Chapter 6
Future Direction and Research Issues

In this chapter, we briefly discuss some future direction and research issues with regard to interference mitigation in the fifth-generation mobile communication systems (5G).

6.1 Hierarchical Games for Small Cell Networks

With the ever-increasing demand for high-speed and high-quality wireless data applications, e.g., video streaming, online gaming, and social networks, small cell technology is emerging as a powerful and economic solution to boost the system capacity and enhance the network coverage [1, 2]. Generally, typical small cells include the operator-deployed micro-cells and pico-cells as well as the user-deployed femtocells. Specifically, femtocells are low-power and short-range access points, which are mainly applied to improve the indoor experience of cellular mobile users and managed by end users in a plug-and-play manner. Because small base stations (SBSs) are deployed in the coverage range of a macro base station (MBS), from the perspective of network operators, SBSs can drastically improve the spectrum efficiency due to spatial reuse and offloading partial traffic load from the main network.

In practice, from the perspective of either an infrastructure or spectrum availability, it is more favorable to deploy two-tier small cell networks in shared spectrum rather than splitting spectrum scheme [3]. However, the co-existing issue of co-channel deployed SBSs and MBSs brings about numerous technical challenges in terms of interference management. Without proper interference control, the cross-tier and co-tier interferences severely affect the overall system performance. Accordingly, the interference mitigation is an important research area and is regarded as the major challenge in spectrum-sharing small cell networks.

Various interference mitigation schemes have been proposed for heterogeneous wireless networks [4–7]. However, these approaches cannot be directly applied to practical two-tier small cell networks, as these schemes are centralized and hence

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need coordination between SBSs and MBSs. As a result, it requires a large number of timely cross-tier and co-tier information exchange and leads to heavy overhead especially in large-cale scenarios. In addition, because of the randomness of mobile users' activity and the small cell access points' placement, it results in the ad-hoc topology of small cell networks, which implies that the networks' topology is essentially affected by end users' behavior. Therefore, centralized optimization approaches seem to be impractical, and hence it is desirable to develop distributed interference management approaches for small cell networks.

Due to the hierarchical decision structure between MBSs and SBSs, it is suitable and natural to apply the Stackelberg game, also known as leader–follower game or hierarchical game, to model the hierarchical interaction and competition between MBS and SBS in two-tier networks. Specifically, the MBS is modeled as leader and moves first. In the sequel, the SBSs are followers and take their actions based on the observation of leaders' actions. Note that the Stackelberg game is the extension of normal non-cooperative game. In a typical non-cooperative hierarchical game, the Stackelberg equilibrium (SE) is commonly used as a universal solution concept. SE is a stable operation point, at which no player can improve its utility by deviating unilaterally in the hierarchical game, which has the similar meaning as Nash equilibrium (NE) in formal game. The hierarchical game addresses the differentiated demands and priorities in tiered communication systems, and thus, it has been shown in [3, 8–13] that Stackelberg games provide a suitable framework to implement interference management in two-tier small cell networks.

Technically, when it comes to apply the Stackelberg games into small cell networks, the following concerns should be addressed:

- **Sophisticated utility function design**. In the hierarchical game, both the leaders and followers are aiming at maximizing their own utility function. Utility function reflects the differentiation demand and preference of player involved in the game. To avoid the tragedy of commons, leading to inefficient SE, the utility function should be well designed to achieve improved performance in concerned metrics. Moreover, the utility function should have the specific physical meaning such as achievable rate, quality of experience (QoE), and energy efficiency.
  To obtain the SE in a relative simple and low-computation way, the utility functions are commonly well designed to satisfy some features, i.e., the utility functions are designed as concave function shown in [3, 9] to facilitate the usage of backward induction, so that the SE can be obtained in a closed form. On the other hand, getting the closed-form SE may be not an easy task, and some works are expecting to obtain SE in a recursive manner that requires the utility function to meet some specific characteristics [10]. For example, if the players' strategy updating strategy follows the standard interference function first introduced by Yates [14], it can be guaranteed to converge to the stable operation point which admits an SE.
- **Robust decision under information uncertainty**. In practical systems, the assisted information for decision making may contain uncertainty, i.e., some parameters involved in the utility function or constraints cannot be precisely observed. The uncertainty may be caused by dynamic communication environment such

