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On the Impact of Backhaul Channel Reliability on Cooperative Wireless Networks

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***Abstract*—We study the effect of unreliable backhaul links on the performance of Coordinated Multi-Point (CoMP) techniques. CoMP has emerged as a powerful scheme to mitigate co-channel interference. Economically viable deployment of Heterogeneous Networks (HetNets) will require the use of lower-performance backhaul options, e.g. non-line-of-sight (NLOS) microwave links. Motivated by HetNets, a backhauling model is introduced, by assigning Link Failure Probability (LFP) to backhaul links, for the cooperative clusters. In this paper we analyze the centralized and semi-distributed CoMP architectures. We investigate the probability of deficient backhaul links reducing quality of service, by impeding transmission. By evaluating the average sum rate of users within a CoMP cluster, we show how backhaul link reliability affects the performance of the cooperative cluster. We conclude, that the performance gains offered by CoMP quickly diminish, as the unreliability of the backhaul links grows.**

I. Introduction

Driven by the increasing popularity of connected devices in wireless communication systems, e.g., smartphones and tablets, mobile broadband traffic is growing rapidly. As cloud-based services become essential to our daily lives, users want to be connected anytime and from anywhere [1]. Traditional macrocell systems fall short to satisfy these needs. Macrocells are inadequate when providing indoor coverage due to the signal attenuation while penetrating the outer walls of the buildings [2]. More importantly, since numerous users are in the coverage area of each macrocell, any single user equipment (UE) gets only a small share of network resources, limiting throughput. To satisfy demand for mobile bandwidth while reducing cost per bit, the spectral efficiency of cellular networks needs to be significantly increased [3].

The spectral efficiency of a cellular network can be improved by increasing the cell density and reducing the transmission power of the network nodes. Hence, embedding low-power nodes into the existing networks, so as to obtain a so called heterogeneous network (HetNet), has emerged as a viable way to increase network capacity [4]. However, a major challenge of HetNets is the management of co-channel interference [5]. From information theory it is known that inter-cell interference can be overcome, if transmission nodes (TN) cooperatively process signals [6]. Recently such techniques are referred to as Coordinated Multi-Point (CoMP) [7]. CoMP schemes allow interference mitigation through joint and coherent transmission from multiple TNs, but at the cost of increased complexity and other overhead [8].

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CoMP requires information exchange between the TNs, in which each TN acquires the counterpart's channel state information (CSI) or user data, prior to the coordinated transmission. The information exchange occurs over the backhaul links that interconnect the TNs. Traditionally, backhaul links are assumed to be highly reliable, which are less likely to be available in the heterogeneous and dense future networks. This is because the high number of access nodes would need to be accompanied by a proportionally high financial investment in order to build high quality wireline backhaul [9]. Furthermore the topology of heterogeneous access points, i.e., some will be mounted on high towers (macro stations), others will be deployed on the street level below roof tops (pico and relay stations) and others will be indoors (femto cells), suggests that backhaul links interconnecting access nodes are wireless and without guaranteed line-of-sight (LOS) [10].

In this paper, motivated by the HetNet scenario, we evaluate the downlink of a cooperative wireless network, and study the impact of backhaul channel reliability on the system performance. A backhauling model is introduced for the cooperative systems under different network architectures, i.e., the centralized and semi-distributed versions. An analytical approach is taken to investigate how backhaul reliability affects the operation of the cooperating TNs. Under each considered network CoMP architecture, the zero-forcing joint transmission scheme and the multi-point coordinated scheduling scheme are studied and compared. We have found, that although higher rates are achievable with joint transmission, it is more sensitive to backhaul link failure. The semi-distributed architecture offers better resistance to LFP, as the performance of the CoMP schemes will converge to the one of traditional single cell transmission, as LFP grows.

The rest of the paper is organized as follows. In Section II, we present the proposed system model. In Section III, we describe the examined backhauling models for different system architectures, and Section IV illustrates how backhaul reliability affects TN operation under the described CoMP architectures. The numerical results are discussed in Section V, and the conclusions are drawn in Section VI.

Notation: Here, $(\,)^H$, $(\,)^T$, $(\,)^{-1}$ and $(\,)^+$ denote the conjugate transpose, transpose, matrix inversion and matrix pseudo-inversion operations, respectively. The notation $\mathbf{1}_{[m\times n]}$ and $\mathbf{0}_{[m\times n]}$ represent the matrix with m rows and n columns filled with ones and zeros, respectively. $(\,)^m_{(n,:)}$ denotes the n^{th} row of matrix m. $\mathbb{N}$ refers to the set of natural numbers. $|\mathcal{M}|$ denotes the cardinality of the set $\mathcal{M}$. $\odot$ represents the element-wise multiplication.

