Evaluation of Coordinated Multi-Point Processing for TD-LTE-Advanced System

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Abstract

Coordinated Multi-Point (CoMP) processing is regarded as a promising technique for the Advanced Long Term Evolution (LTE-A) system to improve the cell-edge spectral efficiency. In the time division duplex (TDD) LTE-A, i.e., TD-LTE-A, the channel reciprocity property could be exploited for downlink channel state information (CSI) estimation through the uplink signal, which makes the channel precoding more precise compared to the limited codebook feedback. The system-level simulations demonstrate that the CoMP system could achieve significant gains for both cell-average and cell-edge throughput.

1. Introduction

Coordinated multi-point (CoMP) processing technique [1] has aroused intensive interest in both academia and industry. In the conventional stand-alone base station (BS) architecture, the user equipment (UE) at the cell edge is under weak coverage and is severely interfered by the neighbor cells. In the CoMP system, the UEs at the cell edge are simultaneously served by multiple cells. By sharing the channel state information (CSI) and scheduling information, the users' data from the CoMP cooperating cell set could be jointly processed to reduce the inter-cell interference (ICI), and thus improve both cell-edge and cell-average spectral efficiency.

Compared to that of frequency-division duplex (FDD) system, the uplink and the downlink signals experience the same channel in the time-division duplex (TDD) system, which property is named as channel reciprocity. The channel reciprocity could be exploited in the TD-LTE-A system to obtain the downlink CSI through the detection of the uplink reference signals. Therefore, the overhead of the downlink CSI feedback is reduced when compared to FDD system. Furthermore, it's more precise than the limited codebook feedback. In this paper, the CoMP scheme for the TD-LTE-A system is studied to evaluate its computational complexity and system performance.

2. Coordinated Multi-point Processing

2.1 CoMP system model in the TDD system

The system model of CoMP is shown in Fig. 1. Multiple cells in the coordination set are selected to serve each UE. The coordination cell set and their served UEs compose a virtual MU-MIMO system.

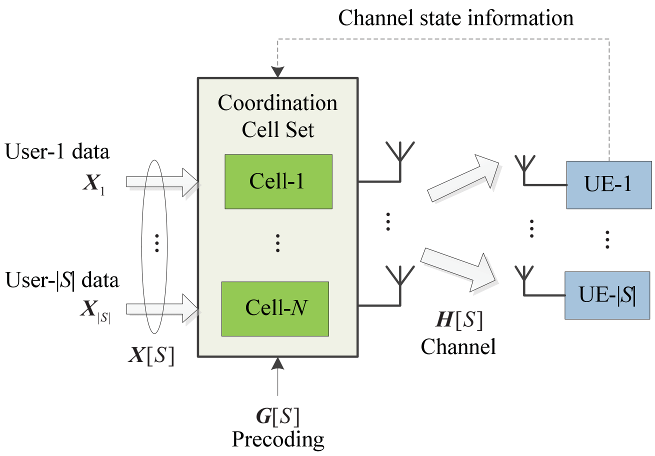

Fig. 1 System model of MU-CoMP

The coordination cell set includes N cells. The UE set sharing the same PRB is denoted as $\boldsymbol{S}$, with $|\boldsymbol{S}|$ denoting the number of elements in $\boldsymbol{S}$. Let $X[\mathbf{S}]$ denote the transmitted $|\boldsymbol{S}|$ UEs' signal vector. Let $\boldsymbol{G}_n[S]$ denote the precoding matrix.

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Considering the interference from other CoMP measurement sets, the received signal on the subcarrier index n of the i-th UE could be denoted as

$$\boldsymbol{y}_{n,i} = \boldsymbol{H}_{n,i}\boldsymbol{G}_n[S]\boldsymbol{X}_n[S] + \sum_{k=1}^{K}\boldsymbol{H}_{n,i}^{k}\boldsymbol{G}_n[S^k]\boldsymbol{X}_n[S^k] + \boldsymbol{\omega}_{n,i} \tag{1}$$

where $\boldsymbol{X}[S^k]$ denotes the interference signal from the k-th cell in the neighbor interfering CoMP coordination set, K is the number of interfering cell sets, $\boldsymbol{\omega}_{n,i}$ denotes the additive white Gaussian noise(AWGN) with zero mean and variance of σ^2. The channel response from the cell set to the i-th UE is

