A Novel Semi-Dynamic Multi-Cell Cooperation Approach for Interference Mitigation in LTE-A

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Abstract
Coordinated Multipoint transmission/reception (CoMP) has emerged as a key enabling technology to improve the average cell throughput and cell-edge user throughput put in 3GPP LTE-Advanced (LTE-A) system. For the next generation of wireless communication networks, CoMP is mostly required for Inter-cell Interference (ICI) mitigation. It has the capability to achieve a significant gain in coverage and capacity as well as to improve spectral efficiency. In this paper we propose a novel semi-dynamic multi cell selection and cooperation technique to improve the performance of CoMP with limited increase in signaling overhead and system architectural and computational complexity. The traditional multi cell cooperation techniques with fixed cooperation sets may encounter significant degradation in quality of service due to changing constraints of the time-variant wireless network. The proposed scheme compensates the lack of diversity in fixed cell cooperation techniques and high computational complexity of the dynamic cell selection techniques with minimal increase in signaling overhead. The unique concept developed in our proposed scheme outperforms the traditional static system and provides a good trade-off between the signaling overhead and system performance. The proposed scheme is evaluated by system level simulations and compared with the traditional CoMP system based on fixed cell cooperation. System level simulation results demonstrate that the proposed scheme achieve superior performance comparing to the conventional system in terms of cell average and cell edge throughput.

Keywords: Coordinated Multi-cell Transmission CoMP, MU-MIMO, LTE-A, Inter-Cell Interference

1. Introduction

The Third Generation Partnership Project 3GPP for LTE-Advanced targets high data rates, decreased latency, high spectrum efficiency and the cell edge user throughput [1-3]. Multi-user MIMO technique can significantly increase the system throughput and spectrum efficiency in wireless communications. This technique has been applied in 3GPP LTE-A. CoMP technique attracts much attention as one of the major means to effectively improve the system average/cell edge throughput and cell coverage as well as to achieve better QoS(quality of service)[4][5]. It has emerged as an effective technique to mitigate inter-cell interference in 4G systems [6][7]. It is based on the principle of coordinated downlink transmissions among different cells in order to increase the SINR of the users thus reducing the Interference. Coordination among multiple geographically separated transmission points (TP) is the basic phenomenon implied in CoMP.

Figure 1. Structure of CoMP

Coordinated Multi-cell Transmission CoMP is mainly categorized into two schemes i.e. joint processing (JP) and coordinated scheduling/beam forming (CS/CBF). JP is further categorized into
joint transmission (JT) and dynamic cell selection (DCS). In joint transmission (JT) data to a single UE is simultaneously transmitted from multiple transmission points. In dynamic cell selection (DCS) cells can be selected at any time in consideration of interference. For joint transmission two methods are considered i.e. non-coherent transmission which uses the soft combining of the signal and coherent transmission which does pre-coding between cells and uses in phase combining at the receiver. In coordinated scheduling /beam forming (CS/CBF) data to a single user is instantaneously transmitted from one of the transmission points and scheduling is done between cells to reduce the interference caused to other cells [8-11]. An example of typical CoMP scenario is shown in Fig.1.

Maximal performance in coordinated networks is achieved by fully coordinated transmission in which base stations are connected by a high speed back bone link, enabling them to coordinate as a single source. The fully coordinated transmission scheme requires that the user data and channel state information (CSI) is shared among all cells [12]. The cooperation of all the cells in the system eliminates the inter-cell interference ICI almost completely but it is impossible to apply in practice owing to its high complexity, large amount of feedback and signaling overhead. These issues have motivated the use of cooperation sets in CoMP. In static CoMP the cooperation sets are built based on geographical positions of the cells and these cooperation sets remain constant over time. It is mainly a network centric scheme and it effectively mitigates the strongest interference which is more likely to come from adjacent cells. Static CoMP has inherent limitation of diversity because sets of cooperation sites remain constant over time regardless of the constantly changing radio conditions. In dynamic CoMP the set of cooperating cells are selected dynamically to adapt to variations such as changing radio environment, mobility of the users and system loading etc. Dynamic CoMP is mainly a user-centric technique which suppresses the inter-cell interference with greater improvements in cell average throughput and cell-edge throughput. However the benefits of dynamic CoMP come at the expense of increased signaling overhead and system complexity.