II. System Model

In this paper, we consider the downlink of a cooperative system, consisting of N single-antenna TNs and M single-antenna UEs. The UEs are grouped together using a particular resource slot. Hence, in the following, the case where $M = N$ will be assumed. The N TNs are assumed to have the same maximum power constraint $P_{\max}$ and to share the same resource slot. Let $\mathbf{x} = [x_1, ..., x_N]^T$ denote the signal vector transmitted from all N TNs, with $x_n^H x_n \leq P_{\max}$ for all $n \in \{1, ..., N\}$. The received signal at UE m can then be expressed as $y_m = \mathbf{h}_m \mathbf{x} + n_m$, where $\mathbf{h}_m = [h_{m1}, ..., h_{mN}]$ denotes the channel state vector between UE m and all N TNs. n_m is the sum of the thermal noise and the uncoordinated out-of-cluster interference, modeled as independent complex additive white Gaussian noise [11].

Each UE m estimates its channel state vector $\mathbf{h}_m$, and feeds it back to its serving TN m via uplink control channels, that are assumed to be fully reliable, since we in this work aim to investigate the impact of unreliable backhaul links. The Control Unit (CU) gathers CSI from the cooperating TNs via backhaul links and designs the transmission parameters [12]. It is assumed that the CSI of all UEs within the system, named as full CSI, is corrupted via backhaul channels. Hence, the system channel matrix available at the CU is denoted as $\hat{\mathbf{H}} = [\hat{\mathbf{h}}_1^T, .., \hat{\mathbf{h}}_M^T]^T \in \mathcal{C}^{M \times N}$, which will be used for the scheduling and transmission scheme design.

A. Joint Transmission

Assume that the data symbols of all the M UEs within the cluster are shared among the N coordinated TNs. A linear precoding approach, zero-forcing, is considered as the coherent joint transmission scheme in this section. Note that with linear precoding among N single-antenna TNs, at most N single-antenna UEs can be served on the same resource slot without inter-user interference.

Let $\mathcal{M}$ denote the set of scheduled UEs in a given resource slot, with $\mathcal{M} \subseteq \{1, ..., M\}$ and $|\mathcal{M}| \leq N$. Let $\mathbf{b} \in \mathbb{C}^{|\mathcal{M}|}$ be the data symbols of the selected UEs in set $\mathcal{M}$. A precoding matrix $\mathbf{W} = [\mathbf{w}_1, ..., \mathbf{w}_{|\mathcal{M}|}] \in \mathcal{C}^{N \times |\mathcal{M}|}$ is designed for mapping the data symbol vector $\mathbf{b}$ into the transmit signal vector $\mathbf{x}$, that is, $\mathbf{x} = \mathbf{W}\mathbf{b}$. The m^{th} column of $\mathbf{W}$, $\mathbf{w}_m = [w_{1m}, ..., w_{Nm}]^T$, is the precoding vector for UE m in the set $\mathcal{M}$. The received signal of UE m can be rewritten as $y_m = \mathbf{h}_m \mathbf{w}_m b_m + \sum_{i \in \mathcal{M}, i \neq m} \mathbf{h}_m \mathbf{w}_i b_i + n_m$.

Let $p_m = b_m b_m^H$ denote the symbol power allocated to UE m across the N TNs. The signal to interference plus noise ratio (SINR) of UE m is then given by

$$\gamma_m = \frac{\|\mathbf{h}_m \mathbf{w}_m\|^2 p_m}{\sum_{i \in \mathcal{M}, i \neq m} \|\mathbf{h}_m \mathbf{w}_i\|^2 p_i + \sigma^2} . \tag{1}$$

Thus, the sum rate of the cluster can be expressed as

$$C = \textstyle\sum_{m \in \mathcal{M}} \log_2(1 + \gamma_m) . \tag{2}$$

Using zero-forcing precoding, the precoding matrix, $\mathbf{W}$, is obtained as the pseudo-inverse of the channel matrix, $\hat{\mathbf{H}}$, available at the CU.

