\right)\right) = \Pi\, Thr_{AF}\end{aligned} \tag{13}$$

being R^{AF} the selected rate and P_{out} the outage probability,

$$P_{out} = \Pr\left(I^{AF} < R^{AF}\right) \tag{14}$$

with I^{AF} the Mutual Information (MI) of the cooperative system (assuming N=R=1 and M≥1):

$$I^{AF} = \log_2 \Psi \tag{15}$$

$$\begin{aligned}\Psi = &\left(1 + \frac{\mathbf{h}_0\mathbf{h}_0^H \frac{P_{BS}}{ML_0}}{N_0}\right)\left(1 + \frac{\frac{P_{BS}}{ML_2L_1} h_2 g \mathbf{h}_1\mathbf{h}_1^H g^* h_2^*}{h_2 g g^* h_2^* N_0 + N_0 + Y}\right) \\ &- \frac{\frac{P_{BS}}{M\sqrt{L_0L_1}}\mathbf{h}_0\mathbf{h}_1^H g^* h_2^* h_2 g \mathbf{h}_1\mathbf{h}_0^H \frac{P_{BS}}{M\sqrt{L_0L_1}}}{N_0\left(h_2 g g^* h_2^* N_0 + N_0 + Y\right)}\end{aligned} \tag{16}$$

with Y the interfering power received in the RL, L_0,L_1 and L_2 the pathloss, $\mathbf{h}_0 \in \mathbb{C}^{1xM}$, $\mathbf{h}_1 \in \mathbb{C}^{1xM}$ and $h_2 \in \mathbb{C}$, the channel coefficients in the BS-MS, BS-RS and RS-MS link, respectively. Finally, $g \in \mathbb{C}$ is the gain factor applied at the RS whose modulus is given by

$$g = \sqrt{\frac{P_{RS}}{R\left(\mathbf{h}_1\mathbf{h}_1^H \frac{P_{BS}}{L_1} + N_0\right)}} \tag{17}$$

After some tedious transformations from (15) and (16),

$$I_{AF} = \log_2\left(\left(1 + SNR_0\right)\left(1 + \frac{SNR_1 \frac{SNR_2}{1+Y/N_0}\Theta}{\left(\frac{SNR_2}{1+Y/N_0} + SNR_1 + 1\right)}\right)\right) \tag{18}$$

with the following variable definition

$$\begin{aligned}&\Theta = \frac{1 + SNR_0(1-\xi)}{1 + SNR_0}\quad \xi = \frac{\mathbf{h}_0\mathbf{h}_1^H\ \mathbf{h}_1\mathbf{h}_0^H}{\mathbf{h}_0\mathbf{h}_0^H\ \mathbf{h}_1\mathbf{h}_1^H} \\ &SNR_0 = \frac{P_{BS}\mathbf{h}_0\mathbf{h}_0^H}{N_0L_0M}\quad SNR_2 = \frac{P_{RS}h_2h_2^H}{N_0L_2R}\quad SNR_1 = \frac{P_{BS}\mathbf{h}_1\mathbf{h}_1^H}{N_0L_1M}\end{aligned} \tag{19}$$

with SNR_0, SNR_1 and SNR_2 the SNR in the BS-MS, BS-RS and RS-MS links, respectively. Needless to say that in order to maximize to Sum-Throughput the transmission rate should be selected so as to maximize,

$$Thr_{AF} = \max_{R^{AF}}\left\{R^{AF}\left(1 - P_{out}\left(R^{AF}\right)\right)\right\} \tag{20}$$

Taking into account the interfering power modeled in (10), equation (20) turns into

$$Thr_{AF} = \max_{R^{AF}}\left\{erfc\left(\frac{K}{2\sqrt{N_0\left(\frac{SNR_2}{1+SNR_1}\left(\frac{SNR_1}{2^{R^{AF}-R^{DL}}-1} - 1\right) - 1\right)}}\right)R^{AF}\right\}$$

Figure 3 depicts the ST for direct, (11) and cooperative transmission (13). Our scenario is defined by M=2,N=R=1, $\lambda=10^{-4}$ users/m^2 and SNR_2=15 dB, (19). Results are obtained varying the simultaneous users in the RL for different values of SNR_0. It can be seen that allowing 1 interfering user, gains of 21% and 18% over the direct transmission can be achieved at SNR_0=6 and 10 dB. These results are better than the non-reuse case (that is without interference, displayed as Int=0). Here, the gain obtained by the reusing factor, Π, is higher than effect of generated interference. In this case, the maximum ST is achieved with 6 interfering users, obtaining gains up to 41% and 36% at SNR_0=6 and 10 dB, respectively. However, adding more interferers penalize the total ST because of the generated interference dominates the total gain.

