

# Chapter 2

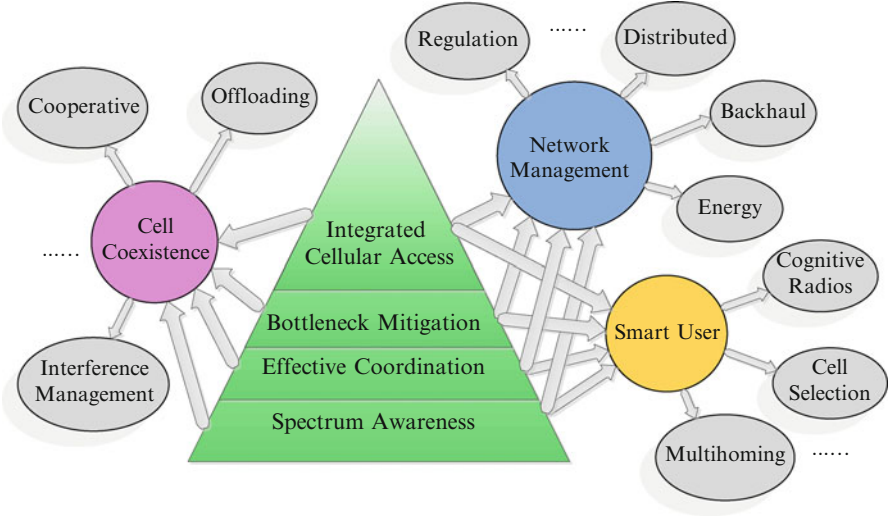
## Cognitive Cellular Network Management

### 2.1 CCN Framework

The emerging HetNet is asking for new network deployment and management methods with flexibility to handle dynamic user demands and diverse radio environments in a tired RAN infrastructure. In this Brief, we present a new framework in the study of HetNet, namely as *cognitive cellular network management* (CCN), by applying cognitive radio techniques. As shown in Fig. 2.1, CCN are built upon four principles from bottom to top, which are spectrum awareness, effective coordination, bottleneck mitigation and integrated cellular access, respectively.

- *Spectrum Awareness* is defined as the capability of HetNet to sense and track spectrum utilization on individual cell sites and utilize the knowledge of available radio resources to fuel cellular transmissions. Since cellular communications are resource-oriented, the activities in HetNet should be aimed to improve spectrum utilization or make an easier way of improvement.
- *Effective Coordination* means that data transmissions and signaling update in HetNet should capture real time service requirements and characteristics of variations in channel/link/topology. In addition, following the cost-effective principle, network nodes should take actions to meet the designed performance requirements given available spectrum and network resources.
- *Bottleneck Mitigation* is the principle that identifies, locates and mitigates the bottlenecks in resource supply, network infrastructure and management procedures, which prohibit the performance of HetNet from further improving.
- *Integrated Cellular Access* treats HetNet problems comprehensively by identifying the corresponding roles of users, access nodes and networks in the game of service demand and resource supply. Marginal gain achieved in single technical enhancement in an access problem should be testified in a whole solution with the analysis of the paid cost.

The presented principles in CCN study are not stand-alone. They are closely interacting with each other in the research efforts to improve HetNet performance.



**Fig. 2.1** The study framework of cognitive cellular network management (CCN)

As the foundation, spectrum awareness helps to obtain a clear picture of the resources HetNet can use, which are measured in various dimensions, e.g., time, frequency, location, and even codes. The other principles are applied on the first one, but also reward it with improved spectrum utilization. For example, effective coordination can encourage more meaningful signaling information to occupy the control bandwidth which in turn directs the network nodes to collaborate more efficiently to improve utilization of data channels. As shown in Fig. 2.1, the principles work together to addressing the challenging issues in HetNet including cell coexistence, network management and smart user. In individual research issues, different principles may take different weights according to the objective in a particular problem. In Sect. 2.2, we will present some typical applications using CCN applications and address the challenging issues in each case.

