Inter-cell Relaying and Base Station Cooperation in Cellular Uplink Systems

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***Abstract*—Joint decoding at the base stations is investigated as a means to improve the uplink/downlink throughput of current cellular systems over fading channels. In this paper, the multi-cell relay-assisted time-division uplink system, i.e. one active user per time slot per cell with a relay serving that user, is studied. A linear mesh network is considered in which a single user per-cell communicates to a local base station via a dedicated relay. Base station cooperation through multi-cell decoding, where each cell has a single relay that amplifies and forwards the desired transmission signals to the base station. All the base stations in the mesh network collaboratively decode the signals received at each. The key contribution of this paper is compare the ergodic sum-rate in single-cell processing with multi-cell processing, under the system model, separately.**

I. INTRODUCTION

Cooperative communications has been considered to be an important method towards providing higher transmission rates and improving robustness to channel impairments in wireless systems. A lot of researches have been focused on intra-cell cooperation, that is to say, one user, one relay (or some relays) and one destination constitute a system model, such as amplify-and-forward (AF, i.e. non-regenerative relays)[1] and decode-and-forward (DF, i.e. regenerative relays)[2][3].

According to the wireless mesh networks' potential to resolve the performance limitations of both infrastructure (cellular) and multi-hop (ad hoc) networks in terms of quality-of-service (QoS) and coverage, they are currently being investigated. Basically, mesh networks prescribe the combination of communication via direct transmission to infrastructure nodes (base stations, BSs) and via multi-hop (ad hoc) transmission through intermediate nodes (relay stations, RS)[4].

Past research on cooperation in cellular systems can be broadly classified into two categories[5]: intra-cell cooperation between users in providing relay-assistance and inter-cell cooperation between base stations through joint signal processing. A lot of researchers have been studying a combination of the two categories.

In the paper, inter-cell cooperation is analyzed, which contains the following solutions that seem to be among the most viable and promising to improve coverage and QoS of cellular systems[6] [11]:

1) collaborative transmission at the mobile terminal (MT) level: cooperative transmission between the source MT and a fixed relay considering to be the simplest form has been investigated by Ikki and Ahmed [1].

2) joint decoding at the BSs: the BSs jointly decode the received signals from RSs or MTs, equivalently creating a distributed receiving antenna array, so we can think the distributed transmission and cooperative transmission are equivalent. The performance gain of this technology within a simplified cellular model was first studied in [7] [8] from an information theoretic perspective, and then extended to fading channels, under the assumption that BSs are connected via high-speed optical fiber backbone with high capacity and low latency, allowing a reliably fast exchanged of information among them.

In this paper, we focus on inter-cell cooperation at BSs. Recently, there has also been considerable interest in further enhancing the performance of infrastructure or mesh networks by endowing the system with a central processor that is able to pool the signals received by the base stations and performs joint processing (this scenario is usually referred to as distributed antennas or multi-cell processing)[4], which can improve the performance of the mesh networks. Finally, the scope of this work is limited to a specific form of collaboration at BSs through the protocol of AF described in [2].

The rest of the paper is organized as follows. The system model and problem formulations are given in Section II. The concept of single-cell processing appears in Section III. Joint multi-cell processing is addressed in Section IV. Some practical concerns are discussed and numerical results are provided in Section V. Finally, Section VI contains some concluding remarks.

II. SYSTEM MODEL AND PROBLEM FORMULATIONS

We consider the uplink of a linear Wyner's cellular model, which has N cells in the cellular systems and adopt the inter-cell orthogonal access protocol (such as TMDA or FDMA) in this paper. At each time, there is only one active source MT in each cell and each active MT communicates with the same-cell BS via a dedicated RS which is illustrated in Fig. 1. The BSs are denoted as $\{B_j\}_{j=1}^{N}$, the source MTs, one for each cell, are referred to as $\{T_j\}_{j=1}^{N}$, and the RSs as $\{R_j\}_{j=1}^{N}$. For

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the sake of simplicity, we assume BSs, MTs and RSs have one antenna respectively. However, all the results in the paper can be extended to the case of multiple antennas at MTs, RSs and BSs.

