Optimal power allocation for downlink cooperative cellular networks

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***Abstract*— In cellular networks, Base Stations can cooperate in order to bring spatial diversity. Cooperative diversity enables to increase link capacity and Signal to Noise Ratio. This paper presents source and relay Base Station's optimal power allocation in order to maximize the sum capacity over all relayed links. Average power allocation is solved by an iterative method which allocates relay and source powers separately, by convex optimization. Then source symbol powers are set with simple water-filling, in order to maximize the capacity. Simulation results show that sum capacity is highly increased by relaying under optimal power values. Relaying is especially efficient for user terminals who would have poor radio conditions without relaying. The paper also presents a simple method, based on path loss characterization, to determine the need for relaying. It can be used independently in the source Base Station's, which is particularly adapted for flat architectures.**

***Keywords*— Cooperation, diversity, power allocation, convex optimization.**

I. Introduction

Cooperative relaying [1] is a promising technique to bring cooperation diversity in wireless networks. Cooperative relaying enables to perform virtual Multiple Inputs, Multiple Outputs (MIMO) arrays and benefit from spatial diversity. User cooperation diversity has originally been introduced by Sendonaris et al. for uplink cooperation [2] [3] [4]. The two main uplink transmission protocols that have been proposed are Amplify-and-Forward (AF) and Decode-and-Forward (DF) [5] [6]. In the AF protocol, the relay simply amplifies the received signal and re-transmits it. In the DF protocol, the relay fully decodes, re-encodes, and re-transmits the message. These protocols are well adapted for uplink transmission in ad-hoc networks. However, cooperative relaying can also be used in cellular networks, in both uplink and downlink. Up to now, most studies on cellular cooperation rely on coverage improvement and do not bring diversity [7].

At system level, great capacity increase can be expected from efficient power allocation in cooperative relaying. Optimal power allocation between source and relay has been studied in [8] for the case when source and relay share a total amount of transmit power over the two time-slots required for relaying. In [9], an iterative joint power allocation method is presented for two-hop communications schemes using OFDM modulation. However, this work has mainly been performed in uplink.

In the present paper, we are interested in downlink cooperation between Base Stations in cellular networks. The rationale for our study is that cooperation between Base Stations seems well suited for defining new Radio Resource Management (RRM) methods in cellular networks based on flat architectures.

Cooperative relaying between Base Stations removes some of the issues of uplink relaying: there is no need for joint power optimization, as both Base Stations have separate resources, and known relaying protocols such as AF and DF do not apply, because inter-Base Station channel is wired and assumed perfect. However, new issues arise, such as interference management and resource usage restrictions, which must be treated at system level.

This paper proposes an optimal power allocation scheme for downlink cooperation between two Base Stations, which proves to be very efficient to increase link capacity and Signal to Noise Ratio (SNR). In order to use this scheme efficiently in flat architecture, we also present a simple method to reduce inter-Base Station signalling without degrading the overall performance.

The remainder of the paper is organized as follows. Section II introduces the system model and notations. Section III presents the optimal power allocation method, first on the average channel and then on each source symbol. Performance results are presented in section IV, as well as an inter-Base Station signalling restriction method. Conclusions are given in the last section.

II. System model

We consider two Base Stations, BS_s and BS_r. BS_s is the source for N users in OFDMA. BS_r may serve as a relay for downlink transmission between BS_s and each user k. Transmission between the two Base Stations is assumed perfect (noiseless wideband channel). However, downlink relaying is constrained by causality: BS_s transmits data symbols to BS_r in time slot t, and BS_r cannot restrannsmit them until time slot $t+1$. A two-time slot relaying scheme is used: at time t, BS_s transmits symbol $x_{k,1}$ to user terminal k and towards BS_r for relaying. At time $t+1$, BS_s transmits symbol $x_{k,2}$ to user terminal k, and BS_r relays symbol $x_{k,1}$ to user terminal k. Let $\vec{y}_k = (y_{k,1}, y_{k,2})$ be the vector of symbols received by the user terminal k.

