Dynamic Frequency Reservation Scheme for Interference Coordination in LTE-Advanced Heterogeneous Networks

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Abstract—Heterogeneous networks are employed in the next generation communication systems to enhance area spectral efficiency (ASE) and reduce system cost. However, the cell splitting gain can only be achieved when both co-tier interference and cross-tier interference are properly handled. To reduce cross-tier interference on the low SINR and interference limited UEs, a dynamic scheme of frequency reservation for interference coordination (DFR-IC) is proposed in this paper. Two factors to model the co-tier and cross-tier interference ratio of user equipments (UEs), namely R_I^{macro} and R_I^{pico} , are introduced. Proper numbers of resource blocks (RBs) in each tier are reserved for these UEs to enhance their SINRs. Simulation results show that the proposed scheme can greatly improve the performance of the UEs at cell edge, but it decreases marginal throughput compared to full-reuse and non-reuse scheme.

Keywords-heterogeneous networks; frequency planning; interference coordination; pico cells

I. INTRODUCTION

With the demand for data services growing at an exponential rate, the spectral efficiency per link is approaching the Shannon limits. Traditionally, cell splitting techniques are employed to provide the required data rates. However, deploying additional macro eNodeBs (MeNBs) is not cost-effective for operators and not optimal in terms of area spectral efficiency (ASE) which is defined as the throughput per unit area. Moreover, the relatively sparse deployment of MeNBs enables potential gains of wireless networks by bringing networks closer to the mobile users [1]. Thus, the 3GPP LTE-Advanced (LTE-A) systems employ heterogeneous networks to overcome the challenges associated with the deployment of traditional MeNBs. Heterogeneous networks consist of planned MeNBs and a diverse set of low power nodes (LPNs). The LPNs overlay high power MeNBs' coverage to boost ASE and provide services in hotspots [2]. The low-cost LPNs are classified into picocells (also known as PeNBs), femtocells and relay nodes, with transmit power of 100mW to 2W.

Since the MeNBs transmit at comparably high power and serve almost equal number of user equipments (UEs), the interference on the cell edge users is identical. The inter-cell interference can be avoided or coordinated by sophisticated frequency planning techniques such as fractional frequency reuse (FFR) or inter-cell interference coordination (ICIC) techniques in LTE/LTE-A systems [3]. In heterogeneous networks, due to the overlay deployment with MeNBs, LPNs not only supply coverage for hotspots, but also radiate strong interference towards the co-channel MeNBs and LPNs. More cell boundaries are created in heterogeneous networks and interference avoidance techniques are required to obtain the designed cell splitting gain [4] [5].

In order to mitigate the mentioned interference, interference cancellation schemes have been initially proposed in such as [6]. These techniques rely on the error-prone cancellation process and are expensive to implement in LPNs due to the cost constraints. Power control techniques dynamically tune LPNs' and MeNBs' transmit power according to the changing condition of passing users, neighboring cells and channel quality. To name a few, Claussen introduced a self-organizing power control mechanism to ensure a constant femtocell coverage radius, where each femtocell sets its power to a value that on average is equal to the power received from the closest macrocell at a target femtocell radius [7]. They also proposed coverage adaptation scheme that uses mobility events of outdoor and indoor users [8]. In their method, each femtocell sets its power to a value that on average minimizes the number of attempts of passing macrocell users to connect to a femtocell. However, power control methods may lead eventually to insufficient coverage of LPNs.

Interference avoidance schemes in frequency dimension usually assume the transmit powers of LPNs and MeNBs are static. How to allocate frequency resources for interference coordination should be determined. In [9] Chandrasekhar proposed an OFDMA subchannel allocation strategy based on an orthogonal assignment of radio resources to macrocells and femtocells that maximizes the ASE. In their scheme, a total of F subchannels are divided into F_M subchannels for the macrocell tier and F_f ones for the femtocell tier. A parameter $\rho = F_M / F$ denotes the portion of spectrum allocated to the macrocell tier, which is chosen dynamically according to the QoS requirement of one tier with respect to the other tier. This approach resorts to the orthogonal spectrum assignment is suboptimal to full reuse of the total frequency band. Ling introduced a measurement based autonomous algorithm in [10] where subchannels with lowest suffered interference are allocated by each femtocell. However, the interference measurement is performed by femtocells and thus may not be optimal for all connected users. In [11], Su proposed an optimization scheme in order to minimize the interference suffered by macrocell users and guarantee a given SINR for all users. However, their method is formulated as a Lagrangian problem and solved by the subgradient method which requires several iterations to converge.

