國 立 交 通 大 學

電信工程研究所

碩 士 論 文

毫微微蜂巢網路中基於賽局理論之干擾避免分散式動態頻譜接取

Game Theoretic Distributed Dynamic Spectrum Access with Interference Avoidance in Femtocell Networks

研 究 生：蔣沐恩 Student: Muh-En Chiang

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碩士論文

A Thesis
Submitted to Institute of Communications Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in
Communications Engineering

July 2013

Hsinchu, Taiwan, Republic of China

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摘要

為了滿足在毫微微蜂巢網路中(femtocell networks)對於分散式頻譜存取的重要要求，吾人利用了貝氏賽局理論(Bayesian game)，引入如通道特性或策略空間的先驗知識(prior knowledge)，提出了一個全新的分散式頻譜存取法。為了進一步提升頻譜的使用效率，吾人在分散式頻譜存取法中加入了分組步驟來提升系統效能，並基於一些自我組織（self-organizing）技術來實現動態部分頻率重複使用，以避免蜂巢內及蜂巢間干擾。吾人所提出的方法可以使用最少的改變，加入現有長期演進系統(Long Term Evolution; LTE)協定的架構中。根據電腦模擬結果，吾人所提出的方式可適用於頻譜存取，並擁有較低的複雜度以及傳輸耗消。與中央式頻譜存取相比，吾人所提出的方法可以達到幾乎相同的效能，並超越原有貝氏賽局理論的效能。

Game Theoretic Distributed Dynamic Spectrum Access with Interference Avoidance in Femtocell Networks

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Abstract

To meet the vital distributed spectrum access requirement of femtocell networks, we propose a new decentralized spectrum access scheme, which exploits the Bayesian game, where prior knowledge like characteristics of channel and strategy space are included. In order to further improve spectrum efficiency, we incorporate a group procedure to improve performance and to avoid intra-cell interference. To deal with critical inter-cell interference in femtocell networks, we further exploit some self-organizing (SON) techniques to implement dynamic fractional frequency reuse. Our proposed scheme can be applied to the existing LTE protocol structure with the minimum change. Computer simulations are presented to verify that the proposed scheme is effective for spectrum access with much lower complexity and transmit overhead. The proposed scheme is comparable to the performance of the centralized scheme and outperforms the Bayesian game scheme.

Acknowledgement

First, I would like to convey my sincere gratitude to my advisor, Dr. Ta-Sung Lee, whose manner of dealing with people and situations inspires me tremendously. I also want to thank my senior Wei-Sheng Lai and Chung-Jung Huang whose knowledge and experience have benefited me in my research. Moreover, I offer my regards and blessings to all members in the Communication System Design and Signal Processing (CSDSP) Lab who supported me in any respect during the completion of the work. Lastly, I would like to show my sincere thanks to my parents for their patience.

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Acronym Glossary

3GPP	Third Generation Partnership Project
AWGN	additive white Gaussian noise
CSI	channel state information
eNodeB	evolved node B
FAP	femtocell access point
FFR	fractional frequency reuse
FUE	femtocell user equipment
IA	interference avoidance
ICIC	inter-cell interference coordination
IEEE	Institute of Electrical and Electronics Engineers
LTE	Long Term Evolution
MBS	macrocell base station
MCS	modulation and coding scheme
MUE	macrocell user equipment
OFDMA	orthogonal frequency division multiple access
PRACH	physical random access channel
PU	primary user
QoS	quality of service
RB	resource block
RRC	radio resource connection
RRSP	received reference signal power
SA	spectrum access
SNR	signal-to-noise ratio
SINR	signal-to-interference-and-noise ratio
SON	self-organizing network
SU	secondary user
UE	user equipment

Notations

Cap_i	capacity for FUE i
D	distance between the FAP and FUE
$e_{i,n}$	cost function of FUE i on RB n
$H_{i,j}$	denotes channel between FAP j and FUE i
$h_{m,p}$	channel effects between PUs and SUs
i	index for FUE
I_j	intra-cell and inter-cell interference from FUEs
j	index for FAP
L_{iw}	penetration losses due to the inner wall between apartments
L_{ow}	penetration losses due to the outer wall of the buildings
N	additive white Gaussian noise
n	index for resource blocks
N_{aRB}	total number of RBs
N_{FAP}	number of FAPs
N_{FUE}	number of FUEs
P	transmit power
$p*$	speculated transmission probability of others by Bayesian prior
$p_{i,n}$	transmission probability of user i on RB n
$pl(d)$	pathloss of distance d
PL	Pathloss in dB
q	number of penetrated walls
R	random variable of Rayleigh fading
$\mathbf{S}_i$	action of FUE i
$\mathbf{S}$	action space of all FUEs
$U_i(\mathbf{S})$	summation of utilities of FUE i on all the RBs
$U_{i,n}$	utility on RB n for user i
y_j	received signal of FAP j

Chapter 1

Introduction

In next-generation wireless communication applications, the increasing demands on spectrum have increased and traditional centralized spectrum utilization is inefficient. A promising technology called femtocell has been proposed by the Long Term Evolution (LTE)/3rd Generation Partnership Project (3GPP) [1]. Femtocells aim to provide a uniform experience and guarantee quality of service (QoS) for indoor mobile users by overlaying femtocells on the existing cellular networks. The motivation behind femtocells is that, despite a large portion of indoor data traffic, their coverage and capacity are relatively poor.

According to [2], a femtocell is defined as a self-organizing, user plug-in, and low cost device, which leads to several constraints such as no coordination center, uncoordinated network planning, and low computation ability. Besides, femtocells connect to each other and the cellular service provider via a wireless internet protocol-based network to serve customers in indoor environments. Therefore, a distributed spectrum access with limited backhaul bandwidth is required for femtocell networks.

The spectrum resource is scarce and limited, and to optimize the spectrum efficiency, the interactions between user equipments must be considered. The game is a theory discussing interactive behaviors, which can model the femtocell network [7]. To minimize the change to LTE, we incorporate the game model into the existing LTE protocol architecture to solve the spectrum access problem fulfilling the distributed requirement. The game we adopted is called incomplete information game or Bayesian game, where prior knowledge like characteristics of channel and strategy space are included. By the knowledge, each player can make the best decision in the distributed sense.

There are several researches focusing on the distributed spectrum access solution provided by the game theory [6]. However, these distributed spectrum access schemes are not feasible, because solutions provides by the game will suffer from the severe inter-user interference. In contrast, the centralized scheme mechanism provides interference-free spectrum utilization.

To improve the spectrum efficiency, LTE-Advanced proposed the deployment of femtocells in local area environments [23]. Inter-cell interference in this scenario degrades the effectiveness of femtocells due to the unplanned deployment of femtocells. The issue called inter-cell interference coordination (ICIC) arises, and there are several research conducted on the issue. The complexity of co-tier and cross-tier ICIC is extremely high. To deal with this problem, some techniques for self-organizing networks are proposed by 3GPP. SON enables femtocells to integrate themselves into the network of operator [19], to learn about their environment (neighboring cells, interference) and change their actions accordingly. SON provides as powerful tools for the interference coordination, and we proposed a multicell spectrum access scheme to exploit the SON techniques for the interference measurement and femtocell priority to avoid excessive interference and to enhance the system performance.

This thesis is organized as follows. Chapter 2 introduces the system and channel models and briefly describes the spectrum access in LTE and also some functionalities adopted in this thesis. A game theoretic spectrum access with intra-cell interference avoidance is presented in Chapter 3. In Chapter 4, the multicell spectrum access with inter-cell interference avoidance is described, and the analyses of computational complexity and transmit overhead are also provided. Finally, Chapter 5 gives the conclusions and future works.

Chapter 2

System Model

In this chapter, we will describe the network architecture and system model for the spectrum access problem. According to [2], a femtocell is defined as a self-organizing, user plug-in, and low cost device, which leads to several constraints such as no coordination center, uncoordinated network planning, and low computation ability. As a result, the intra-cell cooperation between femtocell user equipments (FUEs) and femtocell access point (FAP), and inter-cell cooperations between femtocell access points (FAPs) are totally different from cooperations between macrocell user equipments (MUEs) and macrocell base station (MBS) in the traditional cellular network. In this case, how spectrum resource can be utilized efficiently and feasibly by femtocells needs to be reconsidered.

In the remainder of this chapter, we will introduce the system model for this spectrum access problem. In Section 2.1, the two-tier femtocell network will be discussed. In Section 2.2, we will depict the channel model. In Section 2.3, we will briefly describe spectrum access procedure. A summary of Chapter 2 is given in Section 2.4.

2.1 Two-Tier Femtocell Network

The scenario in **Fig. 2.1** depicts a two-tier femtocell network, where a macrocell system coexists with a number of femtocell systems in an uplink OFDMA network. In order to improve the throughput and quality of service (QoS), these femtocells are deployed in the cell-edge of a macrocell. Femtocell devices are defined as user plug-in devices, and it is very likely that the cell-edge users buy some femtocells from stores and randomly place these femtocell without well-planning. Therefore, in our system model, we assume these femtocells are very close to each other and have some coverage overlapping regions. Besides, because of lack of handover, it may happen that FUEs in the overlapping region are not connected to the nearest FAP.

Referred to the definition of spectrum resource in LTE, the basic frequency resource unit adopted in our environment is called resource block (RB) and each RB is originally occupied and licensed by the macrocell. MUEs acting as primary users (PUs) have higher priority to access these licensed RBs communicating with MBS. In contrast, FUEs acting as the secondary users (SUs) have lower priority to access these RBs to communicate with FAPs, and here these RBs are available to FUEs by spectrum sensing [3] to ensure minimium effect to PUs. This is depicted in **Fig. 2.2** for example,

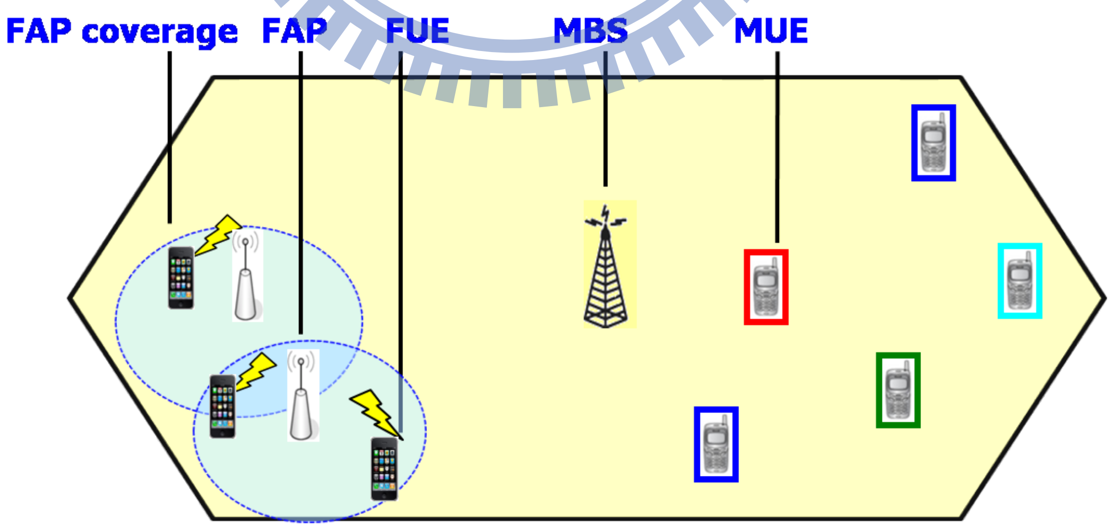

Fig. 2.1 Coexistence of femtocell and macrocell system

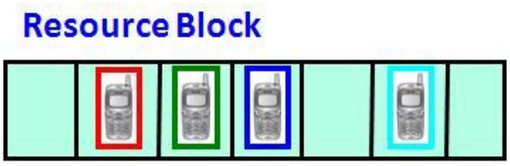

Fig. 2.2 The available RBs by spectrum sensing

where MUEs are depicted as mobile icons and occupy four RBs, and only three RBs left can be used by FUEs.

