Maximum Throughput in a C-RAN Cluster with Limited Fronthaul Capacity

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***Abstract*—Centralized/Cloud Radio Access Network (C-RAN) is a promising future mobile network architecture which can ease the cooperation between different cells to manage interference. However, the feasibility of C-RAN is limited by the large bit rate requirement in the fronthaul. This paper study the maximum throughput of different transmission strategies in a C-RAN cluster with transmission power constraints and fronthaul capacity constraints. Both transmission strategies without cooperation (e.g. "no cooperation transmission") and with cooperation (e.g. "distributed MIMO") between different cells are considered. Simulation results show that "distributed MIMO" has a better performance than "no cooperation transmission" with high RRH power constraint, high fronthaul capacity constraint and when the UEs are located at cell edge area.**

Keywords: RRH; BBU; precoding; fronthaul; quantization; Coordinated Multi-point (CoMP).

I. Introduction

Modern mobile-broadband system Long Term Evolution (LTE) has opted for a frequency reuse factor 1, to maximize the data rates for users close to the Base Station (BS). In reuse-one deployment, low signal-to-interference ratios (SIR) may occur, especially in the cell edge area, where the power of the useful signal has the same order of magnitude as the interference.

In the traditional configuration of mobile base station, both Remote Radio Head (RRH) and Base Band Unit (BBU) are integrated in Base Station (BS). The Centralized radio access network (C-RAN) [1] puts BBUs at the same location (BBU pool). The new architecture can facilitate the cooperation among different cells and allows advanced algorithms (e.g. Coordinated Multi-Point (CoMP)) [2] to manage interference.

However, the digitized baseband signals exchanged between BBU pool and RRHs require a large bit rate [3]. This is a main limitation of the feasibility of C-RAN. Therefore, it is important to include the front-haul capacity constraint when evaluating the performance of different advanced cooperation algorithms in C-RAN. In this paper, we study the performance of different transmission strategies with RRH power constraints and front-haul capacity constraints. [4] and [5] take these constraints into account for precoding design and fronthaul compression in a C-RAN network.

When one UE is near to one RRH and far from the others, single RRH transmission can achieve similar performance compared with multiple RRHs coordinated transmission. We compare the maximum throughput of two types of transmission strategies. One is that each UE is served by only one RRH. The other is that multiple RRHs serve multiple UEs together (e.g. "distributed MIMO").

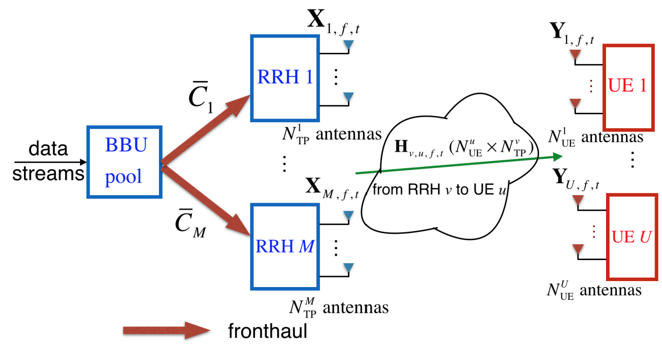

Fig. 1. Downlink of a cluster of RRHs which connect to a BBUs pool via finite-capacity front-haul links in C-RAN.

This rest of the paper is organized as follows. The system model is described in Section II. We study precoding design and fronthaul quantization in Section III. Then , we present system configuration in Section IV. Different downlink transmission strategies are discussed in Section V and their performance simulation results are presented in Section VI. At last, we conclude in Section VII.

Notation: In this paper, $(\cdot)^{\mathrm{T}}$ denotes matrix transpose, $(\cdot)^{\mathrm{H}}$ denotes Hermitian matrix transpose, $\mathrm{tr}\{\cdot\}$ denotes the trace of a matrix, $(\cdot)^{\star}$ denotes complex conjugate, $\mathbf{I}_n$ denotes the identity matrix of size n. The complex field is denoted by $\mathbb{C}$ and $\mathbb{1}$ denotes the two-element set $\{0, 1\}$. We adopt standard information-theoretic definitions for the mutual information $I(\mathbf{X}; \mathbf{Y})$ between the random variables $\mathbf{X}$ and $\mathbf{Y}$.

II. System Model

We investigate the downlink of a cluster $\mathcal{C}$ of M RRHs serving U UEs in C-RAN as shown in Figure 1. The set of all the RRHs is denoted as $\mathcal{N}_{\mathrm{TP}} = \{1,\ 2,\ ...,\ M\}$, and the set of all the UEs is denoted as $\mathcal{N}_{\mathrm{UE}} = \{1,\ 2,\ ...,\ U\}$. A BBU pool controls and connects to the RHHs in the cluster via finite-capacity front-haul links. The capacity of the front-haul link from the BBUs pool to the v-th RRH is denoted by $\overline{C}_v$. Each v-th RRH is equipped with N_{TP}^{v} antennas and each u-th UE is equipped with N_{UE}^{u} antennas.

The time is divided into subframes of typically 1 ms in LTE. We consider ideal OFDM transmission which is equivalent to a set of independent narrow-band transmissions, a transmission being made on a sub-carrier f and during a subframe t. Correspondingly, for f and t, the downlink propagation channel inside the coordinated cluster is defined by a set of matrix $\mathbf{H}_{u,v,f,t} \in \mathbb{C}^{[N_{\text{UE}}^u \times N_{\text{TP}}^v]}$ where $\mathbf{H}_{u,v,f,t}$ is the channel matrix from RRH v to UE u.