To deal with the cross-tier interference, this paper proposed DFR-IC. It assumes that macrocells and LPNs share the same frequency bands [11]. Two factors are introduced to model the cross-tier interference of the UEs. Then, according to UEs' SINR and the two factors, each tier groups its UEs into the protected UEs and the unprotected UEs. A fraction of RBs are reserved for the protected UEs who experience low SINR or suffer dominant cross-tier interference. The number of the reserved RBs is dynamically adapted to the SINR and interference condition of the protected UEs. Finally, the protected UEs in one tier are scheduled on the reserved RBs of the other tier firstly and the other UEs are scheduled on the residual RBs. Since there is no cross-tier interference, the SINRs and throughput of the UEs scheduled on the reserved RBs are enhanced.

The rest of the paper is organized as follow. In section II, the interference analysis and frequency reuse schemes in heterogeneous networks are given. The system model is introduced in section III. In section IV, the proposed DFR-IC algorithm is studied in detail. The system performance and simulation results are analyzed in section V. Finally, section VI concludes the paper.

II. INTERFERENCE ANALYSIS AND FREQUENCY FEUSE SCHEME

A. *Interference analysis in heterogeneous netwroks*

As LPNs overlay the coverage of MeNBs in heterogeneous networks, more cell boundaries are created compared with homogeneous networks. UEs located in the boundary regions suffer both co-tier and cross-tier interference and experience low SINR resulting in low throughput.

- *Co-tier interference* refers to the unwanted signals received by UEs from co-channel LPNs. The term co-tier means that all interfering signal comes from the same network tier. Since open access LPNs, such as picos, relay nodes, are planned by operators, the co-tier interference is less strong between them. ICIC techniques standardized by 3GPP in LTE/LTE-A are efficient to handle this interference. Most severe co-tier interference occurs in femtocell deployment which usually operates in close access mode. Femtocells are usually deployed by end users and lack of powerful backhauls, hence fast reacting ICIC techniques are unavailable [4]. On the other hand, co-tier interference is generated by femtocells due to low isolation of walls or windows. Nevertheless, OFDMA femtocells can avoid co-tier interference by a proper allocation of frequency resources among user in a large time scale or by self-organizing techniques.

- *Cross-tier interference* denotes the signal radiated on LPNs' UEs because of the simultaneous transmissions of surrounding macrocells and vice versa. Particularly, cross-tier interference may be significant for macrocell users near Closed Subscriber Group (CSG) femtocells, since they are not allowed to connect to nearby femtocells with smaller path losses than their serving macrocells due to connectivity rights. Once this case happens, the macrocell users may experience outage and cannot resume to normal communication as there are not efficient backhaul connection between macrocells and femtocells. However, cross-tier interference can be avoided by interference coordination schemes in macro-pico heterogeneous networks thanks to the efficient backhaul connection between them. In this paper, the interference coordination (IC) schemes are examined to avoid or reduce cross-tier interference in frequency dimension without neglect of the co-tier interference.

B. *Frequency reuse schemes*

Since both macrocells and LPNs are deployed in heterogeneous networks, frequency reuse schemes have to be designed to improve the ASE. Generally, there are three options for spectrum allocation:

- Full reuse scheme: This approach can reach a higher network spectral efficiency because both tiers can access all resources. Nevertheless, cross-tier interference may occur and the overall network performance may be degraded.

- Non-reuse scheme: This scheme assigns some frequency resources to macrocells and the left others to LPNs. Cross-tier interference is completely avoided, since both tiers operate at different frequency resource, but the network spectral efficiency may be low.

- Partial-reuse scheme: This is an intermediate approach. The macrocell tier and LPNs have access rights to two partial overlapping frequency resource sets. The benefits of this approach are achieving higher spectral efficiency and lower cross-tier interference.

