Time Domain Coordination for Inter-cell Interference Reduction in LTE Hierarchical Cellular Systems

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Abstract— **In this paper, we present an interference-aware slot allocation technique to improve system performance of the hierarchical picocell/macrocell system, where low-power picocells are underlying a high-power macrocell. Although a hierarchical picocell/macrocell system can improve capacity, it also poses a challenging inter-cell interference (ICI) issue. To control the ICI between pico-cells and macro-cells, one enhanced inter-cell interference coordination (eICIC) technique, called almost blank subframes (ABS), was proposed in the 3rd Generation Partnership Project (3GPP) Long-Term Evolution- Advanced (LTE-A) system. Nevertheless, the current ABS mechanism in 3GPP only defines the fixed ABS ratio, which is not very spectrum efficient and can affect the macrocellular system performance. In this paper, we propose an interference-aware ABS ratio adaptation technique to enhance the total spectrum efficiency of the hierarchical picocell/macrocell system. Compared with the current fixed ABS ratio approach, the proposed method can improve the spectral efficiency of pico-cells and macro-cells by 13% and 7% at the cell edge, respectively.**

I. INTRODUCTION

With the increasing number of mobile devices, small cells (including remote radio heads, femto-cells, pico-cells and relay nodes) are playing a key role in capacity improvement, coverage entension, and power saving. This kind of low-power small cells underlying a high-power macrocell is called a heterogeneous network (HetNet) in the third generation partnership project (3GPP) long term evolution advanced (LTE-A) [1]. Further more, inter-cell interference (ICI) mitigation in HetNet has become an important research topic recently. Enhanced inter-cell interference coordination (eICIC) has been proposed in 3GPP to mitigate the ICI between macrocells and picocells, thereby achieving higher data rates [2].

The various eICIC techniques proposed in the literature can be catergorized into two kinds: frequency-domain and time-domain [3]. For the frequency-domain approach, a method of resource partitioning in frequency domain was proposed to resolve the interference between macro-cell and small cells in [4] and [5]. Since macrocells and picocells use different spectrum, resource partition in the frequency domain can effectively mitigate the interference between macrocells and picocells. However, frequency resource-partition approach is not very spectrum efficient. Hence, a time-domain eICIC approach, called the almost blank subframe (ABS), has been proposed to use the same spectrum for macrocells and picocells, while reducing the interference between macrocells and picocells. In ABS time intervals, macrocells transmit only cell-specific reference signals (CRS), primary synchronization signals (PSS), and secondary synchronization signals (SSS) in some subframes, thereby reducing their interference with picocells. To allow more users to be served by small cells, the concept of cell range expansion (CRE) was proposed and the relation between CRE bias and the number of small cells and users was analyzed [6]. In a macrocell/picocell/femtocell coexisting environment, the eICIC techniques with various CRE bias were further investigated subject to the constraint of satisfying users' quality of service (QoS) [7]. Furthermore, the cooperation technique of RRHs, i.e., coordinated multi-point (CoMP) techniques, was suggested to reduce the interference among small cells. It was shown that the performance of CoMP was slightly worse than that of eICIC [8]. The aforementioned techniques were investigated in a static traffic scenario.

In practice, however, traffic loads at pico-cells and macro-cells are very dynamic. Thus the issue arises of whether the fixed ABS ratio is suitable for a HetNet with dynamic traffic patterns. In this paper, we present an interference-aware ABS allocation method to adjust the ABS ratio dynamically to increase the total throughput of picocells and macrocells.

The remainder of this paper is organized as follows. An overview on heterogeneous networks is introduced in Section II. System models are illustrated in Section III. The proposed method of interference-aware ABS method is introduced in Section IV. Numerical and simulation results are shown in Section V, and Section VI concludes this paper.

II. BACKGROUND

Small cells can bring transmitters closer to users, thereby enhancing system capacity, extending coverage, and saving power. Cellular architectures of HetNet in 3GPP consist of macro-cells, micro-cells, pico-cells, femto-cells, and remote radio heads (RRH). To overcome the ICI, the coordinated multi-point (CoMP) transmission technique was proposed in the 3GPP LTE-A. The CoMP technique applies the joint macro-diversity transmission techniques or the network multiple-input multiple-output (MIMO) to deal with the interference between RRH and macrocells. The CoMP transmission techniques required the neighboring cells to be connected together through a high-speed backhaul for exchanging channel state information as well as data, thus increasing the implementation cost.

