Interference Mitigation and Traffic Adaptation Using Cell Clustering For LTE-TDD Systems

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***Abstract*—Dynamic time-division duplex (TDD) mode has been suggested to be used in LTE systems for small-sized cells with asymmetric traffic. Despite its flexibility, the TDD mode suffers from sophisticated interference patterns, i.e. mobile-to-mobile and Base station-to-Base Station interference. In order to solve this problem, the 3GPP has specified a set of methods for interference mitigation and traffic adaptation (IMTA). Cell clustering is one of these methods, where cells are organized in clusters. Inside each cluster, cells shall have the same frame configuration. The cells are assigned to clusters using specified rules that have to take into account interference levels and traffic asymmetry. In this paper, we propose methods for cell clustering in the context of IMTA. Simulation results have shown that the proposed methods outperform existing methods, especially in uplink.**

I. INTRODUCTION

Time Division Duplex (TDD) has been proposed in the framework of third generation mobile networks due to its flexibility in handling asymmetric traffic, i.e. different traffic load in uplink and downlink. Unfortunately, the TDD mode was not successful with basic Universal Mobile Telecommunications System (UMTS), except with the UMTS Terrestrial Radio Access (UTRA)-TDD Low Chip Rate (LCR) that was adopted mainly in China [1]. The main problem of the TDD mode was its high sensitivity to synchronization problems. This issue was solved in UTRA-TDD LCR systems by adding synchronization and guard mini-slots [1] into the frame structure. This new approach of frame structure was adopted by the 3GPP for TDD mode of the 4th generation, i.e. Long Term Evolution (LTE) systems [2]. In addition, the introduction of femtocells and small cells reduced the problem of synchronization due to the small cell radius.

Despite its advantage in handling asymmetric traffic, the TDD mode suffer from high and uncontrollable interference, especially the interference that appears in crossed slots [3], [4]. Crossed slots appear when a cell is active in downlink and a neighboring cell is simultaneously active in uplink using the same frequency. In this case, the base station (BS) receiving in uplink will experience interference from the other BS, whereas the user equipment (UE) receiving in the downlink will experience interference from the neighboring UE. The first type of interference is dangerous because BSs have usually high antennae, and therefore the propagation losses are small. The second type of interference is equally dangerous and cannot be controlled because UE location is usually unknown to the network; in the worst case the two mobiles can be at the closest edges of the two cells and the one receiving in the downlink will receive extremely high interference (Fig. 1).

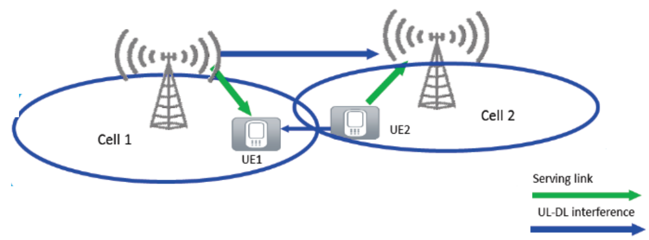

Fig. 1. An example of crossed slots.

Many methods were proposed to solve the problem of interference in crossed slots in 3G networks [3], [5], [6]. In LTE systems, this old problem also became in the center of attention [7], [8]. Furthermore, the 3GPP is advocating a new approach for interference mitigation and traffic adaptation (IMTA) and especially after Release 12, where different approaches were proposed for enhanced IMTA (eIMTA) in a dynamic environment where the cells can change their frame configuration autonomously [9]. These methods include:

- Cell clustering interference mitigation (CCIM).
- Scheduling dependent interference mitigation.
- Interference mitigation based on eICIC/FeICIC schemes.
- Interference suppressing interference mitigation.

In this paper, we are interested in CCIM in LTE-TDD systems. In this context, we have proposed several enhancement to existing methods and evaluated the performance in terms of Signal-to-Interference-and-Noise-Ratio (SINR). More specifically, we have defined two new objective functions that enhance the performance of CCIM methods.

The remaining of the paper is organized as follows. In Section II, we present the frame structure of LTE system, we explain the concept of CCIM, and we introduce the proposed objective functions. The performance of CCIM using the new objective functions is evaluated in Section III. Section IV provides concluding remarks and future work.

