Adaptive and Distributed CoMP Scheduling in LTE-Advanced Systems

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Abstract—Coordinated Multi-Point (CoMP) transmission and reception is one of the most promising technologies introduced in 3GPP Long Term Evolution-Advanced (LTE-Advanced) standard. Especially targeting the User Equipments (UEs) in the cell-edge region, CoMP technology improves the edge throughput and reliability in two ways: Joint Transmission (JT) and Coordinated Scheduling/Beamforming (CS/CB). This paper proposes an adaptive and distributed CoMP scheduling algorithm which allocates the frequency band to each UE and could operate in either JT or CS/CB mode of CoMP. Our contributions include (a) proposing an algorithm resolving subband allocation, UE selection, and CoMP mode decision jointly; and (b) defining the message format exchanged among eNBs for cooperation. The performance of the proposed algorithm is comparatively evaluated along with that of other schemes such as non-coordination and frequency reuse schemes in terms of both average and outage throughput.

Index Terms—Resource Scheduling; Coordinated Multi-Point transmission/reception; LTE-Advanced systems

I. INTRODUCTION

Recently, the Long Term Evolution-Advanced (LTE-Advanced), the most prospective 4G cellular system, has determined to include Coordinated Multi-Point (CoMP) transmission and reception technology. For the first time, the use of CoMP is selected as an option becoming one of the hottest features added in Release 11, the latest version of LTE-Advanced standard. In the near future, the CoMP specifications are expected to be evolved further and realized in actual field based on various scenarios they have. CoMP is a kind of network Multiple-Input Multiple-Output (MIMO) transmission technologies. It allows a group of evolved Node Bs (eNBs) to cooperate in order to improve the coverage, cell-edge throughput, and/or system efficiency. These eNBs, referred to as cooperating eNBs, communicate with one another through the backhaul network such as X2 interface via fiber optics [1].

This paper focuses on two types of CoMP operations, namely, Joint Transmission (JT) and Coordinated Scheduling/Beamforming (CS/CB). With JT mode, the cooperating eNBs jointly serve a specific UE. JT mode is again divided into two modes, i.e., coherent JT and non-coherent JT. With coherent JT, the same data streams are simultaneously transmitted from the cooperating eNBs. This requires tight synchronization and high speed backhaul networks. For non-coherent JT, soft-combining reception of the OFDM signal is used.

With CS/CB mode, each eNB provides a service to the UE associated to it. The eNB operates in such a manner that it reduces the interference toward other UEs as well as enhances the power of its own desired signal. Here, in the view of the UE, the associated eNB is defined as the serving eNB and the other eNBs in the cooperating eNB group are defined as the neighboring eNBs. There are two different ways to reduce the interference to other cells, namely, Precoding Matrix Indicator (PMI) coordination [2] and interference suppression-based beamforming. In the PMI coordination method, each UE feeds back either restriction PMI or recommendation PMI to its serving cell. Then, the neighboring eNB can perform one of the following: (a) using the recommendation PMI, or (b) avoiding the restriction PMI through the coordination among eNBs. In the case of interference suppression-based beamforming, each eNB calculates transmit precoders by using CSI feedback from the serving and neighboring cells while it considers the interference to other cells.

There have been several works on the resource scheduling issue with CoMP in LTE-Advanced systems. The authors of [3] devised a CoMP Cooperation Set (CCS) selection scheme with JT mode. A method for adaptive selection between JT and non-CoMP is also presented in [4]. In [5], the authors propose an improved Dynamic Cell Selection (DCS) scheme which is a kind of non-coherent JT. However, the previous work just focuses only on a single CoMP transmission mode, and how to use multiple CoMP modes simultaneously has not been studied yet. Furthermore, the message format which should be exchanged among cooperating eNBs according to the use of multiple CoMP modes needs to be defined.

Based on these observations, we in this paper propose an...
adapted and distributed CoMP scheduling algorithm which jointly allocates the frequency resource, selects the UE, and decides the CoMP transmission mode between JT and CS/CB. In order to tackle this complicated problem, the proposed algorithm divides it into two phases, referred to as intra-eNB and inter-eNB phases. The intra-eNB phase includes CoMP mode selection per each UE and candidate UE selection per each subband,¹ while the inter-eNB phase includes the final UE selection per each subband through a message exchange. The detailed description of these phases will be delineated in the following sections. The preference table defined as a message format exchanged among eNBs will be also presented. Through an extensive system-level simulation, the performance of the proposed scheme will be evaluated.