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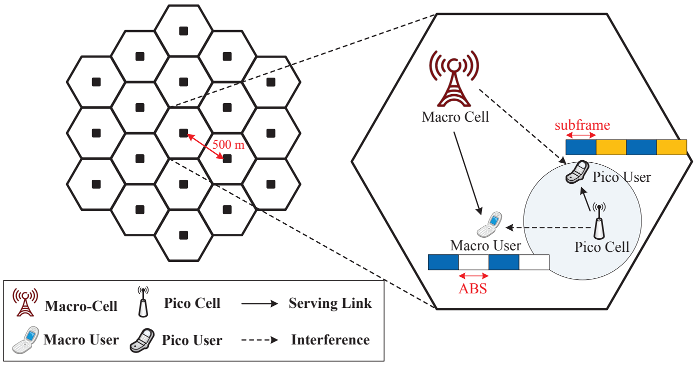

Fig. 1. Heterogeneous networks with ABS allocated and CRE adopted in eICIC time domain

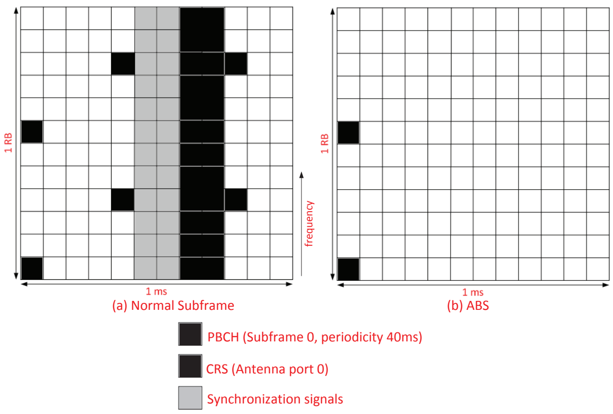

Fig. 2. Normal subframe and Almost Blank Subframe.

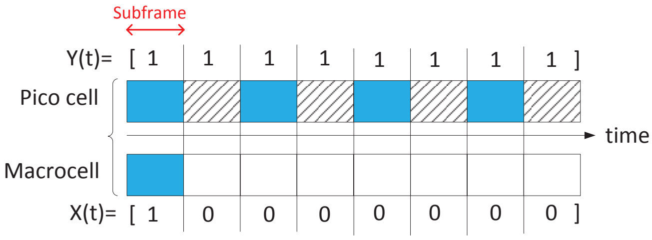

Fig. 3. Example of vectors $\mathbf{x}_t$ and $\mathbf{y}_t$ indicating ABS.

On the other hand, eICIC techniques were proposed to mitigate ICI between a macro-cell and small cells by coordinating transmission between a macrocell and its underlaid picocells in the time domain [2]. The eICIC technique is to allocate *almost blank sub-frames (ABS)* to macrocellular users, which can mitigate its interference to pico-cellular user because only control signals are transmitted and the data portions are silent. The ABS technique in the time domain coordination has been assumed as a baseline solution of eICIC in the 3GPP LTE-A standard. To allow more users to be served by picocells, the concept of *CRE* is implemented to allow more macro-cellular users to be served by the small cells, even though the pilot signal strength from small cells is weaker than the macrocell. In these scenarios, all small cells are deployed with the same frequency band to avoid bandwidth segmentation [9].

III. SYSTEM MODEL

We consider a 19 macro-cell system with an inter-site distance of 500 m, as shown in Fig. 1. Small cells are deployed uniformly within each macro-cell [1] [10].

A. *Almost Blank Subframe*

In order to reduce the interference to the corresponding subframes of the co-channel victim cell users, ABS contains some necessary signals with low power, such as PSS and SSS, the physical broadcast channel (PBCH), CRS and paging channel (PCH) [11]. An ABS is designed as a normal subframe without redundant signalling, as shown in Fig. 2.