Note that the ASE is affected by not only spectral efficiency per link but also frequency reuse scheme in the system. Full reuse scheme and Partial-reuse scheme are preferred by operators due to the costful frequency bands. This paper proposed a novel partial frequency reuse scheme.

III. SYSTEM MODEL DESCRIPTION

To evaluate the proposed scheme, a cluster of N_M macrocell sites is constructed. Each macrocell site is composed of a three-sectored MeNB and N_P PeNBs which are randomly dropped in the MeNB's coverage. A total number of N UEs are uniformly dropped in the macrocell sites and access to picocell or macrocell based on their received Reference Signal

Receiving Power (RSRP). Once accessed to a cell, the UEs feedback their CQIs and suffered interference to its serving eNB. The serving eNB allocates a total number of K RBs to its UEs using proportional fairness (PF) scheduler. The N^{macro} UEs served by MeNB are denoted as MUEs, while PUEs denote the N^{pico} ones served by PeNB.

The SINR of the i_{th} MUE on the k_{th} RB served by the m_{th} MeNB is denoted as:

$$SINR_{i,k}^{MUE} = \frac{S_{m,k}^{macro}}{\sum_{n=1,n\neq m}^{N_M} S_{n,k}^{macro} + \sum_{j=1}^{N_p \times N_M} S_{j,k}^{pico} + N_o} \quad (1)$$

where $S_{m,k}^{macro}$ and $S_{j,k}^{pico}$ represent the RSRPs from the m_{th} MeNB and the i_{th} PeNB on k_{th} RB. N_o is the system noise.

The SINR of i_{th} PUE on k_{th} RB served by p_{th} PeNB is denoted as:

$$SINR_{i,k}^{PUE} = \frac{S_{p,k}^{pico}}{\sum_{n=1}^{N_M} S_{n,k}^{macro} + \sum_{j=1,j\neq p}^{N_p \times N_M} S_{j,k}^{pico} + N_o} \quad (2)$$

IV. DFR-IC DESCRIPTION

From (1) and (2), it is known that the SINR of both PUE and MUE is degraded by both co-tier and cross-tier interference. The UEs at the boundaries between macrocell and picocells may experience awful SINR if the interference is not properly handled. A heuristic method is to use orthogonal frequency bands between the two tiers to avoid cross-tier interference. This method reduces the spectral efficiency and cannot handle co-tier interference. For this reason, DFR-IC is proposed to enhance the cell edge UEs' SINR. DFR-IC aims to reduce the cross-tier interference for the low SINR UEs without neglect of the co-tier interference.

For any UE, the interferences from all interfering macrocells and picocells are collected. The arithmetic sum of the interference from all interfering macrocells over all RBs is obtained as I^{macro}, while the one from all interfering picocells is denoted as I^{pico}. Two factors, namely $R_I^{macro} = \frac{I^{macro}}{I^{pico}}$ and $R_I^{pico} = \frac{I^{pico}}{I^{macro}}$, are introduced to model the cross-tier interference for the MUEs and PUEs separately.

On one hand, for the UEs with SINR below a low threshold Γ_{low}^{SINR}, their interference from both serving tier and the other tier is significant. The UEs' SINR is calculated as the arithmetic sum of $SINR_{i,k}^{*}, \forall k$ (*denote the PUE or MUE). On the other hand, for the interference limited UEs with SINR between a low threshold Γ_{low}^{SINR} and a high threshold Γ_{high}^{SINR}, their RSRPs are relatively high but their SINRs maybe degraded by dominant cross-tier interference. Eliminating the dominant cross-tier interference would greatly improve these UEs' SINR and enhance their throughputs. To identify these UEs, two thresholds, namely $\Gamma_{R_I}^{macro}$ and $\Gamma_{R_I}^{pico}$, are defined as a further screening indicators for R_I^{macro} and R_I^{pico}, respectively.

