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Interference Mitigation in CR-Enabled Heterogeneous Networks

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SUMMARY The heterogeneous network (HetNet), which deploys small cells such as picocells, femotcells, and relay nodes within macrocell, is regarded as a cost-efficient and energy-efficient approach to resolve increasing demand for data bandwidth and thus has received a lot of attention from research and industry. Since small cells share the same licensed spectrum with macrocells, concurrent transmission induces severe interference, which causes performance degradation, particularly when coordination among small cell base stations (BSs) is infeasible. Given the dense, massive, and unplanned deployment of small cells, mitigating interference in a distributed manner is a challenge and has been explored in recent papers. An efficient and innovative approach is to apply cognitive radio (CR) into HetNet, which enables small cells to sense and to adapt to their surrounding environments. Consequently, stations in each small cell are able to acquire additional information from surrounding environments and opportunistically operate in the spectrum hole, constrained by minimal inducing interference. This paper summarizes and highlights the CR-based interference mitigation approaches in orthogonal frequency division multiple access (OFDMA)-based HetNet networks. With special discussing the role of sensed information at small cells for the interference mitigation, this paper presents the potential cross-layer facilitation of the CR-enable HetNet.

key words: *heterogeneous networks (HetNet), small cell, interference management, interference mitigation, cognitive radio*

1. Introduction

The recent development of cellular networks has been directed toward high data rates, low (transmission) power and high mobilities. To accommodate high mobility, the next generation communication systems such as the fourth generation (4G) Long Term Evolution (LTE)-Advanced network adopt a *simple* network architecture (only the mobility management entity, serving gateway and PDN gateway in the evolving packet core) for high speed handover, and the Orthogonal Frequency Division Multiple Access (OFDMA) to combat frequency selective fading channel. To achieve high data rates with low transmission power, information theory reveals the solution to be either wide communication bandwidth or a high signal to interference and noise power ratio (SINR). For this purpose, operators deploy a larger number of base stations (BSs), such that the distance between a transmitter and a receiver in the network can be further reduced. As a result, with lower transmission power, a high SINR can also be maintained for each link, as interference from other transmitters is reduced. This solution also avoids the conventional fixed frequency partition scheme for interference mitigation, as dividing available bandwidth into small portions significantly limits data rates. For this purpose, the heterogeneous network (HetNet) deployment [1]–[3] where low-power and small-coverage small cell BSs are distributed in the coverage of a macrocell, is considered as mandatory architecture in both 3GPP LTE-Advanced and WiMAX 2.0.

In the HetNet deployment, on contrast to conventional macrocells, small cells such as pico, femto, and relay nodes (RNs) deployed at coverage holes of macrocells could extend coverage and increase spectral utilization. Moreover, their small coverage areas facilitate large numbers of concurrent transmissions to improve spatial reuse. Although HetNet deployment potentially yields enhanced wireless capacity, a successful practice of the HetNet is not suggested. The major reason is that, unlike the early assessment by operators that all cells are deployed with a well planning, small cells in the HetNet are underlay coverage of macrocells. Such a multi-tier deployment can result in severe interference among cells. When all cells share the same spectrum, two kinds of interference appear:

Cross-tier interference. The aggressor (e.g., a small cell BS) and the victim of interference (e.g., a macrocell user) belong to different tiers.

Intra-tier interference. The aggressor (e.g., a small cell BS) and the victim (e.g., a neighboring small cell user) belong to the same tier.

Under the impact of interference, some resource blocks (RBs) composed of a number of successive orthogonal frequency division multiplexing (OFDM) symbols and carriers can not be utilized simultaneously by multiple cells, which challenges HetNet toward a *universal frequency reuse* [4] to share all available bandwidth among all cells. To tackle this issue, a multitude of efforts has been recently proposed to study the downlink spectrum-sharing problems between macrocells and small cells considering cross-tier interference mitigation [5]–[13], among small cells considering intra-tier interference mitigation [14]–[18], and both [19]–[24]. Spectrum sharing among heterogeneous cells is typically achieved via *cooperation* or *coexistence* [25]. In such HetNet, the delay of communications via wired backhaul

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obstructs any cooperation between small cells and macrocells [26]; thus, collecting global information for centralized interference control is not possible. In contrast, small cells distributively mitigate interference in a coexistence fashion by using local information without explicit signaling might be more appropriated.

For the goal of distributed automata for interference mitigation, the cognitive radio (CR) has been regarded as a promising technology to enhance the spectrum utilization by spectrum sensing and opportunistic access [27]. There are two roles in the CR spectrum sharing. Unlicensed secondary users (SUs) adapt their transmissions/receptions to exploit the available spectrum resources while spontaneously limiting their interference with licensed primary users (PUs). In *interweave* paradigm [28], a zero-interference rationale is adopted, that is, SU can not interfere at all with the PU. This implies that SUs only use the spectrum that is not temporarily used by PUs and are obligated to evacuate the spectrum upon sensing primary transmission. By regarding macrocells as PUs and small cells as SUs, the CR can be the most suitable technology for a distributed interference mitigation to practice the HetNet deployment.

In this paper, we review potential schemes of CR in the literatures to propose practical and effective approaches to resolve such coexistence challenge. Specifically, by leveraging channel information and corresponding procedures available in state-of-the-art cellular networks, CR-enabled small cells automatically measure the channel condition, interpret the received signals from the macrocell BS (macro-BS) and the surrounding femtocell BSs (femto-BSs), and intelligently allocate resources without introducing excessive cross-tier and intra-tier interference [19], [22], [29], [30]. By such approaches, we show that the CR technology effectively facilitates an autonomous interference mitigation without additional hardware, interface and procedure costs, and thus elegantly enable a successful practice of the HetNet deployment.

The rest of this paper is organized as follows. After introducing the HetNet architecture in Sect. 2, the taxonomy of existing interference mitigation methods is reviewed in Sect. 3. Then, comprehensive studies of CR-enabled interference management and interference avoidance approaches are studied in Sect. 4 and Sect. 5, respectively, followed by the conclusion in Sect. 6.

2. HetNet Architecture

In light of the definition in 3GPP [31], in addition to conventional macrocells, the HetNet is composed of femtocells, picocells, RNs, and remote radio head (RRH).