In order to allocate ABSs adaptively, vectors $\mathbf{x}_t$ and $\mathbf{y}_t$ are used to indicate whether or not macro-cells and pico-cells are allowed to transmit data in the t-th subframe. Figure 3 shows an example of ABS patterns, where 1 means that the specific subframe can be used in the cell, and 0 otherwise.

B. *ABS Allocation Methods*

The HetNet with ABS allocated in eICIC time domain is illustrated in Fig. 1. The underlying small cells use the same frequency band as the macrocells, resulting in the ICI problem between macrocells and smalls. ABS adopts time resource partitioning method to reduce the ICI to small cells at the cost of throughput degradation of macrocells. As shown in Fig. 1, a macro-cell cannot transmit data in those subframes with white color. This point out the problem of how to determine a suitable ABS ratio to optimize the performance tradeoff between the throughput of picocells and macrocells.

As shown in Fig. 3, a centralized method in 3GPP allocates ABS in the predetermined time slots for different ABS ratios. The centralized ABS allocation method is spectrum inefficient because the ABS slot location offered by a macrocell may not be a good match with the interfered picocell slot location. Thus we propose an interference-aware ABS allocation method to allocate ABS slot locations based on the interference index. In order to align with the uplink round trip time [2], the periodicity for time domain configuration of ABS is 20 msec.

IV. INTERFERENCE-AWARE SLOT ALLOCATION IN EICIC SYSTEM

In order to protect pico-cell users who may suffer severe interference from macro-cells at the cell edge, we develop a dynamic ABS allocation method to improve total throughput of each subframe. Thus we must evaluate how to allocate the ABS in the next time period.

A. *Throughput Maximization*

Assume M_l denotes the number of users in macro-cell, and R_l denotes the number of users in pico-cell. The achievable throughput of macro-cell users and pico-cell users with and without interference in a period t are defined as follows

$\mathbf{I}_t^{Macro} \in \mathbb{C}^{t \times M_l}$: macro-cell users achievable throughput matrices with interference from pico-cells and macro-cells.

$\mathbf{S}_t^{Macro} \in \mathbb{C}^{t \times M_l}$: macro-cell users achievable throughput matrices without interference from macro-cells.

$\mathbf{I}_t^{Pico} \in \mathbb{C}^{t \times R_l}$: pico-cell users achievable throughput matrices with interference from pico-cells and macro-cells.

$\mathbf{S}_t^{Pico} \in \mathbb{C}^{t \times R_l}$: pico-cell users achievable throughput matrices without interference from macro-cells.

Note that $\mathbf{I}_t$ and $\mathbf{S}_t$ are throughput matrices at time period t for macro-cells or pico-cells.

$$\mathbf{I}_t = \log_2(1 + \frac{Signal}{\underbrace{Interference}_{\text{macro and pico}} + Noise}) \tag{1}$$

$$\mathbf{S}_t = \log_2(1 + \frac{Signal}{\underbrace{Interference}_{\text{macro or pico}} + Noise}) \tag{2}$$

With the above definitions, we maximize each subframe by the interference and by designing the allocation of ABSs which could be assigned by vector $\mathbf{x}_t = [x_1 ... x_t]_{1 \times t}$, where $x_t \in \{0, 1\}$. The total throughput of N pico-cells can be written as

$$\mathbf{r}_t^{Pico} = N(\underbrace{\mathbf{y}_t \mathbf{S}_t^{Pico}}_{\text{Achievable transmission rate of a pico-cell}} - \underbrace{\mathbf{x}_t(\mathbf{S}_t^{Pico} - \mathbf{I}_t^{Pico}}_{\text{Interference from macro-cell}})) \tag{3}$$

where $\mathbf{y}_t = [y_1 ... y_t]_{1 \times t}$ and $y_t \in \{0, 1\}$. From (3), the first term is the total throughput of a pico-cell without macro-cell interference, while the second term is the interference from macro-cells.