The intrinsic problem of selecting the optimal number of cooperation sets in dynamic cell selection schemes with minimal increase in signaling overhead has been partially investigated and no appropriate solution has been found so far. The limitations in the existing work are the lack of diversity with respect to changing radio channel conditions in case of static CoMP and large signaling overhead and system computational complexity in case of dynamic CoMP. In [13] the CoMP network is divided into fixed groups of adjacent cells for coordinated transmission to suppress the inter-cell interference and provide the sum rate gain. Backhaul signaling requirements, scheduler complexity and lack of spatial degree of freedom are the limitations of the work in [13]. In [14] dynamic CoMP strategy based on exploiting the knowledge of instantaneous channel state information CSI is used in forming the cooperation sets to improve the performance of the system compared to static CoMP but it comes at the cost of increased signaling overhead and system complexity. Similarly in [15] dynamic CoMP has been used to suppress inter-cell interference and give improved system performance compared to static CoMP, with increased signaling overhead and complexity. In our work we have developed a novel idea of multi-cell cooperation based on semi-dynamic selection of the cooperation sets. Our proposed scheme overcomes the drawbacks of static CoMP and increases the performance gain of the system by using semi-dynamic cell selection strategy with relatively low increase in signaling overhead and system computational complexity thus making our scheme more feasible compared to [13][14][15]. The proposed novel scheme compensates the lack of spatial diversity and increased signaling overhead/complexity inherent to static and dynamic cell selection strategies. The presented scheme also improves the fairness of the system.

The rest of this paper is organized as follows. Section 2 describes the system model. In section 3 a novel cooperation set selection scheme is proposed based on maximizing the signal to interference plus noise ratio. In section 4 system level simulation environment and results are presented, necessary analysis is also given in this section. Conclusions are drawn in Section 5.

2. System Model

The system model assumes a general coordinated multipoint transmission MU-MIMO system with E coordinated base stations (BS) serving U user equipments (UEs). Each base station has $N_t$ transmit antennas and each user has $N_r$ receive antennas. So it forms a $E N_t \times U N_r$ MU-MIMO system. Assuming frequency-flat fading, channel may be modeled by a $U N_r \times E N_t$ channel matrix $H$ where each
matrix coefficient represents the fading from each transmit antenna in the base station to each receive antenna at the UE. The received signal model is as follows:

\[ y = HW\sqrt{P}X + \eta \]  

(1)

Where \( H \) (\( \text{UN}_r \times \text{EN}_t \)) denotes the channel matrix, \( W \) (\( \text{EN}_r \times \text{U} \)) denotes the precoding weight matrix and \( P \) (\( \text{U} \times \text{U} \)) denotes the power allocation matrix and \( \eta \) represents the additive white Gaussian noise (AWGN). Besides, we assume that \( \eta \) has complex independent Gaussian element with variance \( \sigma^2 \). The composite channel matrix \( H \) of the cooperative (\( \text{EN}_r \times \text{UN}_r \)) MU-MIMO system is given by:

\[ H = [(H_1)^T (H_2)^T (H_3)^T \ldots (H_d)^T]^T \]  

(2)

Let \( H_u \) be the channel matrix at which the signal is transmitted to the \( u \)-th user, whereas \( W_u \) and \( P_u \) represents the corresponding precoding matrix and power transmission matrix respectively. The received signal at the \( u \)-th user is given by:

\[ y_u = H_uW_u\sqrt{P_u}x_u + \sum_{j=1, j \neq u}^{U} H_uW_j\sqrt{P}jx_j + \eta \]  

(3)

The precoding matrix \( W \) will be obtained using BD criterion as in [16], to ensure that

\[ H_i[w_{i1}, w_{i2}, \ldots, w_{iN_r}] = \begin{cases} 0 : i \neq u \\ U_iS_i : i = u \end{cases} \]  