$$\boldsymbol{H}_{n,i} = \boldsymbol{h}_{n,i}\boldsymbol{l}_{n,i}, 1 \le i \le |S| \tag{2}$$

where $\boldsymbol{h}_{n,i}$ denotes the normalized complex channel gain and $\boldsymbol{h}_{n,i}$ is a matrix with the dim of $n_r \times (Nn_t)$, with n_t transmitting antennas of each cell and n_r receiving antennas of each UE. $\boldsymbol{l}_{n,i}$ is a diagonal matrix, with the diagonal elements denoting the large scale fading factor from Nn_t transmit antennas to the i-th UE.

The first item of Eq. (1) are the signals from the expected coordination cell set, including useful signal and interfering signal transmitted to other UEs in the set, i.e.,

$$\boldsymbol{H}_{n,i}\boldsymbol{G}_n[S]\boldsymbol{X}_n[S] = \underbrace{\boldsymbol{H}_{n,i}\boldsymbol{G}_{n,i}\boldsymbol{X}_{n,i}}_{\text{the } i\text{-th user's data}} + \underbrace{\boldsymbol{H}_{n,i}\sum_{j=1,j\neq i}^{|S|}\boldsymbol{G}_{n,j}\boldsymbol{X}_{n,j}}_{\text{other users' data}} \tag{3}$$

where $\boldsymbol{X}_{n,i}$ and $\boldsymbol{G}_{n,i}$ denote the transmitted data and the precoding matrix on the subcarrier index n for the i–th UE.

2.2 Interference Cancelation scheme

In the TDD system, the channel reciprocity could be exploited for downlink CSI, which makes the precoding based on singular value decomposition (SVD) [2] to be the preferable choice. If the suitable precoding matrix is applied, the interference from the coordination cell set could be totally avoided, and then Eq. (3) turns to be

$$\boldsymbol{H}_{n,i}\boldsymbol{G}_n[S]\boldsymbol{X}_n[S] = \boldsymbol{H}_{n,i}\boldsymbol{G}_{n,i}\boldsymbol{X}_{n,i} \tag{4}$$

The premise of Eq. (4) is to choose a precoding matrix such that [3]

$$\boldsymbol{H}_{n,j}\boldsymbol{G}_{n,i} = 0, \forall j \neq i \tag{5}$$

i.e., the precoding matrix of the i-th UE is in the null space of other UEs' channel space.

In order to get the null space of all the selected UEs' channel matrix, let $\overline{\boldsymbol{H}}_{n,i}$ denote the channel matrix set of the all the UEs in the cooperative set except the i-th UE.

$$\overline{\boldsymbol{H}}_{n,i} = [(\boldsymbol{H}_{n,1})^T \cdots (\boldsymbol{H}_{n,i-1})^T (\boldsymbol{H}_{n,i+1})^T \cdots (\boldsymbol{H}_{n,|S|})^T]^T \tag{6}$$

where $(\cdot)^T$ denotes the matrix transposition.

The null space exists only when

$$N \times n_t \ge |S| \times n_r \tag{7}$$

Since n_t is usually larger than n_r in mobile communication systems, Eq. (7) could be easily satisfied.

The SVD decomposition of $\overline{\boldsymbol{H}}_{n,i}$ is denoted as

$$\overline{\boldsymbol{H}}_{n,i} = \overline{\boldsymbol{U}}_{n,i}\begin{bmatrix}\overline{\boldsymbol{\Sigma}}_{n,i} & 0\\ 0 & 0\end{bmatrix}\left[\overline{\boldsymbol{V}}_{n,i}^{(1)}, \overline{\boldsymbol{V}}_{n,i}^{(0)}\right]^H \tag{8}$$

where $(\cdot)^H$ denotes the conjugation and transposition of a matrix, $\overline{\boldsymbol{\Sigma}}_{n,i}$ is a diagonal matrix with its diagonal elements to be the singular values of $\overline{\boldsymbol{H}}_{n,i}$, and its dim to be the rank of $\overline{\boldsymbol{H}}_i$. $\overline{\boldsymbol{V}}_{n,i}^{(0)}$ and $\overline{\boldsymbol{V}}_{n,i}^{(1)}$ are the eigen vector of the zero and non-zero singular values, respectively. $\overline{\boldsymbol{V}}_{n,i}^{(0)}$ has $N \times n_t - (|S|-1) \times n_r$ columns, which compose the orthogonal basis of $\overline{\boldsymbol{H}}_i$.