## 2.2 Applications and Challenges

### 2.2.1 Femtocell Deployment

Femtocells are a type of small cells deployed by end users to enhance the indoor cellular signal penetration in urban area with the portal to the Internet leased from third-party ISPs. Femtocells can provide the indoor public or private access to cellular users. The coexistence of femtocells with macrocells and other in-band and out-of-band small cells usually requires a spectrum access strategy because of the

“near-far” problem, in which the edge macrocell users would suffer from heavy interference from the neighboring femtocells working in the same frequency band. Using spectrum awareness principle, this problem can be formulated as a prioritized spectrum access problem. Specifically, since femtocells are user-deployed, users in femtocells should yield to the priority of macrocell users in the frequency band. Analog to the similar prioritized access architecture in cognitive radio networks [1] as shown in Fig. 1.4, femtocells can coexist with macrocells under a predefined spectrum sharing method which specifies the visibility of nodes intra- and inter-user groups, priority in spectrum access and conflict resolution. Usually, the spectrum sharing methods can be categorized as overlay, underlay or interweave to agree with the requirements in different deployment scenarios. In overlay mode, for instance, macrocells actively participate in the spectrum sharing and release some bandwidth in exchange for relay assistance from femtocells to assist the transmission to edge macrocell users [2]. While in interweave mode, channel sensing and the coordination between MBS and FBS on the scheduling of resources are the primary solutions to deal with the coexistence issues since in such mode overlapping of transmissions are not allowed in the same resource blocks.

Moreover, in the tiered network infrastructure, the nodes have diverse capabilities in transmissions. The coordination between end users and cells or inter-cells greatly affects the network performance due to the mismatch of the operations or inappropriate transmission settings, which would generate severe interference. When the coordination has constraints in the network topology and limited bandwidth for the control panel, the case becomes worse. For example, the coordination between the femtocell and the macrocell is limited because the femtocell BS is indirectly connected to the cellular core network through a local Internet cable, which prohibits the operators to perform integrated network operations. Distributed decision making has proved to be a promising solution in the cognitive radio study [3]. Based upon partial and/or delayed network information, e.g., channel gains, the decision process can be modeled as a partially observable Markov decision process (POMDP) problem [4], which captures the characteristics in the interworking between the femtocells and the parent macrocell. To achieve efficient spectrum sharing among a large number of distributed users with deviated local utility functions, game theoretical approach has also been introduced into the discussions for resource management of heterogeneous cells [5].

### ***2.2.2 Resource Management in HetNet***

In HetNet, each single user senses the circumstances, e.g., channel conditions and contention level, and makes the best transmission strategy for his own utility. The egocentricity of individual transmission decisions may impair the whole network performance when effective coordination mechanisms are missing. Overall, the resource management in HetNet can be formulated as a network utility maximization problem. Specifically, under a transmission strategy, denoted by  $\mathbf{a}$ , which

specifies the operation parameters of each node, e.g., cell selection, transmit power, etc., the objective is to maximize the aggregated utility functions of all links in the network, i.e.,  $\max_{\mathbf{a}} \sum_{i \in C} \sum_{j \in C_i} U_{\mathbf{a}_j}$  where  $C$  is the set of cells including all macrocells and small cells in the network, and  $C_i$  represents the set of active wireless access connections in cell  $i$ . Given the other nodes' transmissions,  $\mathbf{a}_{-j}$ , each node selects its transmission strategy,  $\mathbf{a}_j$ , to best respond to  $\mathbf{a}_{-j}$ , i.e.,  $U_{\mathbf{a}_j, \mathbf{a}_{-j}} \geq U_{\mathbf{a}'_j, \mathbf{a}_{-j}}, \forall \mathbf{a}_j, \mathbf{a}'_j \in \mathbf{a}, \mathbf{a}'_j \neq \mathbf{a}_j$ . Furthermore, one candidate transmission strategy should not violate the network coexistence rules  $\Gamma$ , which determines the maximum allowable interference in the links, i.e.,  $\mathbf{I}_{\mathbf{a}} \leq \mathbf{I}_{\Gamma}$ . The operators manipulate the decision making of individuals from the network aspect, such as load balance, interference management, and security. Candidate approaches include introducing incentive schemes [5], defining new utility functions for players [6, 7], etc.

In cellular networks, users are usually scheduled for data transmission in the time, frequency, code and space domains by a central controller. In HetNet, the centralized approach may not be available or would be costly from both computational and communication aspects. In cognitive radio networks, however, the available spectrum resources have been finely identified at different locations and times using spectrum sensing techniques [8]. The transmission pairs select the spectrum access opportunities which can satisfy the required transmission qualities, e.g., length and bandwidth. And the traffic flows are routed according to the statistics of available spectrum resources at intermediate nodes [1]. Introducing adaptive resource management in HetNet can improve the resource utilization efficiency via making opportunistic transmission decisions based on the local traffic and channel conditions.