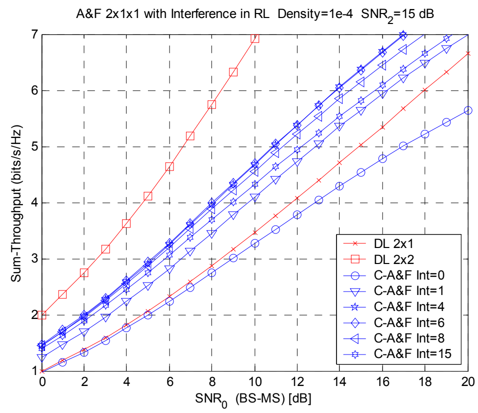

Figure 3.- Sum-Throughput per user for the AF (20)with different number of interferers and SNR_0 values. SNR_2=15, SNR_1=SNR_0. R=1. Density 10^{-4} users/m^2 P_{MAX}=20 dBm. Θ=1

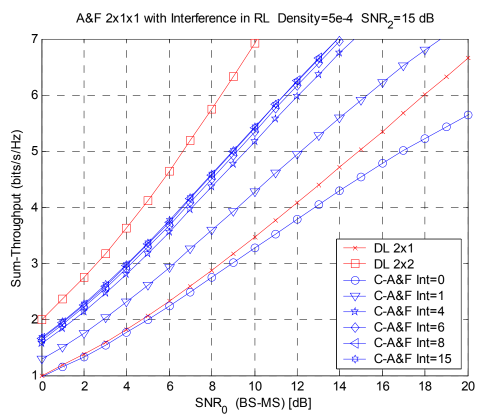

Figure 4.- Sum-Throughput for the AF (20)with different number of interferers and SNR_0 values. SNR_2=15, SNR_1=SNR_0 (dB). R=1. Density 5x10^{-4} users/m^2 P_{MAX}=20 dBm. Θ=1

In Figure 4 we have increased the user density, λ=5x10^{-4} users/m^2. Higher gains are obtained, 63% and 57% at SNR_0=6 and 10 dB over the direct transmission. Finally, figure 5 shows the ST for both densities at SNR_0=8 dB and varying the interfering terminals. The higher density allows better ST and more simultaneous terminals in the RL.

5. CONCLUSIONS

This work has shown that is possible to apply the cooperative transmission to a centralized cellular system and improve the TDMA direct transmission without strict knowledge of the interference. The way considered is the reuse of the relay slot by simultaneous users. To this end we have modeled the interfering power received at each destination in the relay slot as a way to evaluate outage events in this reused, cooperative links. Moreover we have analyzed in terms of Sum-Throughput the performance of the cooperative transmission AF over the direct transmission. It has been shown that it is possible to achieve significant gains in terms of Sum-Throughput for some densities of users. Extension for other cooperative protocols and different antenna configuration is in preparation [12].

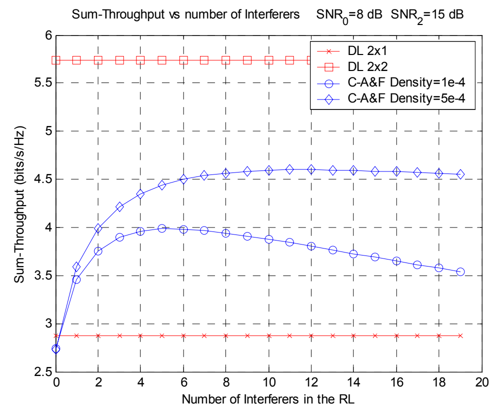

Figure 5.- Sum-Throughput for the AF (20) with different number of interferers and SNR_2=15, SNR_0= SNR_1=8 (dB). Density 10^{-4} and 5x10^{-4} users/m^2 P_{MAX}=20 dBm. Θ=1

5. REFERENCES

[1] I.E Telatar, "Capacity of multi-antenna Gaussian channels", European Trans. on Telecomm. vol10, pp 585-595, Nov/Dec 1999

[2] G.Foschini, M.J.Gans, "On limits of wireless communications in a fading environment when using multiple antennas", Wireless Personal Communications, vol 6, nº3, pp 311-335, 1998

[3] L.Zheng, D.N.C.Tse, "Diversity and Multiplexing: A fundamental tradeoff in multiple antenna channels", IEEE Trans. on Information Theory, vol 49, nº5, May 2003

[4] T.M. Cover, A.A. El Gamal, "Capacity Theorems for the relay channel", IEEE Trans. on IT, vol 25, nº5, pp 474-584, Sep 1979

[5] A. Host-Madsen, J. Zhang, "Capacity Bounds and Power Allocation for Wireless Relay Channels", IEEE Trans. Information Theory., vol 51, nº6, June 2005

[6] A. Sendonaris, E.Erkip, B.Aazhang, "User cooperation diversity part I: System description", IEEE Trans. on Comm., vol 51, nº11, November 2003

[7] J.N.Laneman, D.N.C.Tse, G.W.Wornell, "Cooperative diversity in wireless networks: Efficient protocols and Outage Behaviour", IEEE Tran. on IT, vol 50, nº12, December 2004

[8] G.Scutari, S.Barbarossa, D.Ludovici, "Cooperation diversity in multihop wireless networks using opportunistic driven multiple access", Proc. of SPAWC 2003, Rome, Italy, June 2003

[9] A.Agustin, O.Muñoz, J.Vidal, "A game theoretic approach for cooperative MIMO systems with cellular reuse of the relay slot", Proc. of ICASSP 2004, May 2004, Montreal (Canada)

[10] E.Sousa, J.Silvester, "Optimum trasmission ranges in a direct sequence spread spectrum multihop packet radio network", IEEE Journal on Selected Areas in Comms, vol 8, nº5 June 1990

[11] M.Shao, C.L.Nikias, "Signal Processing with Fractional Lower Order Moments: Stable Processes and their applications", Proc. of the IEEE, vol 81, nº7, July 1993

[12] A.Agustin, J.Vidal, "TDMA downlink cooperation under interference-limited spatial reuse of the relay slot", in preparation.