Notice that this model inherently focuses on MTs which are close to the border of their respective cells. A narrow-band flat-fading channel is considered and a low mobility environment is assumed, such that the channel gains remain constant within several frames. Fading gains are identified by their subscripts, e.g. $h_{T_j B_i}$, is the channel gain between MT T_j and BS B_i and $h_{R_i B_j}$ is the channel gain between RS R_i and BS B_j. These gains are assumed to be independent identical ergodic complex circularly symmetric Gaussian distribution processes (i.i.d Rayleigh fading).

The abstraction of the two-hop mesh network described in Fig. 1 as sketched in Fig. 2 [4] is studied. In the first time slot, the MTs transmit the signals to the RSs only, while in the second time slot, the RSs transmit the signal received in the first time slot to the BSs. Cells are arranged in a linear fashion, and one user transmits on a given time-frequency resource in each cell. Moreover, we focus on Rayleigh fading channels and assume homogeneous conditions for the channel power gains so that the intra-cell MT-to-RS (first hop) and RS-to-BS (second hop) power gains are α^2 and γ^2 respectively, and, similarly, the inter-cell power gains between adjacent cells are β^2 and δ^2 for first and second hop, respectively. Our interest is in the GRE Wyner model described in [6][9], i.e. $E\left[\left|h_{T_i R_{i+j}}\right|^2\right] = \alpha^2 \; for \; j = 0; \; \beta^2 \; for \; j = \pm 1$ $E\left[\left|h_{R_i B_{i+j}}\right|^2\right] = \gamma^2 \; for \; j = 0 \; ; \; \delta^2 \; for \; j = \pm 1$.

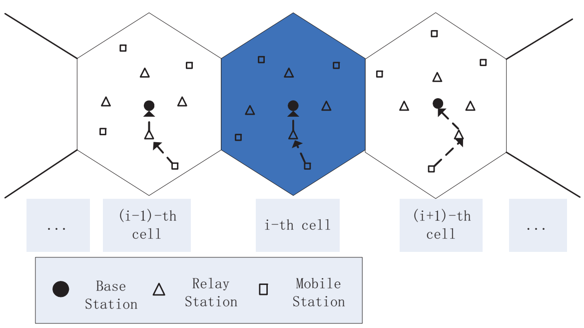

Fig. 1. A linear two-hop mesh work.

Moreover, there exists no direct paths between MTs and BSs and no relevant inter-channels between RSs in adjacent cells which are different from [9] [10]. Because of the latter assumptions, we can deal with either full duplex or half duplex transmission at the relays with minor modifications. Here, the RSs working with full duplex transmission are considered.

III. Single-Cell Processing

In the single-cell processing system, each BS independently processes the received signal (i.e., no collaboration between BSs is employed). According to the Wyner model, only adjacent cells interfere with each other.

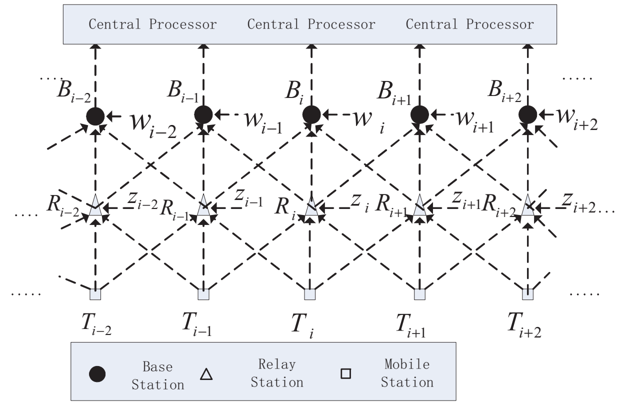

Fig. 2. A schematic model of the linear two-hop mesh work.

Firstly, the signal received at first time slot by the RS R_i can be written as

$$y_{R_i} = h_{T_i R_i} x_i + w_i + z_i \tag{1}$$

with x_i denoting the signal transmitted by the MT T_i, which is assumed to be taken from a Gaussian codebook with $E\left|x_i\right|^2 = P_i$. The additive Gaussian thermal noise has power $E\left|z_i\right|^2 = N_0$.