as time-varying channel state information (CSI), information transmission error caused by limited feedback bandwidth, and so on. The imperfect information scenario is more practical than perfect assumption applied in [9, 11–13]. However, if not well designed and optimized, the performance may degrade drastically under the SE which is obtained with the perfect information assumption. From the perspective of optimization theory, there are two widely used approaches to deal with the information uncertainties in game models [11]: (i) Bayesian approach [9]: it considers the average payoff based on some prior distribution information, and (ii) Robust optimization [11]: it considers the payoff for the worst-case scenario, which is a distribution-free method.

Another efficient method is resorting to learning theory, e.g., the stochastic learning automata [15]. Under the hierarchical learning framework, the SBS and MBS are assumed to behave as intelligent agents and have self-learning ability to automatically optimize their configuration. Each smart agent's overall goal is to learn to optimize its individual long-term cumulative reward via repeatedly interacting with network environment [16].

- **Scalability with dense deployment**. Network densification is the dominated theme in the 5G communication systems [1]. However, the problem of interference management under hyper-dense deployment of SBS is still an open issue. The cost of obtaining the SE solution in large-scale scenario may drastically increase. One possible approach is to split the large-scale optimization problem into several dub-problems. Another possible solution is to build a smart decision system based on cloud infrastructure owning powerful real-time computational capabilities. Using the data mining technique and with the assistance of information base in the cloud center, the users in system can utilize the mixed information, e.g., feedback knowledge from either learning or reasoning, and multi-dimensional context information including spectrum state, channel state information, location, energy, etc., to make efficient decisions. In addition, the users can utilize machine learning methods, e.g., online learning and statistical learning in dynamic scenarios, to make decisions more flexible, efficient, and intelligent.

6.2 Interference Mitigation for Carrier Aggregation

Carrier aggregation (CA) [17] has been regarded as a promising technology for 5G systems, as multiple spectrum bands can be simultaneously utilized to satisfy the large bandwidth demand. Compared with most existing interference mitigation approaches, there are some new challenges and problems for interference mitigation with carrier aggregation. In particular, the inherent characteristics of CA should be well addressed. However, this problem just begins to draw attentions very recently and some research issues are listed below.

- **The cost of non-contiguous CA should be addressed**. In general, CA can be used in three different scenarios: intra-band contiguous CA, intra-band non-contiguous

CA, and inter-band non-contiguous CA. For intra-band contiguous CA, it needs only one fast Fourier transform (FFT). For intra-band non-contiguous CA, it is more complicated than the intra-band contiguous CA. Specifically, the multi-carrier signal cannot be treated as a single signal and hence more transceivers are required, which adds processing complexity significantly. For inter-band non-contiguous CA, it requires separate FFT and needs the use of multiple transceivers. In addition, reducing inter-modulation and cross-modulation from different transceivers also causes future complexity. Thus, the cost for non-contiguous CA should be included in the interference mitigation problem [18], which differs significantly from existing interference mitigation approaches.
- **Autonomous guard band assignment**. In practice, guard bands are needed to prevent mutual interference among multiple users. The guard bands naturally constrain the spectrum utilization. Furthermore, fixed guard bands are not suitable for scenarios where multiple operators independently and autonomously perform CA. Thus, it is timely and important to achieve autonomous guard band assignment. In [19], the authors investigated the problem of assigning channels/powers to opportunistic transmissions, taking into account the constraint of guard bands, and then proposed a guard-band-aware channel assignment scheme for dynamic spectrum access systems with CA. Based on the above preliminary results, further investigation is needed.
- **The heterogeneous channel availabilities cause a new interference paradigm**. In practice, the licensed users always transmit at different times and on different channels, i.e., the channel availabilities are heterogeneous. From the view of interference coordination, the transmission of unlicensed users is dramatically affected if one of the aggregated channels is subjected to severe interference, even when the other aggregated channels are interference-free. This interference diagram is different from traditional interference models without CA, e.g., the modes presented in Chaps. 2–5. Thus, how to model and analyze the new interference paradigm for CA is important and urgent.

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