In order to reduce the complexity, a sub-optimal equal power allocation is considered [13]. As a first step, $\mathbf{W}$ is normalized column-wise, then for any given UE set, $\mathcal{M}$, the power allocation vector is derived as

$$\mathbf{p} = \left\{ \min_{n=1,...N} \frac{P_{\max}}{\sum_{m \in \mathcal{M}} \|w_{nm}\|^2} \right\} \mathbf{1}_{[|\mathcal{M}| \times 1]} . \tag{3}$$

By solving the joint power allocation of (3) for every possible UE set $\mathcal{M}$, the chosen UE set $\mathcal{M}^{\text{JT}}$ and $\mathbf{p}^{\text{JT}}$ will be the ones that achieve the highest $\sum_{m=1}^{M} \log_2(1 + \hat{\gamma}_m)$, where $\hat{\gamma}_m$ is derived from (1) by using the obtained $\hat{\mathbf{h}}_m$ at the CU instead of the true channel vector $\mathbf{h}_m$. In the following, this zero-forcing joint transmission scheme is denoted as JT.

B. Coordinated Scheduling

In the considered coordinated scheduling scheme, data to a single UE is only transmitted from its serving TN, which is selected based on the long term channel quality measurements, including pathloss and shadow fading. Hence, user data exchange between TNs is not needed. It is assumed that a TN can transmit data to at most one UE in any given resource slot.

Let $P_m = b_m^H b_m$ denote the transmit power of TN m to UE m, with $P_m \leq P_{\max}$. Then, the SINR for UE m is given as

$$\gamma_m = \frac{\|h_{mm}\|^2 P_m}{\sum_{j=1, j \neq m}^{j=N} \|h_{mj}\|^2 P_j + \sigma^2} . \tag{4}$$

Thus, the sum rate can be calculated by (2).

UE scheduling and power allocation decisions are jointly made at the CU to control ICI. With the gathered channel matrix, $\hat{\mathbf{H}}$, the CU designs the UE selection indicator matrix $\mathbf{S}$ and the power allocation vector $\mathbf{P} = [P_1, ..., P_n]$, in order to maximize the sum rate subject to per-TN power constraints. Based on [14], a suboptimal binary power control (BPC) is considered for this coordinated scheduling scheme, i.e., $P_n = 0$ or $P_{\max}$ for $\forall n \in \{1, ..., N\}$. Then, the relaxed problem becomes an exhaustive binary search. The CU searches all feasible boundary point sets, i.e., $P_n = 0$ or $P_{\max}$ for $\forall n \in \{1, ..., N\}$. The chosen transmit power vector $\mathbf{P}^{\text{CS}}$ will be the ones that achieve the highest $\sum_{m=1}^{M} \log_2(1 + \hat{\gamma}_m)$, where $\hat{\gamma}_m$ is derived from (4) by using the obtained $\hat{\mathbf{h}}_m$. In this paper, this scheme is named as CS.

III. Backhauling Models

In this section, we introduce the backhauling models considered for single cell transmission and for the cooperative systems under different network architectures, i.e., the centralized and semi-distributed CoMP architectures.

A. Single Cell Transmission

Single cell transmission without TN coordination (Fig. 1), denoted as SC, is used as a baseline. For SC transmission, the data blocks sent from the core network to TN n will only contain the data symbol for UE n. The TNs might fail in decoding the received data blocks, due to backhaul unreliability. This event is modeled by erasing each data symbol, b_n, independently. There is no cooperation, therefore CSI is not to be shared, hence backhaul unreliability only affects the data distribution.

B. Centralized CoMP Architecture

As depicted in Fig. 2, under the centralized architecture each TN n forwards their received local channel state row vector, $\mathbf{h}_m$, to the CU via backhaul links in a first step. Based on the gathered system channel matrix $\hat{\mathbf{H}}$, the CU constructs the precoding matrix for the JT scheme or makes scheduling decisions for the CS scheme. Once the decisions are made, the CU forwards them via backhaul links to each coordinated TN. Hence, backhaul links are used twice, i.e., gathering full CSI and distributing transmission decisions.

All backhaul links are modeled to be prone to errors, leading to losing partial CSI of the system at the CU or losing precoded user data at the cooperating TNs. LFPs are modeled as independent binary discrete random variables. Hence the available system channel matrix at CU, $\hat{\mathbf{H}}$, is obtained as

$$\hat{\mathbf{H}} = \mathbf{H} \odot \mathbf{H}^{\text{mask}}, \tag{5}$$

where $\mathbf{H}$ is the true system channel matrix. Here, $\mathbf{H}^{\text{mask}}$ is a binary mask matrix, where each row vector, $\mathbf{H}^{\text{mask}}_{(m,:)}$, is either $\mathbf{0}_{[1\times N]}$ with probability $P^{\text{C}}_{\text{F}_n}$ or $\mathbf{1}_{[1\times N]}$.