$$y_{k,1} = h_{s,k}\sqrt{\frac{p_{s,k}}{l_{s,k}\sigma^2}}x_{k,1} + n_{k,1}$$

$$y_{k,2} = h_{r,k}\sqrt{\frac{p_{r,k}}{l_{r,k}\sigma^2}}x_{k,1} + h_{s,k}\sqrt{\frac{p_{s,k}}{l_{s,k}\sigma^2}}x_{k,2} + n_{k,2}$$

Let $\mathbf{H}_k$ be the equivalent channel matrix:

$$\mathbf{H}_k = \begin{pmatrix} h_{s,k}\sqrt{\frac{p_{s,k}}{l_{s,k}\sigma^2}} & 0 \\ h_{r,k}\sqrt{\frac{p_{r,k}}{l_{r,k}\sigma^2}} & h_{s,k}\sqrt{\frac{p_{s,k}}{l_{s,k}\sigma^2}} \end{pmatrix} \tag{1}$$

With the following notations:

- $p_{s,k}$ (resp. $p_{r,k}$ is the transmit power from the source (resp. the relay) to user k.
- $l_{s,k}$ (resp. $l_{r,k}$ is the path loss (including shadowing) from the source (resp. the relay) to user k.
- $h_{s,k}$ (resp. $h_{r,k}$) is the fast fading channel coefficient between the source (resp. the relay) to user k.
- σ^2 is the noise variance, which is the same on both links, as it only depends on the destination (user k).
- $\vec{n_k} \sim \mathcal{CN}(0, \mathbf{I})$ is AWGN.

We make the assumption that there is no inter-cell interference, thanks to frequency allocation, and that OFDMA modulation is defined so as to cancel intra-cell interference. We also suppose that all users use only one OFDMA subcarrier at a time.

The transmission channel can consequently be modelled as:

$$\vec{y_k} = \mathbf{H}_k\vec{x}_k + \vec{n}_k \tag{2}$$

If the same power allocation is used on both $\vec{x}_k$ symbols (i.e., $E[\vec{x}_k\vec{x}_k^*] = \mathbf{I}$), link capacity is [11]:

$$\begin{aligned} C_k &= \frac{1}{2}\log_2\left(\det(\mathbf{I} + \mathbf{H}_k\mathbf{H}_k^*)\right) \\ &= \frac{1}{2}\log_2\left(\left(1 + \frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k}\right)^2 + \frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}p_{r,k}\right) \end{aligned} \tag{3}$$

Factor $\frac{1}{2}$ comes from the fact that two time slots (i.e., two channel uses) are needed to transmit the symbols. The sum capacity over all N users in BS_s is

$$C = \sum_{k=1}^{N} C_k \tag{4}$$

NB: If relaying is not used, k-link capacity is:

$$C_k = \log_2\left(1 + \frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k}\right) \tag{5}$$

III. Power allocation optimization

Our goal is to maximize the sum capacity over all links via power allocations on source and relay Base Stations. In the equivalent channel matrix $\mathbf{H}_k$, the transmit powers from the source and the relay are averaged over the two time slots. They correspond to "system-level" powers. The first optimization step consists in setting optimal averaged transmit powers, in order to obtain the $\mathbf{H}_k$ matrix that maximizes capacity when there is no symbol-level optimization (i.e. , when $E[\vec{x}_k\vec{x}_k^*] = \mathbf{I}$). Then, the second optimization step consists in adapting $\vec{x}_k$ in order to maximize C_k once $\mathbf{H}_k$ is fixed. This second step is a classical water-filling optimization, whereas the first step requires a complete analytical study.

A. Iterative optimization for source and relay powers

Each Base Station has separate power constraints. Consequently, the optimization problem is:

$$(\vec{p}_s^{\,*}, \vec{p}_r^{\,*}) = \arg\max_{\vec{p}_s,\vec{p}_r} \sum_{k=1}^{N} C_k \tag{6}$$

$$\vec{1}^T\vec{p}_s = P_s \qquad \vec{p}_s \geq \vec{0}$$

$$\vec{1}^T\vec{p}_r = P_r \qquad \vec{p}_r \geq \vec{0}$$

P_s and P_r are the maximum allowed powers on BS_s and BS_r. As power constraints on BS_s and BS_r are independent, the optimization problem can be solved separatly over the source and the relay. We propose to use an iterative optimization method: first maximize capacity via relay power allocation (assuming that source power allocation is known), then maximize capacity via source power allocation with the previously obtained relay power values. This method is iterated until convergence.