The rest of the paper is organized as follows. Section II introduces the system model considered in this paper and describes the beamforming schemes for both JT and CS/CB. Section III presents the proposed algorithm, which is evaluated in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider LTE-Advanced systems with multiple eNBs equipped with $N_t$ transmit antennas. We also assume that $L$ eNBs are cooperating with each other by sending coordination messages through X2 interface [1, 6], and the delay required for exchanging coordination messages is assumed to be negligible [7].

A. Beamforming for CoMP JT

A coordinating eNB group is assumed to support $M$ UEs equipped with $N_r$ antennas. The received signal vector for UE $i$ is denoted as

$$y_i = H_i F x_i + n_i. \quad (1)$$

The concatenated MIMO channel $H_i \in \mathbb{C}^{N_r \times LN_i}$ is defined as $[\sqrt{\eta_{i,1}} H_{i,1}, \sqrt{\eta_{i,2}} H_{i,2}, \ldots, \sqrt{\eta_{i,L}} H_{i,L}]$, where $\sqrt{\eta_{i,l}}$ denotes path-loss and shadowing component between eNB $l$ and UE $i$. $H_{i,l} = W_{i,l} R_l^{1/2}$ denotes a MIMO channel matrix between eNB $l$ and UE $i$ where $W_{i,l}$ is a random channel matrix whose elements are identically and independently distributed (i.i.d) cyclic symmetric complex Gaussian with unit variance. $R_l \in \mathbb{C}^{N_s \times N_s}$ represents the transmit correlation matrix of eNB $l$. The concatenated beamforming matrix $F \in \mathbb{C}^{L N_s \times N_r}$ is expressed as $[F_1^T, F_2^T, \ldots, F_L^T]^T$, where $F_l$ refers to the beamforming matrix for eNB $l$, and $N_s$ denotes the number of data streams sent to the UE. $n_i \in \mathbb{C}^{N_r \times 1}$ stands for a noise vector whose elements are a cyclic symmetric complex Gaussian with variance $\sigma^2$.

In order to maximize sum-rate of $M$ UEs under JT mode, beamforming matrix $F$ is calculated using the following objective function.

$$F = \arg \max_{F} \sum_{i=1}^{M} C_i(F), \quad (2)$$

$$\text{s.t.} \quad \text{tr}\{F_i F_i^\dagger\} \leq P_i \quad \forall l,$$

where

$$C_i = \log_2 \det(I_{N_r} + \frac{1}{\sigma^2} H_i F F_i^\dagger H_i^\dagger). \quad (3)$$

$P_i$ is the transmit power constraint of eNB $l$. Note that multi-user CoMP JT beamforming scheme is out of scope in this paper, and $M$ is assumed to be one. Thus the maximization problem in (2) is similar to that of point-to-point MIMO systems described in [8]. The solution is to set the beamforming matrix $F$ to be $V_i$ which is the right singular matrix of $H_i$.

B. Beamforming for CoMP CS/CB

For CS/CB mode, $L$ cooperating eNBs support their own associated UEs. Thus $L$ UEs share the same subband, and the received signal vector at UE $i$ is expressed as

$$y_i = H_{i,l} F_i x_i + \sum_{l \neq i} H_{i,l} F_i x_l + n_i. \quad (4)$$

The definition of each element is the same as in (1). The achievable rate of UE $i$ is calculated as

$$C_i = \log_2 \det(I_{N_r} + K_D^{(i)} K_N^{(i)-1}), \quad (5)$$

where $K_D^{(i)}$ represents the covariance matrix of the desired signal and $K_N^{(i)}$ represents the covariance matrix of the noise plus interference at UE $i$. These matrices are expressed as

$$K_D^{(i)} = \eta_{i,i}(H_{i,l} F_i)(H_{i,l} F_i)^\dagger, \quad (6)$$

and

$$K_N^{(i)} = I_{N_r} + \sum_{l \neq i} \eta_{i,l}(H_{i,l} F_i)(H_{i,l} F_i)^\dagger, \quad (7)$$