For the JT scheme, the user data x_n distributed from the CU to TN n contains the precoded data symbols for the scheduled UEs, i.e., $x_n = \mathbf{W}_{(n,:)}\mathbf{b} = \sum_{m\in\mathcal{M}} w_{nm}b_m$.

Similarly, to model the data loss via backhaul links to each TN, a binary mask matrix, $\mathbf{W}^{\text{mask}}$, is applied to the original precoding matrix $\mathbf{W}$ as

$$\hat{\mathbf{W}} = \mathbf{W} \odot \mathbf{W}^{\text{mask}}, \tag{6}$$

which erases each row vector of $\mathbf{W}$ independently, with a probability of $P^{\text{D}}_{\text{F}_n}$. The SINR of the scheduled UEs can be derived by substituting $\hat{\mathbf{W}}$ into (1), the sum rate can then be obtained from (2).

Example 1. A cooperative cluster comprises of $N = 3$ TNs, as shown in Fig. 2. All UEs feed back the local channel state vector to their serving TN. TNs share the received local channel state vector, $\mathbf{h}_m$, with the CU. If, however, $\mathbf{h}_2$ is lost due to failure of the backhaul link, $\hat{\mathbf{H}}$ is obtained as

$$\hat{\mathbf{H}} = \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \\ \mathbf{h}_3 \end{bmatrix} \odot \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix}.$$

Considering an error in the backhaul link when the CU distributes the precoded user data to TN 1, $\hat{\mathbf{W}}$ is calculated as

$$\hat{\mathbf{W}} = \mathbf{W} \odot \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}.$$

For the CS scheme, the user data distributed from the CU is $x_n = z_n b_n$, where z_n is the discrete binary power control bit.

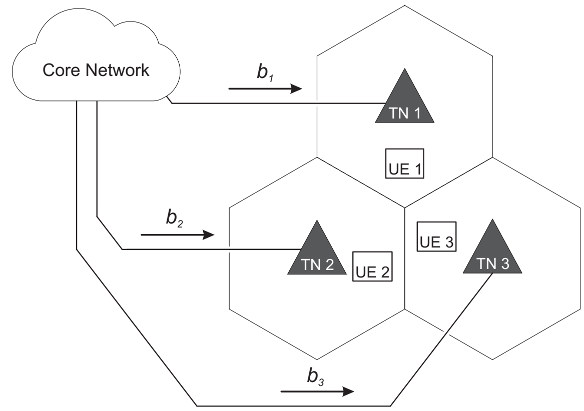

Figure 1. Single cell transmission

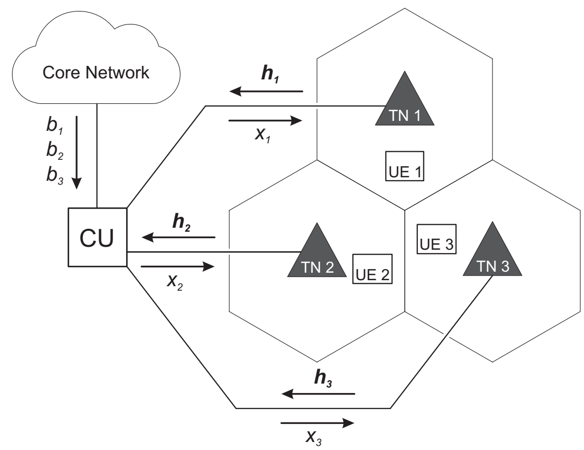

Figure 2. Centralized CoMP architecture

In this case, the data loss due to backhaul unreliability is modeled as

$$\hat{b}_n = b_n b^{\text{mask}}_n, \tag{7}$$

where b^{mask}_n is a binary mask variable which erases the data symbol of UE n with probability $P^{\text{D}}_{\text{F}_n}$. Thus, the SINR of each UE n can be calculated by substituting $\mathbf{P}^{\text{mask}}$ into (4), where the n^{th} element, P^{mask}_n, is derived by $P^{\text{mask}}_n = b^{\text{mask}}_n P^{\text{CS}}_n$.