We formulate the total throughput of macro-cell's as:

$$\mathbf{r}_t^{Macro} = \mathbf{x}_t \mathbf{S}_t^{Macro} - \mathbf{y}_t(\mathbf{S}_t^{Macro} - \mathbf{I}_t^{Macro}) \tag{4}$$

To obtain the total throughput of *all users* in each subframe, we sum up the total throughput of both sides from (3) and (4):

$$r_t = \mathbf{r}_t^{Pico} \mathbf{1}_{R_l \times 1} + \mathbf{r}_t^{Macro} \mathbf{1}_{M_l \times 1} \tag{5}$$

where $(\mathbf{1}_{R_l \times 1})^T = [11...1]_{R_l \times 1}$ and we maximize r_t by designing $\mathbf{x}_t$.

B. Almost Blank Subframe Design

Having a fixed position of time frames causes unnecessary throughput loss. Thus we propose an interference-aware adaptively ABS assignment according to interference index $\mathbf{K}$.

From equation (5), we determine $\mathbf{x}_t$ vector according to $\mathbf{I}_t^{Pico}$, $\mathbf{S}_t^{Pico}$ and $\mathbf{I}_t^{Macro}$ to allocate subframes in the next time period from with achievable throughput with and without interference. The dynamic ABS design procedure is shown in Fig. 4.

First we find the matrices $\mathbf{I}_t$, $\mathbf{S}_t$ and $\mathbf{K}$. Arrange $\mathbf{K}$ in decreasing order and calculate r_t' and r_t''. Here r_t' is the throughput with the ABS pattern of increasing 12.5% blank frames according to $\mathbf{K}$, and r_t'' is the throughput with ABS pattern of decreasing 12.5% blank frames according to $\mathbf{K}$.

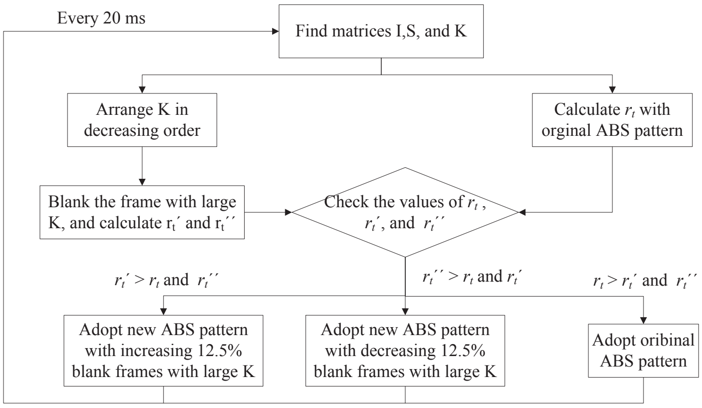

Fig. 4. ABS pattern design procedures

Compare r_t' and r_t'' with the throughput using the original ABS pattern, and then choose the ABS pattern which has the larger throughput. This algorithm repeats every time period every with 20 ms.

V. SIMULATION RESULTS

The simulation setup follows assumptions given in the 3GPP evaluation methodology specification for LTE-Advanced [1]. All simulation parameters are listed in Table I and Table II, which are for macro-cells and pico-cells, respectively.

A. Interference-Aware Slot Allocation

This subsection compares the proposed method with a related work [6], which proposes a fixed 50% ABS allocation method and an 8 dB cell range expansion bias. Figure 5 shows that the proposed method improves cell edge users' spectral efficiency by 15% over the related work when ABS percentage is 25%.

In addition, the proposed distributed and centralized methods can also maintain the mean throughput of users when the spectrum efficiency of cell edge users is enhanced. As shown in Fig. 6, when the ABS percentage at 25%, the spectrum efficiency can reach 2.85 (bps/Hz/user) for the centralized method and 2.83 (bps/Hz/user) for the distributed methods, while the related work only has 2.8 (bps/Hz/user).

We also find that the ABS percentage is highly related to the number of pico-cells deployed. Thus we want to determine what is the best ABS ratio when the number of pico-cells is 12. As shown in Fig. 5, the ABS percentage which provides maximum spectrum efficiency is around 25%.

