

Information theoretic analysis of multicell decoding and Amplify-and-Forward cooperation between mobiles for TDMA cellular systems

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Abstract—Cooperation between base stations and collaborative transmission between mobile terminals are two technologies currently under study as promising paradigms for next generation communications systems. In this paper, a first look to the interplay between these two approaches is provided by studying the per-cell achievable sum-rate (throughput) of different cooperative protocols under a simplified model for the uplink of a TDMA cellular system. The analysis is limited to non-regenerative (Amplify-and-Forward) cooperation between terminals. It is shown that while AF cooperation is generally advantageous for single cell processing (i.e., with no collaboration between base stations), its benefits when combined with multicell processing are limited to the regime of low to moderate transmission rates.

I. INTRODUCTION

An increasing number of applications, ranging from high data rate ubiquitous access to the Internet to emergency and disaster relief, is shifting the attention of the communications community from the standard cellular paradigm to other more promising network structures. In most of the proposals (e.g., multihop cellular systems [1] [2], cellular systems with multicell processing [3], ad hoc/mesh networks), collaboration between different nodes (meaning either base stations, BSs, or mobile terminals, MTs) plays a key role. In this paper, we are interested in investigating the interplay between cooperation among MTs on one hand and multicell processing (i.e., collaboration among BSs) on the other, in the uplink of a cellular system. Collaboration between MTs in a cellular network in the form of multihop transmission has been proposed in [1] as a means to increase coverage, mitigating unfairness in QoS and guaranteeing service even in emergency conditions. On the other hand, multicell processing has been investigated, among others, in [3] [4] [5], showing that relevant performance improvement is expected under the assumption of ideal collaboration among the BSs.

The analytical framework of this paper is inspired by the cellular model proposed by Wyner in [3] and later adopted in a relevant number of references (see, e.g., [5]-[7]). According to the linear variant of this model, cells are arranged in a linear geometry and only adjacent cells interfere with each other. Moreover, intercell interference is described by a single parameter $\alpha \in [0, 1]$, defining the gain experienced by signals travelling to interfered cells (see fig. 1-(a)). Notwithstanding its simplicity, this model is able to capture the essential structure

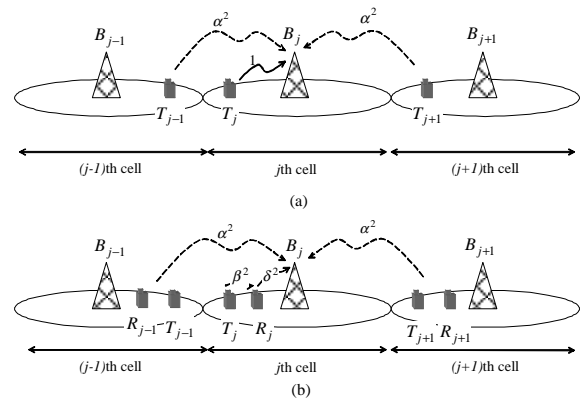


Fig. 1. (a) Linear cellular model proposed by Wyner [3]. (b) Extended model with cooperative transmission between terminals. T_j , B_j and R_j represent source terminal, base station and relay within the j th cell.

of a cellular system and it allows to get insight into the system performance. The results in this paper can be seen as an extension of previous works on the Wyner's model, where the novel contribution concerns the introduction of collaborative communications between MTs.

The goal of this paper is to provide a first look at the interplay between multicell processing (or macrodiversity [8]) and cooperative transmission. Ideal collaboration between BSs (multicell processing) is considered as in [3] [4]: the BSs ($\{B_j\}$ in fig. 1-(b)) are assumed to be able to jointly decode the signals received at different cell-sites, having exchanged the necessary information through noiseless low-latency interconnections (for more practical distributed cooperative schemes between BSs see, e.g., [7] [8]). Therefore, the BSs work effectively as a distributed antenna array. Moreover, our analysis is limited to a specific form of collaboration between MTs, namely Amplify-and-Forward (AF) relaying, also referred to as non-regenerative relaying [9] [10]. According to this approach, the MTs acting as relays (e.g., R_j in fig. 1-(b)) do not attempt to decode the signal transmitted by the active MT (e.g., T_j) but simply forward the received signal after amplification. Finally, we focus on intra-cell TDMA scheduling, i.e., we assume that in each cell there is only one active source MT at