$$w_i = h_{T_{i-1} R_i} x_{i-1} + h_{T_{i+1} R_i} x_{i+1} \tag{2}$$

accounts for inter-cell interference. It is assumed that all MTs transmit signals with the same power, i.e. $P_1 = P_2 = \cdots = P_N = P$. In the single-cell processing, the interference at the RS is regarded as additive Gaussian noise with power:$E\left[\left|w_i\right|^2\right] = P \cdot \left(\left|h_{T_{i-1} R_i}\right|^2 + \left|h_{T_{i+1} R_i}\right|^2\right)$, and $SNR_i = \frac{E\left\{\left|x_i\right|^2\right\}}{N_0} = \frac{P_i}{N_0}$ being the signal-to-noise-ratio (SNR). From the SNR_i equation, we can get $SNR_1 = SNR_2 = \cdots = SNR_N = SNR$.

Secondly, the signal received at the second slot by the BS can be given by

$$\begin{aligned} y_{B_i} =& y_{R_{i-1}} g_{R_{i-1}} h_{R_{i-1} B_i} + y_{R_i} g_{R_i} h_{R_i B_i} + \\ & y_{R_{i+1}} g_{R_{i+1}} h_{R_{i+1} B_i} + n_i \\ =& h^{'}_{T_i B_i} x_i + w^{'}_i + z^{'}_i + n_i \end{aligned} \tag{3}$$

In equation (3), $h^{'}_{T_i B_i}$ denotes the equivalent channel gains that account for the useful signal paths from two adjacent cells, $w^{'}_i$ is the interference from adjacent cells and $z^{'}_i$ is for equivalent noise. n_i denotes the thermal noise at BS B_i , assumed to be independent of the noise z_i in the first time slot but have the same power $E\left(\left|n_i\right|^2\right) = N_0$. The equation of $h^{'}_{T_i B_i}$, $w^{'}_i$, and $z^{'}_i$ are following by (4), (5) and (6):

$$\begin{aligned} h^{'}_{T_i B_i} =& h_{T_i R_{i-1}} g_{R_{i-1}} h_{R_{i-1} B_i} + h_{T_i R_i} g_{R_i} h_{R_i B_i} \\ & + h_{T_i R_{i+1}} g_{R_{i+1}} h_{R_{i+1} B_i} \end{aligned} \tag{4}$$

$$
\begin{aligned}
w_i^{'} = & \left(h_{T_{i-1}R_{i-1}} g_{R_{i-1}} h_{R_{i-1}B_i} + h_{T_{i-1}R_i} g_{R_i} h_{R_i B_i}\right) x_{i-1} \\
& + \left(h_{T_{i+1}R_i} g_{R_i} h_{R_i B_i} + h_{T_{i+1}R_{i+1}} g_{R_{i+1}} h_{R_{i+1}B_i}\right) x_{i+1} \\
& + h_{T_{i-2}R_{i-1}} g_{R_{i-1}} h_{R_{i-1}B_i} x_{i-2} \\
& + h_{T_{i+2}R_{i+1}} g_{R_{i+1}} h_{R_{i+1}B_i} x_{i+2}
\end{aligned} \tag{5}
$$

$$
\begin{aligned}
z_i^{'} = & g_{R_{i-1}} h_{R_{i-1}B_i} z_{i-1} + g_{R_i} h_{R_i B_i} z_i \\
& + g_{R_{i+1}} h_{R_{i+1}B_i} z_{i+1}
\end{aligned} \tag{6}
$$

According to the OAF technique [9], in the second time slot, the relay scales the received signal y_{R_i} in order to keep the average transmitted energy per symbol equal to P_i , and then forwards the resulting symbol. More precisely, in the second time slot, the relay forwards $g_{R_i} y_{R_i} = g_{R_i} h_{T_{i-1}R_i} x_{i-1} + g_{R_i} h_{T_i R_i} x_i + g_{R_i} h_{T_{i+1}R_i} x_{i+1} + g_{R_i} z_i$ with $E\left(\left|g_{R_i} y_{R_i}\right|^2\right) = P_i$. So the relay gain is given by

$$
g_{R_i}^2 = \frac{SNR}{SNR \cdot \sum_{j=-1}^{1} \left|h_{T_{i+j}R_i}\right|^2 + 1} \tag{7}
$$

It is assumed that the BSs are able to know the full channel state information (CSI), i.e. h_{TR}, h_{RB}, so that the ergodic per-cell achievable sum-rate in BS B_i is written in equation (8).