respectively. Similar to the JT operation mode, the beamforming matrix is calculated so that the sum-rate of $L$ UEs is maximized as follows:

$$F = \arg \max_{F} \sum_{i=1}^{L} C_i(F), \quad (8)$$

$$\text{s.t.} \quad \text{tr}\{F_i F_i^\dagger\} \leq P_i \quad \forall l,$$

where $P_i$ is the transmit power constraint of eNB $l$. Unfortunately, it is difficult to find a closed-form solution of this non-convex problem. Therefore, we take the sub-optimal concept referred to as Signal-to-Generating-Interference-plus-Noise-Ratio (SGINR) based solution proposed in [9, 10]. The SGINR metric is defined as

$$K_{SGINR}^{(i)} = \left(\sigma^2 I_{N_r} + H_{GI}^{(i)} H_{GI}^{(i)}\right)^{-1} \left(H_{DI}^{(i)} H_{DI}^{(i)}\right)$$

$$= V_{SGINR}^{(i)} H_{GI}^{(i)} V_{SGINR}^{(i)^\dagger}, \quad (9)$$

where

$$H_{GI}^{(i)} = \begin{bmatrix} \sqrt{\eta_{i,1}} H_{i,1} \\ \vdots \\ \sqrt{\eta_{i-1}} H_{i-1,1} \\ \sqrt{\eta_{i+1}} H_{i+1,1} \\ \vdots \\ \sqrt{\eta_{L}} H_{L,i} \end{bmatrix}. \quad (10)$$

¹A system bandwidth is divided into multiple subbands, and hence, eNBs should schedule a UE for each subband in each time slot.
The above SGINR metric, $K_{SGINR}^{(i)}$, reflects the covariance matrix of the interference which eNB $i$ generates as well as the covariance matrix of the desired channel. By using the eigenmatrix of $K_{SGINR}^{(i)}$ as a beamforming matrix of eNB $i$, we can reduce the interference among cooperating eNBs, but still can increase the rate of each UE. In [9], using this SGINR metric is shown to have excellent performance. Especially, it is proved to maximize the sum-rate of two cooperating eNB case. In the proposed resource scheduling algorithm, this method is employed for the CS/CB beamforming.

III. ADAPTIVE AND DISTRIBUTED CoMP SCHEDULING ALGORITHM

The joint scheduling problem of the CoMP systems operating with both JT and CS/CB includes transmission mode selection and UE selection per each subband of an eNB. Note that the selected UE for a subband of a cooperating eNB group is the same with JT, while it is different with CS/CB. That means, if one eNB wants to support a certain UE with JT, all the other eNBs in the cooperating group should allocate this subband to the same UE. As a result, the joint scheduling problem is very complicated: it is neither linear nor convex.

In order to simplify this problem, the proposed scheduling algorithm works in two phases: the intra-eNB and the inter-eNB scheduling phases as depicted in Fig. 2. First, in the intra-eNB scheduling phase, the best CoMP transmission mode of each UE is determined by comparing the reported Signal-to-Interference-plus-Noise Ratio (SINR) with the threshold which is set in advance. Then, the eNB calculates the Proportional Fairness (PF) metric [11] and nominates the UEs with the highest PF metric as candidate UEs. Second, in the inter-eNB scheduling phase, eNBs build up preference tables which contain such information as candidate UEs for each subband, PF metric and desired CoMP transmission mode of these UEs. Then, for each subband, the eNB associated with the UE with the highest PF metric works as the leading eNB and the other eNBs become the following eNBs. The details of the proposed scheduling algorithm are presented below.

1) Selection of the transmission scheme: In order to reduce the burden of complicated joint scheduling, we use an intuitive assumption. We assume that JT outperforms CS/CB for the UE whose SINR is under a certain threshold. That is, JT is preferred when the UE is located at cell-edge region. Here, the reuse of a frequency band among different eNBs induces strong interference. Instead of selecting multiple UEs for each eNB, JT supports only the common UE for all the eNBs in a coherent manner. Consequently, the UE receives interference-free signal at least from the cooperating eNBs. In contrast, CS/CB performs better than JT for the other UEs whose SINR is above the threshold. These UEs are located in the region near their associated eNBs. In this region, since the effect of the interference is not severe, the reuse of frequency band can multiply the system capacity.