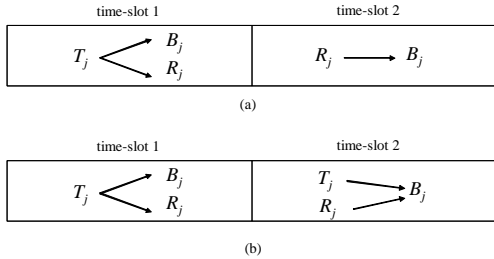


Fig. 2. The two-slot transmission scheme prescribed by AF collaborative schemes between terminals: (a) AF scheme proposed in [9] (referred in the text as OAF); (b) AF scheme proposed in [10] (referred in the text as NAF).

each time instant. Intra-cell TDMA strategy has been shown to be optimal in the absence of fading but suboptimal for fading channels [3] [5].

In order to maintain the simplicity of the Wyner's model, only one additional parameter is introduced in the modelization to investigate the effects of AF collaboration. In particular, each active MT is assumed to have one relay at a normalized distance $d \in [0, 1]$, whereas the relay is separated by its BS by $(1 - d)$ (see fig. 1-(b)). Therefore, in the extended Wyner's model considered in this paper, there are two parameters of interest: (i) the intercell gain $\alpha \in [0, 1]$, ruling the effectiveness of multicell processing (as in the original paper [3]); (ii) the normalized distance $d \in [0, 1]$ between source terminal and relay, that determines the performance of AF collaborative communications between terminals.

A. AF collaboration between terminals

Two alternative AF techniques have been proposed in [9] and [10] respectively. Following [12], we refer to the latter scheme [10] as Nonorthogonal AF (NAF) and, by converse, to the former [9] as Orthogonal AF (OAF). Both methods prescribe a two-slot transmission and differ in the transmission policy within the second time-slot, as illustrated in fig. 2. The first slot is used by each terminal (say T_j) to broadcast its message to the desired BS (B_j) and to the relay MT (R_j), whereas in the second slot: (i) according to OAF [9], the relay forwards the signal received in the first time-slot to the BS after amplification while the source MT remains silent (fig. 2-(a)); (ii) with NAF, the relay behaves as for OAF but the source MT now transmits simultaneously a new independent message¹ (fig. 2-(b)). Both techniques require full channel state information available at the receiver side and no channel state information is assumed to be available at the transmitter. In [12] it is shown that, while more complex, NAF outperforms OAF and is optimal from the point of view of the diversity-multiplexing tradeoff.

II. PROBLEM FORMULATION

As explained in the previous Section, this paper considers the uplink of a linear Wyner's cellular model with intracell

¹Notice that in order to perform a fair comparison between OAF and NAF, the powers transmitted in the second time-slot by the source MT and the relay MT are halved so as to maintain the same total transmitted power.

TDMA. The system layout is illustrated in fig. 1, where the upper part (a) refers to the scenario where no cooperation between MTs is allowed, and the lower part (b) sketches the case where transmission between an active MT and its BS takes place through AF cooperation by a relay node. In each of the M cells, deployed according to a linear geometry, due to the intracell TDMA protocol considered in this paper, there is only one active source MT at each time. The BSs are denoted as $\{B_j\}_{j=1}^M$, the source MTs, one for each cell, as $\{T_j\}_{j=1}^M$, and the MT acting as relays are referred to as $\{R_j\}_{j=1}^M$. It is assumed that each active terminal T_j has available a relay terminal R_j for cooperation. Flat Rayleigh fading is assumed; moreover, the complex circularly symmetric Gaussian distributed channel gains are independent identically distributed and identified by their subscript. In particular, the channels between source MTs and BSs have power

$$E[|h_{T_j B_{j+i}}|^2] = 1 \text{ for } i = 0; \alpha^2 \text{ for } i = \pm 1 \quad (1)$$

and 0 otherwise, where $\alpha \in [0, 1]$ is the interference factor. Channel gains between source MTs and relay MTs read

$$E[|h_{T_j R_{j+i}}|^2] = 1/d^\gamma \text{ for } i = 0; 0 \text{ otherwise,} \quad (2)$$