During subframe t, RRH v transmits the signal on subcarrier f denoted by $\mathbf{X}_{v,f,t} \in \mathbb{C}^{[N_{\text{TP}}^v \times N_s]}$ following the power constraints:

$$\frac{1}{N_s}\,\mathbb{E}(\|\mathbf{X}_{v,f,t}\|^2) \leq \overline{P}_v,\ \forall\ v \in \mathcal{N}_{\text{TP}}. \tag{1}$$

where N_s is number of OFDM symbols transmitted from an antenna during one subframe.

The $N_{\text{UE}}^u \times N_s$ signal received by UE u on frequency f and during subframe t is given by

$$\mathbf{Y}_{u,f,t} = \sum_{v=1}^{M} \mathbf{H}_{u,v,f,t} \cdot \mathbf{X}_{v,f,t} + \mathbf{N}_{u,f,t}, \tag{2}$$

where $\mathbf{N}_{u,f,t} \in \mathbb{C}^{[N_{\text{UE}}^u \times N_s]}$ is the noise matrix, which consist of i.i.d $\mathcal{CN}(0,1)$ entries.

We denote a set of T continuous subframes as $\mathcal{T} = \{1,\ ,2,\ ...,\ T\}$, the i-th element in set $\mathcal{T}$ as $\mathcal{T}[i]$. The set of UEs served in subframe $t \in \mathcal{T}$ is denoted as $\mathcal{N}_{\text{UE},t} = \{u_1^t,\ u_2^t,\ ...,\ u_{K_t}^t\}$, where K_t is the number of UEs served during this subframe. During the T subframes, each UE is supposed to be served at least in one subframe and only in one subframe. Thus, $\bigcup_{t\in\mathcal{T}} \mathcal{N}_{\text{UE},t} = \mathcal{N}_{\text{UE}}$ and $\mathcal{N}_{\text{UE},i} \bigcap_{i\neq j} \mathcal{N}_{\text{UE},j} = \emptyset,\ \forall i \in \mathcal{T},\ \forall j \in \mathcal{T}$.

The UEs in $\mathcal{N}_{\text{UE},t}$ are served together by the RRHs in $\mathcal{N}_{\text{TP}}$ on respecting to the constraints:

$$N_{\text{RL}}^u \ \leq\ N_{\text{UE}}^u, \forall u \in \mathcal{N}_{\text{UE},t}, \tag{3}$$

$$\sum_{u\in\mathcal{N}_{\text{UE},t}} N_{\text{RL}}^u \ \leq\ \sum_{v\in\mathcal{N}_{\text{TP}}} N_{\text{TP}}^v. \tag{4}$$

where N_{RL}^u is the number of parallel symbols (layers) transmitted to UE u.

Here, we assume the channel fading to be constant within a coherence period larger than T subframes, while they vary in an ergodic way across a large number of coherence periods. In this paper, we restrict ourselves on one single sub-carrier. Thus, we omit the index f and t for simplicity within the T subframes. The channel between RRH v and UE u is modeled as:

$$\mathbf{H}_{u,v} = \sqrt{A(\theta_{u,v})\alpha_{u,v}\rho_{u,v}} \cdot \tilde{\mathbf{H}}_{u,v} \tag{5}$$

where the small-scale multipath fading matrix $\tilde{\mathbf{H}}_{u,v} \in \mathbb{C}^{[N_{\text{UE}}^u \times N_{\text{TP}}^v]}$ has i.i.d $\mathcal{CN}(0,1)$ entries, $A(\theta_{u,v})$ is the antenna gain, $\rho_{u,v}$ is the shadow fading coefficient and $\alpha_{u,v}$ is the path loss coefficient for downlink from RRH v to UE u.

The value of $A(\theta_{u,v})$ depends on the angle $\theta_{u,v}$ between the antenna orientation of RRH v and the line (RRH v, UE u). The path loss coefficient $\alpha_{u,v}$ is given as

$$\alpha_{u,v} = \frac{1}{1+\left(\frac{d_{u,v}}{d_0}\right)^{\eta}} \tag{6}$$

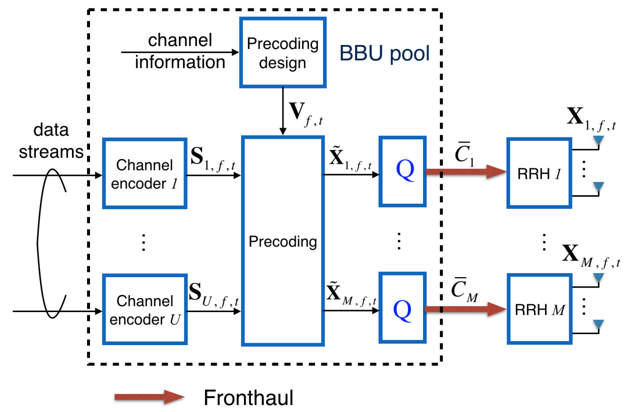

Fig. 2. Downlink transmission scheme from BBU pool to RRHs ("Q" represents fronthaul quantization).

where d_0 is a reference distance, $d_{u,v}$ denotes the distance between the v-th RRH and the u-th UE and η is the path loss exponent.