Unlike in traditional cellular networks the base stations are linked with high speed backbone, in femtocell networks, FAPs are connected by IP-based wireless network to share information. To implement cooperation between FUEs and FAPs, two functionalities are needed for FUEs and FAPs: measurement report and sniffer function.

Measurement report:

(1) FUE: when the connection between an FAP and an FUE is established, each FUE can measure received reference signal strength from the FAP and also from the other FAPs in other femtocells, and then feedback the measurements. FAP can make interference reports, which means the reports of interference to other FAPs by reciprocity.

(2) FAP: when the connections between FAP and FUEs are established, the FAP can measure the signal strength from all FUEs with connection, and sort the measurements as reference.

Sniffer function:

For each femtocell, the FAP will broadcast some information like spectrum sensing information, spectrum utilization information, and interference measurement reports by IP-based wireless network. The sniffer function enables the FAPs to fetch back the information and is for the cooperation between an FAP and its neighboring FAPs.

2.2 Channel Model

For each uplink channel in femtocell j between FAP and FUE i, the received signal is modeled as follows:

$$
\begin{aligned}
y_j &= \sum_{i=1}^{N_{FUE}} H_{j,i} \cdot x_i + I_j + N_0, \\
H_{j,i} &= R \cdot pl\left(d_{j,i}\right)^{-1}, \\
I_j &= \sum_{\forall k,\ k \neq i} H_{j,k} P_k,
\end{aligned}
\tag{1.1}
$$

where N_{FUE} is the number of FUEs in a femtocell, y_j is the received signal of FAP j, x_i is the transmitted signal of FUE i, I_j is intra-cell and inter-cell interference from FUEs, N_0 for additive white Gaussian noise (AWGN), $H_{j,i}$ denotes channel between FAP j and FUE i and consists of two parts: R for random variable of Rayleigh fading and $pl\left(d\right)$ for pathloss of distance d which is suggest by [1] as follows:

(1) Pathloss of FUE to its serving FAP (in dB):

$$PL = 38.46 + 20\log_{10}\left(d\right) + 18.3 + q \times L_{iw} + L_{ow}, \tag{1.2}$$

(2) Pathloss of FUE to other FAPs (in dB):

$$PL = \max\left(38.46 + 20\log_{10}\left(d\right), 15.3 + 37.6\log_{10}\left(d\right)\right) + 18.3 + q \times L_{iw} + L_{ow}, \tag{1.3}$$

where L_{iw} and L_{ow} are the penetration losses due to the inner wall between apartments and the outer wall of the building, and q is the number of penetrated walls, and d is the distance between the FAP and FUE. Here for different RB, the $H_{j,i}$ are uncorrelated, and this results from that the RBs are detected by spectrum sensing and are not consecutive.

2.3 Spectrum Access

In the beginning of LTE spectrum access procedure [4], the user equipments (UEs) need to initialize connection from radio resource control (RRC) idle state by performing the random access procedure. In this case, the UEs need to ask for spectrum resource by transmitting a random access preamble on physical random access channel (PRACH) as depicted in **Fig. 2.3**, and after the base station or eNodeB in LTE collects the requests from the UEs, the base station will decide the spectrum resource allocation for all UEs by sending back random access response messages to the UEs, and the message contains information of modulation and coding scheme (MCS) and RB allocated to UEs. Based on this procedure and RB assignments, the spectrum access can be efficient and has no interference and collisions. As we know, to achieve the optimal spectrum utilization, the eNodeB requires all channel state information (CSI)

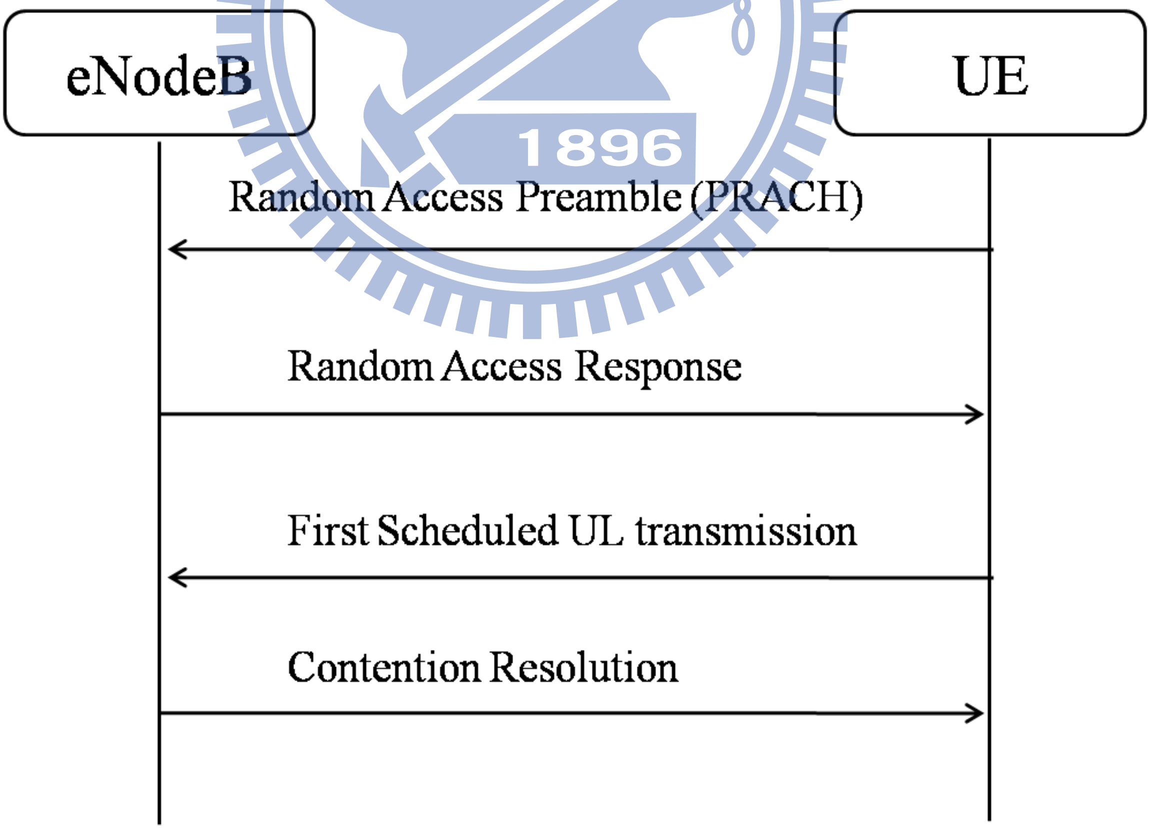

Fig. 2.3 Contention-based random access in LTE

from all UEs and demands a very powerful computation capability, which leads to prolongation of the processing time. Besides, as mentioned above, the available RBs are not consecutive and therefore the channels on the RBs can be seen as uncorrelated, which makes the amount of CSI required grows a lot and hard to exchange. Therefore, for femtocell networks, it is suitable to decide spectrum access in a distributed manner instead of letting coordination center decide for all FUEs, i.e., each FUE decides its own spectrum access based on its own channel status.

However, fully distributed spectrum access is not possible because, the scheduling mechanism provides an interference-free spectrum utilization which is hard to achieve in totally distributed mechanism, and the severe inter-user interference will cause degradation of system throughput. To summarize, the spectrum access problem in femtocell networks becomes a problem of how to develop a mechanism in the distributed way while maintaining the performance of centralized system and low transmission overhead.

In order to focus on the real problem, we divide the spectrum access into two phases as depicted in Fig. 2.4: the allocation phase and the access phase, and we assume the channel to be slow-fading and duration of two phases is less than coherence time. In this thesis, only the allocation phase is considered, that is, after the allocation phase, all the femtocells will maintain the same decision for a while until the channel changes, and newly arriving FUEs will be processed in the next allocation phase in the open access scenario. To simplify our problem, we assume each FUE can access one RB for a time, and each FUE will choose the RB with the best channel response.

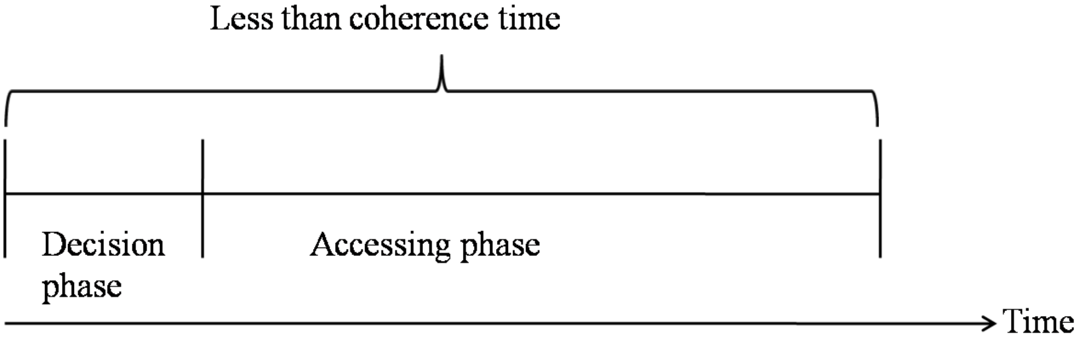

Fig. 2.4 Two phases of spectrum access

2.4 Summary

In this chapter, the network architecture and system model for the two-tier femtocell is introduced, where two functionalities built in the system are also mentioned. The channel model of links between FUEs and FAPs is described, and the spectrum resource unit suggested by LTE is also adopted. We also briefly explain the mechanism of spectrum access in LTE and differences between femtocell networks and traditional macrocell networks which derive some basic constraints for femtocells. Because of these constraints, the spectrum access problem needs a new mechanism or algorithm to achieve high spectrum efficiency in a feasible way.

Chapter 3

Game Theoretic Spectrum Access with Intra-cell Interference Avoidance

In this chapter, we describe the vital requirement for a distributed mechanism. To meet the requirement, we introduce a new spectrum access algorithm for the femtocell networks. In the proposed algorithm, FUEs decide the spectrum access by the Bayesian game. Moreover, a grouping procedure is introduced to reduce the intra-cell interference and to improve the system throughput.

This chapter is organized as follows. In Section 3.1, the motivation of the Bayesian game is presented. Formulation of the Bayesian game is introduced in Section 3.2. In Section 3.3, the proposed algorithm based on the Bayesian game is described. Section 3.4 presents the computer simulation results of the proposed method, and Section 3.5 summarizes this chapter.

3.1 Motivation

What is a game? Modern game theories began with the idea regarding the existence of mixed-strategy equilibrium in a two-person zero-sum game. Nowadays, the game theory becomes the study of a mathematical model of conflicts and cooperations between intelligent rational decision-makers, and the game can be seen as an interactive decision theory. Here the word rational means each decision is made by some reasons or criteria, not made by random, and the word interactive means each decision will influence the decision of other makers, i.e., the game is a theory discussing interactive behaviors. As we can see, it is very similar to communication systems. Because the spectrum resource is scarce and limited, each usage on the resource will affect usages of others, and to optimize the spectrum efficiency, the interactions between users must be considered. As described in Chapter 2, our problem is how to develop a mechanism of spectrum access on the available RBs in a distributed way while maintaining performances in femtocell networks. Therefore, it is rational to model the problem as a game, and to make each FUE play as a decision-maker making decisions based on its criteria. We can say that, game theory fits well and best describes the problem.

There are several researches focusing on using different games as tools solving problems in a distributed manner. However, most of these game theories require strict assumptions or information for the decisions made by others in the game. For example, regret- matching algorithm is a kind of learning algorithms, and its basic idea is, for each decision-maker, to learn about the regret values of all the other actions not taken at every time instant [8]. However, in order to compute these regret values, the channels of all transmissions and interferences are required, which is a strict requirement for a realistic system.