(4)

Where \( U_i \) is a unitary matrix and \( S_i = \text{diag} \left\{ A_{i1}^{1/2}, A_{i2}^{1/2}, \ldots, A_{iN_r}^{1/2} \right\} \) and \( H_i \) with \( i = 1, \ldots, U \) as the \( N_r \times E_u \) channel matrix seen by the user \( u \). If the UE receives one data stream (\( q=1 \)) then the signal to interference plus noise ration SINR for the \( u \)-th user is derived as:

\[ \text{SINR}_u = \frac{|G_{uH_uW_u}P_u|^2}{\sum_{j=1, j \neq u}^{U} |G_{uH_uW_j}|^2P_j + \sigma^2} \]  

(5)

Where \( G_u \) denotes the detection matrix of the \( u \)-th user. Assuming \( A_u = G_uH_uW_u \) and \( A_j^* = G_uH_uW_j^* \), If the UE receives multiple data streams i.e. \( q > 1 \) then SINR for any streams \( s \leq q \) is given by

\[ \text{SINR}_{u,s} = \frac{|A_{u}(s,s)|^2P_u}{\sum_{j=1}^{q} |A_{u}(s,s)|^2P_j + \sum_{j=1}^{q} |A_j^*(s,s)|^2P_j + \sigma^2} \]  

(6)

The first term in the denominator of the SINR expression derived above represents the interference across the streams of the \( u \)-th user whereas the second term represents the interference from other UEs.

2.1. Precoding Scheme

In MU-MIMO communications, base stations coordinate with a number of co-channel users in the same frequency and the same time slots. It is therefore necessary to mitigate the co-channel interference (CCI). Different strategies have been proposed to choose the weights of the precoders. In our work we have used the block diagonalization (BD) algorithm for choosing the precoding weights. BD algorithm is an optimal solution under the restraint that all the multi-user interference is mitigated within the set of cooperative base stations. The principle of block diagonalization is to find the precoding matrix to fulfill the restraint \( H_uW_j = 0 \) for the user \( u \neq j \). It will eliminate all multi-user interference. Let \( H_{u} \) be defined as the channel matrix for all users other than user \( u \).
The zero inter-user interference constraint requires \( W_u \) to lie in the null space of \( \overline{H}_u \). The singular value decomposition (SVD) of \( \overline{H}_u \) is given as:

\[
\overline{H}_u = \overline{U}_u \begin{bmatrix}
\Sigma_u^T \\
0
\end{bmatrix} 
\begin{bmatrix}
\overline{r}_u(1) \\
\overline{r}_u(0)
\end{bmatrix}^H
\]

The subscript \( H \) denotes the Hermitian transpose. \( \overline{U}_u \) and \( \Sigma_u \) are unitary matrices and \( \Sigma_u^T = \text{diag} \left( \lambda_1^2, \lambda_2^2, \ldots, \lambda_p^2 \right) \), \( \lambda_1 \geq \lambda_2 \geq \ldots \geq 0 \) is a diagonal matrix containing the singular value of the \( \overline{H}_u \) as diagonal elements. \( \overline{V}_u^{(1)} \) comprises singular vectors that correspond to the non-zero singular values whereas \( \overline{V}_u^{(0)} \) comprises singular vectors that corresponds to singular values 0. \( \overline{V}_u^{(0)} \) is an orthogonal basis for the null space of \( \overline{H}_u \), i.e., \( \overline{H}_u \overline{V}_u^{(0)} = 0 \). The number of data streams \( (q) \) for the \( u \)-th user should not exceed the number of columns of \( \overline{V}_u^{(0)} \), therefore choosing \( d_u \) column vectors from right of \( \overline{V}_u^{(0)} \), denoted by \( \overline{V}_u^{(0)} \) will give the block diagonalization precoding matrix of user \( u \). So the precoding matrix is given as:

\[
W = \begin{bmatrix}
\overline{r}_u^{(0)} \\
\overline{r}_u^{(0)} \\
\vdots \\
\overline{r}_u^{(0)}
\end{bmatrix}
\]