Besides the competitions in the zero-sum game for radio resources, users and small cells can also cooperate for the channel condition monitoring, handover management and relay transmission. The cooperation can benefit the participants who have limited capability to acquire the necessary network or channel conditions to make effective decisions. No matter competition or cooperation, the participating users require the knowledge of all possible moves of other players or the required coordination information in cooperative communication. In HetNet, effective coordination relies on the connections between nodes with the overhead consideration and performance tradeoff.

### 2.2.3 Backhaul Bottleneck Mitigation

In HetNet, as small cells become more likely to be deployed by users themselves, it is increasingly difficult for operators to perform network resource management in a real-time manner. In addition, the capacity of access links in small cells (e.g., the links between users and SBS), and backhaul links (e.g., the ones between SBS and MBS/neighboring SBS) may vary at different paces. For example, the cellular downlink throughput can achieve 100 Mbps, while the backhaul of femtocell has

limited capacity provided by the Internet service providers using digital subscriber line (DSL), normally up to 10Mbps according to the data plan by regions and price. Therefore, the smaller bandwidth of femtocell backhaul becomes network bottleneck that limits the quality of service of users in radio access links. To tackle this problem, a possible solution is to allow multi-path data transmissions through different network interfaces, e.g., using WiFi and cellular networks [9], for the throughput aggregation at the end users.

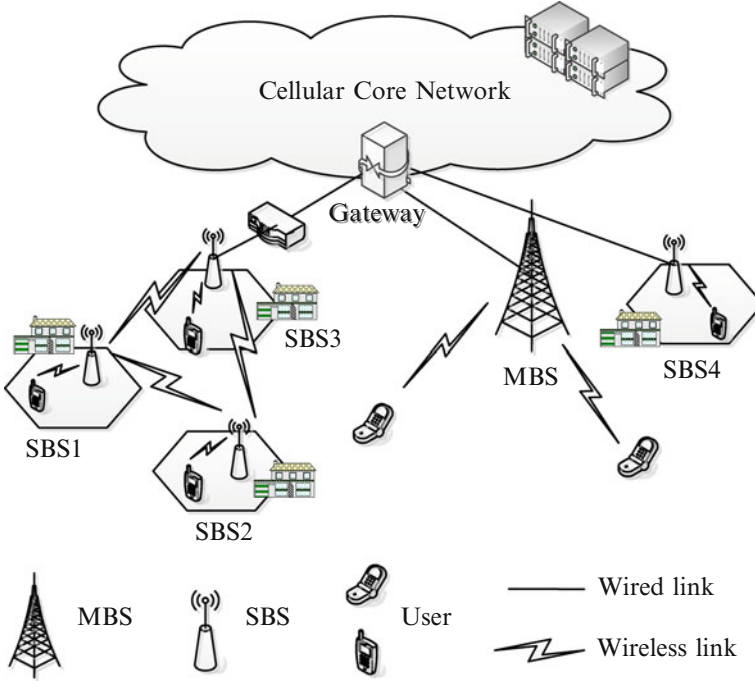
In a HetNet where the wireless backhaul is detected as the bottleneck due to constraint link capacity, opportunistic data forwarding has proved to be an efficient solution by jointly considering the forwarding capability of femtocell BSs and the traffic loads, as proposed in [1]. Specifically, the femtocell BS evaluates its forwarding capability based upon the expected relay advancement in the forwarding direction as well as the interference in the transmission channels, which determines the order of relay candidates along the forwarding path. To fight against the fading in wireless channels, the proposed forwarding scheme incorporates multiple nodes at each transmission so that the successful receiver, if there is any, can continue with the data forwarding if the nodes with higher forwarding capability fail. Such an opportunistic forwarding scheme well adapts to the dynamic channel conditions and significantly reduces the link failures and the resulting retransmissions in the backhaul. Further detailed information of the design is presented in Chap. 3.

## 2.3 Research Topics

In this Brief, we will focus on two research topics, routing in wireless backhaul and interference management, preliminary works using CCN principles in the discussions are presented later in Chaps. 3 and 4, respectively.

### 2.3.1 *Wireless Backhaul Routing*

Backhaul works as a bridge for both data traffic and signaling commands commuting between the in-field SBS and the central controller/scheduler, which is critical to the success of HetNet. As shown in Fig. 2.2, base stations can be connected with each other using high speed wired (e.g., SBS3 and SBS4) or wireless links (e.g., SBS1 and SBS2). In wired backhaul, the existing fiber points of presence at macrocells can be reused to serve as the aggregation points for public access small cells. Since the deployment of these fiber POPs requires dedicate radio planning as macrocells, small cells are in many cases self deployed by users, e.g., at individual houses. In addition, fiber cannot be pulled to every lamp pole cost-effectively in many markets. Therefore, it is necessary to consider the cases when small cells are wirelessly connected to the core network, which is usually referred to as *wireless backhaul* problem in HetNet.



