Introduction

1 Long Term Evolution Over Unlicensed Band (U-LTE)

The phenomenal increase in mobile subscribers and the rich multimedia applications lead to an unprecedented demand for broadband access in next generation wireless networks. It is expected that the next generation of 5G networks will support many new killer applications, such as 4K Ultra High Definition (UHD) video streaming, virtual reality based applications, and massive Internet of Things (IoT). UHD TV requires a bandwidth on the order of tens of megabits per second, and is replacing cable and satellite TV nowadays. Virtual reality based applications are emerging as an integral part of the workplace, education, healthcare and entertainment. Moreover, billions of IoT devices such as wearable electronics, household devices and sensors, pave the way for smart homes and cities, changing the way people lives. It is not surprising that Cisco predicts that the global mobile data traffic will increase seven folds by 2021, reaching 49 exabytes per month, with 78% of which being video traffic [1].

To fulfill the unprecedented demand and provision Quality of Service (QoS) for high densities of mobile users, wireless service providers aim to develop advanced solutions to further augment network capacity at the minimum cost. It is well recognized that dense deployment of a multi-tier heterogeneous network (HetNet), including macro-cell, micro-cell, pico-cell, and femto-cell, is a desirable and feasible solution for increasing the spatial network capacity and QoS provisioning of 5G networks, by exploiting enhanced inter-cell interference coordination (eICIC) techniques. Generally, small cell technology allows energy efficient communications over a shorter distance with a lower power consumption, compared with conventional communications in macro-cells. Besides licensed small cells, Wi-Fi operating over the unlicensed band is also considered as an alternative small cell solution for traffic offloading from the licensed band to the unlicensed band in Long Term Evolution (LTE). Due to the different access technologies

H. Zhang et al., *Resource Allocation in Unlicensed Long Term Evolution HetNets*,
SpringerBriefs in Electrical and Computer Engineering,
https://doi.org/10.1007/978-3-319-68312-6_1

in the unlicensed band, it is hard to coordinate the transmissions in Wi-Fi and cellular networks. Thus, Wi-Fi is usually loosely coupled in LTE HetNets to provide complementary capacity. Recently, the Federal Communication Committee (FCC) opened extra sub-bands in the 60 GHz band for unlicensed use, which opens a door for a new research activity in the 3rd Generation Partnership Project (3GPP) [2], to exploit the unlicensed spectrum bands along with the existing licensed band to provide enhanced capacity in LTE networks, based on the existing LTE network architecture [3–5]. Unlicensed LTE (U-LTE) is considered as a promising solution to provide high user performance and seamless user experience under a unified radio technology by extending LTE to the readily available unlicensed spectrum.

2 Research Challenges

Extending LTE to unlicensed bands is by no means a simple task, due to the different characteristics of the licensed and unlicensed bands. LTE was originally designed to operate on licensed spectrum bands, which are exclusively used by the owner operator. The main objective of LTE operators is to maximize the spectral utilization efficiency of the expensive licensed band to provision seamless mobile services with guaranteed QoS to mobile users [6]. To achieve this goal, LTE adopts centralized Radio Resource Management (RRM) in multi-tiered heterogeneous networks (HetNets), comprising different types of network cells [7–12] to manage the interference among licensed users. However, unlicensed spectrum is usually shared by various unlicensed systems of different access technologies, given that the FCC transmission regulations are met. For example, the ISM (Industrial, Scientific and Medical) band in the 2.4 GHz is shared by various devices including IEEE 802.11 Wi-Fi, IEEE 802.15.1 Bluetooth, IEEE 802.15.4 Zigbee, and cordless phones for a variety of applications, such as wireless internet access, manufacturer monitoring and automation, and telemedication. Compared with the congested 2.4 GHz band, the relatively under-utilized 5 GHz U-NII (Unlicensed National Information Infrastructure) unlicensed band is mainly used for indoor Wi-Fi networks, and also attracts the attention of various wireless internet service providers. Therefore, the foremost issue in unlicensed systems is to allow various unlicensed users to efficiently and friendly coexist with each other without causing severe interference [13, 14]. Due to the difficulty in finding a common central controller for different unlicensed systems, unlicensed users are usually distributively coordinated to access the unlicensed spectrum, and there is no QoS guarantee in the unlicensed band. In addition, the stringent FCC regulations limits the transmit power of unlicensed users so that unlicensed users can only communicate over a limited distance in a local area, while licensed LTE is not subject to such FCC regulations and can provide seamless broadband services to mobile users in a wide area. As an unlicensed system integrated in the licensed LTE, U-LTE should not only comply with unlicensed regulations and distributively coordinate with other unlicensed systems, but should also be tightly coupled with the centralized LTE to provide seamless broadband services to mobile users with guaranteed QoS.