In each game, there must be some information for a rational decision making, or the decision will be made randomly. In 1967, Harsanyi developed the concepts of the Bayesian game interactive decision theory [7], and here the Bayesian game means a kind of incomplete information games. For each decision-making in a Bayesian game, the Bayesian prior knowledge must be included, like characteristics and strategy space. By the knowledge, each player can make the best decision. To summarize, the Bayesian game fits in our spectrum access problem and meets the requirements.

3.2 Game Formulation for Spectrum Access Problem

To describe a game, the following four elements are included:

- **Game**: The spectrum access problem is formulated as a game in the uplink LTE system.
- **Player**: The N_{FUE} FUEs which coexist in the same femtocell are modeled as players to access the N_{aRB} RBs.
- **Actions**: In our system, the transmission probability on all the RBs of each FUE is called an action, and this action is decided by FUE itself based on its channel state information. The action of FUE i denotes $\mathbf{S}_i = \left(p_{i,0}, p_{i,1}, p_{i,2}, \ldots p_{i,N_{aRB}}\right)$, where $p_{i,n}$ is the transmission probability on RB n. Here $p_{i,0}$ is for no transmission and will be omitted in the below discussions, because its corresponding utility value is set to be zero. The action set of all the FUEs denotes $\mathbf{S} = \left(\mathbf{S}_1, \mathbf{S}_2, \ldots \mathbf{S}_{N_{FUE}}\right)$.
- **Utility function**: in order to punish the FUEs who want to use the same RB, we refer to the collision model [5] and set the utility function of FUE i on RB n to be the probability of only FUE i transmitting minus a cost function $e_{i,n}$ as follows:

$$\left(1 - p^*\right)^{N_{aRB}} - e_{i,n}. \tag{2.1}$$

Here p^* is the speculated transmission probability of others by the Bayesian prior [5], and n denotes the index of RB. The reason for this setting is that the throughputs of distributed mechanisms are worse than the throughputs of scheduling mechanisms due to the severe intra-cell interference. The total utility of FUE i is the summation of utilities on all the RBs and shown as follows:

$$\begin{aligned} U_i(\mathbf{S}) &= p_{i,1}U_{i,1} + \ldots + p_{i,N}U_{i,N_{aRB}} \\ &= p_{i,1}\left(\left(1-p^*\right)^{N_{FUE}-1} - e_{i,1}\right) + \ldots + p_{i,N}\left(\left(1-p^*\right)^{N_{FUE}-1} - e_{i,N_{aRB}}\right), \end{aligned} \tag{2.2}$$

where $U_{i,n}$ denotes the utility on RB n for user i, $p_{i,n}$ denotes the transmission probability of user i on RB n, N_{FUE} is the number of FUEs in a femtocell, and $e_{i,n}$ is the cost function of FUE i on RB n. Here the cost function is determined by the channel, i.e., the better the channel, the less the cost will be, and it is set as follows:

$$e_{i,n} = \left(\frac{pl(d_i)}{pl\left(d_{\max}\right)}\right)\frac{1}{R}, \tag{2.3}$$

where $pl(d)$ is the pathloss at distance d, R is the Rayleigh fading channel, and $d_{\max}$ is the distance of the cell coverage of a femtocell. In some conditions, maximizing the utility function is equivalent to maximizing the throughput, and the derivation is shown as follows:

$$\mathbf{S}_i = \left(p_{i,1}, p_{i,2}, \ldots p_{i,N_{aRB}}\right) = \arg \max_{\left(p_1,p_2,\ldots p_{N_{aRB}}\right)} \sum_{n=1}^{N_{aRB}} p_n \cdot U_{i,n}, \tag{2.4}$$

where Equation (3.4) rewrites the action for FUE i, and can be expanded to:

$$\begin{aligned} \mathbf{S}_i &= \arg \max_{\left(p_1,p_2,\ldots p_{N_{aRB}}\right)} \sum_{n=1}^{N_{aRB}} p_n \cdot \left((1-p^*)^{N_{FUE}-1} - \frac{pl\left(d_i\right)}{pl\left(d_{\max}\right)}\frac{1}{R}\right) \\ &= \arg \max_{\left(p_1,p_2,\ldots p_{N_{aRB}}\right)} \left[\left(1-p^*\right)^{N_{FUE}-1} - \sum_{n=1}^{N_{aRB}} p_n \cdot \left(\frac{pl\left(d_i\right)}{pl\left(d_{\max}\right)}\frac{1}{R}\right)\right], \end{aligned} \tag{2.5}$$

where N_{aRB} is the number of available resource blocks, p_n is the variable of transmission probability on RB n, $\left(p_0, p_1, p_2, \dots p_{N_{aRB}}\right) \in [0,1]^{N_{aRB}}$, and $\sum_{n=0}^{N_{aRB}} p_n = 1$.

Because p^* and N_{FUE} are constants and known to FUE i, so Equation (3.5) can be written as follows:

$$\begin{aligned}\mathbf{S}_i &= \arg \min_{\left(p_1, p_2, \dots p_{N_{aRB}}\right)} \sum_{n=1}^{N_{aRB}} p_n \cdot \frac{pl\left(d_i\right)}{R} \\ &= \arg \max_{\left(p_1, p_2, \dots p_{N_{aRB}}\right)} \sum_{n=1}^{N_{aRB}} p_n \cdot \frac{P \cdot pl^{-1}\left(d_i\right) \cdot R}{N_o},\end{aligned} \tag{2.6}$$

where P and N_o denote transmit power and noise power, respectively. The capacity for FUE i is denoted as Cap_i and is expanded as follows:

$$\text{Cap}_i = \sum_{n=1}^{N_{aRB}} p_n \cdot \text{Cap}_{i,n} = \sum_{n=1}^{N_{aRB}} p_n \cdot \frac{P \cdot pl\left(d_i\right)^{-1} \cdot R}{N_0 + \sum_{n=1}^{N_{aRB}} p_n \cdot P_{in}^*}, \tag{2.7}$$

where $\text{Cap}_{i,n}$ is the capacity on RB n of FUE i. Considering the objective function in Equation (3.6) with Equation (3.7), the only difference is the interference term $\sum_{n=1}^{N_{aRB}} p_n \cdot P_{in}^*$. If we can ensure only one spectrum access on each RB, the strategy $\mathbf{S}_i$ in the game will maximize the capacity. How to realize this idea will be addressed in the next section.

As mentioned in Chapter 2, each FUE only accesses a RB. As a result, to maximize the utility, the best choice of $\mathbf{S}_i$ for FUE i must be transmission with probability one on the best channel, and zero for all the other channels, i.e., if channel one is the best, $\mathbf{S}_i = \left(p_{i,1}, p_{i,2}, \dots, p_{i,N_{aRB}}\right) = \left(1, 0, 0, \dots, 0\right)$. Besides, the utility value provided by the channel must be positive. To ensure this, we refer to a strategy called the threshold strategy in [6]. Here the threshold strategy means the threshold for the cost, and we can derive the threshold strategy in Equation (3.2) as follows:

$$\begin{cases} p_{i,n} = 1, & \text{when } \left(1 - p^*\right)^{N_{FUE}-1} > e_{i,n} \text{ and } e_{i,n} = \min_{\forall m} e_{i,m} \\ p_{i,n} = 0, & \text{otherwise} \end{cases} . \quad (2.8)$$

To summarize, the threshold strategy provides the optimal solution for each FUE and the threshold strategy is proved always to provide the Nash Bayesian equilibrium solution [6].

3.3 Proposed Spectrum Access

As mentioned above, there will be severe interferences in a fully distributed mechanism, so the performance in a Bayesian game cannot be comparable to a centralized mechanism. If we can ensure there is only one access on each RB, the action by the Bayesian game is proved to be the action maximizing the capacity. Therefore, we want to incorporate the Bayesian game into the spectrum access procedure in LTE, to coordinate the spectrum access in a decentralized way.

We propose to divide the FUEs into several groups in the spectrum access procedure, and there are less FUEs and less interferences in each group. The group division of FUEs is based on measurements of signal strength of FUEs by measurement functionality mentioned in Chapter 2. The sequence diagram of the proposed procedure based on the architecture of LTE is depicted in **Fig. 3.1**. In the phase one of **Fig. 3.1**, the FUE chooses a random access preamble and transmits it on PRACH. In the next phase, when the FAP receives the preamble, the FAP gives a response which includes a group index for the FUE. In the phase three, the FAP gives group access admittances to the group from the index one in sequence, and in the phase four the FUEs which receive the admittances and can request a RB from the FAP. In the phase five, the original contention resolution phase in LTE is for the FUEs with the same preamble and the same response for resource assignments. Here we propose to add a decision function to the contention resolution phase, i.e., if two or more FUEs want to use the same RB, the FAP will notify the acquisition of the RB to the FUE with the highest signal strength.

Based on the sequence diagram in **Fig. 3.1**, we depict the flowcharts for the FUEs and FAP in **Fig. 3.2** and **Fig. 3.3**, respectively. We add the step two and the step to the original LTE flowchart of the FUEs depicted in **Fig. 3.2**. In the step two, the Bayesian game is introduced to solve the action, and the requests for RBs will be transmitted in the step three. We also add the step one to the step three to the flowchart of the FAP depicted in **Fig. 3.3**. In the step one, FAP is able to measure the signal strength from FUEs and transmit group indices. In the step two, FAP notifies FUEs with admittances for the group spectrum access. In the step three, we enable the contention resolution step with decision function mentioned above. The procedure of the proposed group spectrum for the FAP and the FUEs is shown in **Table 3.1**.