- **Femtocell**. A femtocell formed by femto-BS with smaller coverage is haphazardly deployed by users to enhance the signal strength in the indoor environment. The backhaul of a femto-BS is the users' digital subscription line (DSL), on which the packet delivery delay is around the level of milliseconds. As a result, a real-time communication between a femto-BS and a macro-BS is unavailable.

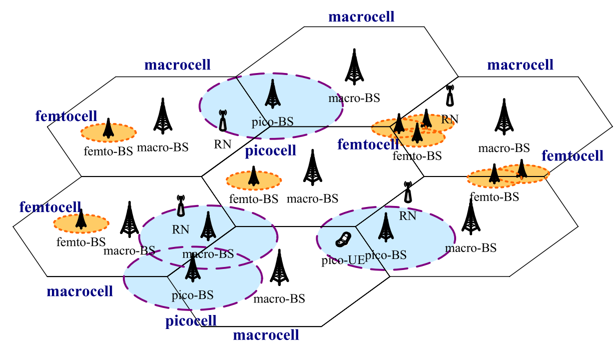

Fig. 1 Network architecture of heterogeneous networks.

- **Picocell**. The purpose of a picocell formed by a picocell BS (pico-BS) underlay a macrocell is to share the traffic load of the macrocell on a hot spot area. A pico-BS is substantially identical to a macro-BS, except smaller transmission power. In light of definition in 3GPP, there is direct interface (known as X2) between a pico-BS and a macro-BS. Thus, a real-time communication between pico-BS and a macro-BS is possible.
- **RN**. RNs are designed to be deployed at the coverage edge of a macrocell to enhance the signal strength of a macro-BS at the coverage edge. In 3GPP, there are two kinds of RNs (Type I and Type II), depends on whether the RN has its own cell identity or not (Type I RN has a cell identity, while Type II RN does not). Therefore, a RN is more than just a signal repeater in Layer 1, but it may also be capable of scheduling and resource allocation. For this reason, a RN may also be regarded as a pico-BS with a wireless backhaul to a macro-BS.
- **RRH**. In 3GPP, the RRH is simply a Layer 1 radio frequency (RF) front end apart from a macro-BS. With a fiber optic line connecting with a macro-BS, a RRH can be deployed to a coverage hold of a macrocell. Since a RRH is fully controlled by a macro-BS, there is no interference issue between a RRH and a macro-BS.

Figure 1 shows the HetNet architecture in 3GPP. In the HetNet, since there is no interference issue between a RRH and a macro-BS, RRHs are typically not involved in the illustration of the HetNet architecture.

2.1 Features of Small Cells

Due to the underlying deployment to macrocells, femtocells, picocells, and RNs are generally referred to small cells in 3GPP. Femtocells, picocells, and RNs may face a similar interference issue, they also encounter diverse challenges on solving the issue according to corresponding specific features, as summarized in Table 1.

Table 1 Features of small cells.

	deployment	coverage	backhauling	access
Femtocell	haphazard	small	xDSL	open/closed
Picocell	planned	medium	X2	open
RN	planned	medium	Un	open

2.2 Challenges of HetNet

Interference mitigation in such HetNet architecture faces practical challenges from following aspects [32]:

- Haphazard deployment: Since femto-BSs are deployed by users in a fully dynamic fashion, it is a challenge for a macro-BS to estimate the number of femtocells underlay the macrocell. This challenge makes the conventional scheme of frequency partition for interference avoidance among cells infeasible to be applied to femtocells, especially under a dense femtocells deployment. As a consequence, a femto-BS can be a aggressors invoke severe interference to macrocell users (macro-UEs). In addition, due to the infeasibility of frequency partition and the lack of cell planning, a femtocell may also suffer severe interference from neighboring femtocells if femtocells are deployed in a very dense fashion.
- Restricted/closed access: Since femto-BSs are paid by the customers, it is reasonable that only users defined by the owners are allowed to access femto-BSs. In this case, the unauthorized users could only connect to macro-BS even if femto-BS exists in vicinity and thus the users suffer heavy cross-tier interference.
- No coordination between macro-BS and femto-BS: The delay of connection via wired backhaul is too long to admit any cooperation [31], which means that centralized interference mitigation approaches are not feasible.
- Backward compatibility: The legacy macro-UE and macro-BS must be supported for market penetration. Thus, any additional impact on macrocell protocols/interfaces is not suggested.

Obviously, femto-BSs distributively mitigate interference in a coexistence fashion by using local information without explicit signaling might be more appropriated. As can be seen throughout this section, we enable CR technology [28] on femto-BSs as a solution for coexistence to tackle the above challenges. A CR-enabled femto-BS could automatically sense environment, interpret received signaling from macro-BS and surrounding femto-BSs, and intelligently allocate resource [12], [19], [20], [22]–[24], [33]–[37]. Consequently, macro-BS and CR-enabled femto-BS are respectively analogous to PUs and SUs in the CR model. With CR capabilities, femto-BS could actively acquire knowledge about environment without the aid of macrocell in a decentralized fashion and automatically prevent from the disturbing macro or surrounding femto transmissions.

Although picocells and RNs show no defects as that of femtocells (providing open access to macro-UE, real-time communications to macro-BS, and potential cell planning), it does not suggest that the interference issues between a picocell and a macrocell, and between a RN and a macrocell can be totally resolved by cooperation (or centralization). The major concern is potentially additional computational load to macro-BS. As a number of picoells and RNs is introduced, the macro-BS may need to take links in picocells and in RNs into considerations for resource allocations, which significantly burdens the macro-BS and limits the available numbers of picocells and RNs. To fully expose the beauty and the capability of deployments of picocells and RNs, the CR capabilities for femto-BS can also be an effective and elegant solution for picocells and RNs.

3. Taxonomy of Interference Mitigation Methods

Authors in [4], [22], [38], [39] provided the overview of interference mitigation methods in the HetNet. These papers further classify the interference mitigation methods by using a novel taxonomy, which identifies the major dimensions of an interference mitigation method: radio resource domain of achieving orthogonality and method of acquiring information.