The shadow fading coefficient can be divided into two different independent parts:

$$\rho_{u,v} = \beta_u \cdot \beta_{u,v} \tag{7}$$

where $10\log_{10}\beta_u \sim \mathcal{N}(0,\sigma_u^2)$ and $10\log_{10}\beta_{u,v} \sim \mathcal{N}(0,\sigma_{u,v}^2)$.

III. Precoding and Fronthaul Quantization

We consider a C-RAN architecture where precoding is done at BBU pool while "FFT" is done in RRH. The transmission symbols are first precoded and then quantized before being forwarded to the corresponding RRHs via front-haul. Inspired by [6] and [4], we adapt their model into our scenario.

A block scheme of downlink transmission from BBUs pool to RRHs is illustrated in Figure 2. The symbols after channel coding to be transmitted to UE u on sub-carrier f and during subframe t is denoted as $\mathbf{S}_{u,f,t} \in \mathbb{C}^{[N_{\text{RL}}^u \times N_s]}$, which consists of i.i.d. $\mathcal{CN}(0,1)$ entries. The whole precoding matrix for all the symbols transmitted on f, during t and in the cluster is denoted as $\mathbf{V}_{f,t}$. As we focus on a single sub-carrier f, index f will be omitted in the following.

Then we have $\tilde{\mathbf{X}}_t = \mathbf{V}_t\mathbf{S}_t$, where $\mathbf{S}_t^{\text{T}} = [\mathbf{S}_{\mathcal{N}_{\text{UE},t}[1]},\ \mathbf{S}_{\mathcal{N}_{\text{UE},t}[2]},\ ...,\ \mathbf{S}_{\mathcal{N}_{\text{UE},t}[K_t]}]$ and $\tilde{\mathbf{X}}_t^{\text{T}} = [\tilde{\mathbf{X}}_{1,t},\ \tilde{\mathbf{X}}_{2,t},\ ...,\ \tilde{\mathbf{X}}_{M,t}]$. The baseband signal for the v-th RRH is given as $\tilde{\mathbf{X}}_{v,t} = \mathbf{V}_{t,v}^r\mathbf{S}_t,\ v \in \mathcal{N}_{\text{TP}}$, where $\mathbf{V}_{t,v}^r$ is obtained by selecting the rows of precoding matrix $\mathbf{V}_t$ for RRH v. The matrix $\mathbf{V}_{t,v}^r$ is defined as $\mathbf{V}_{t,v}^r = {\mathbf{D}_{t,v}^r}^{\text{T}}\mathbf{V}_t$, where matrix $\mathbf{D}_{t,v}^r \in \mathbb{1}^{[(\sum_{v\in\mathcal{N}_{\text{TP}}} N_{\text{TP}}^v)\times N_{\text{TP}}^v]}$ contains an $N_{\text{TP}}^v \times N_{\text{TP}}^v$ identity matrix in the rows from $\sum_{i=1}^{v} N_{\text{TP}}^i - N_{\text{TP}}^v + 1$ to $\sum_{i=1}^{v} N_{\text{TP}}^i$ and all zero elements in the other rows.

After precoding, baseband signal sequence $\tilde{\mathbf{X}}_{v,t},\ v \in \mathcal{N}_{\text{UE},t}$ is quantized and then transmitted to the v-th RRH via the v-th front-haul. The compressed signals $\mathbf{X}_{v,t}$ for v-th RRH is written as :

$$\mathbf{X}_{v,t} = \tilde{\mathbf{X}}_{v,t} + \mathbf{Q}_{v,t},\ \ v \in \mathcal{N}_{\text{UE},t}, \tag{8}$$

where $\mathbf{Q}_{v,t}$ is the quantization noise matrix for the transmission signals on the v-th front-haul (corresponding to the v-th RRH) during t. We assume that the random entries of $\mathbf{Q}_{v,t}$ follows i.i.d $\mathcal{CN}(0, \sigma_{v,t}^2)$. The power transmitted by RRH v is given by:

$$\begin{aligned} P_{v,t}(\mathbf{V}_t, \sigma_{v,t}^2) &= \frac{1}{N_s}\, \mathbb{E}(\|\mathbf{X}_{v,t}\|^2) \\ &= \mathrm{tr}({\mathbf{D}_{t,v}^r}^{\mathrm{T}} \mathbf{V}_t {\mathbf{V}_t}^{\mathrm{H}} \mathbf{D}_{t,v}^r + \sigma_{v,t}^2 \mathbf{I}_{N_{\mathrm{TP}}^v}). \end{aligned} \tag{9}$$