Based on the above observation, the proposed algorithm selects JT (CS/CB) transmission mode if the SINR of the UE is under (over) the threshold. The threshold SINR is determined as the system parameter in advance and can be calculated by

$$\text{SINR}_{\text{threshold}} = \arg\min \{ \left| C_{JT}(x) - C_{CS/CB}(x) \right| \},$$

(11)

where $C_{JT}$ and $C_{CS/CB}$ are the capacity of JT and CS/CB which are investigated in Section II. The JT region and CS/CB region in Fig. 3 are determined according to the threshold SINR. By using this SINR-based CoMP mode selection, the intra-eNB phase can be operated in a distributed manner. It only needs to investigate the SINR of the UE, and the activities of the other eNBs need not to be considered.

We can verify the validity of the proposed SINR-based CoMP mode selection with a simple example. The sum capacity of JT and CS/CB are evaluated and compared by simulation. The simulation environment is illustrated in Fig. 3. Three cooperating eNBs are connected through the wired backhaul network, and three interfering-only eNBs are also considered. UEs are located along with the red line connecting the origin and their serving eNB. We assume that the eNB has four transmit antennas and UE has one receive antenna, and the detailed parameters are presented in Table I. With JT mode, for a subband, a single UE is served by three eNBs...
from the real field test in advance. The threshold can also be determined empirically assuming uniformly distributed cellular structure without loss of generality. We can use computer simulation to obtain threshold value. We can use computer simulation assuming uniformly distributed cellular structure without loss of generality. The threshold can also be determined empirically from the real field test in advance.

2) Calculation of PF metric and candidate UE selection: In this paper, we adopt the PF metric as the scheduling metric of the proposed algorithm. After selecting a transmission mode, the PF metric of UE $i$ associated with eNB $l$ for subband $k$ is calculated as

$$P_{F_{i}^{k}(l)} = \frac{C_{i}^{k}(l)}{E[C_{i}^{k}(l)]}, \quad (12)$$

where $E[C_{i}^{k}(l)]$ is the time-averaged channel capacity of UE $i$, which is associated to eNB $l$. In order to calculate the PF metric, we need to calculate the instantaneous capacity for each transmission mode using (3) and (5). In the case of CS/CB, each eNB needs to know the scheduled UEs of the other eNBs in the cooperating eNB group in advance. This is impossible, however, as it is a chicken-and-egg problem: We can not know the scheduled UEs of the other cells in a distributed manner. Instead, for recommending the candidate UE at the intra-eNB phase of the proposed algorithm, we adopt a single cell MIMO method which approximates the interference from the other cell as noise for the calculation of the capacity to get the PF metric. According to the following equation, eNB $l$ selects UE $U_{i}^{k}(l)$, which has the highest PF metric at subband $k$ among the associated UEs, as the candidate UE for subband $k$:

$$U_{i}^{k} = \arg \max_{i \in U_{i}} P_{F_{i}^{k}(l)}. \quad (13)$$

3) Exchange of the preference table among eNBs: After determining their own candidate UEs at each subband, the eNBs exchange the preference table with one another. The contents of the preference table are defined in Fig. 2. It describes the subband index, candidate UE’s PF metric, selected CoMP scheme, and beamforming matrix for the corresponding CoMP scheme. Since the preference table has small size and is exchanged among the cooperating eNB group only, the use of preference table gives acceptable burden in point of system complexity. At every feedback period, each eNB compares the PF metric of its candidate UE with that of other cells’ candidate UEs. Then the UE $U_{i}^{k*}$, which has the highest PF metric among $L$ UEs selected by $L$ eNBs, is selected at each subband $k$.

$$U_{i}^{k*} = \arg \max_{l=1,2,\ldots,L} P_{F_{i}^{k}(l)}. \quad (14)$$

The eNB which serves UE $U_{i}^{k*}$ is regarded as the leading eNB at subband $k$, and it controls the CoMP transmission mode at the corresponding subband. The remaining eNBs are regarded as the following eNBs at subband $k$ accordingly.