3.1 Target of Orthogonality

In the literatures, the key for interference mitigation is to prevent multiple cells from occupying an identical radio resource in the location, the time-frequency, the spatial (antenna) or the code domain. That is, we shall maintain the orthogonality of radio resources among cells.

3.1.1 Location/Spatiality

In wireless communications, the interference level is not only affected by physical locations of nodes. Instead, the transmission power representing logical locations of nodes is the main factor determining the interference level. Consequently, two nodes physically locating closely to each other do not suggest severe interference to/from each other if a small transmission power is adopted in both nodes. Such concept motivates considerable efforts [10], [12], [17], [40]–[42] to avoid harmful interference to the victim by controlling the transmission power in the aggressor based on the physical distance to the victim in the HetNet. However, in state-of-the-art cellular networks such as LTE and LTE-Advanced, adaptive power control is only applied in uplink communications, while a fixed power level is adopted by downlink communications to avoid complexity in BSs. As a result, additional efforts of radio resources orthogonality is required.

3.1.2 Time-Frequency

Considering that the OFDMA has been a mandatory multiple access scheme for 3GPP LTE/LTE-Advanced and WiMAX 2.0, radio resources in both time and frequency domain are subsequently viewed as RBs. A subframe is composed a number of RBs suffering different levels of fading. By utilizing RBs with acceptable channel quality, the impact of frequency selected fading can be alleviated. Similarly, as all cells only utilize unoccupied RBs by neighboring cells, interference can also be rejected [5], [8], [14], [18], [20], [24], [43]–[45]. Following this concept, a particular solution known as the almost blank subframe (ABS) solution is proposed in Enhanced Inter-cell Interference Coordination (eICIC) in 3GPP LTE-Advanced [3]. By the ABS, a BS suspends the utilization of all RBs in the data channel of a subframe to avoid potential interference to/from neighboring cells. However, the ABS is not efficient, as suspending the utilization of all RBs in a subframe may be destructive for services with timing constraints.

3.1.3 Antenna Orthogonality

Uncorrelated vectors in Multiple Input Multiple Output (MIMO) form different transmission spatial paths. By the orthogonality among spatial paths selected by different cells, interference among cells can be avoided [13], [46]. This is the concept of antenna orthogonality.

3.2 Methods of Information Acquisition

To achieve radio resource orthogonality in the HetNet, a centralized allocation scheme for all cells in the HetNet may not be a feasible solution, since potentially a large number of small cells may lead to unacceptable computational complexity. Thus, the autonomous radio resource management turns out to be a feasible and promising solution. However, to achieve an autonomous radio resource management, each BS may need to know radio resource utilization plans in other cells. By utilizing unoccupied radio resources by other cells, interference can be effectively rejected. To achieve this goal, in the HetNet, there exists three classes of methods.

3.2.1 Exchanging at the BS Side

By leveraging wireless/wired interfaces, small cell BSs and macro-BS could directly exchange information about the radio resource usages (e.g., activity), connection behavior (e.g., channel conditions), as well as resource demands (e.g, codebooks or messages) [8], [10], [17], [18], [21], [42]. Being aware of the present actions and future intentions of macrocells and surrounding small cells, the perfect interference mitigation can be achieved. However, the direct information exchange may not generally available for all small cell BSs. For instance, according to the HetNet architecture of 3GPP LTE/LTE-Advanced, there is no direct interface between a macro-BS and a femto-BS [31]. Moreover, the heavy communication overheads may also make this mechanism inefficient in case of dense femtocell deployments.

3.2.2 Measuring at the UE Side

State-of-the-art UEs are capable of certain channel measurement abilities to estimate channel quality on given radio resources. By performing periodical channel measurement in UEs and reporting the measurement results to its serving BS [14], [20], [46], the serving BS can analyze and acquire the activity and the channel condition about immediate environment of the radio resource usages in neighboring cells, which facilitates the interference mitigation. However, performing measurement quite consumes power in UEs. Thus, it may not be feasible for UEs that are typically power limited unless additional sophisticated scheme assists to further reduce the amount of measurements to reports by UEs.

3.2.3 Measuring at the BS Side

To avoid interference from neighbor cells, in state-of-the-art cellular networks, a BS inherently has the capability of measuring interference [47]. By exploiting such capability, the detection of surrounding cell signals can be achieved without any coordinations [12], [19], [20], [22]–[24], [33]–[37], [48]. For example, if the received interference power on a RB exceeds a certain threshold, femto-BS identifies that this RB is occupied and retrieves activity [23]. Thus, CR-enabled femto-BSs could automatically configure itself and mitigate both tier interferences.

3.3 Interference Mitigation Methods/Spectrum Sharing Paradigm

As shown in Fig. 2(a), by achieving orthogonality at time-frequency, cells are allocated in distinct RBs and interference is avoided. Such interference-aware RB allocation is

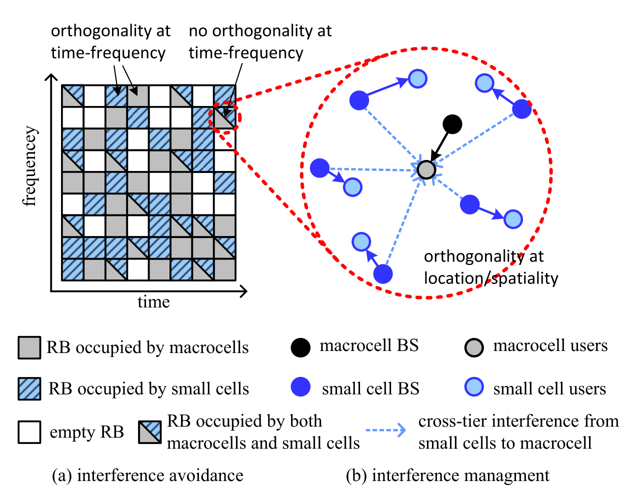

Fig. 2 Interference avoidance and management schemes.

Table 2 The CR-enabled interference mitigation methods.