with $d \in [0, 1]$ denoting the normalized distance between active MTs and the relative relays and γ standing for the path loss exponent. Notice that in (2) it is assumed that a relay is not able to receive the transmissions of MTs belonging to adjacent cells. This assumption is reasonable if the relays are MTs, but it may be questionable if the relays are fixed wireless stations placed at heights comparable to the BSs (as in the scenario investigated in [13]). A more reasonable assumption in this case would be that of setting the powers $E[|h_{T_j R_{j\pm 1}}|^2]$ equal to the intercell factor α^2 . The analysis under this setting can be easily derived from the treatment presented below and it will not be further illustrated here since the conclusions would not be significantly different but the notation would be more involved. Finally, the channels between relay MTs and BSs can be written as

$$E[|h_{R_j B_{j+i}}|^2] = 1/(1-d)^\gamma \text{ for } i = 0; \alpha^2 \text{ for } i = \pm 1; \quad (3)$$

and 0 otherwise, where $(1 - d)$ is the distance between a relay and the corresponding BS. Notice that, as a notational convention the channels from "virtual" cells 0 and $M + 1$ are assumed to be zero. To complete the set of assumptions, each MT (either source or relay) is assumed to transmit an energy per symbol equal to E_s^2 and each receiver (either relay or BS) is modelled as having a Gaussian white one-sided noise spectral density equal to N_0 .

In the following Sections, the per-cell achievable sum-rate (throughput) of the system in fig. 1 is investigated for: (i) *single cell* processing (Sec. III): each BS processes the received signal independently from the other cell-sites, treating intercell interference as Gaussian noise. Both scenarios with direct transmission and AF collaborative transmission are studied;

²apart from the second time-slot under the NAF protocol, where the available power is shared by the source MT and the relay.

(ii) *multicell* processing (Sec. IV): the signals received by the M BSs are jointly processed, assuming a noiseless low-latency interconnection between the BSs. As in the previous case, both scenarios with and without AF cooperation between MTs are studied. The analysis is then corroborated by numerical results in Sec. V, allowing to draw some conclusions on the interplay between multicell diversity and cooperative diversity under the assumption of AF transmission. Notice that in [14] closed form expression for the per-cell achievable sum-rate of multicell processing in AWGN channels are derived.

III. SINGLE CELL PROCESSING

In this Section, the scenario where each BS, say B_j , processes the received signal independently from the other BSs $\{B_i\}_{i \neq j}$ is considered. The per-cell achievable rate for direct transmission between active MTs $\{T_j\}$ and their corresponding BSs $\{B_j\}$ is derived in Sec. III-A, whereas AF collaborative communications (both OAF and NAF) is covered in Sec. III-B.

A. Direct transmission

Here we consider the scenario in fig. 1-(a), where direct transmission between MTs and BSs takes place. The discrete-time baseband signal received in each time instant by the BS B_j ($j = 1, \dots, M$) can be written as (discrete-time dependence is omitted for simplicity of notation)

$$y_j = \sum_{i=-1}^1 h_{T_{j+i}B_j} x_{j+i} + n_j = h_{T_j B_j} x_j + w_j + n_j, \quad (4)$$

with x_j denoting the signal transmitted by the MT T_j , that is assumed to be taken from a Gaussian codebook with $\mathbb{E}[|x_j|^2] = E_s$. The additive Gaussian thermal noise has power $\mathbb{E}[|n_j|^2] = N_0$ and the remaining term $w_j = \sum_{i=-1, i \neq 0}^1 h_{T_{j+i}B_j} x_{j+i}$ accounts for *intercell interference*. In single-cell processing, the interference w_j is regarded at the BS B_j as additive Gaussian noise with power $\mathbb{E}[|w_j|^2] = E_s(|h_{T_{j-1}B_j}|^2 + |h_{T_{j+1}B_j}|^2)$. Therefore, the compound additive Gaussian noise $w_j + n_j$ has power $\mathbb{E}[|w_j|^2] + N_0$. Recalling that the BS is assumed to have knowledge of the channel gains $h_{T_{j+i}B_j}$ with $i = -1, 0, 1$, the ergodic per-cell achievable sum-rate measured in *bit/s/Hz* reads

$$R_{SC-DT} = \mathbb{E}_h \left[\log_2 \left(1 + \text{SNR} \frac{|h_{T_j B_j}|^2}{1 + W_j} \right) \right], \quad (5)$$

with $\mathbb{E}_h[\cdot]$ denoting the ensemble average with respect to the fading distribution, $\text{SNR} = E_s/N_0$ the signal to noise ratio and

$$W_j = \frac{\mathbb{E}[|w_j|^2]}{N_0} = \text{SNR}(|h_{T_{j-1}B_j}|^2 + |h_{T_{j+1}B_j}|^2). \quad (6)$$