1) Optimization of relay power: We assume that $\vec{p}_s$ is given. The optimization problem over $\vec{p}_r$ is:

$$\vec{p_r}^{\,*} = \arg\max_{\vec{p}_r} \sum_{k=1}^{N} C_k$$

$$\text{subject to } \vec{1}^T\vec{p}_r = P_r \text{ and } \vec{p}_r \geq \vec{0} \tag{7}$$

This is a convex optimization problem [12], which can be solved with the Karush-Kahn-Tucker (KKT) conditions. The corresponding Lagragian function is:

$$\begin{aligned} L(\vec{p_r}, \vec{\lambda}, \mu_r) = \sum_{k=1}^{N} &\log\left(\det(\mathbf{I} + \mathbf{H}_k\mathbf{H}_k^*)\right) \\ &+ \vec{\lambda}\vec{p}_r - \mu_r(\vec{1}^T\vec{p}_r - P_r) \end{aligned} \tag{8}$$

The derivative of the Lagragian with respect to $p_{r,k}$ is given by:

$$\frac{\partial L}{\partial p_{r,k}} = \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1 + \frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k})^2 + \frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}p_{r,k}} + \lambda_k - \mu_r \tag{9}$$

The KKT conditions impose that: $\frac{\partial L(p_r, \vec{\lambda}, \mu_r)}{\partial p_{r,k}} = 0$ and $\lambda_k \geq 0$, on top of the original constraints.

$\lambda_k \geq 0$ condition corresponds to

$$\mu_r \geq \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1 + \frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k})^2 + \frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}p_{r,k}} \tag{10}$$

Another KKT condition is that $\lambda_k p_{r,k} = 0$, i.e.,

$$\left(\mu_r - \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1 + \frac{|h_{s,k}|^2}{PL_{s,k}\sigma^2}p_{s,k})^2 + \frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}p_{r,k}}\right)p_{r,k} = 0 \tag{11}$$

If $\mu_r < \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1+\frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k})^2}$ then this condition can only be fulfilled if $p_{r,k} > 0$. In this case, we must have:

$$\mu_r = \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1+\frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k})^2 + \frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}p_{r,k}} \tag{12}$$

If $\mu_r > \frac{\frac{|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(1+\frac{|h_{s,k}|^2}{l_{s,k}\sigma^2}p_{s,k})^2}$ with $p_{r,k} > 0$ this cannot be achieved. Consequently, $p_{r,k} = 0$. Finally, we obtain :

$$p_{r,k} = \left[\frac{1}{\mu_r} - \frac{l_{r,k}\sigma^2}{|h_{r,k}|^2}\left(1 + \frac{|h_{s,k}|^2 p_{s,k}}{l_{s,k}\sigma^2}\right)^2\right]^+ \tag{13}$$

where $[x]^+ = \max\{0, x\}$. The constant μ_r must be chosen so that the power constraint $\vec{1}^T\vec{p}_r = P_r$ is fulfilled.

2) Optimization of source power: We now assume that $\vec{p}_r$ is given. The optimization problem over $\vec{p}_s$ is:

$$\vec{p}_s^{\,*} = \arg\max_{\vec{p}_s} \sum_{k=1}^{N} C_k$$
$$\text{subject to } \vec{1}^T\vec{p}_s = P_s \text{ and } \vec{p}_s \geq \vec{0} \tag{14}$$

Solving this problem with the KKT conditions is a bit more complex than the relay power allocation, is source powers have square coefficients in the capacity expression. However, an analytical solution can be found:

$$p_{s,k} = \left[\frac{1}{\mu_s} + \frac{1}{\mu_s}\sqrt{\left[1 - \frac{\frac{p_{r,k}|h_{r,k}|^2}{l_{r,k}\sigma^2}}{(\frac{|h_{s,k}|^2}{l_{s,k}\sigma^2})^2}\mu_s^2\right]^+} - \frac{l_{s,k}\sigma^2}{|h_{s,k}|^2}\right]^+ \tag{15}$$

μ_s is a parameter that must be chosen so that the power constraint $\vec{1}^T\vec{p}_s = P_s$ is fulfilled.