C. Semi-distributed CoMP Architecture

Under the semi-distributed architecture, depicted in Fig. 3, the received local CSI vectors $\mathbf{h}_m$ are firstly shared between TNs via interconnecting backhaul links. Each TN receives $N-1$ non-local CSI vectors, thus acquiring a local gathered system channel matrix $\hat{\mathbf{H}}_n$, which is obtained independently by using (5). Note that we assume that every TN n receives an error-free local CSI vector, $\mathbf{h}_m$, fed back by UE m in each resource slot. Here $M = N$, hence, the m^{th} row of $\mathbf{H}^{\text{mask}}$ will always be $\mathbf{1}_{[1\times N]}$.

Based on the gathered $\hat{\mathbf{H}}_n$, each cooperating TN acts as a CU, independently designing its own precoding weights and power allocation vector for JT, or make scheduling decisions for CS. Transmission decisions are then locally applied to the user data, which is assumed to be received from the core network.

For the JT scheme, each TN n independently designs the precoding matrix $\mathbf{W}^n$ based on the gathered system matrix $\hat{\mathbf{H}}_n$. The n^{th} row of $\mathbf{W}^n$, i.e., $W^n_{(n,:)}$, is then chosen by TN n as the precoding vector for mapping the user data symbols into the transmit signal. The data blocks, sent from the core network to TN n, will contain all data symbols for the scheduled UEs in the cluster, $d_n = [b_1, ..., b_m]$. We assume that different user data symbols are sent from the core network to all TNs independently via backhaul links. Thus, each user data symbol, b_m, is affected independently by backhaul link failure. To model this LFP a binary mask is applied to $\mathbf{W}$, similarly to (6). In this case, all elements of $\mathbf{W}^{\text{mask}}$ will be independently ones or zeros. Finally the SINR of the scheduled UEs can then be derived by substituting $\hat{\mathbf{W}}$ into (1), and the sum rate can then be obtained from (2).

Example 2. A cooperative cluster comprises of $N = 3$ TNs, as shown in Fig. 3. All UEs feed back the local channel state vector to their serving TN. TN 1 receives the error-free channel state vector $\mathbf{h}_1$ from UE 1. TN 2 and TN 3 share $\mathbf{h}_2$ and $\mathbf{h}_3$ with TN 1 through unreliable backhaul links. Considering the case when $\mathbf{h}_3$ is lost due to failure of the backhaul link, $\hat{\mathbf{H}}_1$ is obtained as

$$\hat{\mathbf{H}}_1 = \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \\ \mathbf{h}_3 \end{bmatrix} \odot \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} .$$

The data symbols from the core network are affected by errors independently, therefore, $\hat{\mathbf{W}}$ is derived as shown in the example below:

$$\hat{\mathbf{W}} = \begin{bmatrix} W^1_{(1,:)} \\ W^2_{(2,:)} \\ W^3_{(3,:)} \end{bmatrix} \odot \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} .$$

For the CS scheme, the downlink data block, d_n, which is distributed from the core network to each TN n, contains only the data symbol of its own UE. Thus, $d_n = b_m$, with $n = m$. The discrete binary power control bit z_n is designed locally at each TN. Modeling backhaul unreliability and calculation of the SINR can be done in the same way as described above for the centralized architecture.

IV. Backhaul Reliability Analysis

In this section we analyze the probability of any TN n staying silent in a resource slot, P^{S}_n, due to unreliable backhaul links. This may cause some UEs unserved, or, as a worst-case scenario, impede all transmission with probability $P^{\text{W}} = \prod_{n=1}^{N} P^{\text{S}}_n$.

A. Single Cell Transmission

No CSI sharing takes place, therefore transmission only depends on the LFP of the backhaul links connecting the TNs to the network. Provided that the LFP of the backhaul link is P_{F_n}, P^{S}_n can be expressed as

$$P^{\text{S}}_n = P_{\text{F}_n} . \tag{8}$$

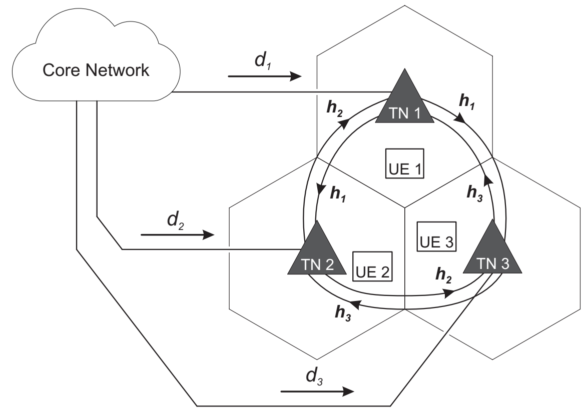

Figure 3. Semi-distributed CoMP architecture

B. Centralized CoMP architecture

Joint Transmission: Considering the JT scheme under the centralized architecture, based on the backhauling model described in Section III, TN n will stay silent if