U-LTE should be integrated into the unified LTE network architecture and use the same network access technologies of the conventional LTE for service provisioning. That is, U-LTE will use the same core network, follow the same authentication, security and management procedures, and be well synchronized with the licensed LTE for integrated services. Similar to other unlicensed networks, U-LTE is also subject to the FCC regulations and thus is more suitable for small network cells. However, RRM for U-LTE small cells faces many new great challenges that beckons for further research:

1. The first challenge is efficient spectrum sharing and harmonious co-existence of U-LTE with various unlicensed systems, especially the widely deployed Wi-Fi network and U-LTE small cells of other operators. Harmonious co-existence means no unlicensed system will dominate or starve any other unlicensed system. As an integral part of LTE, U-LTE is inherently well synchronized for transmissions, while other unlicensed users such as Wi-Fi users may adopt asynchronous channel access. How to allow synchronous U-LTE to autonomously coordinate with various unlicensed systems with no or different time synchronization to achieve adaptive, efficient and fair spectrum sharing is an interesting yet challenging issue.
2. The second challenge is distributed coordination in U-LTE. Like LTE, U-LTE is also a multi-carrier system that exploits all available unlicensed bands for high data rate services. Unlike conventional LTE that adopts centralized RRM schemes, U-LTE requires distributed RRM schemes to coordinate multiple unlicensed users to transmit over multiple unlicensed channels, based on the performance guarantee of other unlicensed systems. Due to the lack of a common central controller for different U-LTE and other unlicensed systems, it is critical to characterize different access technologies in different channels in the distributed RRM to ensure efficient resource utilization and spectrum sharing of multiple unlicensed networks.
3. The third challenge is efficient carrier aggregation of U-LTE. Generally, the existing LTE carrier aggregation (CA) technologies cannot be simply applied to aggregate unlicensed spectrum bands for centralized radio resource scheduling, because the existing CA assumes the exclusive usage of the licensed bands without considering the interference from co-existed unlicensed users. Compared with interference from the licensed users belonging to the same operator, interference from unlicensed users are more random and cannot be managed and predicted. How to appropriately manage the radio resources and offload the traffic into U-LTE HetNets to achieve better integrated services need to be investigated.

3 Resource Allocation in U-LTE HetNets

In this book, we systematically study radio resource allocation for U-LTE HetNets. The first research issue we target is efficient radio access management of U-LTE. We examine various coexistence schemes of U-LTE with other systems over the unlicensed band. Specifically, we study the existing coexistence technologies and develop analytical models to analyze their performance. Based on the analysis, we identify the key performance issues of these technologies with respect to fairness and protocol overheads. To address these issues, we then propose an adaptive coexistence scheme to achieve a better and more harmonious coexistence. The proposed coexistence scheme is further analyzed and the protocol parameters are fine tuned to achieve the best coexistence performance among unlicensed systems. System-level simulations are also carried out to evaluate and verify the performance of various coexistence schemes.

Spectrum sharing plays a critical role in achieving high spectrum utilization among unlicensed users. We then investigate spectrum sharing strategies in the U-LTE HetNets, considering the scenarios where multiple wireless service operators coexist simultaneously in the unlicensed spectrum. Due to the autonomous behaviors of each wireless service operator, game theory is put forward to analyze resource allocation strategies of each wireless service operator in a distributive fashion. In order to guarantee the performance of other unlicensed systems, transmit power of each wireless service operator in the unlicensed spectrum is restricted according to the behaviors of other unlicensed systems. As the transmit power of one wireless service operator can affect the utilities of other wireless service operators, competition among multiple wireless service operators is analyzed. By predicting the corresponding reactions of other operators, the optimal strategy of each wireless service operator is proposed and the Nash equilibrium solution is achieved.

As there are multiple unlicensed bands available to the U-LTE HetNets with various interference from other unlicensed systems, we further analyze the spectrum matching strategies among U-LTE HetNets and Wi-Fi systems for stable and optimal solutions. Due to various spectrum allocations in Wi-Fi system, in order to guarantee the performance of Wi-Fi users and improve the performance of all U-LTE HetNet users, the interaction between LTE and Wi-Fi users, is modeled as the stable marriage (SM) game in matching theory. Based on different preferences of U-LTE HetNet users and Wi-Fi users on different unlicensed bands, how to perform the coupling between U-LTE HetNet users and Wi-Fi users on different unlicensed band is analyzed.

In addition, from the perspective of each wireless service operator in U-LTE HetNet, how to beneficially manage the traffic offloading from the licensed bands to the unlicensed bands remains a significant issue. Due to spectrum sharing among all service operators and other unlicensed systems in the unlicensed spectrum, it is significant for each service operator to predict the behaviors of its users and the resource allocation strategies of other service operators before making decisions to optimize its own performance. Accordingly, a multi-operator multi-user Stackelberg game is proposed, where all wireless service operators act as leaders and all users act as followers. Considering both competitive and coordinative behaviors of all wireless service operators, spectrum allocation and power control strategies are achieved with optimal and equilibrium solutions.

4 Outline

The outline of this book is as follows. In chapter "Radio Access Management of U-LTE", we first investigate existing coexistence technologies in U-LTE, and propose a new coexistence mechanism to achieve harmonious coexistence of U-LTE and Wi-Fi. In chapter "Game Theory Based Spectrum Sharing", considering multiple wireless service operators in the unlicensed spectrum, we propose game theory based spectrum sharing strategies. For the optimal coexistence between U-LTE and Wi-Fi systems in all unlicensed spectrum, in chapter "Spectrum Matching in Unlicensed Band with User Mobility", we propose a spectrum matching for U-LTE users and Wi-Fi users with user mobility. Spectrum management and allocation for each wireless service operator when its congested data traffic is offloaded from the licensed spectrum to the unlicensed spectrum are investigated in chapter "Traffic Offloading from Licensed Band to Unlicensed Band". Finally, we conclude our book in chapter "Conclusions and Future Works" and discuss some promising future development directions.

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