$$
\begin{aligned}
R_{i-BS} = & \frac{1}{2} E_h \left[\log_2\left(1 + \frac{\left|h_{T_i B_i}^{'}\right|^2 P_i}{\left|w_i^{'}\right|^2 + \left|z_i^{'}\right|^2 + |n_i|^2}\right)\right] = \\
& \frac{1}{2} E_h \left[\log_2\left(1 + \frac{SNR\left|\sum_{j=-1}^{1} h_{T_i R_{i+j}} g_{R_{i+j}} h_{R_{i+j}B_i}\right|^2}{W' + \left(\sum_{j=-1}^{1} g_{R_{i+j}}^2 \left|h_{R_{i+j}B_i}\right|^2 + 1\right)}\right)\right]
\end{aligned} \tag{8}
$$

$E_h[\cdot]$ denotes the ensemble average with respect to the fading distribution and $W^{'}$ is written in equation (9).

$$
\begin{aligned}
& W^{'} = E\left(w_i^{'} w_i^{'H}\right)/N_0 = \\
& SNR\left(\left|h_{T_{i-1}R_i} g_{R_i} h_{R_i B_i} + h_{T_{i-1}R_{i-1}} g_{R_{i-1}} h_{R_{i-1}B_i}\right|^2\right. \\
& + \left|h_{T_{i+1}R_i} g_{R_i} h_{R_i B_i} + h_{T_{i+1}R_{i+1}} g_{R_{i+1}} h_{R_{i+1}B_i}\right|^2 \\
& \left. + \left|h_{T_{i-2}R_{i-1}} g_{R_{i-1}} h_{R_{i-1}B_i}\right|^2 + \left|h_{T_{i+2}R_{i+1}} g_{R_{i+1}} h_{R_{i+1}B_i}\right|^2\right)
\end{aligned} \tag{9}
$$

From the Fig. 4-5, we can see that the interference has high impact on the per-cell sum-rate, so interference mitigation is studied by many researchers to achieve higher sum-rate. Joint multi-cell processing in section IV is one of the good methods to make that come true.

IV. Joint Multi-Cell Processing

In this section, it is assumed that the signals received at all BSs are jointly decoded by an optimal central receiver which is connected to the BSs via a high-speed optical fiber backbone such that information can be broadcasted reliably and fast to all base stations in the network. Here we focus again on the scenario described in Fig. 2, where each Relays employs AF collaboration with three MTs except cell border in order to communicate with its BS. However, differently from the previous section, the BSs are herein assumed to be able to jointly decode the received signals in order to detect the transmitted vector $\mathbf{x} = [x_1, \cdots, x_N]^T$.

In the first time slot, by gathering the signals received by all N Relays (1) into the vector $\mathbf{y}_R = [y_{R_1}, \cdots, y_{R_N}]^T$, the signal model becomes

$$
\mathbf{y}_R = \mathbf{H}_{TR} \cdot \mathbf{x} + \mathbf{Z} \tag{10}
$$

where the channel matrix is $\mathbf{H}_{TR} = \left[\mathbf{H}_{TR_1}^H, \cdots, \mathbf{H}_{TR_N}^H\right]^H$ with $\mathbf{H}_{TR_i} = \left[0, \cdots, 0, h_{T_{i-1}R_i}, h_{T_i R_i}, h_{T_{i+1}R_i}, 0, \cdots, 0\right]$, and the additive noise vector is $\mathbf{Z} = [z_1, \cdots, z_n]^T$. The power of $\mathbf{x}$ and $\mathbf{Z}$ is $E\left(\mathbf{x}\mathbf{x}^T\right) = P \cdot \mathbf{I}_N$, and $E\left(\mathbf{Z}\mathbf{Z}^H\right) = N_0 \cdot \mathbf{I}_N$ respectively.