The power $P_{v,t}(\mathbf{V}_t, \sigma_{v,t}^2)$ depends on the precoding matrix $\mathbf{V}_t$ and quantization noise variances $\sigma_{v,t}^2$. The rate required on the front-haul between RRH v and BBUs pool during subframe t can be quantified by

$$\begin{aligned} &C_{v,t}(\mathbf{V}_t, \sigma_{v,t}^2) = \frac{1}{N_s} I(\tilde{\mathbf{X}}_{v,t}; \mathbf{X}_{v,t}) = \\ &\log\det({\mathbf{D}_{t,v}^r}^{\mathrm{T}} \mathbf{V}_t {\mathbf{V}_t}^{\mathrm{H}} \mathbf{D}_{t,v}^r + \sigma_{v,t}^2 \mathbf{I}_{N_{\mathrm{TP}}^v}) - N_{\mathrm{TP}}^v \log(\sigma_{v,t}^2). \end{aligned} \tag{10}$$

which should respect the front-haul capacity constraint

$$C_{v,t}(\mathbf{V}_t, \sigma_{v,t}^2) \leq \overline{C}_v. \tag{11}$$

We define the index g_u of UE u in $\mathcal{N}_{\mathrm{UE},t}$ as $g_u = \{i | \mathcal{N}_{\mathrm{UE},t}[i] = u\}$. The precoding matrix $\mathbf{V}_{t,u}^c$ for UE $u \in \mathcal{N}_{\mathrm{TP}}$ can be obtained by selecting the corresponding columns of $\mathbf{V}_t$. The matrix $\mathbf{V}_{t,u}^c$ is defined as $\mathbf{V}_{t,u}^c = \mathbf{V}_t \mathbf{D}_{t,u}^c$, where matrix $\mathbf{D}_{t,u}^c \in \mathbb{1}^{[(\sum_{u \in \mathcal{N}_{\mathrm{TP}}} N_{\mathrm{RL}}^u) \times N_{\mathrm{RL}}^u]}$ contains an $N_{\mathrm{RL}}^u \times N_{\mathrm{RL}}^u$ identity matrix in the rows from $\sum_{i=1}^{g_u} N_{\mathrm{RL}}^{\mathcal{N}_{\mathrm{UE},t}[i]} - N_{\mathrm{RL}}^u + 1$ to $\sum_{i=1}^{g_u} N_{\mathrm{RL}}^{\mathcal{N}_{\mathrm{UE},t}[i]}$ and all zero elements in the other rows. The corresponding covariance precoding matrix for UE u is defined as

$$\mathbf{G}_u = \mathbf{V}_{t,u}^c {\mathbf{V}_{t,u}^c}^{\mathrm{H}}, \ \forall u \in \mathcal{N}_{\mathrm{UE},t}. \tag{12}$$

We can demonstrate that $\sum_{u \in \mathcal{N}_{\mathrm{UE},t}} \mathbf{G}_u = \mathbf{V}_t \mathbf{V}_t^{\mathrm{H}}$.

We consider linear precoders design in the paper, the achievable rate for UE $u \in \mathcal{N}_{\mathrm{UE},t}$ is [4][6]

$$\overline{R}_u = \log \frac{\det(\mathbf{I}_{N_{\mathrm{UE}}^u} + \mathbf{H}_u (\sum_{k \in \mathcal{N}_{\mathrm{UE},t}} \mathbf{G}_k + \mathbf{\Omega}_t) \mathbf{H}_u^{\mathrm{H}})}{\det(\mathbf{I}_{N_{\mathrm{UE}}^u} + \mathbf{H}_u (\sum_{k \in \mathcal{N}_{\mathrm{UE},t}, k \neq u} \mathbf{G}_k + \mathbf{\Omega}_t) \mathbf{H}_u^{\mathrm{H}})}. \tag{13}$$

where $\mathbf{H}_u = [\mathbf{H}_{1,u}, \ \mathbf{H}_{2,u}, \ \ldots, \ \mathbf{H}_{M,u}]$ and covariance matrix $\mathbf{\Omega}_t$ is diagonal with diagonal blocks given as $\mathrm{diag}([\sigma_{1,t}^2 \mathbf{I}_{N_{\mathrm{TP}}^1}, \ \ldots, \ \sigma_{M,t}^2 \mathbf{I}_{N_{\mathrm{TP}}^M}])$.

Here we consider optimizing the ergodic achievable weighted sum-rate for all UEs during each subframe which is defined as

$$R_{\mathrm{tot}} = \frac{1}{T} \sum_{u=1}^{U} \mu_u R_u, \tag{14}$$

where R_u is the real transmission rate for UE u during the T subframes and the given weights $\mu_u \geq 0, \ \forall u \in \mathcal{N}_{\mathrm{UE}}$.

The weighted sum-rate can be optimized over subframes allocation for different UEs, the precoding matrix and the compression noise under front-haul capacity and RRH power constraints.

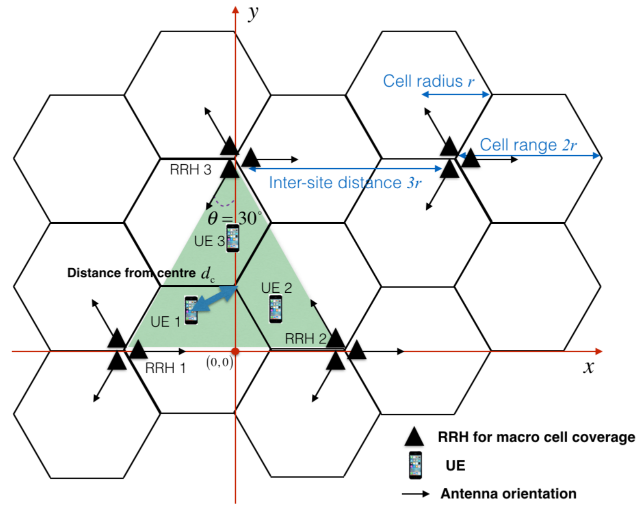

Fig. 3. Geometry distribution of RRHs and UEs.