II. CELL CLUSTERING INTERFERENCE MITIGATION

In this section, we first present the characteristics of LTE-TDD systems in terms of time frame structure and explain

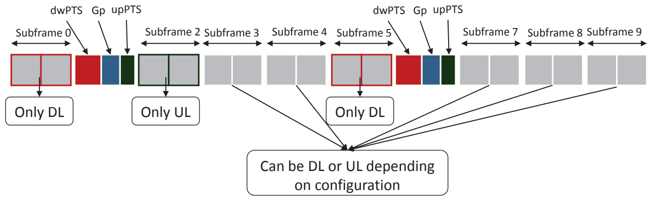

Fig. 2. Frame structure in LTE-TDD systems.

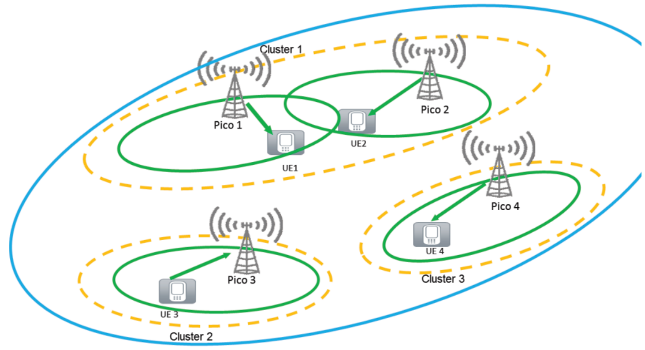

Fig. 3. An example of cell clustering.

how CCIM can solve the problems that appear due to the peculiarity of this structure. Then, we propose two objective functions reflecting the interference and traffic distribution patterns better than existing methods.

A. Frame Structure and Crossed Slots

LTE-TDD frame consists of 10 sub-frames of 1 ms each [2]. Each sub-frame can be used for downlink transmission, uplink transmission, or for special use (i.e., pilot and guard periods). As shown in Fig. 2, there are seven downlink/uplink configuration that were defined in [10].

These seven configurations allow LTE-TDD systems to adapt to any type of traffic, especially asymmetric ones. Previous to Release 12, these configurations could be changed manually using planning tools. However this flexibility can be more exploited, with a faster response time to traffic changes, and with less human intervention using dynamic reconfiguration as it is the case in eIMTA. In this case, the BS or the central unit can decide autonomously about the configuration based on traffic characteristics and some constraints related to interference levels [11]. In case the reconfiguration decisions are made without coordination between the BSs, there is a high probability to obtain crossed slots in the system. As explained in the previous section, same-type interference (i.e. BS-to-BS and UE-to-UE) will appear in crossed slots and probably drastically degrade system performance. Therefore, there is a need for coordination between cells to avoid such interference.

B. CCIM Concept

CCIM as specified by 3GGP involves two tasks [9]: Forming clusters and coordinating transmission inside the clusters. For the latter, there is still no clear approaches to handle it, but it requires the presence of a central unit that will force the decided configuration for all cells in the cluster based on traffic characteristics and interference patterns.

The main idea of cluster forming is to divide the cells into clusters based on some metrics, e.g. coupling losses and interference levels [9]. All cells inside a cluster should have the same frame configuration; the transmission of all cells in each sub-frame should be either uplink or downlink avoiding any crossed slots. Cells belonging to different clusters can choose frame configuration independently from each others, because they have low interaction. The aim of this clustering approach is to control BS-to-BS and UE-to-UE interference, by allowing crossed slots only between cells that has low coupling loss, i.e. the interference experienced by one due to the transmission in the other is small.

In this paper, we are interested in forming cell clusters. These clusters will act like isolated islands that manage their resources independently. In this framework, there is two major problems:

- Defining an objective function that combines interference patterns and adaptability to traffic characteristics.
- Implementing an optimization method that find the clusters maximizing the used objective function. This type of problems can be mapped to MAX N-CUT problem, which is P-complete [12] and requires heuristic or meta-heuristic methods to solve it. In this paper, we will not consider this problem and we will use the same heuristic proposed in [12], [13]. The main idea of the algorithm is to iteratively build the clusters starting from N empty clusters. At each iteration, a cell will be virtually added to a cluster and the intra-cell weight, i.e. the sum of the interactions between the tested cell and all cells inside the cluster, is updated; all clusters will be tested and the one for which the intra-cell weight is minimized will be chosen.

