An Efficient Inter-cell Interference Coordination Scheme in Heterogeneous Cellular Networks

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Abstract—**As a mainstream technology in the 4G TDD (Time Division Duplex) systems, TD-LTE (Long Term Evolution) introduces heterogeneous network topology, utilizing a diverse set of base stations, to improve spectral efficiency per unit area. In heterogeneous network deployment comprised of macrocell and picocell, inter-cell interference coordination (ICIC) is very important to significantly improve the system and cell-edge throughput. Moreover, variety of complex situation of inter-cell interference (ICI) occurs in heterogeneous TDD LTE cellular networks due to different downlink/uplink (DL/UL) sub-frame configurations of macrocell and picocell. Therefore, this paper proposes an efficient ICIC scheme consisting of four sub-schemes according to relevant interference scenarios based on different sub-frame configurations. The scheme first analyzes interference level and finds out strong interference for each scenario. The basic idea of ICIC is that only primary interfering sources of each scenario avoid using the same frequency resource occupied by interfered victim, and other interfering sources can reuse frequency resource. Numerical results show that our proposed ICIC scheme can not only improve performance of whole region including macrocell area and picocell area, but also significantly achieve higher throughput for cell edge users.**

Keywords-Inter-cell interference coordination, Resource allocation, Time Division Duplex, Heterogeneous newtork.

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) has deployed the Long Term Evolution (LTE) project of Universal Mobile Telecommunication System (UMTS) around the world, since it significantly improves system performance by using wider bandwidths [1]. Initial deployments of LTE networks are based on homogeneous networks only consisting of macro eNodeBs (MeNBs) providing basic coverage, in which all MeNBs have the similar transmit power levels, antenna patterns, and backhaul interfaces. Since radio link performance is fast approaching theoretical limits with homogeneous LTE, the next performance leap in wireless networks will come from an evolved network topology. Therefore, the deployments of LTE networks based on heterogeneous networks (HetNets) have recently attracted more attention to improve spectral efficiency per unit area. Unlike homogeneous networks, HetNets consists of planned MeNBs and several unplanned eNodeBs, e.g. femto/pico eNBs and relay nodes. These unplanned eNBs with low power level are deployed to improve system capacity in hot spots and eliminate coverage holes in the macro-only system [2].

In LTE system, Single Carrier–Frequency Division Multiplexing Access (SC-FDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) were accepted as the multiple access schemes for uplink and downlink, respectively [3]. OFDMA-based system can satisfy user's demand for high data rates and avoid intra-cell interference by orthogonally allocating resource with more degrees of freedom [4], [5]. However, inter-cell interference (ICI) can causes significant performance loss to the users, especially the cell edge users. In many literatures, various inter-cell interference coordination (ICIC) schemes have been investigated to reduce ICI, such as soft frequency reuse (SFR) and fractional frequency reuse (FFR) [6]-[8].

Furthermore, a key design feature of HetNets is advanced interference management. Especially, the interference scenario is more complex when cell range expansion (CRE) is introduced to expand coverage area of unplanned eNBs. Plenty of research has been done and a lot of algorithms have been proposed for this issue [9]-[12]. In [9] and [10], the capacity and fairness performance of HetNets with CRE and ICIC were studied by mathematical analysis and system simulation, respectively. In [11], a proper ICIC scheme for downlink (DL) co-channel interference through cognitive sensing in HetNets was proposed. Lopez proposed a novel cooperative macrocell-picocell scheduling approach to mitigate macrocell downlink ICI in [12]. However, these existing studies considered ICIC scheme for only DL connection but not uplink (UL) connection in heterogeneous networks. Since most DL and UL traffic is asymmetric, it's necessary to deploy LTE system based on Time Division Duplex (TDD) to provide high capacity and multimedia services. Additionally, there are seven DL/UL frame configurations for TDD LTE; variety of complex situation of interference occurs in heterogeneous TDD LTE cellular Networks. Therefore, we study ICIC issue in heterogeneous TDD LTE cellular networks in the paper. Different ICIC sub-schemes are proposed according to relevant interference scenarios based on DL/UL sub-frame structure of macrocell and picocell. The basic idea involves resource coordination, where primary interfering sources give up use of the same frequency resource compared with interfered victim.