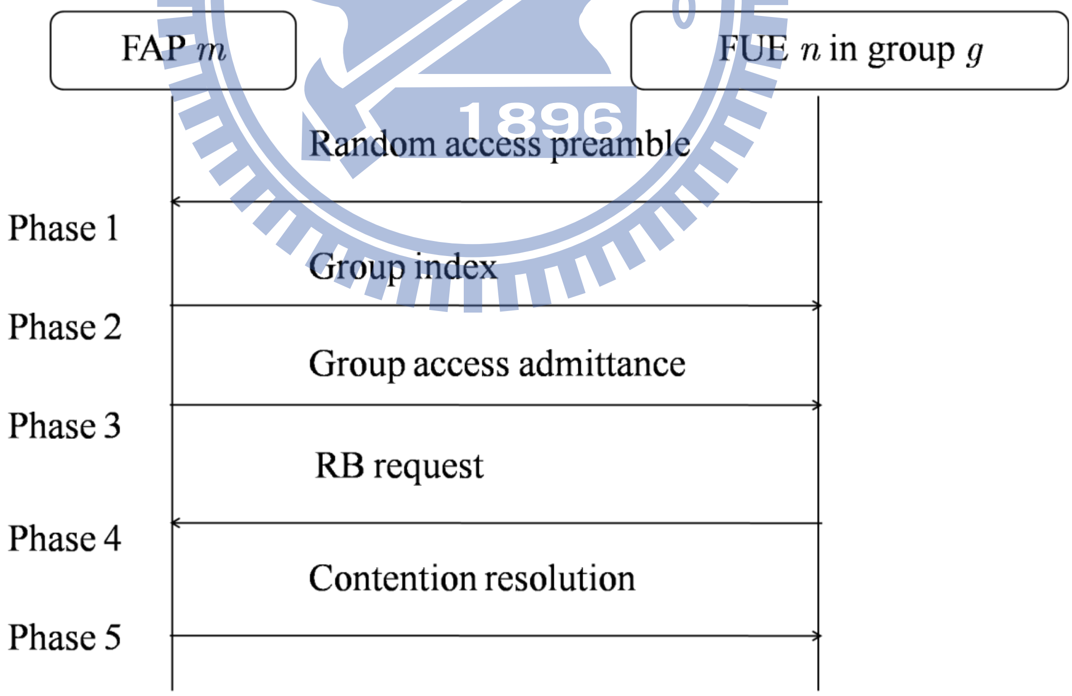

Fig. 3.1 Sequence diagram of proposed spectrum access

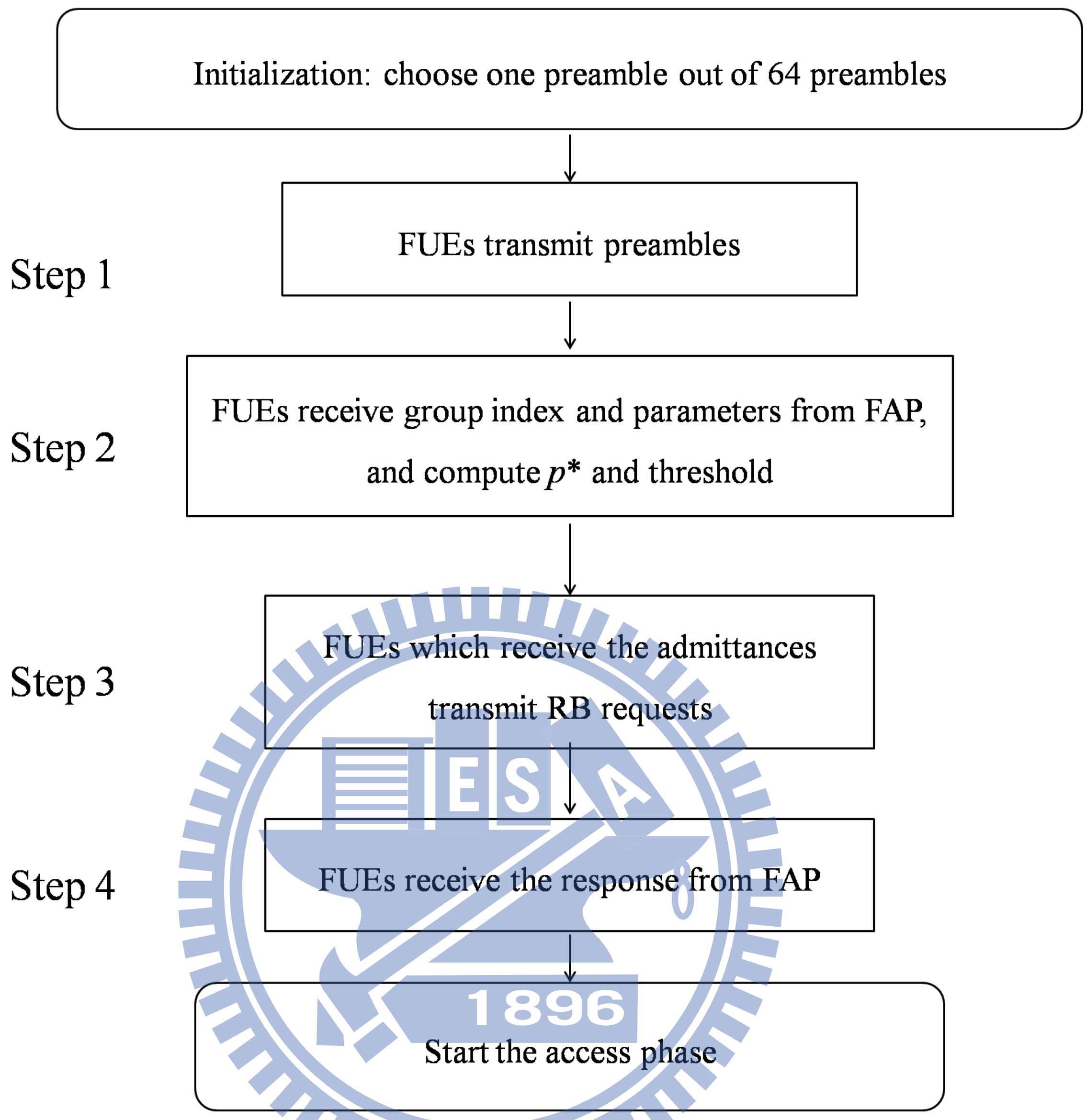

Fig. 3.2 Flowchart of spectrum access by FUEs in a femtocell network

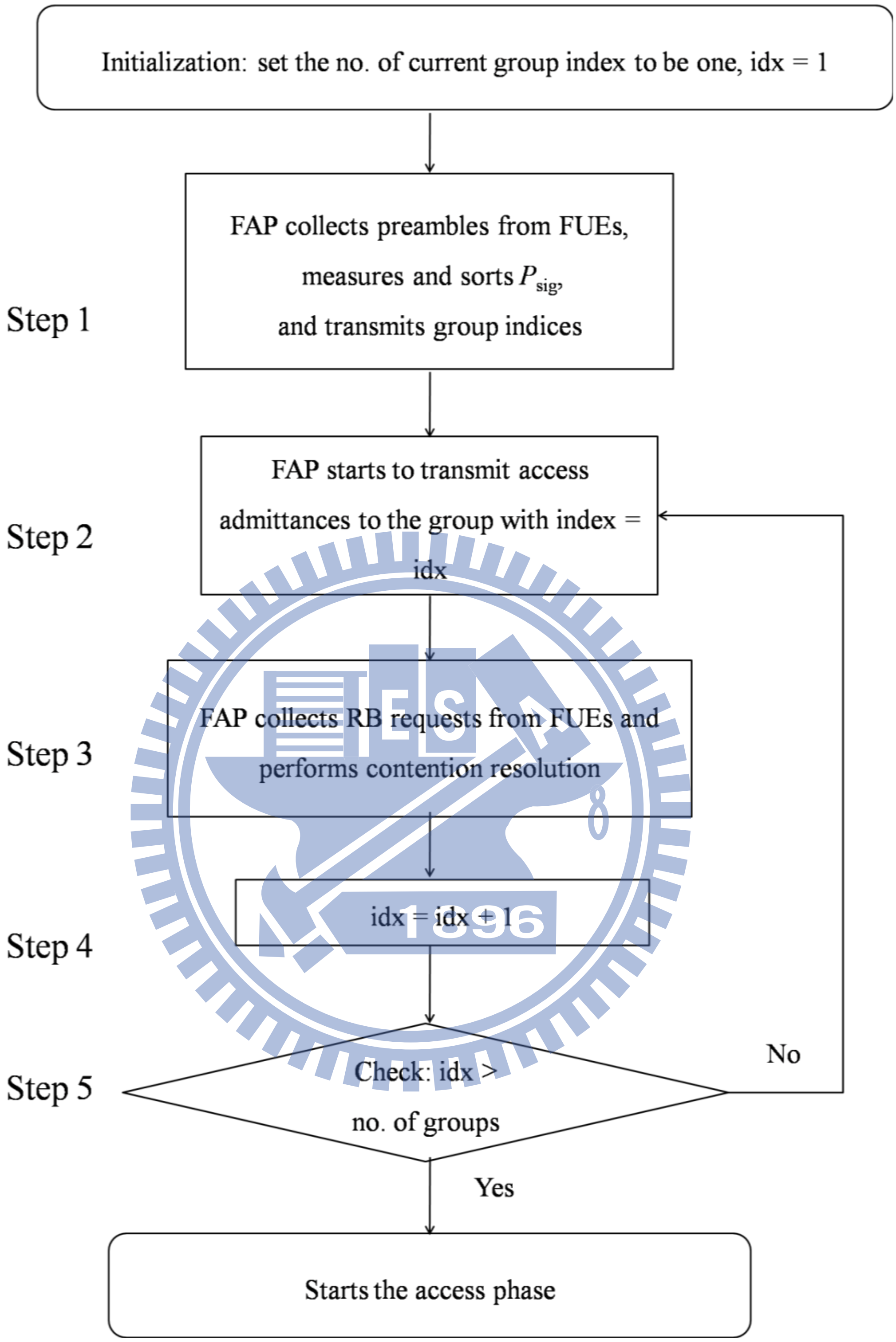

Fig. 3.3 Flowchart of spectrum access by FAP in a femtocell network

Table 3.1 Procedure of the proposed group spectrum access in a femtocell network

Step 1: All FUEs transmit random access preambles to FAP
Step 2: FAP feedbacks group index and system information
Step 3: FAP transmits access admittances
Step 4: FUEs who have admittances start accessing
Step 5: If any two FUEs access the same RB, the FAP starts the contention resolution: the one FUE with the highest priority in group is picked up to access the RB
Step 6: Break the loop if all RBs are used up
Step 7: Go to Step 3 for different groups until all groups have already performed the access of RBs

3.4 Computer Simulations

The simulation environment is shown in **Fig. 3.4** where the simulation parameters are listed in **Table 3.2**. In the environment, there is a femtocell overlaying on a macrocell. In order to verify the proposed method in a densely populated scenario, we adopt the maximum number of supported FUEs, which is mentioned in specifications provided by a femtocell integrated circuits manufacturer in [9]. We increase the number of FUEs scattered in the FAP coverage from four to 32 by four each time. In **Fig. 3.5**, the utility values per RB for the group spectrum access with the Bayesian game for two and four FUEs per group are shown, and both improved obviously from the original Bayesian game and from the lower bound of no coordination. Besides, the proposed group spectrum access also approaches the performance in both small and large number of FUEs obtained in the centralized scheme where the exhaustive search is adopted. The results show the ability of providing simultaneous supports of a larger number of FUEs in the LTE environment. **Fig. 3.6** shows the utility values per FUE, and we can see that if the number of FUEs is larger than two, utility values in the Bayesian game are close to zero. In contrast, the proposed method can still provide positive utility values and be close to the values provided by the centralized scheme.

Table 3.2 Simulation parameters

Parameter	**Value**
FUE transmit power	26 dBm
Path loss model [1]	3GPP TR 36.814 v9
Fading channel	Rayleigh
Resource block bandwidth	180k Hz
The maximum number of FUE [9]	32
The number of available RBs	4
Thermal noise PSD [10]	-174 dBm/Hz