From the viewpoint of macro-cell users, the spectrum efficiency becomes worse when the ABS percentage is higher, as shown in Fig. 7. Jointly considering the overall system performance, we find that the most appropriate ABS percentage is around 25%, which can achieve highest spectral efficiency of the whole system.

We also consider deploying different numbers of pico-cells. Figure 8 shows that the proposed method improves cell edge users' spectral efficiency by 17% over the related work when ABS percentage is 12.5%. We find that when more pico-cells

TABLE I

Simulation Parameters for macro-cell [1]

Parameter	Value
Link Direction	Downlink
Bandwidth	10 MHz
Macrocell layout	19 Base Stations
Inter-site distance	500 meters
Penetration Loss	Macro: 128.1+37.6*log10(d), d in km
Antenna Pattern	$A_H(\phi) = -\min\left[12(\frac{\phi}{\phi_{3dB}}), A_m\right], \phi_{3dB} = 70^\circ, A_m = 25dB$
Max Tx Power	46 dBm
Noise Power Density	-174 dBm/Hz
Shadowing	8 dB
Minimum Distance between User and Macrocell	35 meters

TABLE II

Simulation Parameters for pico-cell Nodes [1]

Parameter	Value
Pico cell layout	Deterministic at a distance of $\frac{3}{4}$ Macrocell radius from the macrocell center
Number of picos per cell	3, 6, 12
Pathloss Model	Pico: 147.7+36.7*log10(d), d in km
Antenna Pattern	Pico: Omni-antennas
Max Tx Power	30 dBm
User Speed	3 km/hr
Bias of Pico Cell Range	8 dB
Shadowing	10 dB

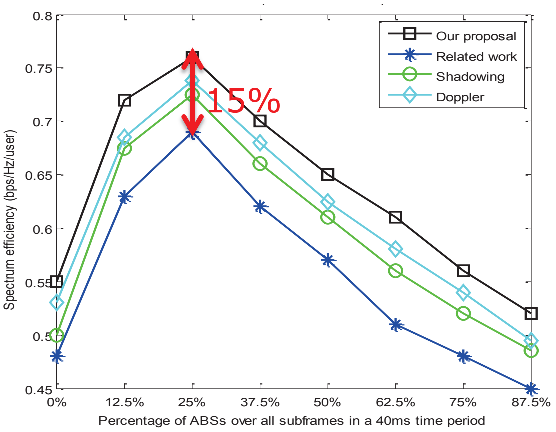

Fig. 5. Comparison of our method and related work for cell edge users' spectral efficiency, where there are 12 pico-cells.

are deployed, a lower ABS percentage is needed to enhance spectrum efficiency. We can also conclude from Fig. 5 and Fig. 8 that when more pico-cells are deployed, the spectrum efficiency of cell edge users is higher.

B. Fairness of Our Method and Related Work

With Jain's fairness index [12], the proposed methods increase fairness compared with the related work [6]. Figure 9 shows the fairness comparisons of our methods, including distributed and centralized method, and related work. From Fig. 9, the fairness indexes are the same at 0% ABS percentage, because there is no ABS techniques adopted there. The fairness indexes reach a maximum at 25% ABS percentage, which is around 0.8, and then decline. Our methods can provide additional 5% gain of fairness index compared with

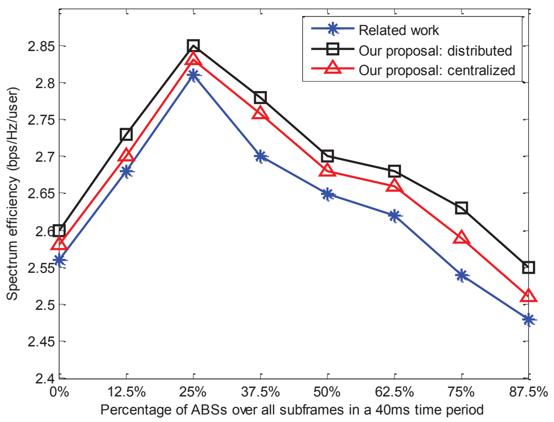

Fig. 6. Comparison of the mean spectral efficiency of our method and related work, where there are 12 pico-cells.