The rest of this paper is organized as follows: Section II

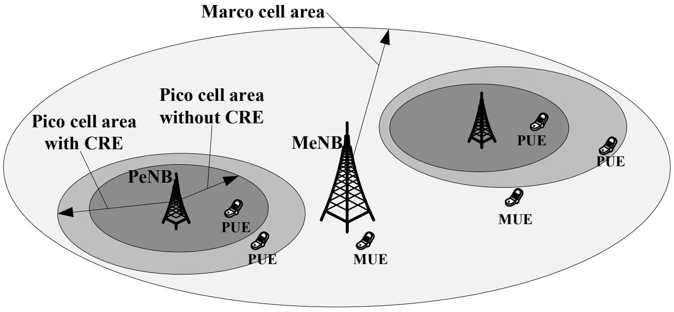

Figure 1. Heterogeneous TDD LTE Cellular Networks

presents the system model, interference scenarios analysis and interference level statistic. In Section III, we propose different ICIC sub-schemes according to relevant interference scenarios. Performance of the scheme is analyzed via simulation in Section IV. Finally, conclusion is drawn in Section V.

II. SYSTEM MODEL AND INTERFERENCE ANALYSIS

A. Heterogeneous TDD LTE Cellular Networks

Consider a heterogeneous TDD LTE cellular network as in Fig. 1. In the macrocell, a MeNB is deployed in a planned regular manner with high transmit power, and some pico eNBs (PeNBs) which number is P are deployed in an unplanned manner. Typically, PeMBs have a relatively small coverage area due to their low transmit power. These overlaid eNBs including MeNB and PeNBs provide wider coverage and improve capacity gain via higher spatial reuse. For LTE deployment, these eNBs can exchange information by X2 signaling. The X2 interface defined as a direct eNB-eNB interface is essential to ICIC.

Additionally, the users which are connected to MeNB are called as macro UEs (MUEs), the users which are connected to PeNB are called as pico UEs (PUEs). In the paper, the users including MUEs and PUEs are connected to optimal eNBs by signal to-interference plus noise power ratio (SINR)-based cell selection method [12]. Due to power level difference, strong received power from the MeNB makes the pico cell areas narrow, and UEs will tend to connect to MeNB rather than PeNBs. As a result, traffic load will be unevenly distributed among cells, thus avoiding an efficient spatial reuse. For this issue, cell range expansion (CRE) is introduced to create the potential for traffic load balancing, which improves the trunking efficiency of the network [13]. Therefore, the PUEs can be defined as PUEs within CRE area (PUE^{e}s) and the PUEs within center area (PUE^{c}s), respectively.

For exact interference analysis and efficient resource allocation in some scenarios, MUEs can be also partitioned into MUE^{n}s which are near PeNB, and MUE^{f}s which are far from PeNB. In the paper, we define a threshold value P_{thr} used to partition MUE^{n}s and MUE^{f}s. The parameter P_{MUE} is the received power from all interfering sources for MUE. The MUE is defined as MUE^{n} when it satisfies $P_{MUE} > P_{thr}$; otherwise the MUE is defined as MUE^{f}.

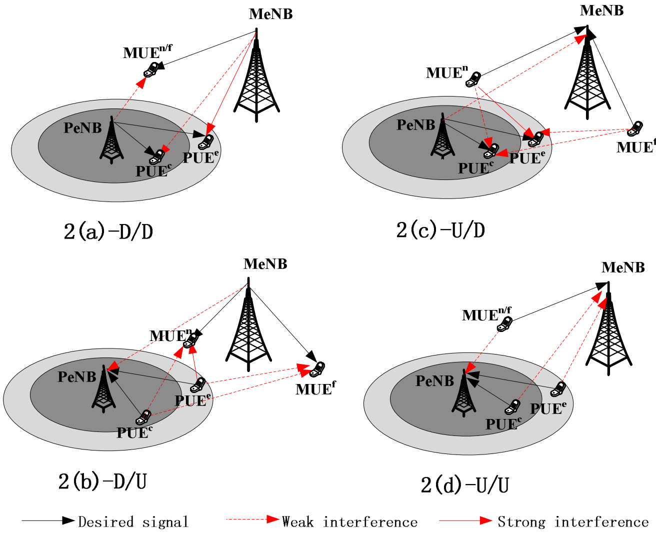

Figure 2. Inter-cell interference scenarios*

B. Interference Scenarios Analysis

In the system, a terminal's SINR is evaluated as:

$$SINR = \frac{P_0}{P_{IOC} + P_{IOR} + N} \tag{1}$$

where P_0, P_{IOC}, P_{IOR}, and N are the received power of desired signal, the interference power from the all neighbor cells, the intra-cell interference in own cell, and the noise power, respectively. The intra-cell interference is assumed to be ignored, since the LTE system adopts SC-FDMA and OFDMA technologies. Additionally, the interference among PeNBs can also be ignored due to low power level of PeNBs. In the next section, we only consider the ICI between macrocell and picocell which is essential to improve system performance.

In TDD LTE system, there are seven DL/UL frame configurations to support various resource ratios between downlink and uplink and accommodate different traffic loads on DL/UL [15]. Therefore, the scenarios of ICI between macrocell and picocell vary with DL/UL structure of macrocell and picocell for every scheduling slot (sub-frame). There are four possible states every scheduling slots since macrocell and picocell both independently configure DL or UL. Accordingly, there are four interference scenarios as follow.

1) Downlink/Downlink (D/D)

In one scheduling slot, macrocell and picocell are both configured on downlink sub-frame as shown in Fig. 2(a). Due to CRE with biased value $\Delta\gamma$, received power of PUE^{e}s from the MeNB is stronger than the power from the PeNB, PUE^{e}s suffer more serious interferences. Furthermore, PUE^{c}s and MUEs both suffer weak interferences due to far distance from interfering eNBs.

2) Downlink/Uplink (D/U)

In one scheduling slot, macrocell is configured on

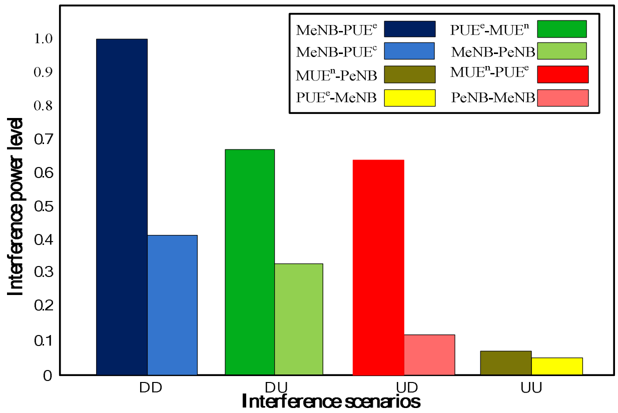

Figure 3. Interference level statistics

downlink sub-frame, and picocell is configured on uplink sub-frame as shown in Fig. 2(b). Accurately, MUEns suffer serious interferences from PUEes since their distance is very close. The interferences from PUEcs to MUEns and the interferences from PUEs to MUEfs can be ignored since they are both far from each other. Furthermore, PeNB suffer weak interference from MeNB. All other interferences can be also ignored.

3) Uplink/Downlink (U/D)

In one scheduling slot, macrocell is configured on uplink sub-frame, and picocell is configured on downlink sub-frame as shown in Fig. 2(c). The scenario is similar to the scenario 2, PUE^{e}s suffer serious interference from MUE^{n}s, and other interferences are weak and can be ignored.

4) Uplink/Uplink (U/U)

In one scheduling slot, macrocell and picocell are both configured on uplink sub-frame as shown in Fig. 2(d). There is no strong interference in the scenario compared with scenario 1. PeNB and MeNB both suffer weak interferences since interfering source UE is far from victim eNB, and UE's transmit power is very low.

C. *Interference Level Statistics*

Fig. 3 shows the two of stronger interference of each scenario in system-level simulation, where each eNB can allocate full frequency resource. In order to reflect different interference levels among various scenarios, the interferences of PUE^{e}s suffered from MeNB in the D/D scenario is defined as the baseline to other interferences. Its interference power P_{max} is equal to 1. If another one interference power is P_{ano}, its relative interference level is defined as $\alpha = P_{ano} / P_{max}$. From the analysis and simulation of the four interference scenarios, we could notice that, for the U/U scenario it has low interference level. In other scenarios, there is a primary interference for each scenario. These characteristic can be used to allocate frequency resource to mitigate the primary ICI. The detailed schemes relative to different frame configurations are proposed in the next section.