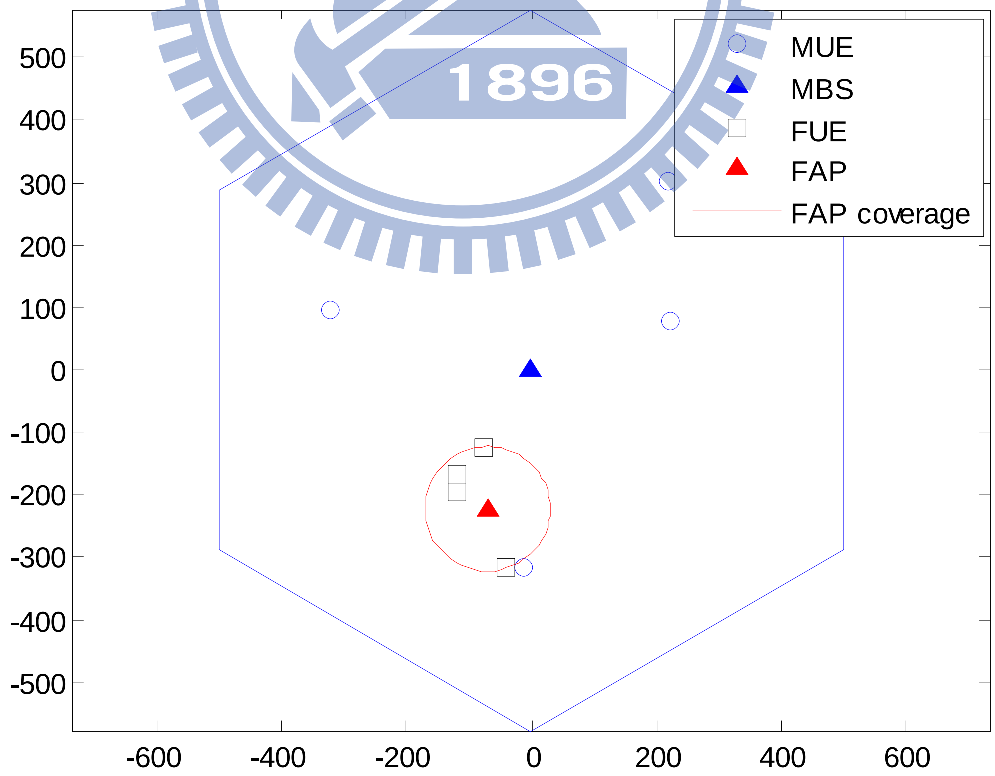

Fig. 3.4 Two-tier femtocell network

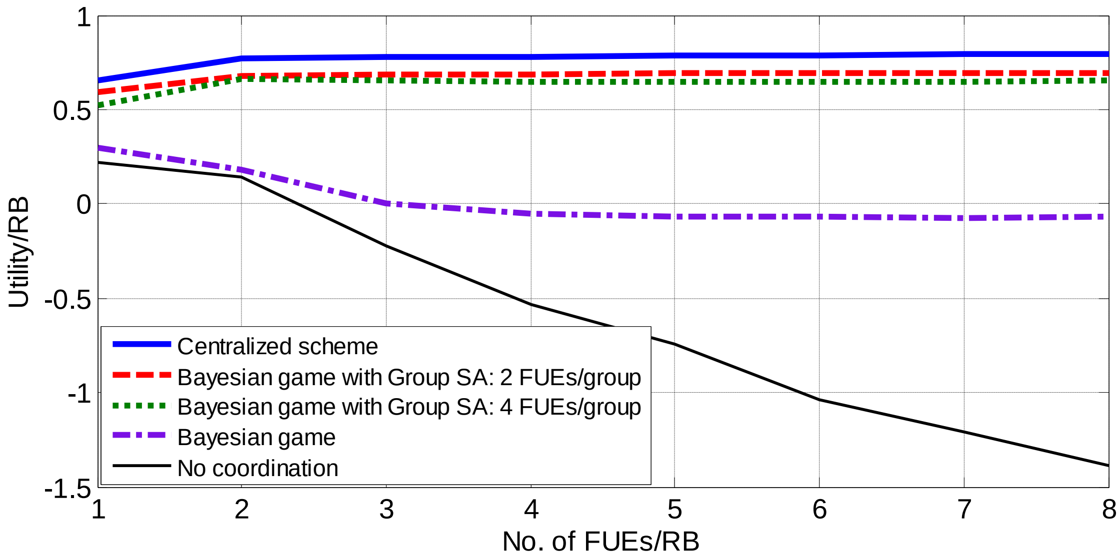

Fig. 3.5 Comparison in utilities per RB between different schemes

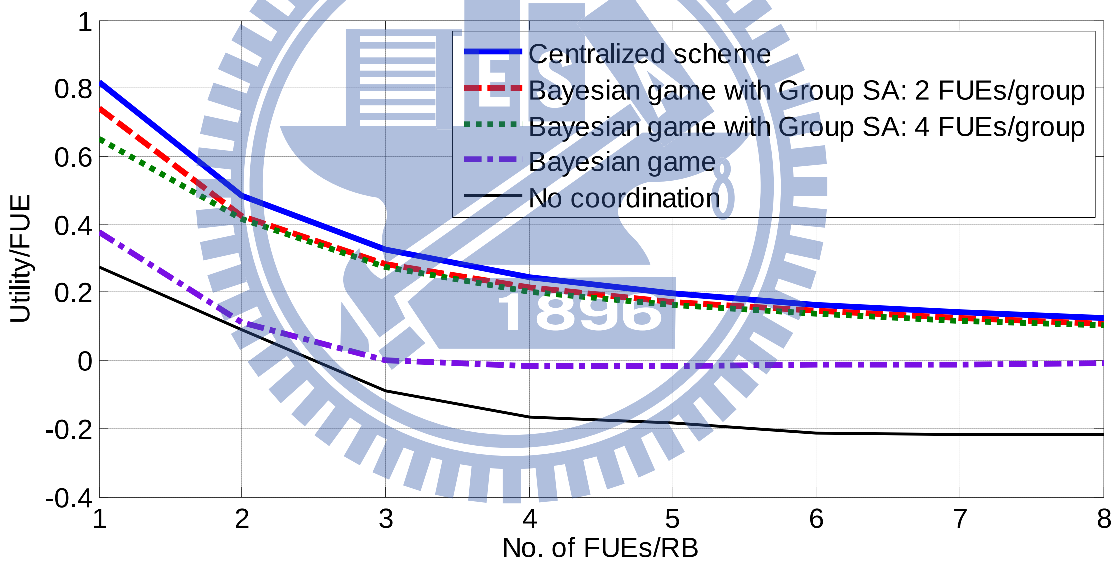

Fig. 3.6 Comparison in utilities per FUE between different schemes

3.5 Summary

In this chapter, we give an introduction of the Bayesian game, and also describe the vital requirement for a distributed mechanism for the spectrum access. To fulfill the requirement, we propose a Bayesian game theoretic spectrum access with intra-cell interference avoidance. The new spectrum access scheme can be adapted to the existing LTE protocol architecture. Compared with the centralized scheme, the proposed scheme improves greatly from the original Bayesian game and exhibits similar utility performances to the centralized scheme.

Chapter 4

Multicell Spectrum Access with Inter-cell Interference Avoidance

In this chapter, we incorporate a multicell interference avoidance scheme into the proposed spectrum access in Chapter 3. In the proposed scheme, we exploit some self-organizing techniques. Based on these techniques, the femtocells can cooperate to avoid excessive inter-cell interference in femtocell networks and the system capacity can be improved.

This chapter is organized as follows. In Section 4.1, the motivation of inter-cell interference avoidance is presented. The proposed scheme is described in Section 4.2. In Section 4.3, complexity and overhead analysis is shown. Section 4.4 presents computer simulation results, and Section 4.5 summarizes this chapter.

4.1 Motivation

To improve the spectrum efficiency, LTE-Advanced proposed the deployment of a large scale cost-effective low-power femtocells in local area environments. Local area environments include indoor office scenarios, or outdoor hotspot scenarios with several low-power FAPs. One of the major challenges for the deployment is the inter-cell interference due to the unplanned deploying of femtocells, which can degrade the effectiveness of femtocells. When both tiers share the whole spectrum, indoor and outdoor user communications are affected by interference from undesignated femtocell and macrocell devices. This problem is more severe when FAPs are randomly deployed by their subscribers. In [20] the authors point out that femto-to-femto interference becomes an important issue for the indoor performance, especially when femtocells are densely deployed. Another challenge for the deployment is, in the femtocell networks, the high speed backhaul cannot be implemented without a direct X2 interface [21]. Therefore, the centralized interference management is not viable due to the heavy information exchange required and intolerable feedback delays.

The optimal configuration will depend on the offered traffic and the location of FUEs, which are likely to be time-variant. Moreover, a subset of the available RBs is enough to guarantee the quality of service (QoS) of a FUE, so a scheme to allocate RBs to serve many FUEs to achieve the optimal spectrum utilization is required. Generally, this spectrum utilization problem in a dynamic multicell multiuser environment is a non-linear, non-convex NP-hard optimization problem [24]. In summary, the centralized spectrum access for the two-tier femtocell networks becomes impractical, and a distributed scheme should be employ for this problem.

In the LTE frequency reuse scenario, co-channel deployment is attractive to operators due to low cost and backward compatibility [21]. In a co-channel deployment, Femtocells are enabled with some cognitive techniques developed to sense their surroundings and change their spectrum access operations to minimize interference to the macrocell. Since femtocells are overlaid within macrocell networks, this cognitive techniques can be exploited to avoid cross-tier interference. After sensing macrocell activities, the utilization of spectral resources is available, and FAPs can exploit unoccupied spectrum. As a result, we only concern the co-tier inter-cell interference issue within femtocell networks.

Some techniques for the self-organizing (SON) network proposed by 3GPP provides some potential solutions. SON enables femtocells to integrate themselves into the network of the operator, learn about their environment (neighboring cells, interference) and change their actions accordingly. Generally, the techniques of SON rely on UE measurements in Releases 8 [24], and support some important SON related objectives, include interference control, coverage optimization, and energy saving management.

4.2 Proposed Multicell Spectrum Access

There are several studies focusing SON techniques for spectrum access, and the SON functionalities adopted in this thesis are the interference measurement report by FUEs, the spectrum utilization reports and broadcasting and sniffing functionalities by FAPs [2]. Borrow the idea from [23], we propose a distributed interference measuring technique. The fundamental principle of the technique is the estimation of potential interference based on downlink received reference signal power (RRSP) strength level measurements performed by FUEs. In the proposed technique, FAPs need to transmit reference signals in the coordinated subframes, which occupy a limited portion of the allocation phase mentioned in Chapter 2. FUEs could learn the potential interference to other femtocells by reciprocity of RRSP, and each FAP gathers the interference information from FUEs. This information gathered by FAP is used in the contention resolution process, allowing each FAP to select the most attractive spectrum access in the view of system capacity. In summary, our scheme relies on the existing UE interference measurement reports and information exchange processes, which means the minimal changes to the standard.

After the procedure of obtaining interference measurement reports, we refer to the dynamic fractional frequency reuse (FFR) [22] and propose an interference avoidance scheme by priorities of femtocell. In LTE-Advanced, OFDMA systems support FFR for interference mitigation and divide frequency and time resources into several resource sets especially in the heterogeneous network with severe interference. The FFR should be dynamic and be adapted to variant traffic based on interference conditions obtained by FAPs. To make the frequency reuse be beneficial, the capacity gain from the increase in SINR must be able to overcome the loss from spectrum. Since the effect of SINR is scaled by a logarithm function, the benefit can only be obtained when the SINR is not too high. A trade-off between bandwidth and SINR is depicted in **Fig. 4.1**. Here FAP a and FUE a are for femtocell a, and FAP b and FUE b are for femtocell b.

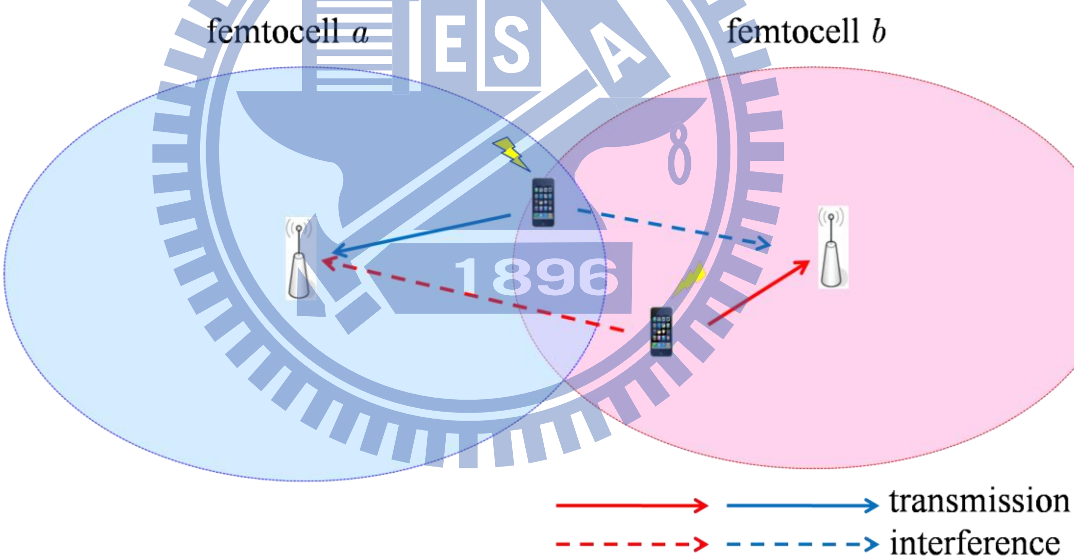

Fig. 4.1 Illustration of two femtocells with asymmetry

As we can see, due to the position of FUE a, the received power of FUE a at FAP a and b are almost equal, and if the SINR for FUE a at FAP a is not too high, the dynamic FFR should apply to avoid excessive interference to femtocell b. The only chance of SINR for FUE a too high is when the interfering FUE is far away, and the chance is asymptotically zero with increase in the number of interfering FUEs. As a result, we examine the potential received interference power to neighboring cells with the received signal power as a threshold for interference avoidance.