To maximize the user data rate, the SVD decomposition is applied once more,

$$\boldsymbol{H}_{n,i}\overline{\boldsymbol{V}}_{n,i}^{(0)} = \boldsymbol{U}_{n,i}\begin{bmatrix}\boldsymbol{\Sigma}_{n,i} & 0\\ 0 & 0\end{bmatrix}\left[\boldsymbol{V}_{n,i}^{(1)}, \boldsymbol{V}_{n,i}^{(0)}\right]^H \tag{9}$$

where $\Sigma_{n,i}$ denotes the singular values of n_r parallel separate channels. Let $V^{(1)}_{n,i,m_i}$ denote the eigen vector of the former m_i singular values, the precoding matrix could be denoted as

$$G_{n,i} = \frac{1}{\sqrt{m_i}} \bar{V}^{(0)}_{n,i} V^{(1)}_{n,i,m_i} \tag{10}$$

where $1/\sqrt{m_i}$ normalizes the total power of the i-th UE's multiple data streams.

After precoding, the equivalent channel transfer function $H_n[S]G_n[S]$ turns to be a block-diagonal matrix, which thoroughly cancels the interference in the CoMP coordination set. The linear minimum mean square error (LMMSE) algorithm [4] could be used for receiver. The detection matrix on the subcarrier n of the i-th user is denoted as

$$W_{n,i} = ((H_{n,i}G_{n,i})^H H_{n,i}G_{n,i} + \tilde{\sigma}_n^2)^{-1}(H_{n,i}G_{n,i})^H \tag{11}$$

where $\tilde{\sigma}_n^2 = \sigma^2 I_{m_i} + \sum_{k=1}^{K} H^k_{n,i} G_n[S^k](H^k_{n,i} G_n[S^k])^H$, and I_{m_i} is the unit matrix with the dim of m_i.

2.3 Dynamic cell clustering

In order to reduce the computational complexity of baseband processing, only those neighbor cells with considerable interferences in the CoMP coordination set are selected for joint processing. The UE detects the reference signal received power (RSRP) of each cell and compares with the main serving cell. If the difference is below the predefined RSRP threshold, the neighbor cell is selected as a cooperative cell. Assuming that there are a total of N cells in the CoMP coordination set, each of which is denoted as Cell_1, Cell_2, …, Cell_N, the dynamic cell selection process could be described as the following steps:

Step1. Detect the RSRP from the main serving cell to the UE, with the result denoted as P_{main} (dB);

Step2. for i = 1:N

- Step2.1. Detect the RSRP from Cell_i to the UE, with the result denoted as P_i (dB);
- Step2.2. if P_{main}- P_i < RSRP_{th}, add Cell_i into the CoMP cooperating set, where RSRP_{th} is the predefined RSRP threshold.

3. Simulations and analysis

In this section, system-level simulations are performed to evaluate the performance of the discussed MU-CoMP scheme. Each cell has 8 transmitting antennas, while each UE has 2 receiving antennas and supports up to two separate data streams. Other system parameters follow 3GPP LTE proposal [5].

3.1 Evaluation of number of cooperative cells

In the simulations, the selected cooperative cells in the inter-site CoMP scenario (CoMP scenario 2 in [1]) are statistically analyzed. The RSRP threshold is set to 10dB. The statistical results in 3GPP Case 1-3D scenario (with 500m inter-site distance) and ITU UMi scenario (with 200m inter-site distance) are shown in Fig. 2 and Fig. 3, respectively. It's observed that for most cases, only two or three cells are cooperative for each UE in the CoMP coordination set, which would effectively reduce the computational complexity of the CoMP system.