The condition that \( H_u W_f = 0 \) for the user \( u \neq j \) is fulfilled which will eliminate the inter user interference. To further improve the capacity/throughput MIMO eigen beam forming is applied to the effective channel matrix \( \overline{H}_u \overline{V}_u^{(0)} \). The SVD factorization of the effective channel matrix \( \overline{H}_u \overline{V}_u^{(0)} \) is given as:

\[
\overline{H}_u \overline{V}_u^{(0)} = \overline{U}_u \begin{bmatrix}
\Sigma_u \\
0
\end{bmatrix} \begin{bmatrix}
\overline{r}_u(1) \\
\overline{r}_u(0)
\end{bmatrix}^H
\]

\( \overline{V}_u^{(1)} \) comprises the singular vectors that corresponds to non-singular values which can be used to enhance the SINR of user \( u \) while the zero co-channel interference condition is still satisfied. Hence the precoding matrix is given as:

\[
W = \begin{bmatrix}
\overline{r}_u^{(0)} \\
\overline{r}_u^{(0)} \\
\vdots \\
\overline{r}_u^{(0)}
\end{bmatrix}
\]

Let \( \overline{V}_u^{(1)} = Y \) \( \overline{V}_u^{(0)} = Y \) and \( \overline{V}_u^{(1)} = Z \) \( \overline{V}_u^{(0)} = Z \), the precoding matrix can be expressed as:

\[
W = \begin{bmatrix}
\overline{r}_u^{(0)} \\
\overline{r}_u^{(0)} \\
\vdots \\
\overline{r}_u^{(0)}
\end{bmatrix}
\]

### 3. Cooperation set selection scheme

In CoMP there are different approaches for cooperative cells selection. Coordination between all the sectors i.e all sector CoMP can totally eliminate the ICI. In practice it is almost impossible to implement all sector coordination schemes due to its high complexity and signaling overhead. In practical systems only a limited number of sites can coordinate in order for signaling overhead to be
within affordable limits[17][18]. In case of static CoMP the cooperation sites are prefixed and are time invariant. The idea of static CoMP is based on the fact that the strongest interference is faced from the geographically closest sites. Therefore geographically closest sites are selected to coordinate in the network. These sets of coordinated sites are predefined and remain fixed over a long period of time. Static CoMP requires less signaling overhead and system computational complexity. Although it significantly improves the performance of the system especially for the users which are near to the centre of the cooperation sites yet it has an inherent problem of degraded system performance for the users at the edge. So static CoMP is not an optimal solution in all situations.

Figure 2. Super sets with varying cooperation sets

In Dynamic CoMP the cooperation sets are flexible and keep on changing with varying channel conditions. The dynamic CoMP is based on the idea to improve the system performance by enabling it to adapt to the variations of radio environment and user locations. The capability of dynamic CoMP to adapt to the varying channel conditions enables it to give significantly improved performance than static CoMP. However the associated large signaling overhead and high system computational complexity are the critical issues in dynamic Comp. In our work we have proposed a novel semi-dynamic scheme to optimize the system performance with reduced signaling overhead and computational complexity. We design a scheme with some potential candidate super sets shown in Fig.2. where sites with the same color coordinate for transmission. The super sets are predefined and each super set comprises of several cooperation sets of varying sizes for coordinated transmission. The scheme is designed in such a way that participating sites in the cooperation sets are different in each super set to provide diversity to cell edge users. Table 1. provides the detailed design of the proposed scheme.