**Fig. 2.2** Small cell backhaul in HetNet

Specifically, as part of the effort for a new “last 100 m”, wireless backhaul is to be built out at low cost, which obtains new characteristics by cellular operators. Wireless backhaul needs to maintain both the data and control exchange over the mesh like wireless network of small cells access nodes. Existing microwave solutions using frequencies in the 6–42 GHz band cannot support discrete antennas of the kind typically required at street level [10]. These frequencies may also be running out in some cases. Therefore, the major research issue in wireless backhaul is to build the route from end SBS to the core network in a cost-effective way in terms of both spectrum and energy utilization. Given the user statistics of macrocell users in a tiered cellular access, the deployment of wireless backhaul is mainly focused on the mesh routing problem and the distributed resource management problem.

Aforementioned problem has been discussed in CRN which share the similar network model of tiered access as HetNet. The vacant *UHF/VHF* frequency bands for analog TV broadcasting, or “TV white spaces” (TVWS), have been proposed for wireless backhaul implementation where SBS would work as SU in CRN [11]. Routing can then be formulated as a global optimization problem with the channel-link allocation for data flows in the network [12]. Xin et al. [13] propose a layered graph to depict the topology of the SU sublayer of CRN in a snapshot and allocate multiple links over orthogonal channels to enhance the traffic throughput

by establishing a near-optimal topology. Pan et al. [14] propose a joint scheduling and routing scheme according to the long term statistics of the link transmission quality for nodes. Gao et al. [15] develop a flow routing scheme which mitigates the network-wide resource for multicast sessions. These works on cognitive routing pre-determine an end-to-end relay path based on the global network information. However, the channel conditions of secondary links in wireless backhaul are highly dependent on public macrocell activities in HetNet. In addition to the limited coordination with central controller, SBS usually needs to track the channel status by periodic sensing [16] or field measurements [17]. When the channel status changes, source nodes need to re-calculate a path. Khalif et al. [18] show that the involved computation and communication overhead for re-building routing tables for all flows is nontrivial, especially when the channel status changes frequently.

Compared with centralized scheduling, distributed opportunistic routing is more suitable for the HetNet backhaul since SBS can select the next hop relay to adapt to the variations of local channel/link conditions [19, 20]. Instead of using a fixed relay path, a source node broadcasts its data to neighboring nodes, and selects a relay based on the received responses under current link conditions [19]. Liu et al. [21] propose to apply an opportunistic routing algorithm to utilize these released spectrum access opportunities in CRN where the forwarding decision is made under the locally identified spectrum opportunities. So far, most opportunistic routing protocols have been studied in a single channel scenario. In a multi-channel system, the channel selection and relay link negotiation may introduce extra delay, which degrades the performance of the network. How to extend opportunistic routing in a multi-channel HetNet is still an open research issue.

It is also recognized that with available localization services, geographic routing can achieve low complexity and high scalability under dynamic link conditions in various wireless networks, such as wireless mesh networks [22], ad hoc networks [23] and vehicle communication networks [24]. With geographic routing, a node selects a relay node that is closer to the destination for achieving distance advances in each hop. Chowdhury and Felice [25] introduce geographic routing in CRN to calculate a path with the minimal latency. However, their work still focuses on building routing tables and thus is not suitable for dynamic HetNet. Considering the unique features of HetNet, it is essential to design a distributed opportunistic routing algorithm by tightly coupling with physical layer spectrum sensing and MAC layer spectrum sharing to adapt to the network dynamics in HetNet for wireless backhaul routing.

### 2.3.2 *Interference Management*

In cognitive cellular networks, small cells are employed to enhance the link quality and improve the network capacity. When small cells operate in the same frequency band as the macrocells, severe co-channel interference degrades the performance of macrocell and small cell users. As shown in Fig. 1.2, when the mobile users served

by the macrocell move to the edge of cell, they may experience strong signals from the private femtocells. Similarly, the low power transmissions in small cells are also likely interfered with macrocell users. To mitigate the co-channel interference, some candidate approaches have been proposed, including:

*Spectrum splitting* approach refers to the resource allocation by assigning orthogonal resources, e.g., subcarriers, to the transmission pairs with strong interference. In the tiered network, the operator can split the spectrum into subbands and assign them to the neighboring small cells to reduce the interference between the neighboring cells [26]. However, such static allocation may cause waste of spectrum and lose synchronization with the varying traffic demands.