Case 1. All local CSI vectors sent from the TNs are lost at the CU, otherwise,

Case 2. The user data distributed from the CU to TN n is lost.

The probability that Case 1 happens is $\prod_{i=1}^{N} P^{\text{C}}_{\text{F}_i}$, where $P^{\text{C}}_{\text{F}_n}$ is the LFP when TN n forwards the CSI to the CU. Case 2 happens with probability $P^{\text{D}}_{\text{F}_n}$, where $P^{\text{D}}_{\text{F}_n}$ is the LFP when the CU distributes precoded user data to TN n. Therefore, P^{S}_n for the JT scheme under centralized architecture can be expressed as

$$P^{\text{S}}_n = P^{\text{D}}_{\text{F}_n} + (1 - P^{\text{D}}_{\text{F}_n}) \cdot \prod_{i=1}^{N} P^{\text{C}}_{\text{F}_i} . \tag{9}$$

Coordinated Scheduling: In case of the CS scheme, it is possible that the TN will not be scheduled for transmission in the current resource block even if CSI sharing is not affected by failure of backhaul links, because BPC is performed to control the interference, depending on the system architecture and the current channel conditions. Hence, TN n will stay silent if

Case 1. The TN will not be scheduled for transmission in the current resource block, due to BPC, otherwise,

Case 2. The user data distributed from the CU to TN n is lost.

The probability that Case 1 happens is P^{NS}_n, while Case 2 happens with probability $P^{\text{D}}_{\text{F}_n}$. Therefore, P^{S}_n for the CS scheme under centralized architecture can be expressed as

$$P^{\text{S}}_n = P^{\text{D}}_{\text{F}_n} + (1 - P^{\text{D}}_{\text{F}_n}) \cdot P^{\text{NS}}_n . \tag{10}$$

C. Semi-distributed CoMP architecture

Joint Transmission: In case of the JT scheme P^{S}_n depends on whether CSI from other TNs has reached TN n, and whether the user data has reached the TN in question. Hence, TN n will stay silent if

Case 1. All non-local CSI vectors, sent from other TNs, and the data symbol of UE n, sent from the core network, are lost at TN n, otherwise,

Case 2. All user data symbols distributed from the core network to TN n are lost.

The probability that Case 1 happens is $P^{\mathrm{D}}_{\mathrm{F}_{n,n}} \cdot \prod_{k=1,k\neq n}^{N} P_{\mathrm{F}_{n,k}}$. $P^{\mathrm{D}}_{\mathrm{F}_{m,n}}$ is the LFP between the core network and TN n, while user data symbol m is distributed. $P_{\mathrm{F}_{n,k}}$ is the LFP when CSI is sent from TN k to TN n. Case 2 happens with probability $\prod_{m=1}^{M} P^{\mathrm{D}}_{\mathrm{F}_{m,n}}$. Transmission from TN n to a UE m, if $m \neq n$, will happen with probability $\left(1 - P^{\mathrm{D}}_{\mathrm{F}_{m,n}}\right) \cdot \left(1 - P_{\mathrm{F}_{n,m}}\right) = 1 - \left[P^{\mathrm{D}}_{\mathrm{F}_{m,n}} + \left(1 - P^{\mathrm{D}}_{\mathrm{F}_{m,n}}\right) \cdot P_{\mathrm{F}_{n,m}}\right]$. Therefore, P^{S}_{n} for the JT scheme under semi-distributed architecture can be expressed as

$$P^{\mathrm{S}}_{n} = P^{\mathrm{D}}_{\mathrm{F}_{n,n}} \cdot \prod_{i \in T} \left[P^{\mathrm{D}}_{\mathrm{F}_{n,i}} + \left(1 - P^{\mathrm{D}}_{\mathrm{F}_{n,i}}\right) \cdot P_{\mathrm{F}_{n,i}}\right], \qquad (11)$$

where $T = \{x \in \mathbb{N} : 1 \leq x \leq N, \, x \neq n\}$.