For a certain RRHs and subframes allocation for different UEs, the problem of optimizing R_{tot} can be formulated as below:

$$\begin{array}{rc} \text{maximize} & R_{\mathrm{tot}} \\ \text{over} & \mathbf{V}_t, \quad \mathbf{\Omega}_t, \ \forall t \in \mathcal{T} \\ \text{s.t.} & R_u \leq \overline{R}_u \\ & C_{v,t}(\mathbf{V}_{t,j_{v,t}}, \sigma_{v,t}^2) \leq \overline{C}_v, \ \forall v \in \mathcal{N}_{\mathrm{TP}} \\ & P_{v,t}(\mathbf{V}_{t,j_{v,t}}, \sigma_{v,t}^2) \leq \overline{P}_v, \ \forall v \in \mathcal{N}_{\mathrm{TP}}. \end{array} \tag{15}$$

Optimization 15 is a non-convex problem. We apply an adapted Majorization Minimization scheme proposed in [5] to solve this problem.

IV. System Configuration

A. Network geometry

As shown in Figure 3, we consider a simple cluster including three RRHs serving three UEs. Thus $M = 3$ and $U = 3$. The set of RRHs $\mathcal{N}_{\mathrm{TP}} = \{1, 2, 3\}$ and the set of UEs $\mathcal{N}_{\mathrm{UE}} = \{1, 2, 3\}$. The positions of RRHs 1, 2 and 3 are $Z_{\mathrm{RRH}}^1 = [-\frac{3}{2}r, 0]$, $Z_{\mathrm{RRH}}^3 = [\frac{3}{2}r, 0]$ and $Z_{\mathrm{RRH}}^3 = [0, \frac{3\sqrt{3}}{2}r]$. The position of the center of RRH 1, 2 and 3 is $[0, \frac{\sqrt{3}}{2}r]$. UE u is located on the line connecting RRH u and the center of RRH 1, 2 and 3, $\forall u \in \mathcal{N}_{\mathrm{UE}}$. The distances between each UE and the center of RRH 1, 2 and 3 are the same which is denoted by d_{c}.

We assume each RRH is subject to the same front-haul constraint $\overline{C}$ and has the same power constraint $\overline{P}$. Thus, $\overline{C}_v = \overline{C}$ and $\overline{P}_v = \overline{P}, \ \forall m \in \mathcal{N}_{\mathrm{TP}}$. Each RRH and UE is supposed to be equipped with only one antenna. Thus $\mathbf{H}_{u,v}$ becomes a scalar. To simplify the notation, let $h_{u,v} = \mathbf{H}_{u,v}$, $\forall u \in \mathcal{N}_{\mathrm{UE}}, \ v \in \mathcal{N}_{\mathrm{TP}}$. Let the weight of UE u rate be set to $\mu_u = 1, \forall u \in \mathcal{N}_{\mathrm{UE}}$.

B. Channel model parameters

When possible,we took all parameters from the reference scenarios defined by 3GPP in [7]. We perform simulations in an urban area LTE downlink scenario where the cell radius r is 500 m, the carrier frequency is 2000 MHz and the base station antenna height is 15 m above average rooftop level. The antenna gain is defined as:

$$10\log_{10}A(\theta_{u,v}) = -\min\left[12\left(\frac{\theta_{u,v}}{\theta_{3dB}}\right)^2, A_m\right] + A_0 \quad (16)$$

where $-180^\circ \leq \theta_{u,v} \leq 180^\circ$, $\theta_{3dB} = 65^\circ$, $A_m = 20$ dB, and $A_0 = 15$ dBi.

The propagation from RRH to UE attenuation model is

$$L = 128.1 + 37.6\log_{10}(d_{u,v}) \text{ dB}, \quad (17)$$

where $d_{u,v}$ is in kilometers. It can be rewritten as

$$10^{-\frac{L}{10}} = \left(\frac{d_{u,v}}{d_0}\right)^{-\eta}, \quad (18)$$

with $\eta \approx 3.76$ and $d_0 \approx 3.92 \times 10^{-4}$ km. To avoid singularity when $d_{u,v} = 0$, our propagation model (see (6)) is slightly different. But it fits (17) well for $d_{u,v} > d_0$. We will take $\eta = 3.76$ and $d_0 = 3.92 \times 10^{-4}$ km for the following simulation.

As in [7], we take $10\log_{10}\rho_{u,v} \sim \mathcal{N}(0, 10 \text{ dB})$ in (7) and a shadowing correlation factor of 0.5 for the shadowing between sites. As RRH 1, 2 and 3 belong to different sites, we take $10\log_{10}\rho_u \sim \mathcal{N}(0, 5 \text{ dB})$ and $10\log_{10}\rho_{u,v} \sim \mathcal{N}(0, 5 \text{ dB})$.

For Universal Terrestrial Radio Access (E-UTRA) FDD and E-UTRA TDD downlink with a bandwidth of $W = 20$ MHz, the maximum RRH transmission power is 46 dBm in 3GPP technical specification. At the UE side, noise figure is 9 dB and the white Gaussian noise power is -101 dBm for a noise temperature of 300 K. The corresponding RRH power constraint in unit of dBm can be given as

$$\overline{P}_{\text{W}} = -101\text{dBm} + 9\text{dB} + \overline{P}. \quad (19)$$

V. Different Transmission Strategies

In this section, we apply the system model in Section II to several different transmission strategies for the system configuration in Section IV.