In both cases, proper RBs without cross-tier interference from the other tier should be reserved for these protected UEs. Define $N_{macro}^{reserve}$ as the set of the protected MUEs and $N_{pico}^{reserve}$ as that of the protected PUEs. Based on above analysis, the proposed scheme is described below:

$$Criterion: \forall MUE, PUE$$

$$\{MUE \mid SINR_i^{MUE} \prec \Gamma_{low}^{SINR}\} \subset N_{reserved}^{macro} \quad (3)$$

$$\{PUE \mid SINR_i^{PUE} \prec \Gamma_{low}^{SINR}\} \subset N_{reserved}^{pico} \quad (4)$$

$$\forall \{MUE, PUE \mid \Gamma_{low}^{SINR} \prec SINR_i^{MUE} \prec \Gamma_{high}^{SINR}\}$$

$$\{MUE \mid R_I^{macro} \prec \Gamma_{R_I}^{macro}\} \subset N_{reserved}^{macro} \quad (5)$$

$$\{PUE \mid R_I^{pico} \prec \Gamma_{R_I}^{pico}\} \subset N_{reserved}^{pico} \quad (6)$$

$$RB_{reserved}^{macro} = \left\lceil \frac{\left|N_{reserved}^{pico}\right|}{\left|N^{pico}\right|} \times K \right\rceil_+ \quad (7)$$

$$RB_{reserved}^{pico} = \left\lceil \frac{\left|N_{reserved}^{macro}\right|}{\left|N^{macro}\right|} \times K \right\rceil_+ \quad (8)$$

Note $| \, |$ is to get the cardinality of a set, and $[\ ]_+$ denotes the ceiling operation. $RB_{reserved}^{macro}$ and $RB_{reserved}^{pico}$ are the number reserved RBs of MeNB and pico separately. The other $K - RB_{reserved}^{macro} - RB_{reserved}^{pico}$ RBs are reusable in the two tiers. The partition of RB set is shown in Fig. 1.

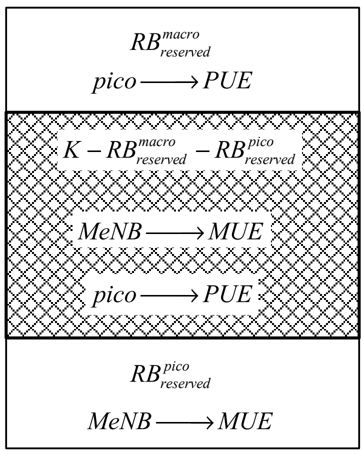

Figure 1. frequency reservation scheme

The macrocells tier schedules the protected MUEs $N_{macro}^{reserve}$ firstly on the reserved $RB_{reserved}^{pico}$ RBs, and then all MUEs are scheduled on the reused $K - RB_{reserved}^{macro} - RB_{reserved}^{pico}$ RBs. The method in picocells tier is similar.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In the simulation, a total number of 19 macrocell sites and 12 PeNBs per macrocell site are deployed. UEs are uniformly dropped ten times in the central 7 macrocell sites during the total 6×10^3 *ms* simulation time. The statistics are only collected for the centre one site (denoted as target cell site). The simulation model is based on 3GPP LTE-A heterogeneous deployments [12]. Note that the DFR-IC is implemented in a scale of 30 *ms*. Detail parameters and models are listed in Table I.

TABLE I. SIMULATION PARAMETERS FOR MACRO-PICO SCENARIO [12]

Parameters	Heterogeneous networks	
	Macro	***Pico***
Inter-site distance (ISD)	500 m	
Carrier frequency	2 GHz	
System bandwidth	10 MHz	
Minimum distance between UE and eNodeB	35 m	10 m
Distance-dependent path loss	128.1 + 37.6log10(R) dB, R in km	140.7 + 36.7log10(R) dB, R in km
Shadowing standard deviation	8 dB	10 dB
Shadowing correlation	0.5 (between cells), 1 (between sectors)	0.5
Channel model	TU channel model	
Total BS TX power	46 dBm	30 dBm
Antenna pattern	See Table 2.1.1-2 [12] 3D mode	A(θ) = 0 dB (horizontal)
Antenna gain	14 dBi	5 dBi
Penetration loss	20dB	
UE placement	Configuration #1 (Total 25 UEs per sector) See Tables A.2.1.1.2-4 [12]	
Scheduling algorithm	Proportional Fairness	
Traffic model	Full buffer traffic	