Coordinated Scheduling: Considering the CS scheme under the semi-distributed architecture, P^{S}_{n} can be calculated using (10). In this case, however, P^{NS}_{n} will depend on the reliability of the backhaul links interconnecting the TNs, and $P^{\mathrm{D}}_{\mathrm{F}_{n}}$ models LFP between the core network and TN n.

V. Performance Evaluation

We consider the downlink of a CoMP cluster with $N = 2$ and $N = 3$ neighboring sectors respectively. For each cluster size, N, $M = N$ single-antenna UEs are grouped together using a particular resource slot. The cluster radius R is 500 m. The path loss model is $PL(d) = 128.1 + 37.6 \log_{10}(d)$ in dB, with d given in km. Shadowing is log-normally distributed with zero mean and standard deviation 8 dB. The system SNR is set to 18 dB, which is defined as the received SNR at the boundary of the cell, assuming full power transmission $P_{\max}$ from the TN, accounting only for pathloss $PL(R)$ and ignoring shadowing and fast fading [11]. For each value of LFP, the average sum rate, $\overline{C}$, is obtained by averaging the sum rate of the cluster, obtained from (2), over $2 \cdot 10^5$ independent UE set realizations.

UEs are uniformly distributed over the cell area. Each TN has a single UE allocated in the shared frequency, time-slot or code resource. SC transmission without TN coordination, denoted as Single Cell, is used as baseline. For each of the analyzed CoMP architectures, i.e., the centralized and semi-distributed versions, the considered JT, CS, and SC transmission schemes are evaluated and compared. For the sake of simplicity, it is assumed that all backhaul links have the same LFP, P_{F}.

Fig. 4a and Fig. 4b plot $\overline{C}$ against LFP. If LFP is close to zero the coordinated transmission schemes offer a significant performance gain under both the centralized and semi-distributed CoMP architectures. However, this gain diminishes quickly as backhaul unreliability grows. Note that when $N = 2$, the performance of the JT scheme under the semi-distributed architecture always outperforms the one achieved under the centralized architecture. However, if $N > 2$, the centralized version outperforms the semi-distributed one for the JT scheme when the LFP is low. Moreover, within the distributed architecture, $\overline{C}$ of both JT and CS schemes converge to the performance achieved by SC transmission when the backhaul is highly unreliable. This is because, as mentioned in Section III-C, the TNs will always have at least one received local CSI vector $\mathbf{h}_m$. This causes the TNs operate similarly to the SC transmission scheme, where the performance is limited only by the reliability of the backhaul links transmitting data symbols to the TNs.

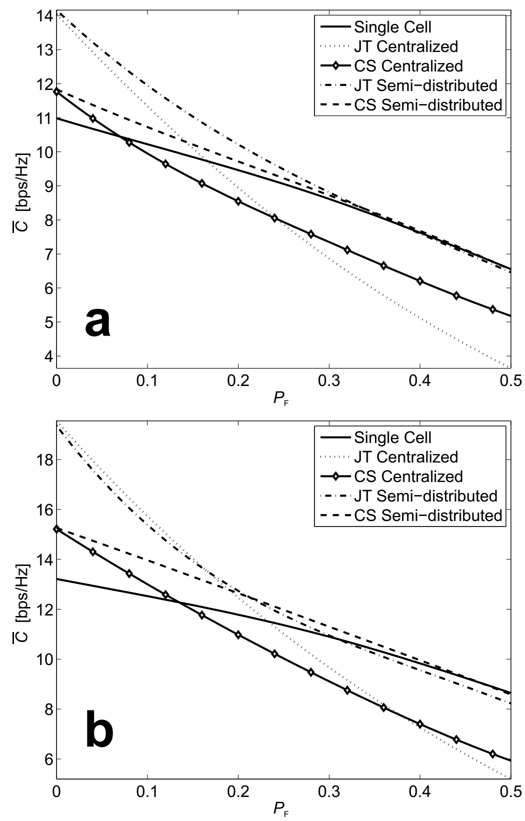

Figure 4. $\overline{C}$ vs. LFP, *a)* Cluster size = 2, *b)* Cluster size = 3

In case of the JT scheme under the centralized architecture, the CU distributes the precoded symbols in one data block towards each TN. Therefore, the data symbols of all UEs will be lost at a TN if a packet is affected by failure of the backhaul link, and this results in bad performance when LFP is high. In case of CS, if LFP is high, it is more likely that only a reduced set of TNs will be scheduled, this however increases the chance of all TNs staying silent, since the data symbols distributed for the scheduled TNs can be lost. It should be pointed out that although the semi-distributed architecture offers better performance in most cases, it requires each cooperating TN to be acting as a CU, and also backhaul links interconnecting all TNs.