CR-enabled interference mitigation methods	CR sharing paradigm	Orthogonality
Interference management	Underlay	Location/Spatiality or Antenna path
Interference avoidance	Interweave	Time-frequency
Interference cancellation	Overlay	None

thus regarded as interference avoidance in this literature. Extending the concept of allocating resource cells at different RBs to different antenna paths, the interference mitigation methods achieving orthogonality by antenna spatiality are also classified as interference avoidance methods. If orthogonality at time-frequency can not be achieved, such as the RB occupied by both macrocells and small cells in Fig. 2(a), we could achieve orthogonality at location/spatiality. As shown in Fig. 2(b), the interferers (i.e., small cell BSs) are managed to prevent generating severe interference to the victim (i.e., macro-UE) to ensure the successful transmission. To analyze the performance of such interference mitigation methods, spatial progresses of network entities are needed to get tractable results of outage probability on the victim. Furthermore, if orthogonality can not be achieved, coding techniques such as Sphere Decoding or Dirty Paper Coding (DPC) can be exploited to allow victim actively canceling interfering signals from the desired signal [49]–[52], which is known as interference cancellation.

Table 2 classifies the existing CR-enabled interference mitigation methods in the HetNet according to proposed taxonomy and details are described as follows.

By enabling CR in traditional interference mitigation methods, the interference avoidance, management, and cancelation methods are respectively analogous to interweave, underlay, and overlay CR sharing paradigms [28]. In CR-enabled interference mitigation methods, the low-tier small cells acting as SUs can passively seek temporary frequency voids of RBs for opportunistic allocation. Consequently, macrocells and small cells are operating on orthogonal RBs, and cross-tier interference is avoided. To break the restriction of no spatial reuse of interweave paradigm, underlay paradigm suggests small cells aggressively exploit RBs occupied by macrocells as long as the resulting aggregated cross-interference is constrained. If small cells are able to leverage location information, the set of RBs that can be reused without generating interference to macro-UEs in its vicinity are determined. By deactivating the small cells on the RBs dedicated to a neighboring macro-UE, more concurrent transmissions in small cells are allowed and the transmission capacity is increased. If small cells could further acquire the knowledge of codebooks or messages of macrocell users (e.g., in case of message retransmission), overlay paradigm suggests that small cells could exploit such knowledge to either cancel or mitigate the interference seen at both macrocell and small cell receivers [50].

4. Interference Management

In this section, we introduce the framework of stochastic geometry and how the performance of typical and CR-enabled interference management schemes can be evaluated by the framework. The coverage and throughput analyses for cellular networks are typically based on the simulation assuming a hexagonal grid deployed BSs and uniformly scattered UEs who connect to the closest BS. By simulations, we can evaluate and aid in the widespread deployment of the new proposed techniques according to the sufficiently accurate results. To obtain tractable results, Wyner model [53] is proposed by treating other-cell interference as a fixed value and get inaccurate results in general case.

4.1 Embracing Stochastic Geometry

Recently, applying the approach of stochastic geometry [54]–[57] to model the the performance of wireless networks has received much attention. As we know, the performance of communications among spatially scattered nodes in wireless networks is highly constrained by the received power and interference. To model the interference, the spatial distribution and transmission features of the interferers as well as the propagation characteristics of the media shall be addressed. Consequently, spatial point process is adopted to model the node locations and interference distributions and analyze the link outages in wireless networks.

Due to its analytical tractability and practical appeal in situations where transmitters and/or receivers are located or randomly move around over a large area, the (homogeneous) Poisson point process (PPP) has been by far the most popular spatial model. For example, in the 2-D PPP, each node takes up an independent location characterized by a pair of coordinates (x_i, y_i), the density of nodes in a unit area is λ, and so the average number of nodes in an area $\mathcal{H}$ is $\lambda\mathcal{H}$. Finally, the probability that there are n nodes in $\mathcal{H}$ is given by the Poisson distribution and thus equal to

$$\Pr(n) = (\lambda\mathcal{H})^n e^{\lambda\mathcal{H}}/n!. \tag{1}$$

It has been recently shown that modeling macro-BSs by a homogeneous PPP and associating macro-UE to their closest macro-BSs is a tractable yet accurate macrocell network model [58]–[61]. It is surprising since the deployment of macro-BSs is well-planned, centralized, and hence regular and one might assume that the modeling of lattices or hexagonal cells has a more accurate results comparing with the PPP. It is concluded [59] that the PPP approach provides lower bounds of the coverage probability of real cellular networks. This enables better understanding the design in the cellular networks due to its simplicity and analytical tractability. Furthermore, more complex point processes can be introduced to model repulsion between BSs (such as Matern process [62]) or clustering features (such as Poisson cluster process; PCP [63]).

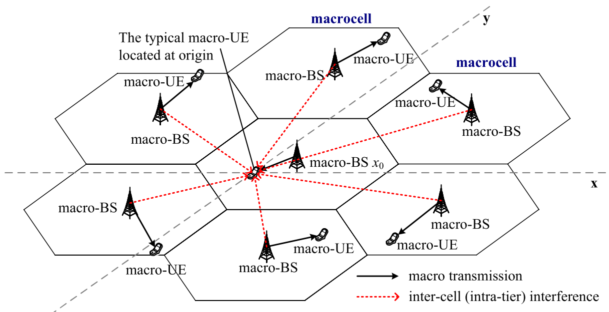

Fig. 3 Spatial modeling of macro-BSs. Without loss of generality, we assume the origin of the coordinate system coincides with the probe macro-UE.

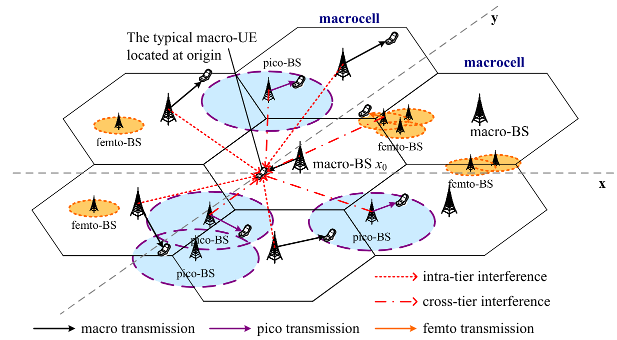

Fig. 4 Spatial modeling of HetNet. Without loss of generality, we assume the origin of the coordinate system coincides with the probe macro-UE.