The deployment of femtocells might be random and the geometric asymmetry of deployment causes some femtocells have more interference to others. This can be known by the interference measurement reports. To minimize the potential interference in the femtocell networks, it is obvious that the femtocell with the lowest interference to others is given with the highest priority. The priority means the right to access the spectrum, and for a FAP, the higher priority, the more RBs can access. As the result, the interference can be reduced, because less potential interference occurs. Incorporate the spectrum utilization reports, interference measurement reports, and femtocell priorities into the scheme we proposed in Chapter 3, we depict a sequence diagram in **Fig. 4.2**.

The sequence diagram of the proposed procedure is based on the architecture of LTE. We add four phases into the sequence diagram in **Fig. 3.1** in Chapter 3 for the interference reports and spectrum usages reports. In the phase one, FUE chooses a random access preamble and transmits it on PRACH. In the next phase, when FAP receives the preamble, FAP gives a response which includes a group index for the FUE. In the phase three, the FUE measures the received reference signal strength from FAPs and computes the interference reports by reciprocity. In the phase four and five, the FAP broadcasts and sniffs the interference reports from other FAPs. In the next phase, FAP also sniffs the RB usages from the prior FAPs. Based on the sniffed RB usages and the interference reports, the FAP can ensure that the interference from its serving FUEs to other FAPs is not excessive. If all the prior femtocells perform the spectrum access, the FAP will enter the phase seven, which is transmitting group access admittances to the group from the index one in sequence, and in the phase eight the FUEs which receive the admittances can request a RB from the FAP. In the final phase, an interference-checking function is added to the contention resolution phase in **Fig. 4.2**, i.e., if there are excessive interferences to other FAPs, the FAP will check and close the transmission.

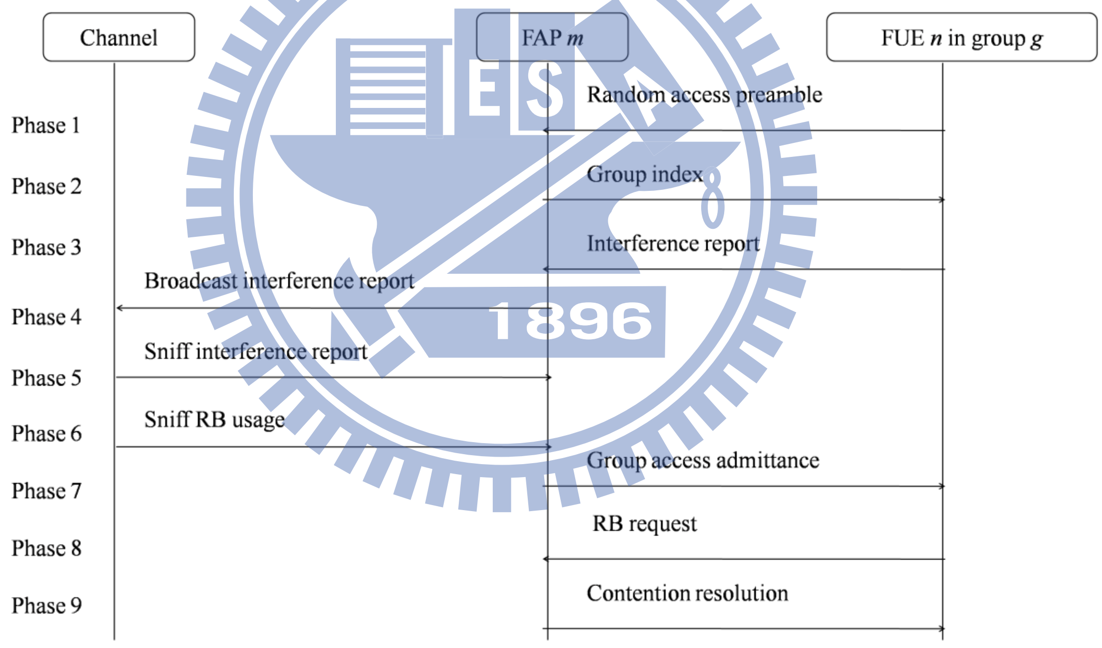

Fig. 4.2 Sequence diagram of proposed multicell spectrum access

Based on the sequence diagram in **Fig. 4.2**, we depict flowcharts of spectrum access by the FUEs and FAP in **Fig. 4.3** and **Fig. 4.4**, respectively. Different from the flowchart of spectrum access in Chapter 3, we install the step three in **Fig. 4.3** for the FUEs. The step three is for the interference reports exchange between the FAP and FUEs. We also install the step two and the step three to the flowchart in **Fig. 4.4**. In the step two, FAP is able to collect and broadcast the interference reports from FUEs. In the step three, FAP collects and sorts the interference reports from other FAPs by the sniffer function. The procedure of the proposed spectrum is shown in **Table 4.1**.

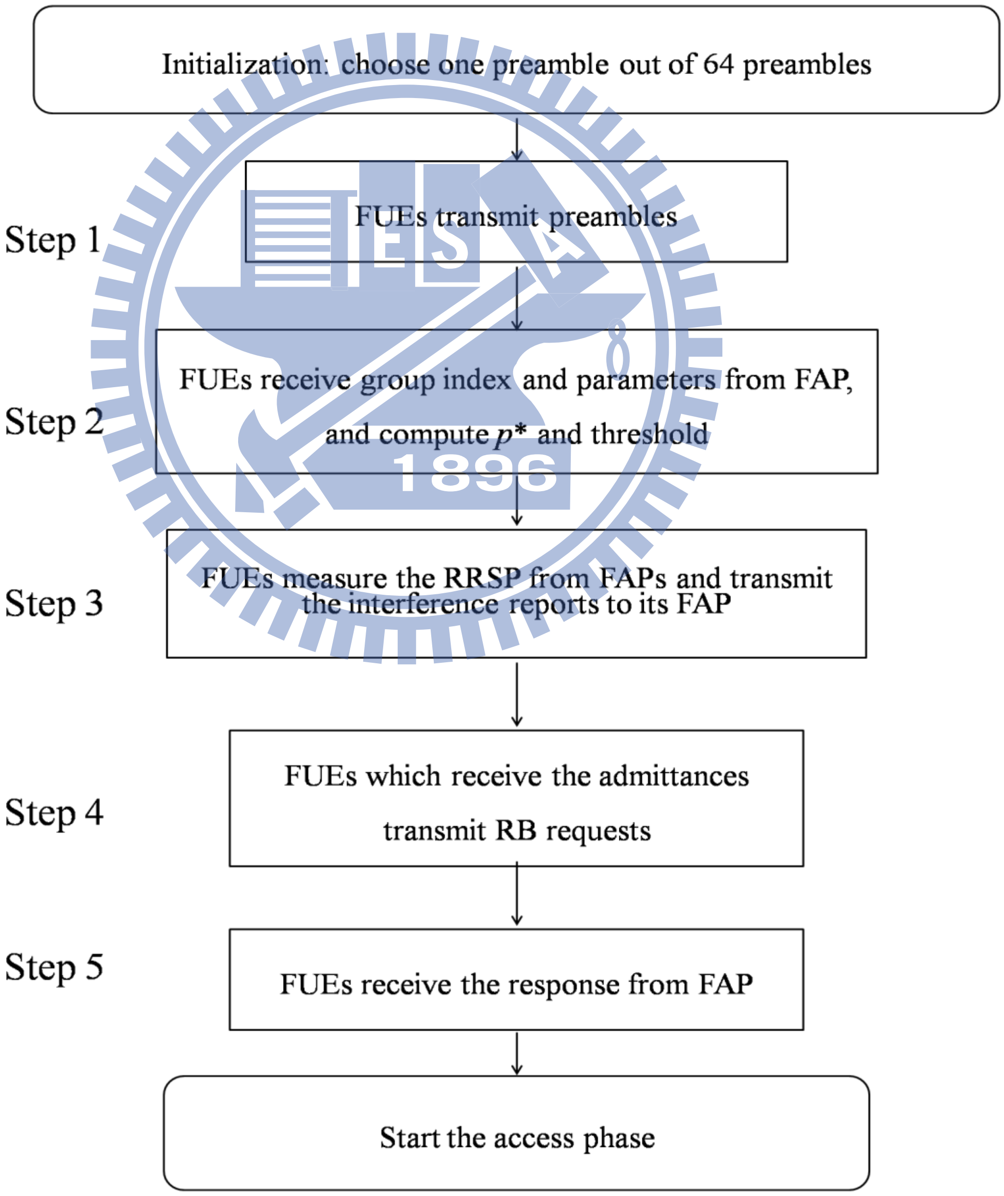

Fig. 4.3 Flowchart of spectrum access by FUEs in femtocell networks

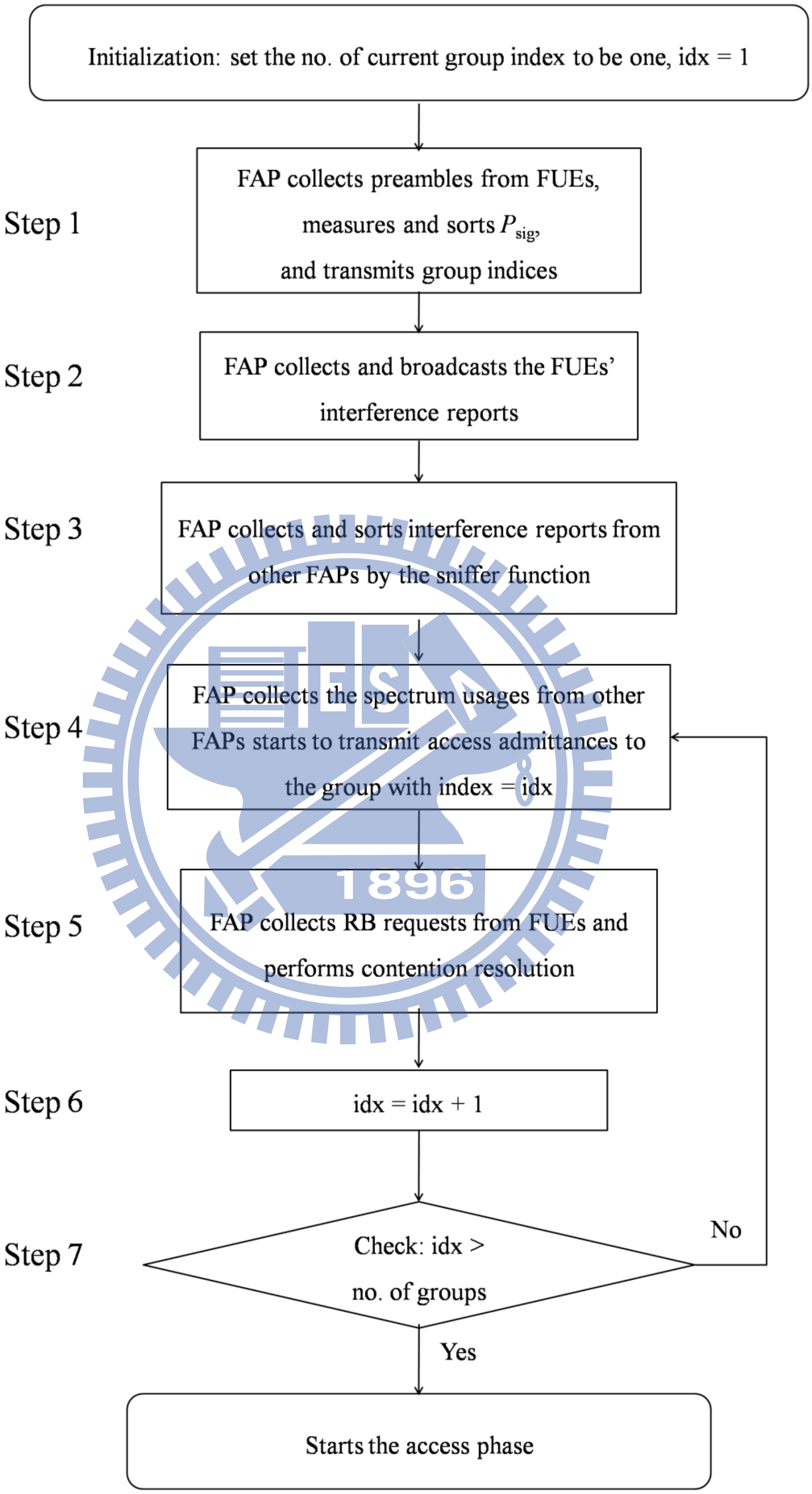

Fig. 4.4 Flowchart of spectrum access by FAP in femtocell networks

Table 4.1 Procedure of the proposed multicell spectrum access in femtocell networks