III. INTER-CELL INTERFERENCE COORDINATION SCHEME

As motivated in the previous section, inter-cell interference coordination plays an important role in heterogeneous networks. The basic idea of our proposed ICIC scheme is that only primary interfering sources give up use of same resource compared with interfered victim. In LTE system, the minimum scheduling unit for the DL and UL is referred to as a resource block (RB) in order to limit the signaling overhead of resource allocation [15]. Therefore, the key problem is how to reuse and schedule RB to variety of UEs which are connected to different eNBs. For low complexity, we only focus on primary inter-interference when scheduling orders are designed.

Let us define a heterogeneous TDD LTE network as a set of:

- A set of all RBs: $\mathbf{R} = \{1, \ldots, R\}$
- A set of RBs which are assigned to MUE: $\mathbf{R}^{M}$
- A set of all RBs which are assigned to MUE^{n} near p^{th} picocell: $\mathbf{R}_p^{n}$ (only for scenario 2, 3)
- A set of RBs which are assigned to PUE^{e} in p^{th} picocell: $\mathbf{R}_p^{e}$
- A set of all RBs which are assigned to MUE^{f}: $\mathbf{R}^{f}$ (only for scenario 2, 3)

To sum up the above analysis, the four ICIC sub-schemes are introduced as follow.

1) Downlink/Downlink

The resource allocation algorithm for Downlink-Downlink scenario is showed in Fig. 4. The ICI of primary interfered victim PUE^{e} is from MeNB, thus the relationship of variety of sets of RBs should be satisfied, that is $(\bigcup_{p=1}^{P} \mathbf{R}_p^{e}) \bigcap \mathbf{R}^{M} = \{\}$, $\mathbf{R}_p^{e} \bigcup \mathbf{R}_p^{c} = \mathbf{R}$,and $\mathbf{R}_p^{e} \bigcap \mathbf{R}_p^{c} = \{\}$. For reusing resource fully, the eNBs firstly schedule MUE.

Algorithm 1: Downlink-Downlink Scenario

1. *Max C/I* algorithm is used for available RBs $\mathbf{R}$ for the MUE
2. exclude the used RBs $\mathbf{R}_M$ (step 1) by the MUE and compute available RBs $\mathbf{R}^{-} \leftarrow \mathbf{R} / \mathbf{R}_M$ for PUE^{e}

For each PeNB

3. *Max C/I* algorithm is used for available RBs $\mathbf{R}^{-}$ for the PUE^{e}
4. exclude the used RBs $\mathbf{R}_p^{e}$ (step 3) and compute available RBs $\mathbf{R}_p^{c} \leftarrow \mathbf{R} / \mathbf{R}_p^{e}$ for PUE^{c}
5. *Max C/I* algorithm is used for available RBs $\mathbf{R}_p^{c}$ for the PUE^{c}

End For

Figure 4. Resource allocation with ICIC for Downlink/Downlink scenario

2) Downlink/Uplink

The resource allocation algorithm for Downlink-Uplink scenario is show in Fig. 5. The ICI of primary interfered victim MUE^{n} is from PUE^{e}, thus the relationship of variety of sets of RBs should be satisfied, that is $\mathbf{R}_p^e \cap \mathbf{R}_p^n = \{\}$, $\mathbf{R}_p^e \cup \mathbf{R}_p^c = \mathbf{R}$, $\mathbf{R}_p^e \cap \mathbf{R}_p^c = \{\}$, $(\bigcup_{p=1}^{P} \mathbf{R}_p^n) \cup \mathbf{R}^f = \mathbf{R}$, and $(\bigcap_{p=1}^{P} \mathbf{R}_p^n) \cap \mathbf{R}^f = \{\}$. Although the scheduling order is complex in the scenario, resource allocation is more accurate, in which it achieve more performance gains.