Notice that (5) assumes that the channel coherence time is small enough so that the transmitted codeword spans a large (theoretically infinite) number of channel states (i.e., for delay tolerant applications or fast-varying channels).

B. Amplify-and-Forward (AF) transmission

In this case, the system is exemplified in fig. 1-(b) and transmission is time-slotted according to fig. 2. In particular, as explained above, we consider two different AF schemes (OAF [9] and NAF [10]), whose transmission policies differ only in the second time-slot. The main result in this Section is the derivation of the per-cell achievable rates attained by the OAF and NAF cooperative schemes in a single cell scenario (equations (13) and (15) respectively).

As for direct transmission, in the first time-slot, under both OAF and NAF protocols, the active terminals $\{T_j\}_{j=1}^M$ transmit Gaussian symbols x_j with $\mathbb{E}[|x_j|^2] = E_s$ and, therefore, the signal received by the BS B_j is (4). However, the signals transmitted in the first time-slot by terminals T_j are also overheard by the relay nodes R_j , that receive $y_{R_j} = h_{T_j R_j} x_j + n_{R_j}$, where the noise term n_{R_j} has power $\mathbb{E}[|n_{R_j}|^2] = N_0$. The signal model in the second time-slot differs for the two considered AF schemes, as detailed in the following.

1) *Orthogonal AF (OAF) [9]* : According to the OAF technique, in the second time-slot the relay scales the received signal y_{R_j} in order to keep the average transmitted energy per symbol equal to E_s , and then forwards the resulting symbol. More precisely, in the second time-slot, the relay forwards $\mu_j y_{R_j} = \mu_j h_{T_j R_j} x_j + \mu_j n_{R_j}$ with

$$\mu_j^2 = \frac{E_s}{E_s |h_{T_j R_j}|^2 + N_0}. \quad (7)$$

Therefore, the signal received by the j th BS B_j in the second time-slot is (prime refers to quantities transmitted in the second time-slot) $y'_j = \sum_{i=-1}^1 h_{R_{j+i}B_j} (\mu_{j+i} y_{R_{j+i}}) + n'_j$, with n'_j denoting thermal noise at B_j , assumed to be independent of the noise in the first time-slot and with power $\mathbb{E}[|n'_j|^2] = N_0$. In order to get some insight into the signal structure of y'_j , it is useful to define the *equivalent channel gains* experienced by the signals x_{j+i} with $i = -1, 0, 1$ toward the BS B_j in the second time-slot. These equivalent channel gains account for the signal paths from the source MTs T_{j+i} to the BS B_j through the corresponding relays R_{j+i} and read:

$$h'_{T_j B_j} = \mu_j h_{T_j R_j} h_{R_j B_j}, \quad h'_{T_{j \pm 1} B_j} = \mu_{j \pm 1} h_{T_{j \pm 1} R_{j \pm 1}} h_{R_{j \pm 1} B_j}. \quad (8)$$

Using the definitions in (8), the signal received by B_j can be written as

$$y'_j = \sum_{i=-1}^1 h'_{T_{j+i} B_j} x_{j+i} + n'_j = h'_{T_j B_j} x_j + w'_j + z_j + n'_j, \quad (9)$$

where w'_j accounts for intercell interference, $w'_j = \sum_{i=-1, i \neq 0}^1 h'_{T_{j+i} B_j} x_{j+i}$, and z_j is the thermal noise generated at the relays and forwarded to the BS, $z_j = \sum_{i=-1}^1 \mu_{j+i} h_{R_{j+i} B_j} n_{R_{j+i}}$. Therefore, for single cell processing, the equivalent noise power in the second time-slot reads $N_0(1 + W'_j + Z_j)$, where

$$W'_j = \mathbb{E}[|w'_j|^2]/N_0 = \text{SNR}(|h'_{T_{j-1} B_j}|^2 + |h'_{T_{j+1} B_j}|^2) \quad (10)$$

and

$$Z_j = E[|z_j|^2]/N_0 = \sum_{i=-1}^1 \mu_{j+i}^2 |h_{R_{j+i}B_j}|^2. \quad (11)$$