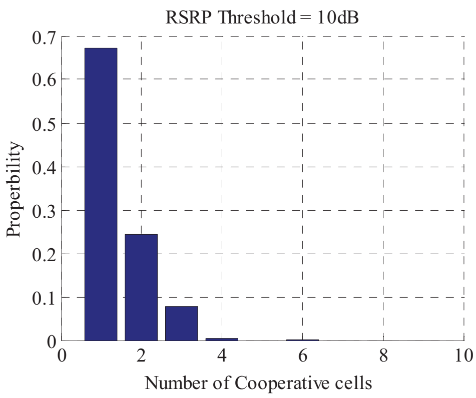

Fig. 2 Probability of the number of cooperative cells (3GPP Case 1-3D channel)

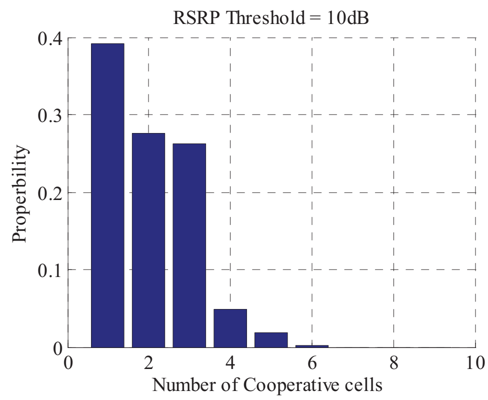

Fig. 3 Probability of the number of cooperative cells (ITU UMi channel)

3.2 Performance evaluation

The downlink cell-average and cell-edge spectral efficiency of the above four scenarios for eight-antenna systems are listed in Fig. 4 and Fig. 5, while Fig.4 compares the results for 3GPP Case 1-3D channel and Fig.5 compares the results for ITU UMi channel, respectively.

From the simulation results of 3GPP Case1-3D channel, the intra-site CoMP could improve the average and cell-edge spectral efficiency by 12.6% and 24.0% compared to the conventional non-cooperative MU-MIMO for 8-antenna system, respectively. In the inter-site CoMP with three sites coordination, the system could achieve 20.5% average gain and 45.4% cell-edge gain, respectively. In the ITU UMi channel, the intra-site CoMP could improve the average and cell-edge spectral efficiency by 20.1% and 75.0% compared to the conventional non-cooperative MU-MIMO for 8-antenna mode, respectively. In the inter-site CoMP with three sites coordination, the system could achieve 41.5% average and 119.6% cell-edge gain, respectively. Furthermore, higher gain is expected in larger coordination cell set.

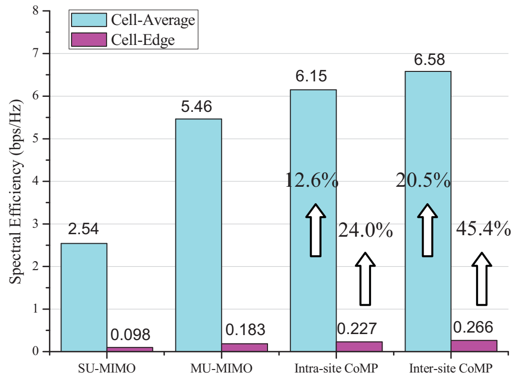

Fig. 4 Performance in 3GPP Case 1-3D scenario

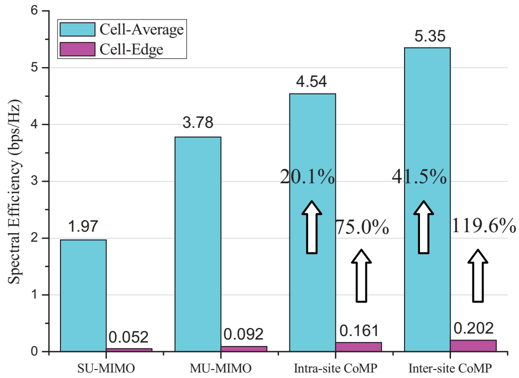

Fig. 5 Performance in ITU UMi scenario

4. Conclusion

In this paper, the downlink CoMP performance and its complexity increase are evaluated for TD-LTE-A system. The system-level simulations demonstrate that only two or three cells are active for certain UE in the coordination cell sets in most cases, which would effectively reduce the computational complexity of the CoMP system. With inter-site 9 cells CoMP, the system could achieve 41.5% cell-average and 119.6% cell-edge gain, respectively, in the UMi channel model.

5. References

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