Algorithm 2: Downlink-Uplink Scenario

1. *Max C/I* algorithm is used for all RBs $\mathbf{R}$ for the MUE^f and MUE^n
For each PeNB
2. exclude the used RBs $\mathbf{R}_p^n$ (step 1) by MUE^n and compute available RBs $\mathbf{R}^- \leftarrow \mathbf{R} / \mathbf{R}_p^n$ for the PUE^e
3. *Max C/I* algorithm is used for available RBs $\mathbf{R}^-$ for the PUE^e
4. exclude the used RBs $\mathbf{R}_p^e$ (step 3) by PUE^e and compute available RBs $\mathbf{R}_p^c \leftarrow \mathbf{R} / \mathbf{R}_p^e$ for the PUE^c
5. *Max C/I* algorithm is used for available RBs $\mathbf{R}_p^c$ for the PUE^c
End For

Figure 5. Resource allocation with ICIC for Downlink/Uplink scenario

3) Uplink/Downlink

The resource allocation algorithm for Uplink-Downlink scenario is show in Fig. 6. The ICI of primary interfered victim PUE^e is from MUE^n, thus the relationship of variety of sets of RBs that should be satisfied is the same as scenario 3. The differences lie in scheduling order, where interfered victim is firstly scheduled in order to diminish ICI.

Algorithm 3: Uplink-Downlink Scenario

For each PeNB
1. *Max C/I* algorithm is used for all RBs $\mathbf{R}$ for the PUE^e
2. exclude the used RBs $\mathbf{R}_p^e$(step 1) by PUE^e and compute available RBs $\mathbf{R}_p^c \leftarrow \mathbf{R} / \mathbf{R}_p^e$ for the PUE^c
3. *Max C/I* algorithm is used for available RBs $\mathbf{R}_p^c$ for the PUE^c
End For
For each PeNB $(p = 1 : P)$
4. exclude the used RBs $\mathbf{R}_p^e \cup (\bigcup_{p'=1, p' \neq p}^{P} \mathbf{R}_{p'}^n)$ and compute available RBs $\mathbf{R}^- \leftarrow \mathbf{R} / (\mathbf{R}_p^e \cup (\bigcup_{p'=1, p' \neq p}^{P} \mathbf{R}_{p'}^n))$ for the MUE^n
End For
5. *Max C/I* algorithm is used for available RBs $\mathbf{R}^-$ for the MUE^n
6. exclude the used RBs $\mathbf{R}_p^n$ (step 4) and compute available RBs $\mathbf{R}^f \leftarrow \mathbf{R} / (\bigcap_{p=1}^{P} \mathbf{R}_p^n)$ for MUE^f
7. *Max C/I* algorithm is used for available RBs $\mathbf{R}^f$ for the MUE^f

Figure 6. Resource allocation with ICIC for Uplink/Downlink scenario

4) Uplink/Uplink

There is no obvious ICI for Uplink-Uplink scenario. Macrocell and picocell can independently schedule all frequency resource. Max C/I algorithm is used for all UEs in each eNB.

At each time slot, these eNBs can exchange frame configurations by X2 signaling. According to different scenarios, eNBs adopt flexible resource allocation with ICIC as described above.

IV. SIMULATIONS AND DISCUSSIONS

The performance of the proposed scheme in heterogeneous TDD LTE cellular network is evaluated in this section. A MeNB is located at the center of the macrocell with radius equal to 289 m. It's assumed that 4 PeNBs are randomly located within the cell with a uniform distribution. Additionally, the minimal distance among eNBs should satisfy some constraints, i.e., minimal distance between MeNB and each PeNB, and minimal distance between a PeNB and another PeNB. The locations of the 8 UEs in the macrocell and the 4 UEs in each picocell are assigned randomly with a uniform distribution. There are some similar constraints of the distance between eNBs and UEs as Table I. In the system, we assume that the distance-dependent path loss and shadowing are constant, and the channel condition of each RB varies independently with each other. In addition, the transmission power of MeNB and each PeNB are set as fixed values. The antenna gain of MeNB and PeNB are 14 dBi, and 5 dBi, respectively. In the evaluation, full buffer traffic model is used. The frame structures are selected randomly. The detailed values of the simulation parameters are listed in Table I.