In the second time slot, the received signals by BS B_i can be expressed as (3). However, differently from single-cell processing, in multi-cell processing, the interference terms $w_i^{'}$ in (3) is treated as useful signal for decoding. Therefore, similarly to (10), the $N \times 1$ vector $\mathbf{y}_B = [y_{B_1}, \cdots, y_{B_N}]^T$ reads

$$
\mathbf{y}_B = \mathbf{H}_{RB} \cdot \mathbf{y}_R^{'} + \mathbf{N} \tag{11}
$$

with $\mathbf{H}_{RB} = \left[\mathbf{H}_{RB_1}^H, \mathbf{H}_{RB_2}^H, \cdots, \mathbf{H}_{RB_N}^H\right]^H$ and $\mathbf{H}_{RB_i} = \left[0, \cdots, 0, h_{R_{i-1}B_i}, h_{R_i B_i}, h_{R_{i+1}B_i}, 0, \cdots, 0\right]$. The additive noise is $\mathbf{N} = [n_1, \cdots, n_N]^T$. Equation $\mathbf{y}_R^{'} = \mathbf{G} \cdot \mathbf{y}_R$ is with $\mathbf{G} = diag\left[g_{R_1}, \cdots, g_{R_N}\right]$ and g_{R_i} satisfies the equitation of (7). Substituting equation (10) and $\mathbf{y_R}$ (11) into equation (11), it can be get

$$
\begin{aligned}
\mathbf{y}_B & = \mathbf{H}_{RB} \cdot \mathbf{y}_R^{'} + \mathbf{N} = \mathbf{H}_{RB} \cdot \mathbf{G} \cdot \mathbf{y}_R + \mathbf{N} \\
& = \mathbf{H}_{RB} \cdot \mathbf{G} \cdot (\mathbf{H}_{TR} \cdot \mathbf{x} + \mathbf{Z}) + \mathbf{N} \\
& = \mathbf{H}_{RB} \cdot \mathbf{G} \cdot \mathbf{H}_{TR} \cdot \mathbf{x} + \mathbf{H}_{RB} \cdot \mathbf{G} \cdot \mathbf{Z} + \mathbf{N} \\
& = \mathbf{H}_{RB} \cdot \mathbf{G} \cdot \mathbf{H}_{TR} \cdot \mathbf{x} + \mathbf{Z}^{'} + \mathbf{N}
\end{aligned} \tag{12}
$$

with $\mathbf{Z}^{'} = \left[z_1{}^{'} \cdots z_N{}^{'}\right]^H$ and $z_i^{'}$ being equal to (6). The correlation matrix of $\mathbf{Z}^{'}$ with $[\mathbf{R}_{\mathbf{Z}'}]_{i,i+j} = \frac{E\left[z_i^{'} z_{i,i+j}^{'*}\right]}{N_0}$ is shown in (13).

$$
\frac{E\left[z_i^{'} z_{i+j}^{'*}\right]}{N_0} =
\begin{cases}
\sum_{k=-1}^{1} g_{R_{i+k}}^2 \left|h_{R_{i+k}B_i}\right|^2 & j = 0 \\
g_{R_i}^2 h_{R_i B_i} h_{R_i B_{i\pm1}}^* + g_{R_{i\pm1}}^2 h_{R_{i\pm1}B_i} h_{R_{i\pm1}B_{i\pm1}}^* & j = \pm1 \\
g_{R_{i\pm1}}^2 h_{R_{i\pm1}B_i} h_{R_{i\pm1}B_{i\pm2}}^* & j = \pm2
\end{cases} \tag{13}
$$

It follows that the ergodic per-cell achievable sum-rate in the BSs can be expressed

$$R_{BS} = \frac{1}{2N} E_h \left[\log_2 \left| \mathbf{I}_N + SNR \left(\mathbf{H}_{RB} \mathbf{G} \mathbf{G}^H \mathbf{H}_{RB}^H + \mathbf{I}_N \right)^{-1} \cdot \mathbf{H}_{RB} \mathbf{G} \mathbf{H}_{TR} \mathbf{H}_{TR}^H \mathbf{G}^H \mathbf{H}_{RB}^H \right| \right] \tag{14}$$

V. Performance Comparison

Some results are presented here, in order to demonstrate the analysis reasonable in the previous sections. The same as [6] [9], in order to get a better insight into the performance of the scenarios but without loss of generality, we specialize the results of the previous sections to be a simple geometric model. As described in Fig.3, the relay station R_i is assumed, for simplicity, to be on a line that connects the active MT T_i to the BS B_i at a normalized distance. From T_i to R_i, the normalized distance is equal to $0 \leq d \leq 1$, while $1-d$ is from R_i to the BS B_i.