The main metric in a cellular network is the SINR distribution at receiver. The link outage, average rate, transmission capacity, even connectivity can be computed accordingly. As shown in Fig. 3, denote $\mathcal{H} \in \mathbb{R}^2$ as the interior of a reference HetNet. The macrocell with serving area radius R_m and transmission power P_m. The spatial distribution of macro-BSs is assumed to follow a homogeneous PPP with density λ_m, and the locations of the macro-BSs are denoted as $\Phi_m = \{X_i\}$. Each macro-UE connects to the macro-BS with the strongest signal, which is not necessarily the closest one. In a baseline model with no interference management, the SINR offered by a macro-BS at location X_0 to a macro-UE at the origin can be expressed as

$$SINR_0 = \frac{P_m h_0 \|X_0\|^{-\alpha}}{\sum_{X_i \in \Phi_m \setminus X_0} P_m h_{i0} \|X_i\|^{-\alpha} + N_0}, \tag{2}$$

where α is the path loss exponent, h is the fading to the UE, N_0 is noise power, Φ_m is the point process of macro-BSs which has density λ_m, and its points m generically refer to all the interfering macro-BSs, and $\Phi_m \setminus X_0$ is the set of interfering macro-BSs. To ensure a successful transmission, the received SINR at the typical macro-UE should larger than an SINR threshold (denoted by γ_m). The probability that a randomly chosen user can achieve a target SINR is denoted as the coverage probability p_c. Under the assumptions of Rayleigh fading (i.e., h is exponentially distributed with unit mean) and negligible noise, the coverage probability can be derived as [59]

$$p_c = \frac{\pi}{C(\alpha)\gamma^{2/\alpha}}, \tag{3}$$

where $C(\alpha) = (2\pi^2/\alpha)\csc(2\pi/\alpha)$ is a simple constant. It shows that coverage probability is independent of the density of the macro-BSs, and is solely dependent upon the target SINR ratio γ. Comparing with the grid model and the real data, stochastic solution provides lower bound of the coverage probability [59]. Authors in [64] further compare PPP and hexagonal grid model with real base station deployment data of different cities and the results show that PPP model is still optimistic.

4.2 Stochastic Geometry Model for HetNet

Recently, stochastic geometry is applied to model cross-tier interference in macro/femto two-tier networks [7], [22], [44], [65], [66] and K-tier general HetNet [67]–[70]. Please note that femto-BSs might be deployed independently by customers and thus be distributed randomly, which justifies the modeling of femto-BSs by PPP, whereby each point is distributed independently and uniformly at random. Regarding the modeling of femtocell users, they are usually indoor and have close proximity to their femto-BSs, such that the ring model for the users is still sufficiently accurate.

As shown in Fig. 4, by including the small cell BSs with also Poisson spatial distribution, the resulting HetNet shall consider additional cross-tier interference from small cell BSs to the macro-UE. The small cell with serving area radius R_s and transmission power P_s. The spatial distribution of small cell BSs is assumed to follow a homogeneous PPP with density λ_s, and the locations of the small cell BSs are denoted as $\Phi_s = \{Y_j\}$. In this case, the SINR received at macro-UE at the origin becomes

$$SINR_0 = \frac{P_m h_0 \|X_0\|^{-\alpha}}{\sum\limits_{X_i \in \Phi_m \setminus X_0} P_m h_{i0} \|X_i\|^{-\alpha} + \sum\limits_{Y_j \in \Phi_s} P_s h_{j0} \|Y_j\|^{-\alpha} + N_0} \tag{4}$$

Under the same assumptions of Rayleigh fading and negligible noise and denoted η_s as the SINR threshold of small cells, the coverage probability becomes [68]

$$p_c = \frac{\pi}{C(\alpha)} \frac{\lambda_m P_m^{2/\alpha} \gamma_m^{-2/\alpha} + \lambda_s P_s^{2/\alpha} \gamma_s^{-2/\alpha}}{\lambda_m P_m^{2/\alpha} + \lambda_s P_s^{2/\alpha}}. \tag{5}$$

Typically, SINR thresholds of macrocell and small cell are the same (i.e., $\gamma_m = \gamma_s$). Then (5) becomes (3). This means that the coverage probability is not affected by the number and density of small cell BSs, the type of small cells, and their relative power levels in this simplified model. The result surely contradicts the common sense that small cells such as femtocells or picocells generates additional cross-tier interference and degrade the performance of HetNet.

However, in case of interference-limited HetNet and UEs connecting to the strongest BS, the SINR distribution does not change statistically [68].

The throughput of macro/femto two-tier HetNet under the ring model of femto-UE is further analyzed, that is, each femto-UE is distributed uniformly and independently in an infinitesimally thin ring centered around its designated femto-BS [44]. A throughput maximization subject to quality of service constraints on coverage probability is formulated, which provides insights into the optimal joint/disjoint spectrum allocation.

4.3 CR-enabled Interference Management

Enabling CR capability, small cell BSs can acquire additional knowledge from surrounding small cells or macrocells. Small cells consequently can exploit such information to achieve orthogonality at physical spatiality. Following the PPP assumption on spatial distribution of small cell BSs, we further simplify that each small cell UE is located at the cell boundary with an arbitrary direction. In the following, we briefly describe the current techniques applied in CR-enabled interference mitigation.

4.3.1 Random Access

The most straightforward approach to achieve orthogonality even without sensing any information is to apply Slotted Aloha on small cells [71], that is, every small cell BS tosses a coin independently in each RB with probability p and transmits if it gets heads. In this case, the active subset of small cell BSs is realized by independent thinning and is denoted as $\Phi_s^p = \{Y_i : B_i(p) = 1\}$ with node density $p\lambda_s$, where $B_i(p)$ are i.i.d. Bernoulli random variables with parameter p. As a result, the aggregated cross-tier interference received at macro-UE is reduced and orthogonality is achieved.

If additional information can be acquired in small cells, variant Aloha schemes were proposed [24] to improve the coverage probability. For example, when channel information of other small cells is known, we can combine the random selection of small cell BSs with the occurrence of good channel conditions [72] for a better result. Each small cell BS computes a certain threshold distributively and only the small cell BSs with channel gains larger than the threshold are activated in a reference RB. The idea is similar to allocating resources to the best link in multi-user networks to retrieve multi-user diversity gain. Another improvement introduces the concept of a *guard zone* [73] to prohibit the presence of simultaneous interfering transmissions in proximity. The resulting active small cells can be modeled by a hard-core point process [62], where each point of the process is the center of a disc that contains no other points except itself. It is achieved by allowing each small cell to randomly generate a real number between $[0, 1]$ and broadcast this information to surrounding small cells within its guard zone to determine the one with the smallest value [24].