A. Transmission strategies without precoding

For the transmissions strategies discussed in this subsection, each RRH serves only one UE during each subframe. We assume that each RRH transmits signals with maximum power. Each RRH is equipped with only one antenna, thus no precoding is needed. Furthermore, as the "FFT" function is located in RRH, BBU pool can transmit discrete symbols to the corresponding RRHs. Therefore, for these transmission strategies with the system configuration in Section IV, quantization noise introduced by fronthaul transmission is not considered.

1) No cooperation transmission (NC): The slow fading channel information is shared among different cells, while the fast fading channel information is not (no perfect channel state information). The 3 RRHs transmit signals to different UEs at the same time. We have $T = 1$, and $\mathcal{T} = \{1\}$. UE u is served by RRH u where u is the best choice depending on slow fading channel information during subframe 1.

The achievable transmission rate without front-haul capacity limitation for UE u is

$$\overline{R}_u = \log\left(\frac{\overline{P}\|h_{u,u}\|^2}{1 + \overline{P}\sum_{i=1,\ i\neq u}^{3}\|h_{u,i}\|^2} + 1\right). \quad (20)$$

As no precoding is done and no fronthaul quantization noise is introduced, Optimization 15 can be simply resolved by

$$R_{\text{tot}} = \frac{1}{T}\sum_{u=1}^{3} R_u, \quad (21)$$

where the maximum rate for UE u during subframe u is given by

$$R_u = \min(\overline{R}_u,\ \overline{C}). \quad (22)$$

2) Dynamic point selection (DP): As shown in Figure 4 (a), only one UE is served during a given subframe. The RRH bringing the highest channel gain for the served UE does transmission, while the other 2 RRHs are muted during this given subframe. A RRH may do transmission during several continuous subframes or keep muted. We assume that the BBU pool knows the instantaneous channel information between each RRH and each served UE in the cluster. We have $T = 3$, and $\mathcal{T} = \{1,\ 2,\ 3\}$. UE u is supposed to be served during subframe u.

The achievable transmission rate without front-haul capacity limitation during subframe u for UE u is

$$\overline{R}_u = \log\left(1 + \overline{P} \times \max\left(\|h_{u,1}\|^2, \|h_{u,2}\|^2, \|h_{u,3}\|^2\right)\right). \quad (23)$$

The maximum rate for UE u during subframe u is the same as (22), where $u = 1,\ 2,\ 3$.

3) Round robin selection (RR): We assume that only average channel gains are known at BBU pool (no instantaneous channel knowledge). Each RRH serves one and only one UE. As shown in Figure 4 (b), each RRH transmits in a round robin way and during one subframe for each turn. Like for "dynamic point selection", only one RRH transmits at a given time while the other two are muted. Here, we have $T = 3$, and $\mathcal{T} = \{1,\ 2,\ 3\}$. In "round robin selection", 3 subframe duration can be used on the fronthaul to transmit the symbols on one radio subframe. Thus, "round robin selection" can have a virtual each front-haul link capacity $3\overline{C}$.

The achievable transmission rate without front-haul capacity limitation during subframe u for UE u is

$$\overline{R}_u = \log\left(1 + \overline{P}\|h_{u,u}\|^2\right)\ \forall\ u \in \mathcal{N}_{\text{UE}} \quad (24)$$

The maximum rate for UE u during subframe u is

$$R_u = \min(\overline{R}_u,\ 3\overline{C}) \quad (25)$$

where $u = 1,\ 2,\ 3$.

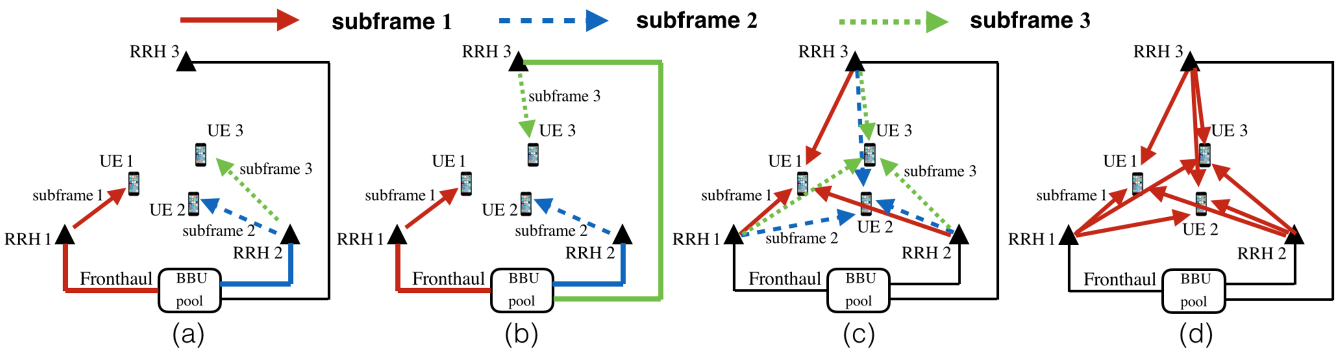

Fig. 4. Different transmission strategies: (a) dynamic point selection; (b) round robin selection; (c) joint transmission; (d) distributed MIMO.