*Power control* approach is to adjust the transmit power of nodes in the network to secure the reception quality at the receivers. It is a good candidate to reduce the interference in the network and encourage the energy efficient transmissions. However, the central controller needs to acquire actual channel conditions and nodes' operational parameters to optimize the performance, which introduces heavy coordination cost, especially in the tiered network infrastructure [27].

*Offloading* approach tries to reduce the strong interference source by arbitrarily handover these users to the cells with better link qualities to mitigate their interference over the neighbors. In this approach, both link qualities and the resource allocation needs to be considered before the handover [28]. The availability of such cell is another issue when the targeted femtocell is of closed access for its private user only.

Validation of HetNet is built on the coexistence of macrocell users and small cell users in the same frequency band, which depends on intra- and inter-cell interference management. Interference management uses a coordination mechanism among access nodes in a centralized or decentralized manner, so as to mitigate mutual interference and improve the network performance. Unlike macrocells which have been well planned before MBS deployment and managed based upon decades of research and implementation experience, the emerging small cells in HetNet are under loose control of cellular operators and have various backhaul capabilities in the coordination with macrocells and the neighboring small cells. If fibre backhaul is used to aggregate MBS and SBS links, cellular operators can centrally control the transmissions with stringent QoS as they operate macrocells. However, if the backhaul is not deterministic or with limited bandwidth, such as *DSL* via the Internet or wireless backhaul [11], the effective coordination and interference management are still open.

In prioritized spectrum access network, e.g., CRN, proactive and passive interference management mechanisms have been studied. In a single channel case, power control is used to maximize SUs' overall performance subject to an interference constraint at the PU side [29,30]. While in a multi-channel case, SU first choose the operating channels and then perform power control algorithms in individual channels [31,32]. Konrad et al. in [33] demonstrate that channel characteristics exhibit time-varying effects in a long time period, which is caused by the change of physical channel conditions, e.g., a light-of-sight (LOS) path between transceivers may exist for some time and disappear when the path is blocked temporarily. To make accurate



estimation, the physical channel conditions should remain stable for a sufficient time to provide enough channel samples. To avoid excessive interference caused by channel uncertainty, power control methods treat the channel gain fluctuations with a stochastic model or in the worst-case approach. Zheng et al. in [34] consider the uncertain component in the channel as Gaussian noise and convert interference outage probability into a generalized Marcum's Q function [35]. In a similar way, Dall'Anese et al. in [36] approximate PUs' aggregate interference power (AIP) levels and SUs' signal to noise and interference ratios (SINRs) as log-normal distributed random variables, and then solve the resulting problem via sequential geometric programming. Gong et al. in [37] propose a robust power control method by taking the worst case calculation of the channel estimation error.

Chandrasekhar and Andrews in [38] show that the near-far problem cannot be mitigated with power control alone. Higher-layer interference management is needed, e.g. time division and spectrum splitting for mutually interfering cells, and aggressive handover from macrocell to public access small cells. Spectrum-aware MAC can facilitate small cells to find the channels with fewer active macrocell users nearby so that they can transmit at higher power for better link quality while maintaining tolerable interference on macrocell transmissions. CRN promote the MAC design by coupling the physical layer with cognitive hardware support [39], e.g., spectrum access opportunity is detected by physical layer radio frequency (RF) unit with the sensing scheduling at MAC layer, which differs from classic MAC protocols. As spectrum sensing is the key enabling functions in CRN MAC, most of the previous work mainly focus on optimal spectrum sensing policies [16, 40] or cooperative spectrum sensing among multiple SUs [41]. Kim and Shin in [16] present a sensing-period adaptation mechanism and an optimal channel sequencing algorithm. They also propose a channel usage pattern estimation technique, which can be used for efficient MAC layer scheduling. Recently, researchers pay more attention on QoS provisioning in the cognitive MAC design for real time multimedia applications. In [42], voice capacity, the maximum number of voice connections that can be supported with QoS guarantee, is analytically derived in a voice only CRN, assuming there is only one available spectrum band shared by both PUs and SUs. Kushwaha et al. in [43] distributed multimedia content over multiple unused spectrum bands based on digital fountain codes.

## 2.4 Summary

In this chapter, we have presented a new framework of studying HetNet, namely as CCN. Typical applications and challenges have been addressed. The research effort of wireless backhaul deployment and interference management in HetNet have been given a brief survey along with the comparative study on potential cognitive radio support. Background knowledge and literature survey on two research topics discussed in this Brief have also been presented.

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