Fig. 2 and Fig. 3 show the cumulative distribution function (CDF) curves of SINR, R_I^{pico} and R_I^{macro} separately in full reuse scheme. As shown in Fig. 2 PUEs experience lower SINR against MUE because PeNBs transmit with low power but receive strong interference from macrocell tier. Fig. 3 reveals that most of PUEs are limited by interference from MeNBs. The proposed scheme is designed to protect 5%-ile strongly interfered UEs. According to this, Γ_{low}^{SINR}, Γ_{high}^{SINR}, $\Gamma_{R_I}^{macro}$ and $\Gamma_{R_I}^{pico}$ are set to be 0dB, 15dB, -25dB and -2dB, respectively.

The average throughput per site and the 5%-ile UEs' throughput are depicted by Fig. 4 and Fig. 5, respectively. These throughputs are compared with that of full-reuse scheme (FRS) and non-reuse scheme (NRS). Full-reuse scheme uses all the 50 RBs of the 10MHz system band and non-reuse scheme

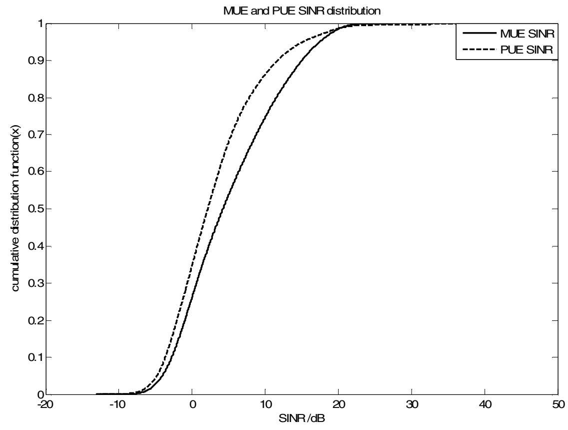

Figure 2. UEs' SINR cumulative distribution function

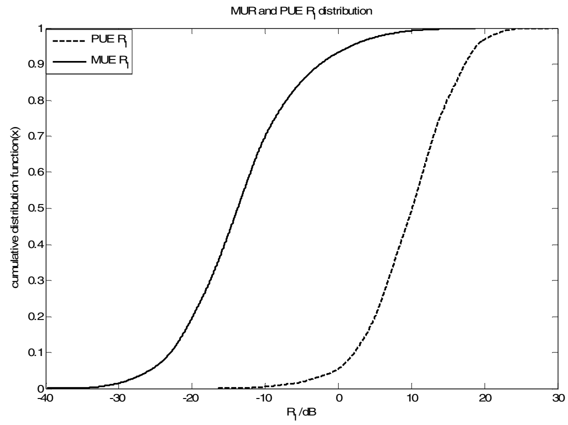

Figure 3. UEs' interference ratio cumulative distribution function

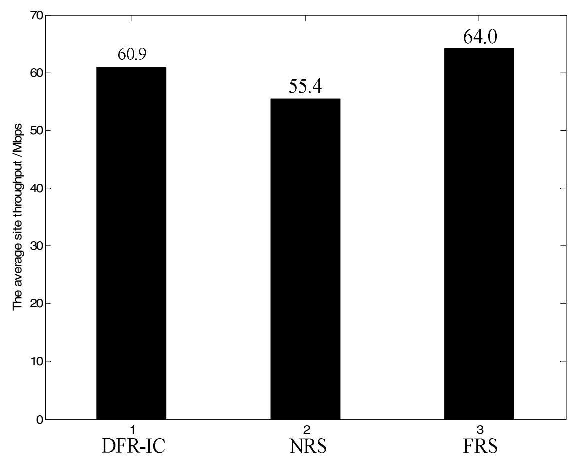

Figure 4. The average throughput per site

of the frequency bands (25 RBs per half) to macrocell tier and picocell tier, respectively. Fig. 4 shows that although a part of RBs of the two tiers are reserved to avoid cross-tier interference, the average site throughput of DFR-IC only slightly degrades thanks to the obtained interference avoid gain. On the other hand, the 5%-ile UEs' throughput is greatly improved from 83.9 kbps to 111.5 kbps, approaching 32% enhancement. Although the non-reuse scheme eliminates cross-tier interference but provides only 61.2 *kbps* of the 5%-ile UE throughput since the available RBs are few in each tier. Moreover, the non-reuse scheme experiences 13% average site throughput loss as the effect of high reuse factor. The proposed scheme efficiently uses the RBs and enhances the cell edge UEs' throughputs.