Step 1: All FUEs transmit random access requests to FAP
Step 2: FAP feedbacks group index
Step 3: FUEs feedback interference reports
Step 4: FAP broadcasts interference reports
Step 5: FAP sniffs interference reports from other FAPs
Step 6: FAP sniffs RB spectrum usage from prior FAPs
Step 7: If all prior FAPs' usage is obtained, FAP transmit access admittances and system information
Step 8: FUEs who have admittances start accessing
Step 9: If any two FUEs access the same RB, the FAP starts contention resolution
Step 10: Break the loop if RBs are all used up
Step 11: Go to Step 7 for different groups until all groups have already performed the access of RBs

4.3 Complexity and Overhead Gain Analysis

We evaluate the complexity and overhead of the proposed spectrum access presented in Section 4.2. The complexity is measured in terms of the average number of floating point operations to floating points, excluding the complexity and overhead of the operations defined in the original LTE protocol architecture. All real additions, subtraction, multiplications, and comparisons are treated equally, and divisions are weighted by two as shown in **Table 4.2**.

The complexity of the proposed scheme comprises three parts: the complexities of calculation for cost function, of comparison with threshold, and sorting, and is shown as follows:

$$N_{FAP} \cdot N_{FUE} \cdot \left(N_{aRB} - 1\right) + N_{FAP} \cdot N_{FUE} \cdot \left(N_{FAP} + 2\right) \cdot N_{aRB} \qquad (3.1)$$

Table 4.2 Complexity weight of different operations

Operation	Weight
Addition/subtraction	1
Multiplication	1
Division	2
Data comparison	1

The transmit overhead is measured as the overhead per second, and we assume the two phases of spectrum access should be renewed in a coherence time, and the coherence time of a object with the speed of 5 km/hour is $4\cdot 10^{-3}$ second. The major part of transmit overhead of the centralized exhaustive scheme is for the channel state information, which is shown as follows (in real numbers):

$$N_{FAP}\cdot N_{FUE}\cdot N_{aRB}\,/\left(4\cdot 10^{-3}\right)=250\cdot N_{FAP}\cdot N_{FUE}\cdot N_{aRB} \tag{3.2}$$

The transmit overhead of the proposed scheme comprises three terms: the terms for the group index and access admittance, the interference measurement reports, and the spectrum usage reports, and is shown as follows (in real numbers):

$$250\cdot\left(2\cdot N_{FAP}\cdot N_{FUE}+N_{FAP}\cdot N_{FUE}+N_{FAP}+N_{FAP}\cdot\log_2 N_{aRB}\right) \tag{3.3}$$

The major difference of transmit overhead of both schemes is for the centralized scheme, the channel state information is needed on every RBs. In contrast, the number of overheads of the proposed scheme is independent of the number of RBs.

4.4 Computer Simulations

In this section, the simulation results of the proposed scheme are presented. The simulation environment is shown in **Fig. 4.5**, where the simulation parameters are listed in **Table 4.3**. In the environment, the FAPs are closely located, and the FUEs are randomly distributed within the femtocell coverage. In order to verify the proposed method in a densely populated scenario, we adopt the maximum number of supported FUEs [9]. We increase the number of FUEs scattered in the FAP coverage from four to 32 by four each time. **Fig. 4.6** shows comparison between multicell spectrum access with interference and without interference, and we can see that the inter-cell interference really degrades the capacity greatly, which leave a room for interference avoidance and capacity improvement. In **Fig. 4.7**, the capacity per channel (bits/sec/hertz) for the proposed spectrum access with inter-cell interference avoidance (IA) is shown, and is improved from the spectrum access without IA, and both of these are away from the lower bound of no coordination. Besides, the proposed spectrum access with IA also approaches the performances in both small and large numbers of FUEs obtained in the centralized scheme where the exhaustive search is adopted. The results show the ability of providing simultaneous supports to a larger number of FUEs in the two-tier femtocell networks. **Fig. 4.8** shows the capacity per FUE (bits/sec), and we can see that with the increase in number of FUEs, the capacities provided by the proposed schemes and the centralized scheme decrease, and when the number of FUEs per RB is larger than two, the difference between them is small. However, the capacity of no coordination scheme is close to zero in both small and large numbers of FUEs, which shows the benefits in capacity from coordination in the multi-cell spectrum access.

The comparisons in complexity and overhead are shown in **Fig. 4.9** and **Fig. 4.10**, respectively. Referring to the specification of spectrum release for LTE-Advanced in Taiwan [19], the bandwidth for an operator is up to 45 MHz, and the number of divisions of the total bandwidth by the minimum bandwidth configuration is 37. Applying this figure into simulations, we can see that in **Fig. 4.9** the complexity for the centralized scheme grows exponentially with the number of FUEs, while the complexity for the proposed scheme grows linearly. In **Fig. 4.10**, the transmit overhead of the centralized scheme and the proposed scheme both grow linearly with the number of FUEs, and the exponent of the latter is less than the former by one, which means the transmit overhead of the proposed scheme is only tenth of the centralized scheme.

Table 4.3 Simulation parameters

Parameter	**Value**
FUE transmit power	26 dBm
Path loss model [1]	3GPP TR 36.814 v9
Fading channel	Rayleigh
Resource block bandwidth	180k Hz
The maximum number of FUE [9]	32
The number of available RBs	4
The number of femtocells	4
Thermal noise PSD [10]	-174 dBm/Hz