B. Source symbols power optimization

Once averaged power values have been set in $\mathbf{H}_k$, the second optimization step consists in adapting $\vec{x}_k$ to maximize the capacity. Indeed, if $E[\vec{x}_k\vec{x}_k^*] = \mathbf{Q}$ is different from $\mathbf{I}$, then the capacity becomes:

$$C_k = \frac{1}{2}\log_2\left(\det(\mathbf{I} + \mathbf{H}_k\mathbf{Q}\mathbf{H}_k^*)\right) \tag{16}$$

According to the Singular Value Decomposition theorem, $\mathbf{H}_k$ can be written as $\mathbf{H}_k = \mathbf{U}\mathbf{\Delta}\mathbf{V}^*$, where $\mathbf{U}$ and $\mathbf{V}$ are two singular matrixes, and $\mathbf{\Delta}$ is a diagonal matrix whose eigenvalues λ_i^2 are the eigenvalues of $\mathbf{H}_k\mathbf{H}_k^*$.
Let $x'_k = \mathbf{V}^*x$. The capacity then becomes:

$$C_k = \frac{1}{2}\log_2(\det(\mathbf{I} + \mathbf{\Delta}\mathbf{Q}\mathbf{\Delta}^*)) = \frac{1}{2}\sum_{i=1}^{2}\log_2(1 + \lambda_i^2 x'^2_{k,i}) \tag{17}$$

This is a classical water-filling problem, whose solution is:

$$x'^2_{k,i} = \left[\mu_x - \frac{1}{\lambda_i^2}\right]^+ \tag{18}$$

μ_x must fulfill the total power conditions: $x^2_{k,1} + x^2_{k,2} = 1$ which is equivalent to $x'^2_{k,1} + x'^2_{k,2} = 1$ because $\mathbf{V}$ is a unitary matrix.

IV. Performance

In this section, the performance of power allocation for downlink cooperation diversity are presented. The method's performance are assessed with Monte-Carlo simulations. Simulations are performed with $N = [16, 64, 128, 256, 512, 1024]$ users.

A. Simulations' model

Our model consists of one source Base Station, BS_s, which is surrounded by 6 neighboring Base Stations with hexagonal deployment. Each Base Station is composed of one omnidirectional antenna. Inter-site distance is $0.7\sqrt{3} = 1.212$ km. User terminals' positions are randomly drawn within the source Base Station's coverage area. Path loss model is Okumura-Hata [10]: $l(d) = 137.74 + 35.22\log(d)$ in dB. Shadowing's standard deviation is 7 dB. We suppose that the downlink noise is $\sigma^2 = -105$ dBm. The maximum transmit power on each antenna is $P_s = P_r = 43$ dBm.
For each user, we first determine the Base Station relay, among the 6 neighboring Base Stations. Optimum average power allocation on each neighboring Base Station is independent of the other neighboring Base Stations. It only depends on the powers allocated to the source. Consequently, given an initial $\vec{p}_s$ value, we first compute $\vec{p}_{r_i}^{\,*}$ for $i = [1, 6]$. Then $\vec{p}_s^{\,*}$ is computed with $\vec{p}_{r_i}^{\,*}$ as inputs. We use 5 iterations in order to reach convergence.

B. Capacity performance

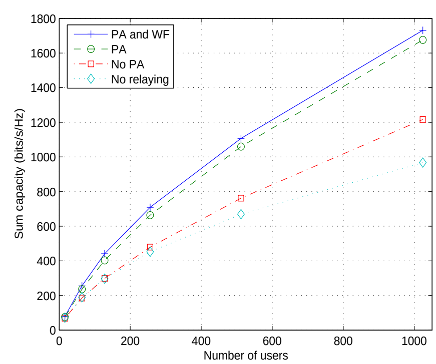

Fig. 1. Sum capacity, depending on the power allocation method

Fig. 1 shows the sum capacity performance with average power allocation ("PA") and with average power allocation and source symbol power optimization ("PA and WF"). They are compared with two simple schemes: first, a relaying scheme in which all powers are set to the same value $\frac{P_s}{N}$ for the source and $\frac{P_r}{N}$ for each relay ("No PA"). Second, a non-relaying scheme in which source power is however optimized via direct Water-filling ("Non relaying"). Optimal average power allocation highly increases sum capacity, if compared with the non-relaying case. More important gain is achieved when the number of users increases. Indeed, relaying enables to avoid (or at least delay) power saturation, which is reached with less