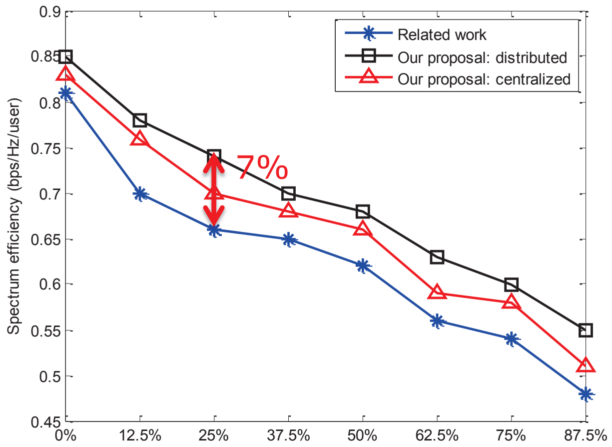

Fig. 7. Comparison of our method and related work for macro-cell users' spectral efficiency, where there are 12 pico-cells.

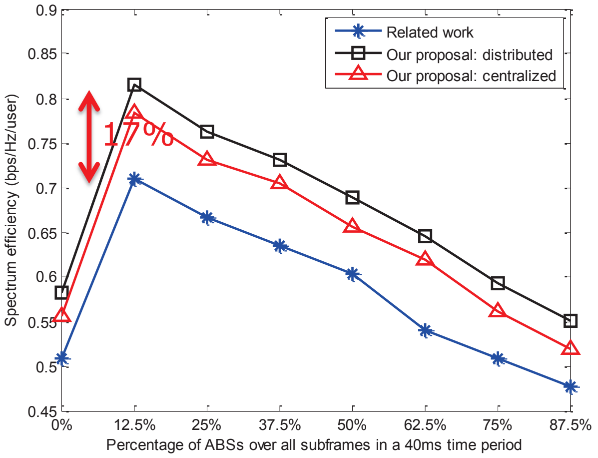

Fig. 8. Comparison of our method and related work for cell edge users' spectral efficiency, where there are 24 pico-cells.

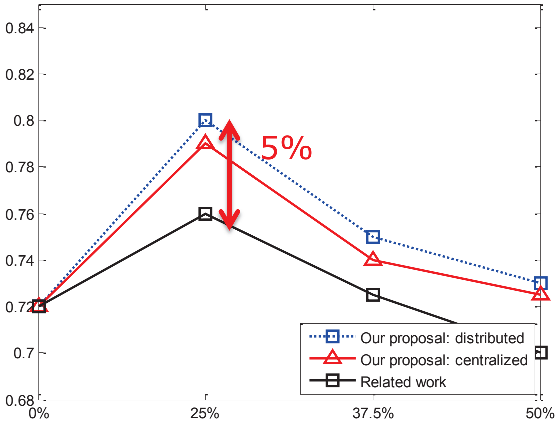

Fig. 9. Fairness index of our method and related work for cell edge users, where there are 12 pico-cells.

the related work. This phenomenon corresponds to the results stated before at Fig. 5, in which the maximum is located at 25% ABS percentage. Hence, we can conclude that the proposed method can improve both spectrum efficiency and fairness of users.

VI. CONCLUSIONS

In this paper, we present two interference-aware slot allocation methods in eICIC time domain cooperation, which are distributed and centralized methods for ABS times slots allocation. We find that the spectrum efficiency decreases if the ABS percentage has been determined faulty. In contrast to the original method of fixed ABS patterns and ABS percentage, we propose a methodology to dynamically reallocate ABS subframes based on the interference index in order to improve the spectral efficiency of each time frame. The numerical results show that the proposed dynamic ABS ratio can enhance spectral efficiency when macro-cells and pico-cells share the same frequency band. The proposed method can also guarantee the spectral efficiency of macro-cell users without sacrificing too much performance in order to compensate the pico-cell's users. Compared with the current fixed ratio ABS design approach, the proposed method can improve users' spectral efficiency of pico-cells and macro-cells by 13% and 7% at the cell edge, respectively.

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