In addition, other methods were proposed in 3GPP meetings [14], [15] where cells are added to clusters if the coupling loss, i.e. path loss between cells, does not exceed certain threshold. This type of methods is simple and can be suitable for eIMTA more than the methods solving the optimization problem. However, they normally lead to less efficient solutions.

C. Identifying Suitable Objective Functions

The difficulty in finding the best objective function is the complex nature of mobile networks, as there is no clear mapping between system configuration and system performance. As mentioned before, the objective function should reward the flexibility of adapting frame configuration to traffic load and penalize the presence of high interference, especially same-type interference. These two goals are usually conflicting when using CCIM; the flexibility is maximized by reducing the number of cells inside a cluster because the traffic is different in each cell. However, this will increase the number of cells that might have different configurations, and thus increase the probability of having high same-type interference. Therefore, a tradeoff should be considered in designing the objective function, which still an open problem.

Most of the proposed objective functions consider only the interference factor reflected by path loss functions [16], [17], [18]. Other methods include the traffic characteristics in the objective function, such as in [12], where the objective function depend on the Differentiating Metric (DM) between two cells i and j defined as

$$u_{ij} = \delta \frac{L_{ij}}{\overline{L}} + \beta \frac{|UT_i - UT_j|}{UT_i + UT_j}, \quad (1)$$

where $\overline{L}$ is the average of path losses between the BSs used as a normalization factor, UT_i reflects the uplink traffic in cell i, δ and β are tunable parameters, L_{ij} is the path loss between the BS serving cell i and the one serving cell j. The latter is defined as

$$L_{ij} = k + \alpha \log_{10} d_{ij} + G_i + G_j, \quad (2)$$

where α and k are propagation constants, G_i is the antenna gain of equipment i, and d_{ij} is the distance between the two BSs. The path loss between the BSs is considered because it is the only fixed path loss in the network.

Using this definition, the problem is to find N clusters $\mathcal{C}_k|_{k=1,\ldots,N}$, such that the below objective function is maximized:

$$O = \sum_{k=1,..,N-1} \sum_{l=k+1,\ldots,N} \sum_{i\in\mathcal{C}_k, j\in\mathcal{C}_l} u_{ij}, \quad (3)$$

It should be noted that the above DM does not take into account the total traffic. In fact, two cells might have big difference in the ratio of uplink to downlink traffic, but the total traffic is low. In this case, the DM will penalize these two cells although the probability of having a crossed slot might be very low. This will lead, most probably, to put these two cells in different clusters and risk high interference, although this is not necessary. Therefore, we propose two objective functions to solve this problem.

The first proposed objective function is a simple amelioration of DM, and is defined as

$$u_{ij}^{(1)} = \delta \frac{L_{ij}}{\overline{L}} + \beta \frac{|UT_i - UT_j|}{2\overline{T}} \left(T_i + T_j\right), \quad (4)$$

where T_i is the total traffic of cell i and $\overline{T}$ is the average traffic in the network used as a normalization factor. The main difference in this function is the inclusion of the total traffic of both cells. This will increase the probability of putting cells with high traffic in different clusters, and therefore increasing the flexibility of frame configuration in these cells.

The second proposed objective function tries to capture the number of crossed slots, and is defined as

$$u_{ij}^{(2)} = \beta \frac{\max\left[0, \max\left(DT_i, DT_j\right) + \max\left(UT_i, UT_j\right) - 9\right]}{5} + \delta \frac{L_{ij}}{\overline{L}}, \quad (5)$$

BS to BS	if $R < 2/3\,\text{km}$, $98.4 + 20\log_{10} d_{ij}$ else $101.9 + 40\log_{10} d_{ij}$, d_{ij} in km
BS to UE/UE to BS	$103.8 + 20.9\log_{10} d_{ij}$, d_{ij} in km
UE to UE	If $R \leq 50\,\text{m}$, $98.45 + 20\log_{10} d_{ij}$, d_{ij} in km else $55.78 + 40\log_{10} d_{ij}$, d_{ij} m

TABLE I
SIMULATION PARAMTERS [9].

where DT_i reflects the downlink traffic in cell i. The denominator of the second factor is set to 5 because the maximum number of crossed slots is 5 based on the seven configuration.