The focus of this work is to make a selection in such a way to maximize the SINR there by enhancing the through put of the cell edge users. Our proposed scheme first calculates the minimum SINR from the base stations in a cooperation set of one super set as given in equation (13).

$$\text{minSINR}_u = \min_{b=1,...,B} \left\{ \frac{|A_u(s,s)|^2 P_u}{\Sigma_{i=1}^{q} |A_u(s,s)|^2 P_u + \Sigma_{j=1}^{q} |P_j|^2 + \sigma^2} \right\}$$ (13)
Where \( b \) is the number of base stations in a cooperation set. After calculating the minimum SINR from cooperation sets that corresponds to different candidate super sets it will select that cooperation set \( (C_n) \) which will maximize the signal to interference plus noise ratio.

\[
C_n = \arg\max_{S \in S} \{\text{maxSINR}_n\}
\]  

Where \( S \) denotes the candidate supersets.

\begin{table}[h]
\centering
\begin{tabular}{|l|}
\hline
Super Set 1 \[ \{13 14 15 37 38 39 40 41 42\}, \{16 17 18 43 44 45 46 47 48\}, \{1 2 3  7 8 9 10 11 12\}, \{19 20 21 49 50 51 52 53 54\}, \{4 5 6 22 23 24 55 56 57\}, \{25 26 27 28 29 30\}\} \\
Super Set 2 \[ \{13 14 15 40 41 42 43 44 45\}, \{16 17 18 46 47 48 49 50 51\}, \{1 2 3 4 5 6 7 8 9\}, \{19 20 21 52 53 54 55 56 57\}, \{28 29 30 31 32 33\}, \{22 23 24 25 26 27\}\} \\
Super Set 3 \[ \{1 2 3 10 11 12 13 14 15 16 17\}, \{18 37 38 39 40 41 42 43 44 45\}, \{7 8 9 25 26 27 28 29 30\}, \{4 5 6 22 23 24 55 56 57\}, \{19 20 21 52 53 54\}, \{31 32 33 34 35 36\}\} \\
Super Set 4 \[ \{1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17\}, \{18 37 38 39 40 41 42 43 44 45\}, \{7 8 9 25 26 27 28 29 30\}, \{4 5 6 22 23 24 55 56 57\}, \{19 20 21 52 53 54\}, \{31 32 33 34 35 36\}\} \\
\hline
\end{tabular}
\end{table}

So in this way different cooperation sets can be selected from predefined super sets for coordinated transmission. The algorithm in our proposed scheme is summarized as below.

1. It starts by calculating the minimum SINR from the base stations in a cooperation set corresponding to one predefined super set according to equation 13. After that it calculates the minimum SINR from cooperation sets in other supersets.
2. After calculating the minimum SINR from cooperation sets in each of the candidate super set it will select that cooperation set \( (C_n) \) which maximizes the signal to interference plus noise ratio.
3. The coordination will be performed according to the selected super set for downlink transmission.

Our proposed scheme aims at increasing the system performance especially for the cell edge users by providing them to select from the best optimal cooperation set from various predefined cooperation sets. This not only increases the system performance but also decreases the back haul signaling overhead and computational complexity of the system.

4. Simulation results

In this section system level simulations results are provided to evaluate the performances of the proposed scheme. The results are compared with the traditional static CoMP. We use a 3GPP reference network layout with 19 hexagonal sites wrap around layout and three cells (sectors) within each site as shown in Fig.2. The sectors are numbered from 1 to 57 in counter clockwise direction, starting from centre and increasing with each tier. A number of 10 users are considered per cell and proportional fairness scheduling is used in all the schemes. Synchronous HARQ is used and the maximum transmission times are four at the most. A strong antenna down tilt of 12 degrees is used which prevents the signal going to more distant UEs. Main Simulation assumptions are given in Table 2.

Fig.3 shows the cumulative distribution function (CDF) of the user throughput for different transmission scenarios. Results indicate that our proposed semi-dynamic scheme based on best superset selection is capable of outperforming the traditional static CoMP scheme. It indicates that the proposed scheme has the capability of sufficiently suppressing the inter-cell interference than the traditional
schemes. It compensates the limitations of the static CoMP with minimal increase in the signaling overhead and system computational complexity.