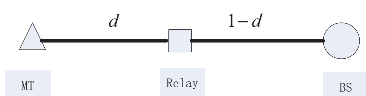

Fig. 3. The normalized distance between MT, Relay and BS.

The average channel gain is defined by d and the path loss exponent σ ($\sigma > 1$ and integer for simplicity) as $\alpha^2 = d^{-\sigma}$ and $\gamma^2 = (1-d)^{-\sigma}$. In this paper, we choose $\sigma = 3$ under urban cellular conditions.

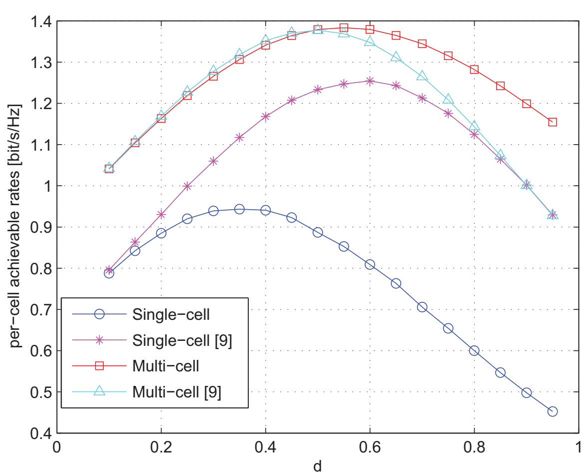

Fig. 4. Ergodic per-cell achievable rates of different schemes for single-cell and multi-cell processing versus the normalized distance d (SNR = 5dB, $\beta^2 = -3$dB, $\delta^2 = -10$dB, $\sigma = 3$).

Fig. 4 compares the per-cell sum-rates of single-cell and multi-cell processing in [9] with the scenarios presented in the paper versus the normalized distance d for $N = 10$, SNR = 5dB, $\beta^2 = -3$dB, $\delta^2 = -10$dB, $\sigma = 3$. It can

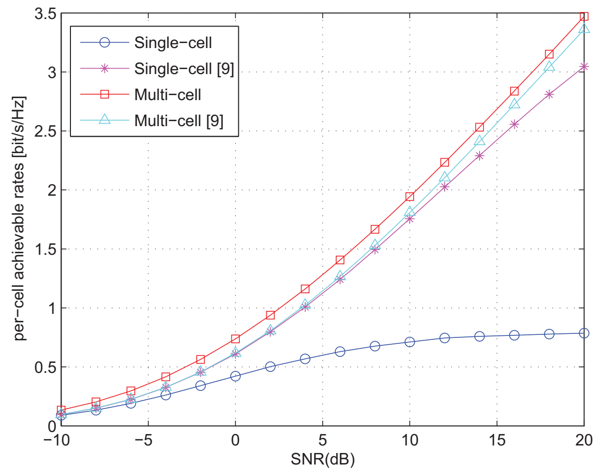

Fig. 5. Ergodic per-cell achievable rates of different schemes with or without cooperation between MTs and BSs versus SNR ($\beta^2 = -3$dB, $\delta^2 = -10$dB, $d = 0.8$, $\sigma = 3$).

be seen from Fig.4 that, notwithstanding single-cell or multi-cell processing, the maximum sum-rate is for a range of d around 0.5. In most cases, the Relay is in the middle of the MT and BS for its maximum achievable rates, but in order to compare with the performance of paper [9] with the channels $E\left[\left|h_{T_i R_{i+j}}\right|^2\right] = \alpha^2 \; for \; j=0; \; 0 \; for \; j = \pm 1$ along with no direct transmission between MTs and BSs exiting, $d = 0.8$ is chosen. The difference between Fig. 4 and Fig. 5 [9] is caused by the number of paths from MT to BS in this paper larger than [9].

Collaboration between BSs overcomes the inter-cell interference existing in single-cell processing, which affects the system performance deteriorating. According to the AF protocols, Relays amplify not only the useful signals but also the noise, which do harm to the achievable rate. As shown in Fig. 5, multi-cell processing outperforms single-cell processing for rates larger than $2.0 bit/s/Hz$. The main difference between this paper and [9] is that there exists transmitting channels between MTs and RSs not only in the same cell but also in adjacent cells, which causes rates decrease in single-cell processing because the signals from adjacent cells are considered as interference, while paper [9] analyzes the channel only existing between BS and Relay in the intra-cell. With the SNR increasing, the rates of the multi-cell processing are going to the same, and the scenario of this paper degenerates into [9] by setting $h_{T_i,R_{i+j}} = 0, j = \pm 1$.