4) Re-scheduling after the decision of leading eNB: At each subband and every feedback period, if a certain eNB is chosen as a leading eNB, the following eNBs should obey the decision of the leading eNB. That is, if the leading eNB serves the associated UE with CS/CB mode, then the following eNBs shall join the CS/CB transmission by re-scheduling an appropriate UE in their own cell, i.e., the UE that achieves the best PF metric with CS/CB mode. However, if the leading eNB’s associated UE demands JT transmission, then the following eNBs should give up their own scheduled UEs; in this case, the following eNBs refer to the preference table, and use the beamforming matrix to participate in the JT transmission to the leading eNB’s scheduled UE.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheduling algorithm through the MATLAB simulation. We implement a system-level simulator which reflects realistic channel and system environments of LTE-Advanced systems. The simulation topology is shown in Fig. 3, where 12 UEs are randomly distributed in each cell. We assume 5 MHz bandwidth whose center frequency is 2 GHz. The total number of subcarriers is 300, and 50 subcarriers constitute one subband according to the standard [6]. We employ Modified Ped. B model of ITU-R as an OFDM channel delay profile, and assume that the channel varies every 1 ms according to a Markov chain; the channel matrix $H_{i,j}^{(n)}$ is updated according to $H_{i,j}^{(n+1)} = \rho H_{i,j}^{(n)} + \sqrt{1-\rho^2} N_{n}$, where the elements of $N_{n}$ are independent and identically distributed Gaussian with zero mean and variance 1/2. The correlation coefficient is given by $\rho = J_{\rho}^{2}(2\pi f_{DL} \Delta t)$, where $J_{0}$ is the zero-order Bessel
function of the first kind and $\Delta t$ is a slot time which is set to 1 ms. $f_D$ represents the Doppler frequency, which is assumed to be zero by considering no UE mobility. For the MIMO Spatial Channel Model (SCM), we refer to IEEE 802.16m Evaluation Methodology Document (EMD). We assume that the UE scheduling and resource allocation are conducted at every 10 ms, which is equal to the channel feedback period. As a performance measure, UE throughput is defined as the product of sum capacity and bandwidth, indicating the total amount of data transmitted per one second.

We consider the non-cooperative and 1/3 Frequency Reuse (FR) algorithm as reference schemes. For these two reference schemes, each eNB operates with a single cell MIMO mode, and do not try to reduce the interference they can induce to other cells in determining the beamforming matrix. With the 1/3 FR algorithm, each eNB uses 1/3 separate frequency resource of the entire frequency band (i.e., 300 subcarriers) in order to avoid the interference among neighboring cells. The reference schemes also take the PF metric as UE scheduling criterion.

Fig. 5 presents the CDF of the UE throughput. In Fig. 5, the proposed algorithm shows better UE throughput in the whole region. When we compare the average throughput calculated from this data, the proposed algorithm outperforms the non-cooperative and 1/3 FR algorithm by 7.6% and 28.5%, respectively. The 50th-percentile UE throughput in Fig. 7 also shows that the proposed algorithm has 8% and 26.3% performance gain compared to the non-cooperative and 1/3 FR algorithm. This indicates that the adaptive selection of JT and CS/CB modes enables performance improvement over the non-CoMP systems. Fig. 6 enlarges the scale of Fig. 5 to emphasize the performance at the low SINR region, i.e., cell-boundary region. The proposed algorithm achieves 23.2% and 13.3% throughput gain compared to the non-cooperative and the 1/3 FR algorithms, respectively, for the 5th-percentile UE throughput. This shows that the proposed algorithm improves especially the cell-edge throughput by adaptively selecting the CoMP JT as well as CS/CB.

V. CONCLUSION

In this paper, we have proposed an adaptive and distributed CoMP scheduling algorithm for LTE-Advanced systems. The proposed algorithm determines the CoMP transmission mode for each UE according to the SINR threshold adaptively, and schedules UEs and the corresponding subband by exchanging preference tables among cooperating eNBs. We have implemented a system-level CoMP simulator which reflects realistic 3GPP LTE-Advanced system environments, and demonstrate that the proposed algorithm outperforms the non-cooperation and 1/3 FR algorithms, in the whole SINR region. Especially, the improvement of the cell-edge throughput shows the potential of the adaptive transmission mode selection. Furthermore, the proposed algorithm is operated in a distributed manner without any centralized coordinator, thus avoiding complicated controlling burden of CoMP systems.

REFERENCES