The equivalent additive Gaussian noise at the BS in the two slots is correlated as (recall (4) and (9))

$$\begin{aligned} \rho &= E[(w_j + n_j)(w'_j + z_j + n'_j)^*]/N_0 = \\ &= \text{SNR}(h_{T_{j-1}B_j} h_{T_{j-1}B_j}^* + h_{T_{j+1}B_j} h_{T_{j+1}B_j}^*). \end{aligned} \quad (12)$$

It follows that the resulting ergodic per-cell achievable rate can be expressed as

$$R_{SC-OAF} = \frac{1}{2} E_h \left[\log_2 \left(1 + \text{SNR} \left[\begin{array}{c} h_{T_j B_j}^* \\ h_{T_j B_j} \end{array} \right] \right. \right. \\ \left. \left. \left[\begin{array}{cc} 1 + W_j & \rho \\ \rho & 1 + Z_j + W'_j \end{array} \right]^{-1} \left[\begin{array}{c} h_{T_j B_j} \\ h'_{T_j B_j} \end{array} \right] \right) \right], \quad (13)$$

where the pre-log scaling by $1/2$ depends on the two-slot structure of the AF transmission [9].

2) *Nonorthogonal AF (NAF)* [10]: According to this scheme, proved in [12] to be optimal from a multiplexing-diversity trade-off standpoint, the source MTs T_j transmit two independent messages, x_j in the first time-slot and x'_j in the second time-slot. On the other hand, the relays R_j forward the signal received in the first time-slot exactly as explained in the previous Section for OAF. In order to present a fair comparison between different techniques, the powers transmitted in the second slot by source and relay MTs are halved in such a way that the total transmitted power is not increased. It follows that the signal received by the relay y_{R_j} is scaled by $\mu_j/\sqrt{2}$ before forwarding, and the power of the Gaussian symbol x'_j is $E_s/2$. This introduces some technicalities in the derivation of the signal model, as discussed in the following.

According to the discussion in the previous Section, the received signal in the second time-slot is (to uniform the notation we set $E[|x'_j|^2] = E_s$, the power scaling is accounted for as shown below)

$$y'_j = \frac{1}{\sqrt{2}} h'_{T_j B_j} x_j + \frac{1}{\sqrt{2}} h_{T_j B_j} x'_j + \tilde{w}'_j + \frac{1}{\sqrt{2}} z_j + n'_j, \quad (14)$$

where n'_j accounts for thermal noise, z_j is defined as in the previous Section and the intercell interference \tilde{w}'_j contains the additional interference contribution of the source MTs of adjacent cells as compared to w_j : $\tilde{w}'_j = \frac{1}{\sqrt{2}} w'_j + \frac{1}{\sqrt{2}} \sum_{i=-1, i \neq 0}^1 h_{T_{j+i}B_j} x'_{j+i}$. Therefore, the equivalent noise power in the second time-slot modifies as $N_0 + \frac{1}{2} W'_j + \frac{1}{2} W_j + \frac{1}{2} Z_j$. The ergodic per-cell achievable sum-rate of this scheme then reads:

$$R_{SC-NAF} = \frac{1}{2} E_h \left[\log_2 \left(1 + \text{SNR} \left(\mathbf{A}^H \left[\begin{array}{cc} 1 + W_j & \rho \\ \rho & 1 + \frac{1}{2} W'_j + \frac{1}{2} W_j + \frac{1}{2} Z_j \end{array} \right]^{-1} \mathbf{A} \right) \right) \right], \quad (15)$$

with

$$\mathbf{A} = \begin{bmatrix} h_{T_j B_j} & 0 \\ h'_{T_j B_j}/\sqrt{2} & h_{T_j B_j}/\sqrt{2} \end{bmatrix},$$

and ρ denoting the correlation of the equivalent noise in the two time-slots, as defined in (12).