Next, the fading parameter δ, which has effects on the sum-rate of the system, is studied. The relevant parameters are selected as $N = 10$, SNR = 5dB, $d = 0.8$, $\beta^2 = -3dB$. Illustrated in Fig. 6, the ergodic rates under single-cell and multi-cell processing are plotted versus the inter-cell gain factor δ. As described in [9], parameter δ has different effects on the two scenarios: for single-cell processing, increasing δ causes a performance degradation for larger inter-cell interference, while multi-cell processing keeps the performance constant.

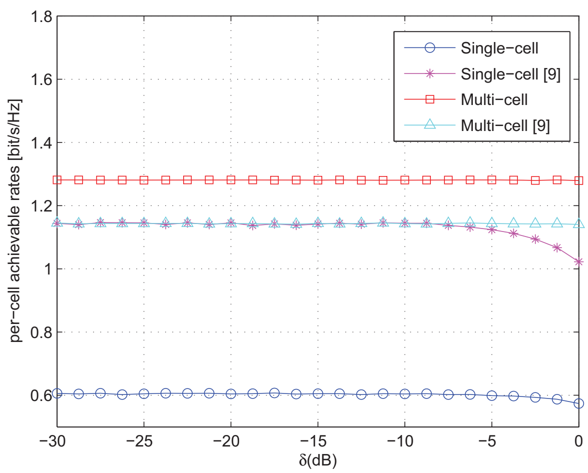

Fig. 6. Ergodic per-cell achievable rates of different schemes for single-cell and multi-cell processing versus the inter-cell gain $\delta(SNR = 5\text{dB}, \beta^2 = -3\text{dB}, d = 0.8, \sigma = 3)$.

From Fig. 7, it can be seen that β has different effects on single-cell and multi-cell processing in this paper but have no influence on [9] for $h_{T_{i+j}R_i} = 0, j = \pm 1$. As β increasing, the system performance becomes better in joint multi-cell processing, on the contrary, in single-cell processing, the performance turns bad.

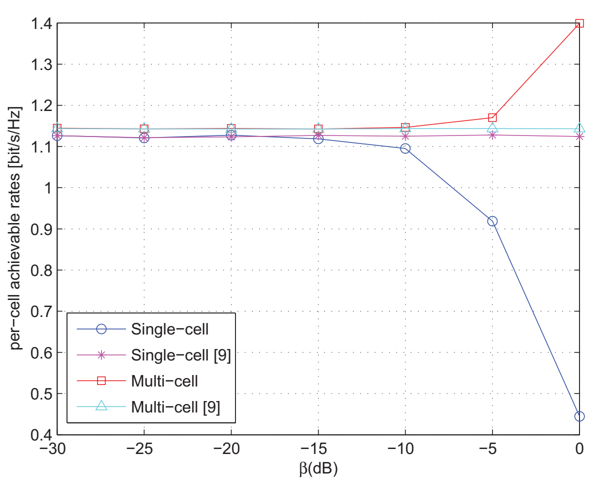

Fig. 7. Ergodic per-cell achievable rates of different schemes for single-cell and multi-cell processing versus the inter-cell gain $\beta(SNR = 5\text{dB}, \delta^2 = -10\text{dB}, d = 0.8, \sigma = 3$).

VI. Conclusion

In this paper, we place special emphasis on single-cell processing and multi-cell processing in mesh networks. The uplink of a TDMA system for simplicity in analysis and focus on AF cooperation techniques is considered. According to the analysis in the paper, we get that the multi-cell processing has better performance than the single-cell processing. In joint multi-cell decoding scenarios, the more adjacent cells jointing in cooperation, the better of the system performance. So this technology has a promising prospect in future wireless communication systems. The drawback of AF techniques is that it not only forwards the useful signals but also the noise (z_i), which affects the systems performance. To avoid this problem, we can use DF techniques, that can be further discussed in [4][6].

Acknowledgment

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