We can also see that there is a cross point for JT under different architectures. As the cluster size increases the relative

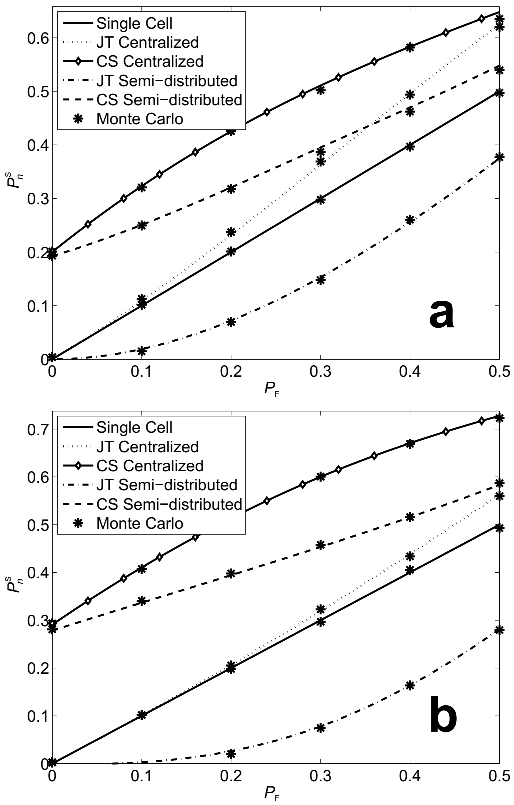

Figure 5. P_n^{S} vs. LFP, *a)* Cluster size = 2, *b)* Cluster size = 3

performance of JT under centralized architecture improves, however, it drops faster in the high LFP domain. In the evaluated scenarios the best performance can be achieved with JT under the semi-distributed architecture, however, this scheme has a higher backhaul capacity requirement, since all data symbols have to be shared with all TNs.

Fig. 5a and Fig. 5b plot the probability of any TN n staying silent in a resource slot against LFP, for each transmission scheme and system architecture. If all backhaul links have the same same LFP, P_{F}, (9) - (11) are reduced to

$$P_n^{\mathrm{S}} = P_{\mathrm{F}} + (1 - P_{\mathrm{F}}) \cdot (P_{\mathrm{F}})^N \ , \tag{12}$$

for JT under the centralized architecture,

$$P_n^{\mathrm{S}} = P_{\mathrm{F}} + (1 - P_{\mathrm{F}}) \cdot P_n^{\mathrm{NS}} \ , \tag{13}$$

for CS under both introduced architectures, and

$$P_n^{\mathrm{S}} = P_{\mathrm{F}} \cdot [P_{\mathrm{F}} + (1 - P_{\mathrm{F}}) \cdot P_{\mathrm{F}}]^{N-1} \ , \tag{14}$$

for JT under the semi-distributed architecture.

The simulated data is plotted with markers only, while the continuous lines show the values calculated by (12) - (14). Note, that P^{S} does not directly limit $\overline{C}$, since the silence of a TN also decreases the inter-cell interference in the neighboring cells.

VI. Conclusions

In this paper we have examined the effects of backhaul reliability on the performance of a cluster of cooperative transmission nodes. In particular, two transmission schemes, joint transmission and coordinated scheduling were evaluated under the centralized and semi-distributed CoMP architectures. The scenarios were assessed in terms of average sum rate in the coverage region, and traditional single cell transmission served as a baseline for comparison. Analytical results were presented to show how unreliable backhaul degrades quality of service, by leaving some user equipments unserved.

Numerical results show that cooperative transmission techniques have the potential to greatly reduce harmful interference, therefore, increasing the system sum rate. However, the performance of the system highly depends on the reliability of the backhaul network. Although all examined scenarios suffer from performance degradation as LFP increases, the coordinated scheduling scheme always shows a better performance under the semi-distributed architecture. For the joint transmission scheme, if the number of cooperating transmission nodes is greater than two, better system performance can be achieved under the centralized architecture, but only up to a certain value of LFP, which is determined by the cluster size.

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