TABLE I. SYSTEM PARAMETERS

Simulation Parameter	Value	
	Macrocell	Picocell
Number of eNB	1	2, 4
Number of UE per eNB	8	4
Path loss model	128.1 +37.6 $\log_{10}$(R) dB, R in Km	140.7 +36.7 $\log_{10}$(R) dB, R in Km
Total eNB TX power	46dBm	30dBm
eNB antenna gain	14dBi	5dBi
Cell radius	289 m	40 m
Carrier Frequency	2 GHz	
Total bandwidth	10 MHz	
Frame duration	1ms	
Frame duration	10ms	
Simulation time	200 s	
Thermal noise density	-174 dBm/Hz	
Duplex mode	TDD	
Scheduling algorithm	Max C/I	
Subcarriers per RB	12	
Min. dist. MeNB-PeNB	75m	
Min. dist. PeNB-PeNB	40m	
Min. dist. MeNB-MUE	35m	
Min. dist. PeNB-PUE	10m	
Modulation and coding	MCS based on LTE transport formats	
Biased value of CRE	2,8,14 dB	

To evaluate the system performance, we take "Resource Partitioning" (RP) scheme and "without Resource Partitioning" (woRP) scheme for performance comparison [13]. The RP scheme means that half of the RBs are used by the macrocell, and the other half are reused by the picocell. In this way, the ICI between macrocell and picocell is fully avoided. The woRP scheme means that macrocell and picocells can independently use all the RBs, in which ICIC is not considered. In Tables II and III, the results of our system-level simulation in terms of average cell throughput and average cell edge throughput are presented, respectively.

As can be observed that, the woRP scheme without ICIC can achieve limited improvement of throughput performance when bias of CRE is an appropriate value. Unlike the woRP scheme, where high biased value bring serious interference, both the RP scheme and the proposed scheme can be of help in improving throughput performance with a convex tread, when the biased value is increasing. This is because that the two schemes with ICIC not only can achieve the larger offloading from macrocell, but also mitigate additional interference due to bias of CRE. For the impact of biased value, there are the same conclusions for average cell throughput and average throughput of edge user. Table II also shows that the proposed scheme can yield higher average cell throughput than woRP scheme and RP scheme whatever the biased value and the number of PeNBs are. It's remarkable to improve system performance since the proposed scheme adopt effective ICIC scheme with the consideration of better spatial reuse according to different interference scenario. Especially, when the biased value and the number of PeNBs are 14 dB and 4, the proposed scheme increase the average cell throughput 188.3% with respect to woRP scheme and 29.7% with respect to RP scheme, respectively.

TABLE II. AVERAGE CELL THROUGHPUT

Biased Value(dB)	Num of PeNB	woRP (Mbps)	RP (Mbps)	Proposed scheme (Mbps)
2	2	11.036	9.548	12.645
	4	10.986	10.130	13.993
8	2	11.659	13.774	18.803
	4	11.264	15.208	20.433
14	2	10.589	17.138	23.316
	4	10.036	22.300	28.934

Similarly, the proposed scheme outperforms woRP scheme and RP scheme in term of average throughput of edge user as shown in Table III. Additionally, the proposed scheme can achieve more remarkable improvement of average throughput of edge user compared with average cell throughput. The reason is that we focus on the objective of mitigating primary ICI which occurs in cell edge. For example, additional improvements are approximately 236.9% with respect to woRP scheme and 34.8% with respect to RP scheme.

TABLE III. AVERAGE THROUGHPUT OF CELL EDGE USER

Biased Value(dB)	Num of PeNB	woRP (Kbps)	RP (Kbps)	Proposed scheme (Kbps)
2	2	96.036	94.355	121.691
	4	95.642	96.013	151.886
8	2	100.306	162.349	213.354
	4	96.918	196.114	236.710
14	2	91.330	190.800	293.013
	4	90.594	226.370	305.216

V. CONCLUSION

In this paper, an efficient inter-cell interference coordination scheme in heterogeneous TDD LTE cellular networks is proposed. There are four interference scenarios as described above due to variety of sub-frame structure for macrocell and picocell in TDD LTE system. According to different scenarios, we adopt flexible resource allocation with ICIC. The basic idea is that only primary interfering sources of each scenario avoiding using the same resource used by interfered victim, and other interfering sources can reuse frequency resource. The proposed ICIC scheme can achieve better spatial reuse and superior throughput performance compared with traditional ICIC scheme.

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