IV. MULTICELL PROCESSING

Here we extend the results of the previous Section to a scenario where the signals received by all the BSs are jointly processed in order to decode the transmitted signals $(\{x_j\}_{j=1}^M)$ for direct transmission and OAF; $(\{x_j, x'_j\}_{j=1}^M)$ for NAF).

A. Direct transmission

The discrete-time signal received by the j th BS is (4). Differently from the single cell case, multicell processing treats adjacent cells' contribution w_j as useful signal and not as an additive noise term. Since the signals received by the M BSs are jointly processed in order to detect the $M \times 1$ transmitted vector $\mathbf{x} = [x_1 \cdots x_M]^T$, it is convenient to gather the received signals in a $M \times 1$ vector $\mathbf{y} = [y_1 \cdots y_M]^T$ and restate the model (4) according to a matrix formulation

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (16)$$

where the $M \times M$ channel matrix \mathbf{H} is tridiagonal due to the Wyner's model assumption about intercell interference [3]:

$$\mathbf{H} = \begin{bmatrix} h_{T_1 B_1} & h_{T_2 B_1} & 0 & \cdots \\ h_{T_1 B_2} & h_{T_2 B_2} & \ddots & \cdots \\ 0 & \ddots & \ddots & h_{T_M B_{M-1}} \\ \vdots & 0 & h_{T_{M-1} B_M} & h_{T_M B_M} \end{bmatrix}, \quad (17)$$

and $\mathbf{n} = [n_1 \cdots n_M]^T$. This expression clearly highlights the fact that signals from all the cells, collected in vector \mathbf{y} , are jointly considered for detection of the transmitted vector \mathbf{x} . The ergodic per-cell achievable rate of this scheme reads:

$$R_{MC-DT} = \frac{1}{M} E_h \left[\log_2 |\mathbf{I}_M + \text{SNR} \mathbf{H}^H \mathbf{H}| \right]. \quad (18)$$

Bounds on this expressions can be found in [5].

B. Amplify-and-Forward (AF) transmission

The derivation of the per-cell achievable rates for both OAF and NAF collaborative schemes in a multicell scenario builds on the analysis of Sec. III-B. The distinctive feature here is that, differently from single cell processing, intercell interference terms are treated as additional signals, as explained above in the context of direct transmission. The signal received at the BS B_j in the first slot can be written as (16) for both AF protocols. The signal model for the second slot is detailed in the following according to the two AF schemes of interest.

1) *Orthogonal AF (OAF)*: For OAF, as explained in Sec. III-B.1, the received signal by BS B_j can be expressed as (9). However, differently from single cell processing, in multicell processing, the intercell interference term w_j in (9) is treated as signal useful for decoding. Therefore, similarly to (16), the $M \times 1$ vector $\mathbf{y}' = [y'_1 \cdots y'_M]^T$ reads $\mathbf{y}' = \mathbf{H}'\mathbf{x} + \mathbf{n}' + \mathbf{z}$, with \mathbf{H}' being a tridiagonal matrix with the same form as (17), containing the equivalent channel gains (8), and $\mathbf{n}' = [n'_1 \cdots n'_M]^T$, $\mathbf{z} = [z_1 \cdots z_M]^T$. The correlation matrix of the equivalent additive Gaussian noise in $\mathbf{n}' + \mathbf{z}$ reads $E[(\mathbf{n}' + \mathbf{z})(\mathbf{n}' + \mathbf{z})^H] = N_0 \mathbf{I}_M + N_0 \mathbf{R}_z$, where \mathbf{R}_z is

a pentadiagonal Toeplitz correlation matrix with $[\mathbf{R}_z]_{j,j+i} = E[z_j z_{j+i}^*]/N_0$:

$$E[z_j z_{j+i}^*] = \begin{cases} Z_j & i = 0 \\ \mu_j^2 h_{R_j B_j} h_{R_j B_{j\pm 1}} + & i = \pm 1 \\ \mu_{j\pm 1}^2 h_{R_{j\pm 1} B_j} h_{R_{j\pm 1} B_{j\pm 1}} & \\ \mu_{j\pm 1}^2 h_{R_{j\pm 1} B_j} h_{R_{j\pm 1} B_{j\pm 2}} & i = \pm 2 \end{cases} \quad (19)$$