TABLE I

RELAYING EFFICIENCY AND COST

N	% of useful relaying	required subcarriers per relay
16	17.92	0.48
64	40.66	4.34
128	45.57	9.72
256	50.65	21.61
512	49.18	41.97
1024	44.74	76.36

TABLE II

CAPACITY GAIN PROVIDED BY RELAYING WHEN RELAYING IS USEFUL

N	C_{relay} (b/s/Hz)	$C_{\text{no relay}}$(b/s/Hz)	$\frac{C_{\text{relay}}}{C_{\text{no relay}}}$
64	0.951	0.307	3.10
128	0.897	0.242	3.71
256	0.764	0.169	4.52
512	0.602	0.108	5.55
1024	0.459	0.065	7.11

users when relaying is not used. Besides, Fig. 1 shows that when the same transmit power is used for all users, relaying is not efficient. It should be noted that in the non-relaying case, single source power optimization is performed, which explains why it is better than the relaying case with similar power allocations at high number of users. Finally, Fig. 1 shows that using source symbol power optimization enables to slightly increase the capacity. The gain is not important because there are only two symbols: we can expect greater gain with higher number of symbols (which also implies higher number of time slots and relays).

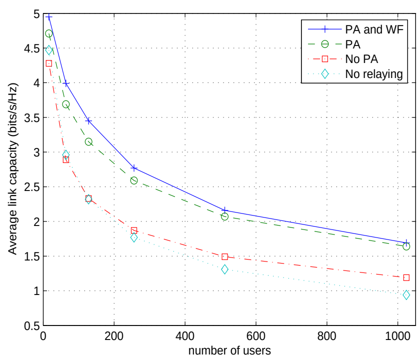

Fig. 2. Average Link capacity, depending on the power allocation method

The average link capacity is presented on Fig. 2. The same conclusions can be drawn than from the sum capacity results. This figure however enables to see that link capacity decreases when the number of users increases, because of power saturation. Using relaying and optimal power allocation enables to slightly mitigate this decrease, however the limitation remains, especially because relaying is not used (neither useful) in many cases, especially when the user is not located at the source cell's border.

We assume that relaying is useful for user terminal k whenever the power transmitted from the relay to user k is different from zero after optimal power allocation. The percentage of useful relaying is an important statistics to evaluate relaying cost. Indeed, relaying uses power and frequency resources on each relay. An important issue is to prevent useless relaying, in order to keep low relay resource usage. We will see in the next section that useful relaying can be easily characterized thanks to path loss characteristics. Table I shows that the ratio of useful relaying does not exceed 50%. It increases when the number of users is less than 256 and then slightly decreases as the number of users increases. When the number of users is low, the source has enough power to provide for all users, even the ones at the cell's border, so relaying's requirement is low. Then when the number of users increases, power saturation on the source explains for the relaying's need. Finally, at high number of users, the relays start saturating in power, which explains for the decrease in relaying requirement. Table I also presents the number of subcarriers required on each of the 6 relay Base Station. We can see that it remains quite low, but this is due to the fact that we have modelled only one user's source Base Stations to relay, with 6 relaying Base Stations.