4.3.2 Distributed Optimization

Even with CR, small cells can acquire limited knowledge about the global HetNet. In this case, distributed schemes are of much importance, and researchers have provided a number of distributed schemes for interference management in small cells, in those, some key techniques are discussed. The spectrum sharing problem in the HetNet is formulated as optimization problem to maximize the downlink capacity of all small cells while guaranteeing the SINR constraints [20]. By applying dual decomposition [74], the problem can be efficiently resolved in a distributed fashion.

5. Interference Avoidance

5.1 3GPP LTE-Advanced eICIC

There have been devoted intensive efforts on cross-tier interference management in 3GPP LTE-Advanced, known as eICIC [26]. In eICIC, to avoid interference between small cells and macrocells, each time-frequency radio resource (i.e., a RB) is not allowed to be utilized by more than one cells, especially for macro-femto deployment [75] and macro-pico deployment [76]. Typically, fractional frequency reuse (FFR) is adopted to partition the spectrum into subbands and assign them to a cell in a coordinated manner that minimizes intra-tier interference [49]. In the following, we address on ABSs [3] adopted for small cells in eICIC. In an ABS, all small cells can only broadcast control signals via the control channel of the subframe to maintain the network connection, while data transmissions and receptions shall be postponed in the data channel of the subframe. Consequently, by deterministic assigning ABSs to certain small cells, interference to macrocells and other small cells is avoided in an ABS. However, avoiding deterministically using all RBs in an ABS regardless the traffic load in macrocells or in other small cells results in inefficiency of radio resources utilization. It also degrades QoS performance in the small cell adopting ABSs. Consequently, an efficient radio resources management for interference avoidance lies in an effective autonomous detection of RB utilizations in other cells, which is the major technical merit of the CR-enabled interference avoidance schemes.

5.2 3GPP Self-Organization Network

By introducing the concept of *self-organization*, in which small cells are aware of the environment and automatically adapt their radio resources or power for network performance optimization, interference can be mitigated and resources can be utilized without high operating costs. Therefore, it is considered as a promising method for efficient operation in LTE-advanced systems and consequently receives much attention in the standardization progress [31], [77].

Typically, the self-organization method can be modeled as a distributed spectrum sharing problem by controlling transmission power or allocating resource. Following the definition of LTE-Advanced [31], the proposed self-organization process consists of three phases: *self-configuration*, *self-optimization*, and *self-healing*. The self-configuration phase provides the initial settings of a small cell BS when it is turned on. In the self-optimization phase, all network parameters (transmit power, physical resources, access modes, admission control etc) are tuned to an acceptable level. To achieve interference avoidance, we shall guarantee optimized results on allocating resource in this phase. In the self-healing phase, we concentrate on resolving the decoding errors due to heavy interference.

5.3 CR-enabled Cross-Tier Interference Avoidance

Since a small cell may suffer interference from the macrocell when the small cell utilizes RBs occupied by the macrocell, each small cell BS shall avoid allocating RBs occupied by the macrocell to its UEs. As a result, the key idea of the cross-tier interference avoidance is that each small cell BS autonomously acquire the RBs usage of the macrocell (that is, identifying which RB is occupied by the macrocell in a subframe). Then, each small cell BS only allocates unoccupied RBs to its UEs [23], [78]–[81]. Such an autonomous time-frequency orthogonality is described in details as follows.

1) For all small cells, there are two kinds of subframes: measurement subframe and data subframe. In each measurement subframe, each small cell BS identifies those RBs in a measurement subframe which are occupied. Then, in subsequent data subframes, the small cell BS only allocates unoccupied RBs (measured in the latest measurement subframe) to its UEs. As a consequence, a small cell can not perform data transmission nor reception in a measurement subframe. The measurement period (in the unit of the number of subframes) is dynamic for small cells.
   a. For a femtocell, to identify occupied RBs in a measurement subframe, the femto-BS measures the received interference power on all RBs in a measurement subframe. If this quantity exceeds a certain threshold on a RB, this RB is identified as occupied by macrocells.
   b. For a picocell or a RN with the coverage typically larger than that of a femtocell, only the measurement by pico-BS or the RN may not completely reflect the interference situation of all UEs distributed over the coverage. Thus, all UEs shall measure interference on RBs in a measurement subframe, and report the measurement result to the pico-BS or the RN. However, if there is a large number of UEs, the uplink channel for measurement report may suffer severe congestions. In addition, as mentioned above, performing interference measurement quietly consumes energy for UEs that is typically energy limited. As a consequence, the number of UEs involved in a measurement shall be minimized. To overcome this huge challenge, the *compressed sensing* technology can be applied (this part will be elaborated later) for the pico-BS or the RN to obtain interference on all locations within the coverage with an outstanding error rate performance by only leveraging a small portion of UEs for interference measurement.
2) By identifying occupied RBs in a measurement subframe, a small cell BS can further infer: (i) the traffic load of the macrocell, (ii) the RBs allocation correlation probability of the macrocell, and (iii) the fraction of correlated RBs allocation of the macrocell.

In Step 2, the traffic load of the macrocell can be defined by $\rho \triangleq M_{Macro}/M$, where M_{Macro} is the number of RBs occupied by the Macroell in a subframe and M is the number of RBs in a subframe. The parameter of RBs allocation correlation probability of the macrocell denoted by η is the probability that the macrocell will occupy a RB in the subsequent subframe if this RB is occupied by the macrocell in current subframe. The fraction of correlated RBs allocation of the macrocell can be defined by $\varphi \triangleq M_\eta/\rho M$, where M_η is the number of RBs with non-zero η in a subframe. By inferring these parameters from measurements, the measurement period as well as the RB allocation can be further optimized. By the procedure for autonomous orthogonality at time-frequency stated above, interference between a small cell and a macrocell can thus be mitigated. In the following, we introduce the compressed sensing for picocells and RNs [36], [78].