4) Joint transmission (JT): As illustrated in Figure 4 (c), all the 3 RRHs transmit signals coherently to one and only one UE during each subframe. We have $T = 3$, and $\mathcal{T} = \{1,\ 2,\ 3\}$. UE u is supposed to be the only one being served during subframe u, where $u = 1,\ 2,\ 3$.

The achievable transmission rate without front-haul capacity limitation during subframe u for UE u is

$$\overline{R}_u = \log\left(1 + \overline{P}\sum_{v=1}^{3}\|h_{u,v}\|^2\right)\ \forall\ u \in \mathcal{N}_{\mathrm{UE}} \qquad (26)$$

The maximum rate for UE u during subframe u is the same as (22), where $u = 1,\ 2,\ 3$.

B. Distributed MIMO (D-MIMO)

If instantaneous channel knowledges are shared among different cells in the cooperation cluster, the 3 RRHs can transmit parallel data together to the 3 UEs using different Multi-User MIMO technologies, as illustrated in Figure 4 (d). In this paper, we denote this transmission scheme as “distributed MIMO”. Here, we have $T = 1$, and $\mathcal{T} = \{1\}$.

In this study, we consider Zero-Forcing (ZF) algorithm [8] for the parallel data transmission. Applying Zero Forcing algorithm, the precoding matrix is given as:

$$\mathbf{V} = \gamma\mathbf{H}^{\mathrm{H}}(\mathbf{H}\mathbf{H}^{\mathrm{H}})^{-1} \qquad (27)$$

where $\mathbf{H}$ is the channel matrix between the 3 RRHs and the 3 UEs, and γ is a normalization factor which is selected to satisfy the RRH power constraint and fronthaul capacity constraint.

We apply precoding matrix $\mathbf{V}$ to (15) to calculate the maximum sum transmission rate.

VI. Simulation Results

In this section, we compare the performance of different transmission strategies discussed in the previous section.

We start by investigating the effect of RRH power limitation on the average achievable sum rate with $d_{\mathrm{c}} = 0$ m. In other words, the 3 UEs are at the same location: at the common conner of Cell 1, 2 and 3, where RRH u locates at Cell u and $u = 1,\ 2,\ 3$.

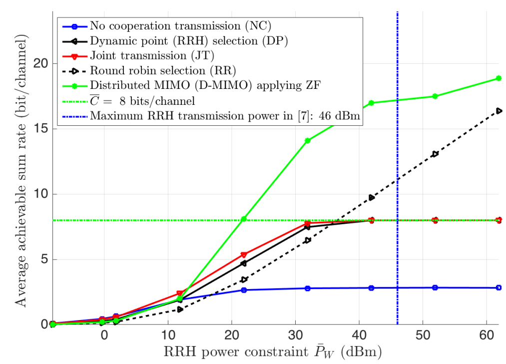

Fig. 5. Average achievable sum rate vs. RRH power constraint $\overline{P}_{\mathrm{W}}$ ($\overline{C} =$ 8 bits/channel, $d_{\mathrm{c}} = 0$ m).

The simulation results with $\overline{C} = 8$ bits/channel are shown in Figure 5. D-MIMO applying ZF can achieve the highest average sum rate and NC can achieve the lowest in RRH high-power regime. However, D-MIMO applying ZF is less preferred in RRH low-power regime. RR has a better performance than other transmission strategies except for D-MIMO applying ZF in RRH high-power regime. For DP and JT, each front-haul link has to guarantee enough capacity to convey all the symbols transmitted to the RRHs during each subframe. Therefore, the sum transmission rates for these transmission schemes are always less than $\overline{C}$.

When the fronthaul capacity is small ($\overline{C} = 2$ bits/channel, see Figure 6), RR has the best performance in RRH high-power regime. The performance of NC is better than JT and DP. The performance difference between NC and D-MIMO applying ZF becomes smaller in RRH high-power regime.

Then, the effect of UE distance from the center of RRH 1, 2 and 3 on the achievable sum rate is tested, with $\overline{P}_{\mathrm{W}} = 41.4$ dBm. The simulation results with $\overline{C} = 8$ bits/channel are illustrated in Figure 7. D-MIMO applying ZF has a better performance than the others. However, the performance difference between it and NC becomes smaller and smaller with the increasing of UE distance from center. NC has a worse performance than RR in low UE distance from center regime, but better in high regime. The average achievable sum rates

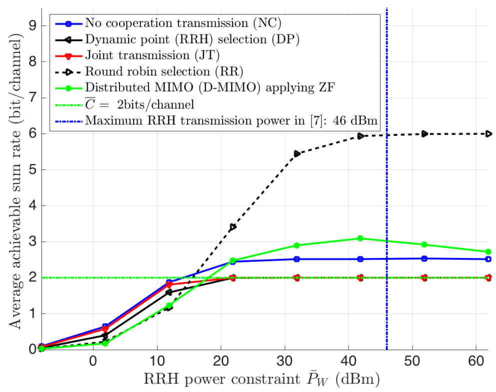

Fig. 6. Average achievable sum rate vs. RRH power constraint $\overline{P}_{\mathrm{W}}$ with small fronthaul capacity ($\overline{C} = 2$ bits/channel, $d_{\mathrm{c}} = 0$ m).