Finally, defining the $2M \times 1$ vector $\bar{\mathbf{y}} = [\mathbf{y}^T \mathbf{y}'^T]^T$, the $2M \times M$ channel matrix $\bar{\mathbf{H}} = [\mathbf{H}^T \mathbf{H}'^T]^T$ and the $2M \times 1$ noise vector $\bar{\mathbf{n}} = [\mathbf{n}^T (\mathbf{n}' + \mathbf{z})^T]^T$, the compound model for the received signal over the two time slots can be stated as $\bar{\mathbf{y}} = \bar{\mathbf{H}}\bar{\mathbf{x}} + \bar{\mathbf{n}}$, where the noise correlation matrix reads:

$$\bar{\mathbf{R}}_n = \frac{1}{N_0} E[\bar{\mathbf{n}}\bar{\mathbf{n}}^H] = \begin{bmatrix} \mathbf{I}_M & \mathbf{0}_M \\ \mathbf{0}_M & \mathbf{I}_M + \mathbf{R}_z \end{bmatrix}. \quad (20)$$

The ergodic per-cell achievable sum-rate is then:

$$R_{MC-OAF} = \frac{1}{2M} E_h [\log_2 |\mathbf{I}_{2M} + \text{SNR} \bar{\mathbf{H}}^H \bar{\mathbf{R}}_n^{-1} \bar{\mathbf{H}}|], \quad (21)$$

2) *Nonorthogonal AF (NAF)*: In the case of NAF, as discussed in Sec. III-B.2, the received signal by the BS B_j is (14). Therefore, following the same reasoning of the previous Sections, the $M \times 1$ vector \mathbf{y}' can be written as

$$\mathbf{y}' = \frac{1}{\sqrt{2}} \mathbf{H}' \mathbf{x}' + \frac{1}{\sqrt{2}} \mathbf{H} \mathbf{x}' + \mathbf{n}' + \frac{1}{\sqrt{2}} \mathbf{z}, \quad (22)$$

with $\mathbf{x}' = [x'_1 \dots x'_M]^T$. Notice that the equivalent noise has correlation matrix $E[(\mathbf{n}' + \frac{1}{\sqrt{2}} \mathbf{z})(\mathbf{n}' + \frac{1}{\sqrt{2}} \mathbf{z})^H] = N_0 \mathbf{I}_M + \frac{1}{2} N_0 \mathbf{R}_z$. Therefore, the ergodic per-cell achievable sum-rate of this scheme is

$$R_{MC-NAF} = \frac{1}{2M} E_h \left[\log_2 \left(1 + \text{SNR} \mathbf{B}^H \begin{bmatrix} \mathbf{I}_M & \mathbf{0}_M \\ \mathbf{0}_M & \mathbf{I}_M + \frac{1}{2} \mathbf{R}_z \end{bmatrix}^{-1} \mathbf{B} \right) \right] \quad (23)$$

with

$$\mathbf{B} = \begin{bmatrix} \mathbf{H} & \mathbf{0} \\ \frac{1}{\sqrt{2}} \mathbf{H}' & \frac{1}{\sqrt{2}} \mathbf{H} \end{bmatrix}. \quad (24)$$

V. NUMERICAL RESULTS

Here, some numerical results are presented in order to corroborate the analysis carried out in the previous Sections. Where not stated otherwise, relevant parameters are selected as $M = 10$, $\text{SNR} = 3\text{dB}$, $\gamma = 3$ and $\alpha = -10\text{dB}$. Moreover, distance d is set to 0.5 since it is shown in [14] that the benefits, if any, of collaborative AF communication are achieved when the relay is placed halfway.

Let us first focus on single cell processing. Fig. 3 shows the ergodic per-cell achievable sum-rate versus the SNR. From this figure, the interference-limited behavior of single cell processing is apparent. Moreover, it can be concluded that by increasing SNR (or equivalently the achievable rate), the performance gain of OAF decreases while NAF retains its benefits. These results are in accordance to the analyses in [9] [12] for the single relay channel.