Compressed sensing [82], [83] origins as a signal processing technology, which is able to sample an (audio/image) signal with a sampling rate far lower than that of the Nyquist rate and the sampled signal can be recovered with an acceptable error rate if certain constraints can be satisfied. Specifically, at each measurement subframe, if each UE only performs interference measurement with a probability q, then the expected number of UEs involved in interference measurement and reporting result is $Mq \leq M$. For this purpose, the coverage of a picocell or a RN is divided into N isotropic grids. Our objective is to obtain RB occupations in the measurement subframe on all N grids. Denote the true RB occupation by the macrocells as $\Psi = [\phi_1 \phi_2 \dots \phi_N]^T$, the compressed sensing is obtained by multiplying a sample matrix on Ψ as

$$\mathrm{y} = \Phi\Psi + \varepsilon, \tag{6}$$

where ε is the noise in the compressed sensing, Φ is a $R \times N$ matrix with each element taking "1" with probability of qM_n/M, and taking "0" with probability of $1 - qM_n/M$, M_n is the number of UEs in the nth grid. After obtaining qM measurement reports, interference from the macrocell can be reconstructed by searching the minimum l_1 norm of Ψ as

$$\Psi^* = \arg\min \|\Psi\|_1 \text{ s.t.} \|\Phi\Psi - \mathrm{y}\|_2 \leq \epsilon \tag{7}$$

through applying the second order corn programming if

$$R = O\left(\kappa \log \frac{NM}{\kappa}\right), \tag{8}$$

where l_p norm of Ψ is defined by

$$\|\Psi\|_p \triangleq \left(\sum_{n=1}^{N} |\phi_n|^p\right)^{1/p}, \tag{9}$$

κ is the sparsity of Φ, $\epsilon = \|\Omega\varepsilon\|_2$ and Ω is a random basis.

5.4 CR-enabled Intra-Tier Interference Avoidance

To mitigate cross-tier interference, the autonomous time-frequency orthogonality should be applied to each small cell. However, multiple small cells may identify the same set of unoccupied RBs. Without an effective scheme to share these unoccupied RBs, small cells may suffer intra-tier interference from other small cells. To mitigate intra-tier interference, it has been suggested that [7] each small cell randomizing the RBs utilization among unoccupied RBs can potentially alleviate intra-interference. The interference avoidance is typically achieved by applying game theory [23], [33], [34], [37] and distributed optimization techniques. In this section, we introduce two types of randomization schemes, one-shot and sequential randomization, respectively corresponding to the above main solutions.

5.4.1 One-Shot Randomization

In the one-shot randomization [23], a small cell BS determines a randomized RBs usage pattern among unoccupied RBs before randomization takes place. However, the key factor impacting the performance of this scheme is the maximum number of unoccupied RBs that can be utilized by each small cell, especially when each small cell has diverse demands. Under the limitation that it is unavailable for small cells to exchange information with each other, one typical solution is that all small cells equally share unoccupied RBs. However, this scheme may not be effective, especially when each small cell generally has diverse demands. To reach the automation in a distributed way for practical operations, *game theory* is thus employed as the foundation.

Consider that there are S small cells indexed by $s = 1, \ldots, S$. The sth small cell adopts the strategy profile $\mathbf{p}_s = \{p_{l_s}\}_{l_s=1,\ldots,M_a}$, where p_{l_s} is the probability that the sth small cell utilizes l_s RBs among M_a unoccupied RBs. Therefore, $\sum_{l_s=1}^{M_a} p_{l_s} = 1$. Each small cell takes the same strategy. That is, $\mathbf{p}_1 = \mathbf{p}_2 =, \ldots, = \mathbf{p}_S$. As the spirit of game theory, each small cell maximizes its own payoff. The payoff of each small cell is the expected number of RBs without suffering interference. The payoff of the first small cell that utilizes l_1 (unoccupied) RBs can thus be formulated by

$$u_1(l_1; \boldsymbol{P}) = \sum_{l_s, s\neq 1} \sum_{y=0}^{M_a-\max(l_2,\ldots,l_S)} \sum_{x=0}^{M_a} (l_1 - x)\frac{\mathrm{C}_x^{M_a-y}\mathrm{C}_{l_1-x}^{y}}{\mathrm{C}_{l_1}^{M_a}} \cdot \mathrm{C}_y^{M_a} q_0^y (1-q_0)^{M_a-y} p_{l_2}\ldots p_{l_S} \tag{10}$$

where $\mathrm{C}_b^a \triangleq \frac{a!}{b!(a-b)!}$ and $q_0 = \prod_{s=2}^{S}(1 - \frac{l_s}{M_a})$ is the probability that a RB is not utilized by any small cells, x is the number of RBs utilized by more than one small cells and y is the number of RBs not utilized by any small cells. The payoff of an arbitrary small cell can be obtained likewise. In this game, not all strategy profiles are feasible. A set of strategy profiles is feasible only if it reaches the *Nash equilibrium*. Since the developed game has a finite strategic form (the number of RBs that can be utilized is finite), the developed strategic game has at least one equilibrium. To select the best from potential multiple equilibria, the best equilibrium shall be the one maximizing the overall throughput of all small cells among all equilibria. Denote the expected total number of RBs utilized by all small cells without suffering interference as $\mathbb{E}[j]$, which is given by

$$\mathbb{E}[j] = \sum_{j=1}^{M_a} \sum_{l_1,\ldots,l_S} j\mathrm{C}_j^{M_a} q_1^j (1-q_1)^{M_a-j} \prod_{s=1}^{S} p_{l_s} \tag{11}$$

where q_1 is the probability that a RB is utilized by exactly one small, which is given by

$$q_1 = \sum_{s=1}^{S} \frac{l_s}{M_a} \prod_{s'=1, s'\neq s}^{S} \left(1 - \frac{l_{s'}}{M_a}\right). \tag{12}$$

The optimum strategy profiles $\boldsymbol{P}^* = \{\boldsymbol{p}_s^*\}_{s=1,\ldots,S}$ can be found by examining all Nash equilibria ($\boldsymbol{P}^* \in \mathcal{A}$), where $\mathcal{A}$ is the set of all Nash equilibria, such that

$$\boldsymbol{P}^* = \arg\max_{\mathcal{A}} \mathbb{E}[j]. \tag{13}$$

Consequently, we can summarize above results into the following procedure.