In addition, the path loss considered in the DM is between the BSs. However, the path loss between UEs can be more harmful, as the locations of the UEs are not known. Therefore, we consider also the path loss between the closest UEs in two cells. This is important especially in the case where cells of different radii are present in the system; let us consider three equidistant BSs with radii $R1$, $R2$, and $R3$ such that $R1 > R2 > R3$. Using the path loss between the BSs, the three BS couples will have the same DMs. However, if we consider the path loss between the closest UEs of the cells, the DM between cell 1 and cell 2 will be the highest, which reflects the probability of having close UEs transmitting in different directions. This fact is not considered in [12] and can lead to put cells with high UE-UE interference in different clusters with different frame configurations.

III. Simulation and Results

In order to evaluate the performance of the proposed methods, we consider a system with the following characteristics as depicted in Fig. 4:

- An area of 500x500 m^2 where 19 BSs are created with random locations and a minimum separation distance of 40 m.
- The number of users is randomly and uniformly chosen in each cell.
- The minimum distance between a BS and a UE is set to 10 m.
- A heterogeneous traffic reflected by the different uplink/downlink ratios as shown in Fig. 4. The number of users in a cell range between 1 and 6 users for UL, and 1 and 8 for DL to reflect the maximum number of users supported in a frame.
- The propagation constants are depicted in Table I. The antenna gain were considered to be equal to 5 dBi in all equipment.
- A cell radius uniformly chosen between 20 and 30 m.
- The noise power is assumed to be -110 dBW in each channel.

The performance of the system was evaluated after 100 snapshots using the following methods:

- No clustering: Each cell decide its frame configuration based on its own traffic.
- Legacy clustering method: Clusters are formed using DM.
- Method1: Clusters are formed using $u_{ij}^{(1)}$.

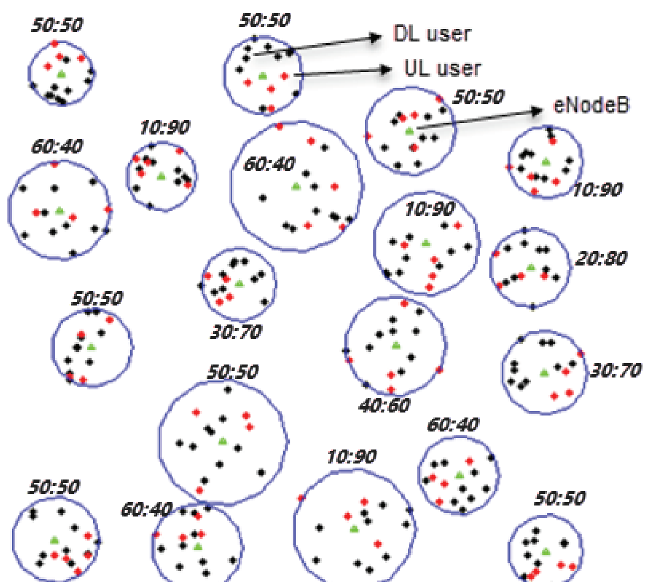

Fig. 4. The simulated model.

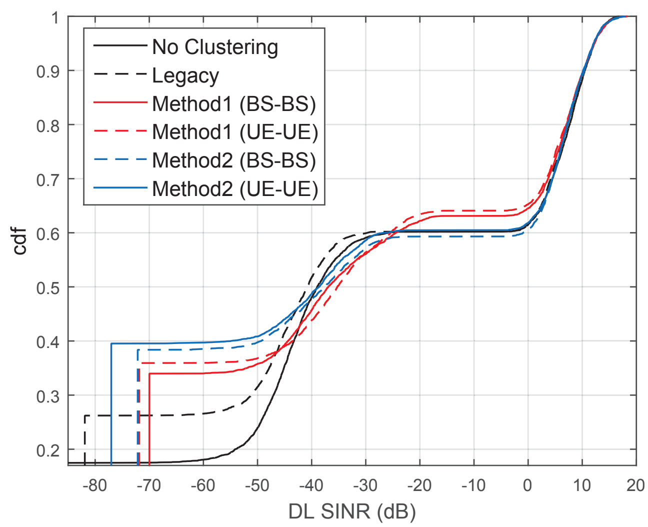

Fig. 5. The cdf of the SINR in downlink.

- Method2: Clusters are formed using $u_{ij}^{(2)}$.

Method 1 and 2 are simulated using BS-BS path loss and UE-UE path loss. We evaluated different values of δ and β and we found that the best results are obtained when both of them are equal to 1.