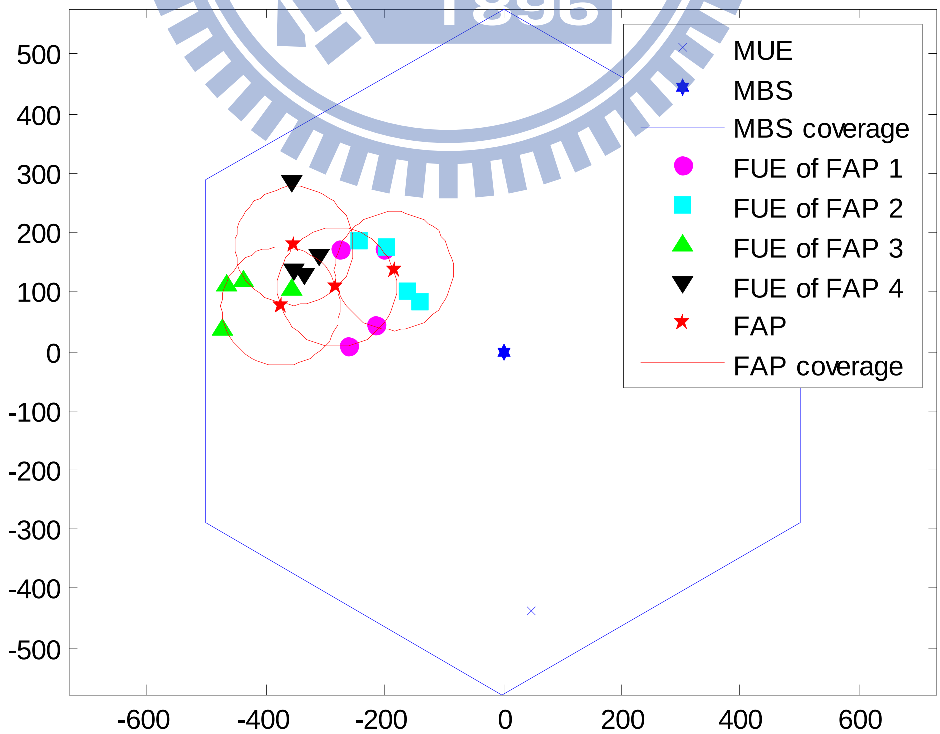

Fig. 4.5 Multiple femtocells in two-tier networks

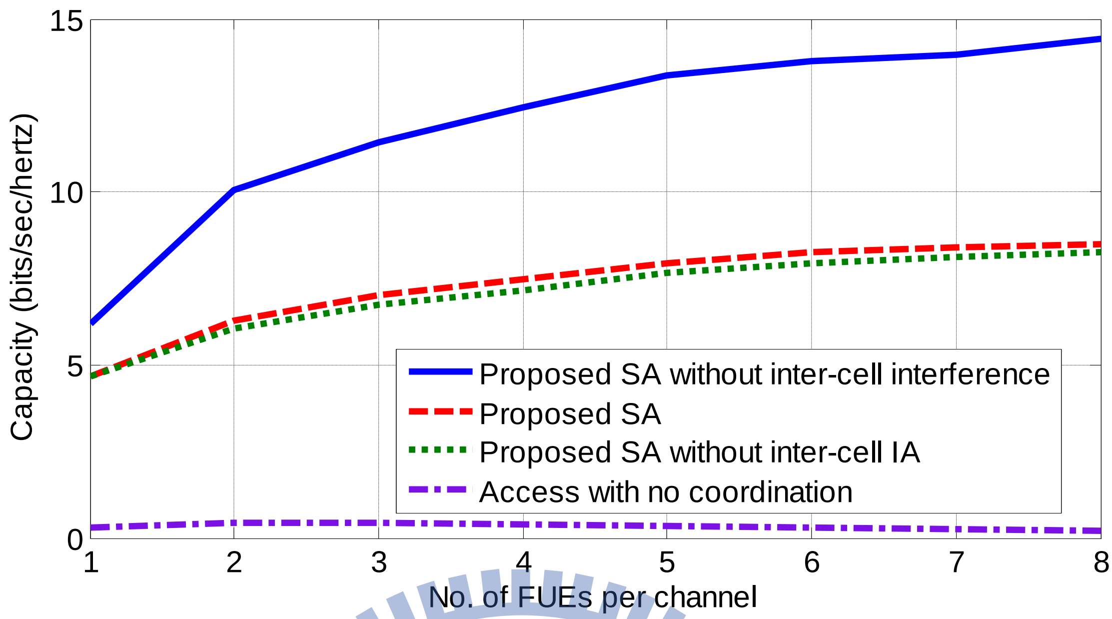

Fig. 4.6 Comparison in capacity per channel

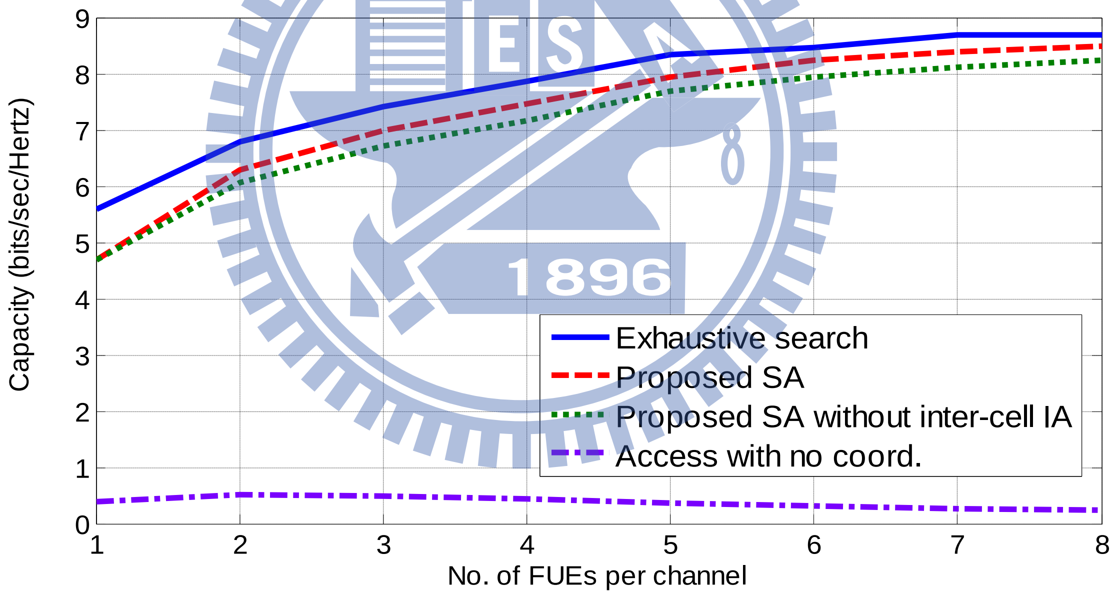

Fig. 4.7 Comparison in capacity per channel

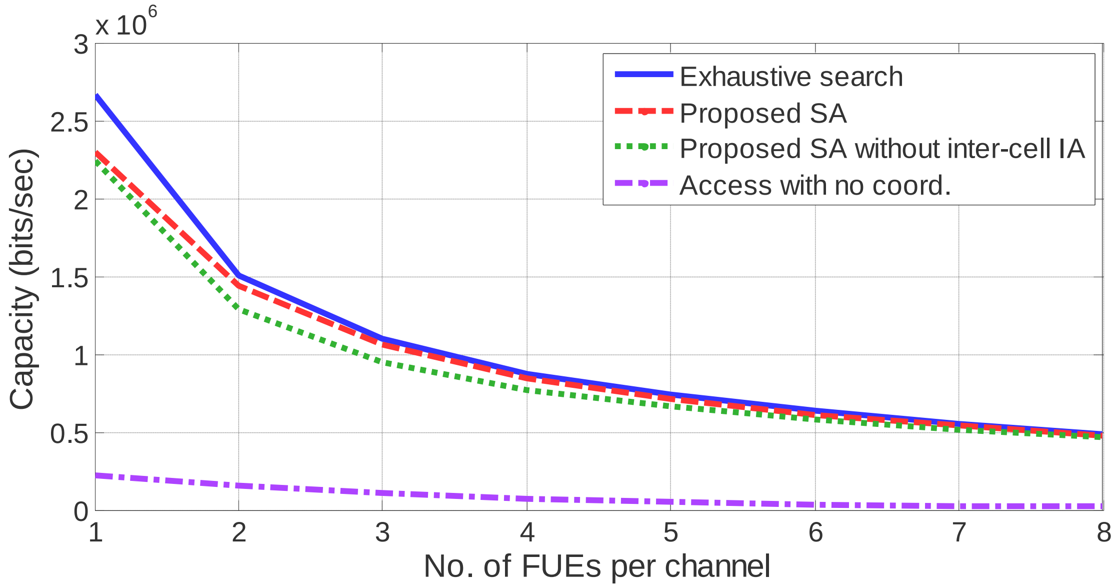

Fig. 4.8 Comparison in capacity per FUE

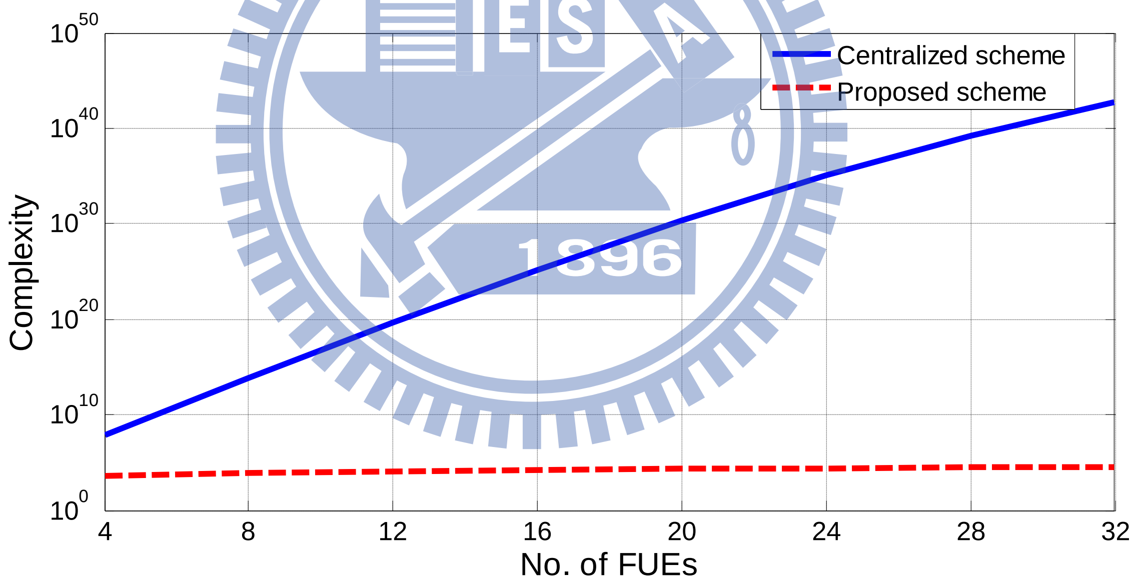

Fig. 4.9 Comparison in complexity

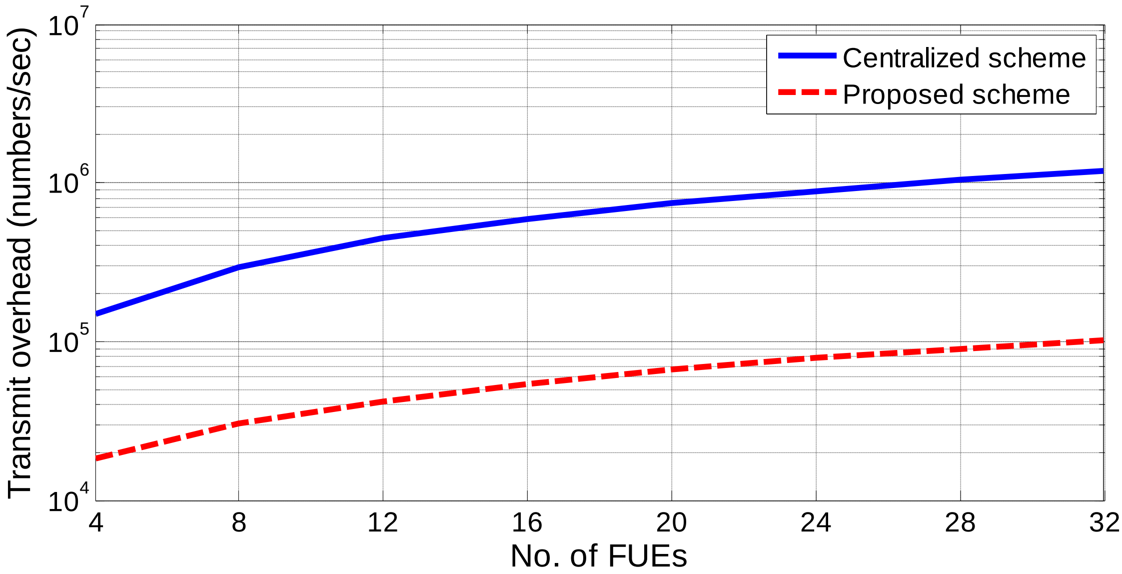

Fig. 4.10 Comparison in overhead

4.5 Summary

In this chapter, we first describe the requirement for distributed inter-cell interference coordination. To fulfill the requirement, we propose a multicell spectrum access with inter-cell interference avoidance. The new spectrum access scheme is based on the scheme proposed in Chapter 3 and can be adapted to the existing LTE protocol architecture. Analyses of complexity and overhead are also presented. Compared with the centralized scheme, the proposed scheme improves over the spectrum access without inter-cell interference avoidance and exhibits similar capacity performance to the centralized scheme.

Chapter 5

Conclusions and Future Works

To fulfill the increasing demands on the spectrum resource and to develop an efficient communication system in the next generation wireless communication systems, the femtocell network has been proposed. Femtocells feature no coordination center, low computation ability, and limited backhaul, which make the spectrum access hard to be efficient. Besides, uncoordinated network planning also introduces the interference issue. In this thesis, we propose a novel distributed multicell spectrum access with interference avoidance.

The network architecture and system model for the two-tier femtocell are introduced in Chapter 2, where two SON functionalities built in the system are also mentioned. The channel model of links between FUEs and FAPs is depicted, and the spectrum resource unit suggested by LTE is also adopted. We also briefly describe the mechanism of spectrum access in LTE and differences between femtocell networks and traditional macrocell networks. In the following Chapter 3 and 4, we propose a game theoretic distributed spectrum access in the femtocell networks.

In Chapter 3, we first give an introduction of the game theory, and also describe the vital requirement for a distributed mechanism. To meet the requirement, we propose a Bayesian game theoretic spectrum access with intra-cell interference avoidance. The new spectrum access scheme can be adapted to the existing LTE protocol architecture. Compared with the centralized scheme, the proposed scheme improves greatly from the original Bayesian game and exhibits similar utility performances to the centralized scheme.

In Chapter 4, we first describe the requirement for inter-cell interference coordination. To fulfill the requirement, we propose a multicell spectrum access with inter-cell interference avoidance. The new spectrum access scheme is based on the scheme proposed in Chapter 3. Analyses of complexity and overhead are also presented. Compared with the centralized scheme, the proposed scheme improves over the spectrum access without inter-cell interference avoidance and exhibits similar capacity performance to the centralized scheme.

There are still some issues remaining to be further investigated. The inter-cell interference avoidance problem can be modeled as a game where FAP acts as player making actions, and each action chosen by each player is the power allocation. In the power allocation problem, each BS determines the power allocation using local information by iterative water-filling algorithms, i.e., SINR in each channel. The SINR measured at each iteration reflects transmission power changes of the other FAPs. However, the water-filling algorithm may provide solution falling at some undesired equilibria [26]. How to develop an efficient scheme exploiting group spectrum access to pre-avoid this condition need to be further discussed.

Besides, the 3GPP proposed the incorporation of femtocells, picocells, microcell, and metrocells, and named the small cells. The deployment of small cells are managed by the operators and equipped with high speed fibre backbone [16]. Besides, the small cells are served as some hotspots deployed in some public areas to offload peak traffic, and the backhaul between small cells and macro cells is provided. In such scenario, inter-cell interference coordination plays a more important role and needs to be reconsidered to achieve better system performance. For instance, interference coordination can be implemented by a victim detection procedure [17]. In this procedure, the interfered victim MUEs can be determined by eNodeBs, and their identities can be signaled to the FAP through the backhaul provided by the operators, so the spectrum efficiency can be further improved.

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