Collaboration between BSs overcome the intercell interference-limited behavior of single cell processing and

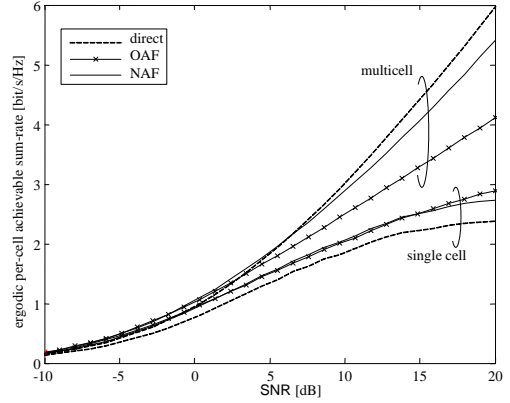


Fig. 3. Ergodic per-cell achievable rates of different transmission schemes for single and multicell processing versus SNR ($\alpha = -10\text{dB}$, $d = 0.5$, $\gamma = 3$).

allows to obtain considerable larger achievable rates. Furthermore, at large spectral efficiencies, noise forwarding due to AF protocols become deleterious to system performance. In particular, as shown in fig. 3, direct transmission outperforms OAF for rates larger than 1.4 bit/s/Hz and NAF for rates larger than 2 bit/s/Hz . It can be then concluded that, when combined with multicell reception, the advantages of AF collaboration are limited to moderate transmission rates. Moreover, notice that for both single and multicell processing OAF can yield larger achievable rates than NAF in the regime of very low spectral efficiencies. As a final remark, altering the path loss exponent γ would not modify qualitatively the conclusions above: increasing γ would however improve the performance of AF collaborative schemes (due to the increased power gain attainable).

The interplay between gains obtained from multicell processing (or from macrodiversity) and from cooperative AF transmission between terminals is better illustrated in fig. 4. Herein, the ergodic rates under single and multicell processing are plotted versus the intercell gain factor α for $d = 0.5$. Parameter α has opposite effects on the two scenarios: while for single cell processing increasing α causes a performance degradation due to larger intercell interference, multicell reception benefits from a stronger signal paths toward adjacent cells (unless the SNR is very large [5]). Moreover, in accordance to the discussion above, AF collaboration is always effective for single cell processing, with OAF outperforming NAF for low spectral efficiencies (i.e., large α). On the other hand, when the intercell gain α is large enough, the performance improvement due to collaboration among BSs renders the additional noise forwarded to the BS by relays a limiting factor to the performance and direct transmission outperforms AF protocols.

VI. CONCLUDING REMARKS

In this paper, a first look at the interplay between multicell processing (i.e., cooperation between base stations) and coop-

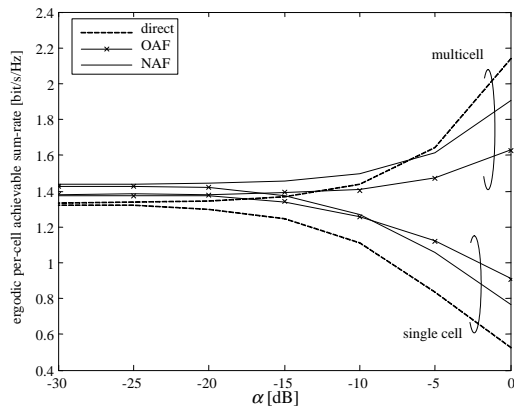


Fig. 4. Ergodic per-cell achievable rates of different transmission schemes for single and multicell processing versus the intercell gain α (SNR = 3dB, $d = 0.5$, $\gamma = 3$).

eration between terminals has been presented. We considered the uplink of a TDMA cellular system, modelled according to an extended Wyner's model, and focused on AF collaborative techniques. Based on the analysis and on numerical results, some general conclusions have been drawn: (i) non-regenerative (AF) collaboration is a useful means to improve the performance of the uplink channel for simple systems that employ separate processing at different BSs; (ii) when collaboration between BSs is possible and effective (i.e, the intercell attenuation is small enough), multicell diversity renders the benefits of added diversity from non-regenerative relaying negligible and direct transmission can in fact outperform AF. When interpreting these results, it should be stressed that some of the drawbacks of collaborative communications pointed out above are due to the simple strategy employed, namely AF. It is expected that with more refined forms of collaboration, such as Decode and Forward [9], some of the results could be significantly different.

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