In Fig. 5 and Fig. 6, we plot the cumulative distribution function of the SINR in downlink and uplink.

In uplink, method2 provides the best performance for acceptable values of the SINR (i.e. above -4 dB). Also, Method1 provides better results than the legacy method and the method without clustering (for SINR higher than -8 dB). Below these values, the legacy method and the method without clustering perform better. This is due to the fact that method1 and method2 allow more cells to enter in a cluster, and hence

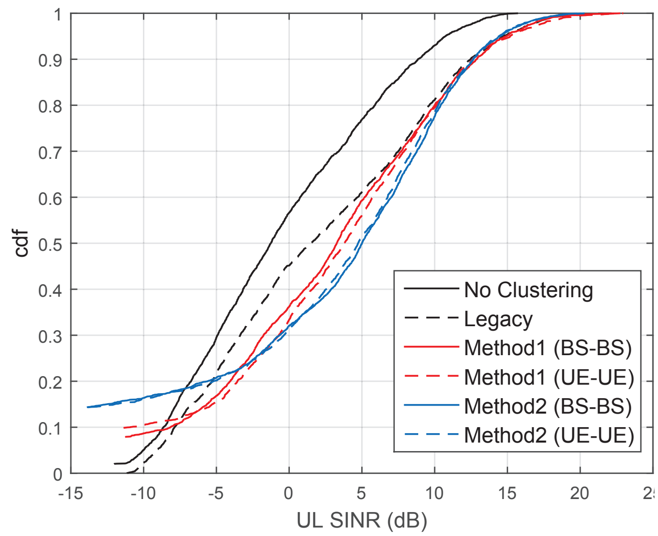

Fig. 6. The cdf of the SINR in uplink.

reducing slightly the flexibility and increasing the interference in non-crossed slots. However, this slight decrease is not very significant because in this region the SINR is very low and most applications would not work even if no-clustering methods are used. In addition, we observed a 3 dB (resp. 5 dB) increase in the median SINR between method1 (resp. method2) from one side, and the legacy method from the other side. In addition, method1 performs better with UE-UE path loss, whereas method2 has similar performance with the two path loss models.

In downlink, as expected, the methods did not provide high gain. In fact, we observed only a slight increase in the median SINR (i.e. around 0.1 dB) using methods 1 and 2. From Fig. 5, one can notice that method2 has better performance than the legacy and no-clustering methods at high SINR, and especially with BS-BS path loss model. Method1 provides lower performance than method2. The low performance in downlink is due to the high traffic load (i.e. downlink to uplink ratio can reach 9). Because the proposed methods allow more cells in the cluster, the flexibility is slightly reduced and the downlink users suffer more interference due to congested channels.

IV. Conclusions and Discussion

In this paper, we have studied different cell clustering methods in the framework of Interference Mitigation and Traffic Adaptation (IMTA) for LTE-TDD systems. This is a relatively new topic with not too much existing work. In particular, one of the main issues that are still missing is a clear definition of what goal should the system optimize in order to enhance the performance.

The main problem in LTE-TDD systems is crossed slots where some cells work on downlink and other cells works in uplink, leading to harmful and uncontrollable interference.

Cell clustering is used to solve this problem, and we have proposed several metrics that capture system performance. The metrics were used in heuristic algorithm and compared to existing methods. Simulation results have shown that the proposed methods provide a gain up to 5 dB, in terms of SINR, in uplink while keeping similar results in downlink.

The main focus of this paper was to propose objective functions for cell clustering methods. The proposed functions have provided relatively good results, as they represent interference and traffic distribution impact on system performance better than other methods.

The used heuristic to form the clusters is very simple and can be enhanced using meta-heuristic methods such as genetic algorithms. Furthermore, such methods can be used for mid to long term planning but cannot be used for fast reconfiguration, because they require some time to converge. Therefore, threshold-based methods can be more effective in this context but, unfortunately, they do not always provide good results. In order to combine the advantages of the two approaches the heuristic/meta-heuristic method can be used as a mid-term planning technique running in the background and the threshold-based method can be used as a short-term radio resource management technique. This combination is the subject of a current work in the framework of self-organizing networks.

Another important issue under investigation is the estimation of the objective function, especially because the path loss and the traffic distribution change frequently.

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