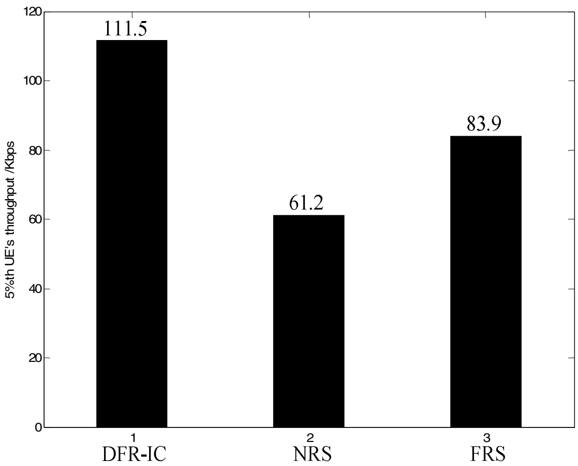

Figure 5. The 5%-ile UEs' throughput

Fig. 6 denotes the UEs' SINR CDF curves of all the three mentioned schemes. It can be seen that non-reuse scheme promotes the UEs' SINR greatly at the cost of reducing usable RBs. However, since DFR-IC only reserves a small part of RBs for the interference limited or low SINR UEs, it results in comparable SINR distributions as the full-reuse scheme. Fig. 4 and Fig. 6 show that the non-reuse scheme achieves the lowest system throughput although its SINR distribution is higher than the other two. The reason is that DFR-IC obtains a reuse factor larger smaller than non-reuse scheme and enhanced the cell edge users SINR. The interference avoidance gain is obtained by scheduling the identified UEs on reserved RBs. Therefore, the overall system throughput is determined by both frequency reuse scheme and UEs' SINR distribution.

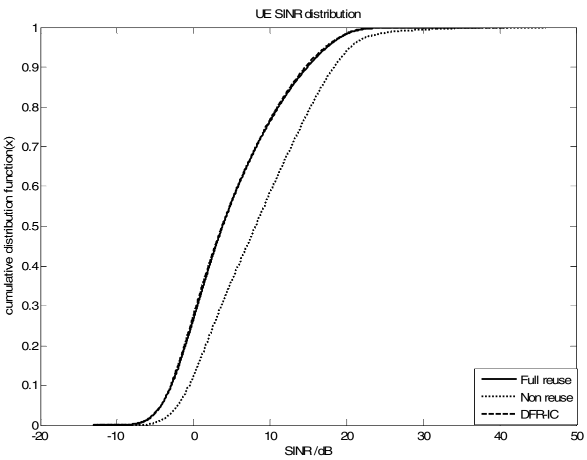

Figure 6. The UEs' SINR CDF in Full reuse, Non-reuse and DFR-IC

VI. CONCLUSIONS

In this paper, a novel DFR-IC scheme in LTE-A heterogeneous networks is proposed. Two factors, namely R_I^{macro} and R_I^{pico}, are employed to evaluate the cross-tier interference of MUEs and PUEs, respectively. Based on UEs' SINR, R_I^{macro} and R_I^{pico}, DFR-IC identifies low SINR UEs and interference limited UEs, then partitions the total RB set into three distinct RB sub-sets according to the proportion of the identified UEs. The macrocells and picocells partially reuse the RB sets to avoid cross-tier interference. Simulation results prove that DFR-IC sacrifices little site throughput but greatly enhances the cell edge users' performance. It compensates the spectral efficiency lost due to partial frequency reuse by interference avoidance gain. The overall system throughput is affected by both the frequency reuse schemes between the two tiers and the SINR distributions of the UEs.

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