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A two-timescale graph-based resource allocation scheme combing dynamic eICIC in Heterogeneous Networks

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ABSTRACT

Heterogeneous Network (HetNet) has been viewed as an effective way to meet the tremendous growth of mobile traffic, in which the cross-tier and co-tier interference are the key limitations. Most of the traditional interference management strategies only focus on addressing either cross-tier interference or co-tier interference. We in this paper propose a resource allocation scheme to systematically cope with both of them in Orthogonal Frequency Division Multiple Access (OFDMA)-based HetNets. Specifically, the proposed scheme combines the dynamic enhanced inter-cell interference coordination (eICIC) and orthogonal resource allocation (ORA), to eliminate the cross-tier and co-tier interference respectively. Furthermore, with tracking the real-time variations of the user information (e.g., locations or service requirements), the proposed scheme is separated into two timescales. At the large timescale, a centralized strategy is performed to roughly allocate resource blocks (RBs) to cells; at the small timescale, a distributed strategy is performed to further schedule RBs among users. Also, we formulate two optimization problems to maximize the minimum of users' throughput satisfaction rate (TSR) for our proposed scheme, followed by two graph-based algorithms to solve them with low complexity. Simulation results manifest the superiority of our proposed scheme in guaranteeing the fairness of users' TSR.

1. Introduction

The flourish development of smart phones and tablets has resulted in a sudden surge of traffic load to be served by existing cellular wireless networks [1]. In this regard, small cell networks, served by low-cost low-power small base stations (SBSs), are foreseen as a key solution to accommodate the tremendously growing data tsunami. The intensive deployment of small cells can improve the spectral efficiency, as well as ease the data burden of the macrocells [2,3]. In addition, small cells can also provide power and battery saving due to the short transmit–receive distance. The multi-tier networks where small cells are overlaid on macrocells are generally referred to as heterogeneous networks (HetNets). Unfortunately, the unplanned and self-organized attributes of small cells inevitably induce the HetNets to be exposed to severe interference [4–8].

Generally, interference issues in HetNets could be divided into two categories: *cross-tier interference* (interference between macrocells and small cells) and *co-tier interference* (interference among small cells), according to the 3rd Generation Partnership Project (3GPP) Technical Report [9]. Taken the downlink of the HeNet in Fig. 1 as an instance, the macrocell user (MUE) m3 is hampered by cross-tier interference from adjacent small cells B and C, while the small cell user (SUE) b1 is hampered by cross-tier interference from macrocell as well as co-tier interference from small cells A and C.

Almost blank subframe (ABS) is an appealing solution to cope with the cross-tier interference in HetNets [10–14]. As a time domain technique proposed in enhanced inter-cell interference coordination (eICIC) framework, ABS could avoid interference through muting several subframes for the transmission of victim users. Different ratios of ABS were recommended in [10], e.g., 1/4 (i.e., one ABS in every four subframes) or 3/8 (i.e., three constant ABSs in every eight subframes). Specifically, the performance of HetNets with various ABS ratios and cell range extension bias was assessed in [11]. Moreover, in [12], a distributed method named DP was proposed to determined whether a user was a victim user or not. Then based on the ratio of victim users, a network-wide utility maximization problem was formulated to optimize the configuration of ABS. Nevertheless, the approach presented in [12] as well as those in [10,11] apply only for static scenarios, which could not adapt to the dynamically-changing *user information* (e.g., locations or service requirements). Then, authors in [13] suggested two dynamic eICIC schemes, i.e., Sum-rate ABS Adaptation and Product-rate ABS Adaptation to maximize the sum-rate and product-rate

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utilities. By adapting ABS in response to the dynamic variations of network load, the two utilities of the HetNets could be continuously optimized. To further facilitate the interfere control in HetNets, a generation of ABS termed almost blank resource block (ABRB) was proposed in [14], which could be scheduled over both time and frequency domain. Despite empowering a more fine-grained resource allocation, the excessively complicated interference management faded the attractivity of this approach.

More specifically, orthogonal resource allocation (ORA) is the emblematical approach to address co-tier interference [15–19]. In [15,16], a joint resource allocation and admission control problem was formulated to provide quality of service (QoS) guarantees for high-priority users while maximize the throughput of best-effort users. However, the complexity of the proposed algorithm would grow at exponential rate with the increase of the population of users or the number of resource blocks (RBs). Furthermore, several low-complexity graph-based resource allocation schemes were investigated in [17–19]. The basic principle behind these approaches is to chordalize the given conflict graph, and then employ the property of chordal graph to allocate the subchannels. However, the over-regulation of aggregate interference in [17,18] may lead to performance degradation. In addition, a algorithm named SMALL CIR with interference restricted was suggested in [19]. The synthetical considerations of the aggregate of interference as well as asymmetry of interference further enhance the performance of [17,18]. Nevertheless, as with [10–12], all the approaches in [15–19] are practicable only for static networks scenarios where the user information remain unchanged.