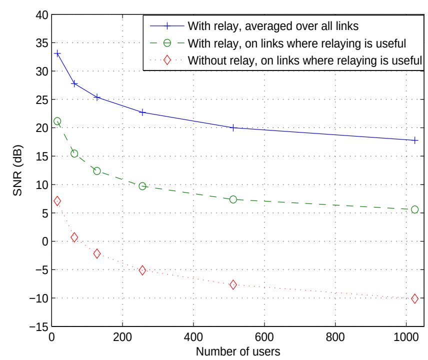

Fig. 3. SNR gain provided by relaying on links where relaying is useful

The previous results have shown the relaying cost and capacity results averaged over all links. We are now interested in relaying efficiency for users who actually need relaying. Table II shows the capacity gains which is provided by relaying, restricted on links where relaying is useful. Link capacity is importantly increased by relaying in these cases, and the gain increases with the number of users. Similar results can be seen on average Signal to Noise Ratio (SNR) on Fig. 3. On links where relaying is needed, if no relaying was used, then the SNR would be very low, probably leading to packet losses or even to a dropped connection. However, relaying enables to recover from these bad conditions and to mitigate SNR degradation. Our power allocation scheme is consequently an interesting method to smooth down radio conditions degradations, which is particularly useful for real-time applications. It could be very beneficial when combined with system level Radio Resource Management (RRM) schemes such as handover.

C. Characterization of useful relaying

In the previous section, we have seen that it is necessary to reduce relaying cost, while maintaining its efficiency on capacity and SNR gains, especially for the links that require relaying to avoid degradations. Relaying cost in terms of frequency resources can not be directly mitigated with our method: indeed, it would require system-level RRM methods such as admission control and resource allocation control. Relaying cost in terms of power is already reduced by our power allocation scheme.

Another relaying cost is induced by signalling: indeed, whenever BS_s asks a neighboring Base Station for relaying for user terminal k, BS_s must send the symbols data $\vec{x}_k$ to the chosen BS_r. If power allocation leads to $p_{r,k} = 0$, then data transferring between the two Base Stations has been useless.

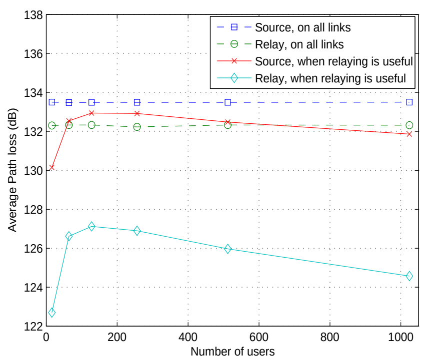

Fig. 4. Characterization of useful relaying with average path loss values

In this section, we propose a simple method for directly characterizing in the source Base Station when relaying is usefull, so that the source Base Station can restrict its user's data transferring to the neighboring Base Stations which will actually be useful. Fig. 4 shows the path loss values from the source and the relay to the user terminal averaged over all links, and restricted to links where relaying is useful. Useful relaying cases correspond to low path loss values between the relay and the user terminal. This is coherent with the intuition that relaying is useful when users are close to their candidate relay.

As a consequence, a method for restricting inter-Base Station signalling is to send symbol data information to the candidate relay only when pre-determined path loss conditions are fulfilled. The user terminal performs measurements on the different Base Stations periodically for normal operations, and sends this information to its source Base Station. The source Base Station has previous knowledge of path loss threshold values that characterize relaying utility: $l_{s,\text{trigger}}$ is the minimum path loss from the source above which relaying is useful, and $l_{r,\text{trigger}}$ is the maximum path loss from the relay under which relaying is useful. At reception of path loss information for user k, BS_s checks if $l_{s,k} > l_{s,\text{trigger}}$ and if $l_{r,k} < l_{r,\text{trigger}}$, with r the index of the neighboring Base Station that minimizes the path loss. If these conditions are fulfilled, then BS_s sends user's k data symbol information to BS_r for relaying in the next time slot. As seen on Table I, this method enables to restrict inter-Base Station signalling by at least a factor 2.

V. Conclusions

An iterative average power allocation scheme for downlink cooperation diversity is proposed, to maximize the sum capacity over all relayed links. Downlink cooperation between Base Stations is a promising technique at system-level to increase capacity in flat-architecture cellular networks, which should be used in coordination with adapted radio resource management schemes. Our method importantly improves the sum capacity, and is especially efficient for links where the user terminal would be in degraded radio conditions, if relaying was not used. We also combine average power allocation with source symbol power allocation, which improves performance results even more. A simple method, based on path loss evaluations, enables to determine whether relaying is necessary or not for any user terminal. This can be used directly in the source Base Station, based on normal-operations user terminal's measurements. It therefore enables to restrict inter-Base Stations signalling efficiently. Future work will consist in associating optimal power allocation with RRM techniques for mobility and scheduling.

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