Table 2. Main simulation assumptions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular Layout</td>
<td>Hexagonal grid, 19 sites with three sectors/cells per site</td>
</tr>
<tr>
<td>System Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>2GHz</td>
</tr>
<tr>
<td>ISD</td>
<td>500 -m</td>
</tr>
<tr>
<td>Distance dependent path loss</td>
<td>37.6 + 128.1 log (d) dB , d in kilometers</td>
</tr>
<tr>
<td>Shadowing standard deviation</td>
<td>8 db</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>20 dB</td>
</tr>
<tr>
<td>Number of users</td>
<td>570 , 10 per cell</td>
</tr>
<tr>
<td>Antenna separation Tx, Rx</td>
<td>2.2</td>
</tr>
<tr>
<td>Number of Antennas Tx, Rx</td>
<td>0.5λ spacing, 0.5λ spacing</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>14 dB for sector antenna</td>
</tr>
<tr>
<td>Scheduling algorithm</td>
<td>Propotional fairness</td>
</tr>
<tr>
<td>Service Type</td>
<td>Full Buffer</td>
</tr>
<tr>
<td>UE speed</td>
<td>3km/hr</td>
</tr>
<tr>
<td>HARQ</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Retransmission time</td>
<td>4</td>
</tr>
<tr>
<td>Channel Model</td>
<td>SCM-E</td>
</tr>
<tr>
<td>Antenna pattern</td>
<td>A(θ) = −min 12 \frac{θ}{θ_{\text{min}}} , θ_{\text{min}} = 20dB</td>
</tr>
</tbody>
</table>

Table 3. Average cell throughput and cell-edge user throughput results.

<table>
<thead>
<tr>
<th>CoMP Configuration</th>
<th>Average Cell Throughput (Kbps)</th>
<th>Cell-Edge User Throughput (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Cooperation</td>
<td>865.13</td>
<td>245.45</td>
</tr>
<tr>
<td>Static-CoMP</td>
<td>1545.82</td>
<td>530.76</td>
</tr>
<tr>
<td>Proposed Scheme</td>
<td>1696.64</td>
<td>690.36</td>
</tr>
</tbody>
</table>

Figure 3. The cumulative distributive function of the user throughput for different scenarios.

Table 3 provides the average cell throughput and cell-edge user throughput results for the non-cooperative system, static-CoMP and the proposed scheme. The results presented in Table 3 demonstrate that the proposed scheme is capable of outperforming its counterparts in terms of average cell throughput as well as cell edge user throughput. Significant performance improvements are observed in the cell edge user throughput i.e. 30% and 181% as compared to static CoMP and no cooperation scenarios respectively. The proposed scheme also enjoys performance gains in average cell throughput compared to static CoMP and no cooperation schemes. It is also observed that the super set selection.
and thus the performance gains are very much sensitive to changes in the received SINR. Further investigations of other criterions for superset selection are therefore an interesting topic for future work.

5. Conclusion

Multi cell cooperation is an effective technique for inter-cell interference mitigation and increasing spectral efficiency in LTE-A networks. Its main limitations are increased signaling overhead and system computational complexity. In practice only a limited number of sites can cooperate, in order for the signaling overhead to be affordable. One of the possible solutions is the static CoMP but still it is not optimal as it does not fully exploit the gains of multi-cell cooperation technique due to lack of diversity. Furthermore it also compromises the system fairness due to the degraded performance experienced by the cell edge users. In this paper a novel semi dynamic multi cell cooperation technique for interference mitigation in coordinated cells has been proposed and analyzed. The proposed scheme compensates the lack of diversity in static CoMP and high computational complexity of the dynamic CoMP with minimal increase in signaling overhead. The proposed algorithm in our scheme is based on so called super set selection to identify the best cooperation sets for inter cell interference mitigation. System level simulation results are provided to show that our proposed scheme achieve greater improvements in cell edge user throughput as compared to static CoMP and no cooperation scenarios. The proposed scheme also attain greater performance gains in average cell throughput compared to its counter parts. The simulation results suggest that our proposed scheme has the capability to significantly improve the cell edge user throughput and make a very good tradeoff between overhead signaling and system performance compared with the other cooperation techniques. The investigation reveals that the performance gains of the proposed scheme are sensitive to received SINR. Further investigations and analysis of other criterions for super set selection are therefore interesting topics for future work.

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