It should be noted that, most of the traditional interference management strategies only focus on addressing either cross-tier interference or co-tier interference. Besides, except for [13,14], all the schemes presented are static schemes that could not track the real-time variations of user information. To the best of our knowledge, the most effective way to track the dynamically-changing user information is to empower the granularity of resource allocation epoch finer. However, the finer the granularity of that epoch, the higher overhead in control signaling would incur. To this end, a two-timescale graph-based resource allocation strategy for an Orthogonal Frequency Division Multiple Access (OFDMA)-based HetNet is proposed in this paper. The distinct features of this paper are as follows:

- To enable the mitigation of both the cross-tier and co-tier interference, the resource allocation scheme combining dynamic eICIC and ORA techniques is proposed in this paper. Particularly, by carrying out dynamic eICIC, we firstly divide the RBs in the system into two types: ABRB and regular RB (RRB). The former ones are dedicatedly occupied by the SUEs while the latter ones are assigned to MUEs, so that the cross-tier interference can be eliminated. Then, ORA is employed to alleviate the co-tier interference caused by the reuse of ABRBs.
- To guarantee a stable system performance, we track the real-time variations of the user information via separating our proposed resource allocation scheme into two timescales. A centralized strategy is performed at the large timescale, with which the Central Controller (CC) roughly assigns orthogonal RBs to each cell; at the small timescale, a distributed strategy is performed, with which the base station (BS) of each cell independently schedules the RBs among the associated users in a more sophisticated manner.
- Two optimization problems are formulated for our proposed scheme to maximize the minimum of users' throughput satisfaction rate (TSR), respectively corresponding to the large and small timescales. And we propose two graph-based algorithms with polynomial computational complexity to solve the formulated problems. At the large timescale, Exhaustive Search based Resource Allocation (ESRA) algorithm with two sub-algorithms is introduced for the CC; while at the small timescale, Distributed Resource Allocation (DRA) algorithm is presented for each BS.

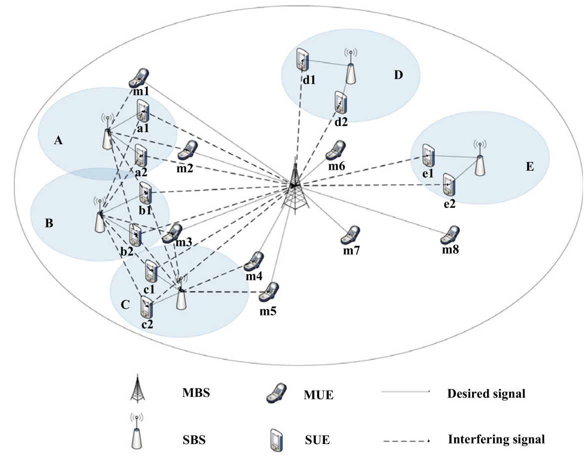

Fig. 1. An illustrative example of a two-tier HeNet.

The rest of this paper is organized as follows. Section 2 introduces the system model and detailedly analyzes the interference avoidance scheme. The resource allocation problems for the CC and BS are formulated respectively in Section 3, with the corresponding graph-based algorithms proposed in Section 4. The complexity of the proposed algorithm is also analyzed. Then extensive numerical results obtained from computer simulations are presented in Section 5, followed by the conclusion of this work in Section 6.

Notations: $\mathbf{A}_{M\times N}$ represents matrix $\mathbf{A}$ with the size of $M \times N$. $\mathbf{0}_{P\times Q}$ stands for $P \times Q$ matrix with all elements being 0. $\lceil a \rceil$ and $\lfloor a \rfloor$ denote rounding up and rounding down to the nearest integer of a, respectively. For set $\mathcal{C}$ and $\mathcal{C}'$, $\mathcal{C}\backslash\mathcal{C}'$ denotes the relative complement of $\mathcal{C}'$ in $\mathcal{C}$, i.e., $\{c : c \in \mathcal{C}, c \notin \mathcal{C}'\}$. $|\mathcal{C}|$ stands for the cardinality of set $\mathcal{C}$. $\mathcal{C}(a : b)$ denotes all the elements between $\mathcal{C}(a)$ and $\mathcal{C}(b)$ in the ordered set $\mathcal{C}$. $\bigcup_{d:d\in\mathcal{D}}\mathcal{C}_d$ represents the union of $\mathcal{C}_d(\forall d \in \mathcal{D})$, i.e., $\{c : c \in \mathcal{C}_d, d \in \mathcal{D}\}$.

2. System model and interference avoidance scheme

In this section, we first describe the system model; then, we analyze the interference avoidance scheme for the OFDMA-based HeNet detailedly.

2.1. System model

A standard downlink of a two-tier HeNet is considered, where OFDMA is applied. Without loss of generality, we assume that the network is comprised of S small cells and a macrocell, with a toy example depicted in Fig. 1 [7,8]. All the small cells and macrocell are integrated into one set $\mathcal{B} = \mathcal{S} \cup \mathcal{M}$, where $\mathcal{S}$ indicates the set of small cells while $\mathcal{M} = \{S + 1\}$ indicates the set of macrocell. There are U users in the network, each of them assigned with one service and attached to only one BS. Specifically, the user set of cell s (small cell/macrocell) is denoted as $\mathcal{U}_s$. RB is the minimum assignable resource unit in this OFDMA system with a total number of K [20]. Let us define the network as follows:

- Small cells and macrocell:
  $\mathcal{B} = \mathcal{S} \cup \mathcal{M} = \{1, \ldots, s, \ldots, S, S + 1\}$,