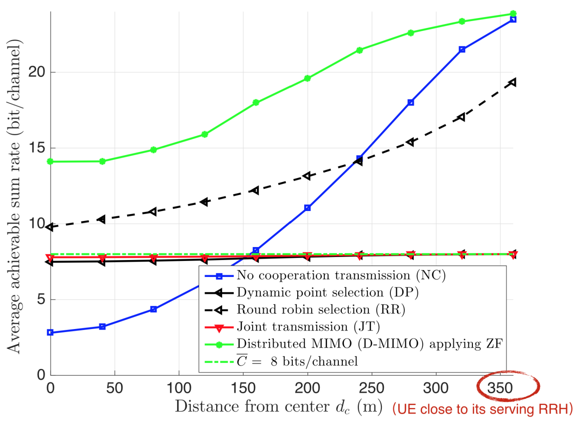

Fig. 7. Average achievable sum rate vs. UE distance from the center of RRH 1, 2 and 3 d_{c} ($\overline{P}_{\mathrm{W}} = 41.4$ dBm, $\overline{C} = 8$ bits/channel).

of DP and JT are limited to be less than $\overline{C}$.

When the fronthaul capacity is small ($\overline{C} = 2$ bits/channel, see Figure 8), RR have the best performance in small UE distance from center regime. The average achievable sum rates of DP and JT are limited to be no more than 2 bits/channel. The performances of NC and D-MIMO applying ZF are similar to each other with different values of UE distance from center.

VII. Conclusion

We have studied the performance of different coordinated transmission strategies for a cooperation cluster of 3 RRHs serving 3 UEs with RRH power constraints and front-haul capacity constraints. Each RRH and UE is assumed to be equipped with only one antenna.

With each front-haul link capacity $\overline{C} = 8$ bits/channel, D-MIMO applying ZF is preferred in RRH high-power regime. When each UE is near to one different RRH, the performance difference between NC and D-MIMO applying ZF becomes smaller and smaller. However, D-MIMO applying ZF needs much more calculation resources, precise channel information feedback from UEs and requires high level of synchronization

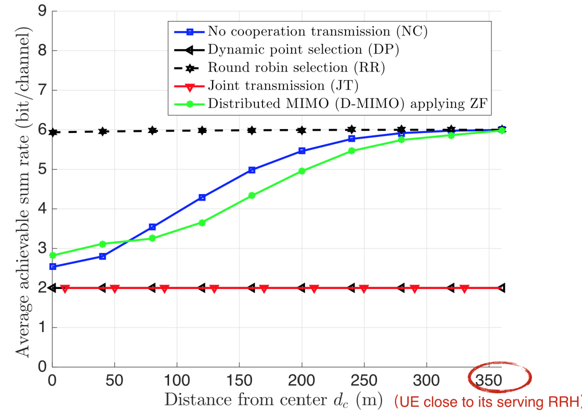

Fig. 8. Average achievable sum rate vs. UE distance from the center of RRH 1, 2 and 3 d_{c} with small fronthaul capacity ($\overline{P}' = 41.4$ dBm, $\overline{C} = 2$ bits/channel).

among coordinated RRHs. It is not interesting to apply D-MIMO applying ZF for only a few theoretic sum rate improvement compared with NC.

When we reduce the each front-haul link capacity to $\overline{C} = 2$ bits/channel, RR has the best performance in RRH high-power regime and in the case that each UE is near to one different RRH. There is no much performance difference between NC and D-MIMO applying ZF.

In future work, we will extend the number of antennas of each RRH and the number of served UEs in the cooperation cluster for further studies.

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References

[1] C. Mobile, "C-RAN: the road towards green RAN," China Mobile Research Institute, White Paper ver.2.5, Oct. 2011.

[2] D. Lee, H. Seo, B. Clerckx, E. Hardouin, D. Mazzarese, S. Nagata, and K. Sayana, "Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges," *IEEE Communications Magazine*, vol. 50, no. 2, pp. 148–155, Feb. 2012.

[3] M. Peng, C. Wang, V. Lau, and H. Poor, "Fronthaul-constrained cloud radio access networks: insights and challenges," *IEEE Wireless Communications*, vol. 22, no. 2, pp. 152–160, Apr. 2015.

[4] J. Kang, O. Simeone, J. Kang, and S. Shamai, "Fronthaul Compression and Precoding Design for C-RANs over Ergodic Fading Channels," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1–1, 2015.

[5] S.-H. Park, O. Simeone, O. Sahin, and S. Shamai, "Joint Precoding and Multivariate Backhaul Compression for the Downlink of Cloud Radio Access Networks," *IEEE Transactions on Signal Processing*, vol. 61, no. 22, pp. 5646–5658, Nov. 2013.

[6] C. T. K. Ng and H. Huang, "Linear Precoding in Cooperative MIMO Cellular Networks with Limited Coordination Clusters," *IEEE Journal on Selected Areas in Communications*, vol. 28, no. 9, pp. 1446–1454, Dec. 2010.

[7] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) Radio Frequency (RF) system scenarios version 13.0.0 Release 13," 3rd Generation Partnership Project (3GPP), TR 36.942, Jan. 2016. [Online]. Available: http://www.etsi.org/deliver/etsi_tr/136900_136999/136942/13.00.00_60/tr_136942v130000p.pdf

[8] Q. Spencer, A. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Transactions on Signal Processing*, vol. 52, no. 2, pp. 461–471, Feb. 2004.