1) Each small cell BS finds the corresponding optimum strategy profile according to the developed strategic game, by which each small cell BS can obtain the optimum number of unoccupied RBs (denoted by L) available to be allocated to its UEs.
2) In each data subframe, each small cell BS can allocate l unoccupied RBs ($l \leq L$) to its UEs, according to the actual demand.
3) These l unoccupied RBs are allocated in the randomized manner.

5.4.2 Sequential Randomization

Although the one-shot randomization leads to a low computational complexity, a small cell BS may exploit its intellectual capability by adaptively changing its randomization pattern according to the past measurement history, which motivates us to note the sequential scheme known as *Gibbs sampler* randomization [13], [22].

Consider an undirected graph with S femtocells, in which two femtocells are neighbors if they are connected by an edge. The sth femtocell is with a state $k_s \in \mathbf{K}$ of the state vector for the graph $\mathbf{k} = [k_1 k_2 \ldots k_S]^T$. In our case, the state k_s is the set of RBs selected by sth femtocell. A clique of order n is defined as a set with n femtocells in which every pair of femtocells are neighbors, while the set of all cliques with order n is represented as $\mathcal{D}(n)$. A global energy function $E(k)$ is then defined as

$$E(\mathbf{k}) = \sum_{n} \sum_{\mathcal{B}\in\mathcal{D}(n)} V(\mathcal{B}) \tag{14}$$

where $V(\mathcal{B})$ is potential function which associates nonnegative real number to all subsets of femtocells in $\mathcal{B}$. Based on the global energy function in (14), the local energy function of the sth femtocell can be obtained by

$$E_s(k_s; k_{n,n\neq s}) = \sum_{n\in\mathcal{B}} \sum_{\mathcal{B}\in\mathcal{D}(n)} V(\mathcal{B}). \tag{15}$$

Given the global and the local energy functions, Gibbs sampler provides a procedure to minimize global energy. In other words, every femtocell updates its state by sampling a random variable over the state space $\mathbf{K}$ according to the following probability distribution $p(s)$ which equivalently depends only on local energy.

$$p(s) = \frac{e^{-\frac{E_s(k_s;k_{n,n\neq s})}{T}}}{\sum_{k'\in K} e^{-\frac{E_s(k'_s;k_{n,n\neq s})}{T}}}. \tag{16}$$

In the case of the HetNet, the $I(s, s')$ is the interference from the s'th femtocell to the sth femtocell if both of them are utilizing the same set of RBs. The local energy function can then be specified as

$$E_s(k_s; k_{n,n\neq s}) = \sum_{s',s'\neq s} I(s, s'). \tag{17}$$

Since Gibbs sampler can minimize global energy (and thus minimizing total interference), all femtocells are eventually selecting distinct sets of RBs among that of other femtocells. In the following, a systematic procedure for femtocells to select different sets of RBs is introduced.

1. Compute the temperature parameter in Gibbs sampler $T = \frac{T_0}{\log_2(2+t)}$, where t is the iteration index and T_0 is a constant.
2. Compute the local energy $E_s(k_s; k_{n,n\neq s})$ for each set of RBs.
3. Compute $p(s)$ for every set of RBs.
4. Sample a random variable over K according to $p(s)$ and update its set of RBs accordingly.

5.5 Optimal Control for QoS Guarantees in Small Cells

The major concern of above interference avoidance schemes is the waste of radio resources. To avoid interference, a femto-BS or UEs in a picocell shall perform interference measurement. These radio resources for interference measurement are overheads, as UEs in a femtocell or in a picocell can not perform data transmissions nor receptions by these radio resources for interference measurement. If radio resources for interference measurement are allocated very frequently, although time-varying interference can be accurately estimated, there is a severe resources waste. On the other hand, if radio resources for interference measurement are allocated very rarely, although overhead is reduced, interference may not be alleviated. As a result, the measurement period can be a very critical factor influencing the performance of UEs in a small cell, especially QoS guarantees.

The real-time services typically require bounded delays. Due to the impact of time-varying fading channels, it had been shown that providing *deterministic* QoS guarantees (that is, the probability that the delay violates the delay requirement is zero) over the Rayleigh fading channel is impossible [84]. As a result, a practical solution turns out to provide the *statistical* QoS guarantees (the probability that the delay violates the delay requirement is bounded by a required value). For this purpose, we particularly note an equilibrium of statistical delay guarantees that

$$\Pr\{Delay > d_{max}\} \approx e^{-\theta\delta d_{max}} \tag{18}$$

where d_{max} is the delay bound and δ is jointly determined by the arrival process of traffic and the service process of the small cell. From (18), it can be observed that a small θ implies that the system can only support a *loose* QoS requirement, while a large θ means that a *strength* QoS requirement can be supported.

To provide statistical delay guarantees, the effective bandwidth and the effective capacity provide significant foundations. The effective bandwidth [85], [86], denoted by $\mathrm{E_B}(\theta)$, specifies the *maximum constant service rate needed by the given arrival process subject to a given* θ. On the other hand, the effective capacity, denoted by $\mathrm{E_C}(\theta)$, is a duality of the effective bandwidth, which specifies the *maximum constant arrival rate that can be supported by the system subject to a given* θ [84]. If θ^* can be found as the solution of $\mathrm{E_B}(\theta^*) = \mathrm{E_C}(\theta^*)$, δ can be obtained by [87] as

$$\delta = \mathrm{E_B}(\theta^*) = \mathrm{E_C}(\theta^*). \tag{19}$$

Consequently, the system can achieve the statistical delay guarantee

$$\Pr\{Delay > d_{max}\} \approx e^{-\theta^*\delta d_{max}}. \tag{20}$$

The effective capacity can be formally defined as [84]

$$\mathrm{E_C}(\theta) \triangleq -\frac{\Lambda_c(-\theta)}{\theta} = -\lim_{t\to\infty} \frac{1}{\theta t} \log\left(\mathbb{E}\left[e^{-\theta\sum_{i=1}^{t} R[i]}\right]\right) \tag{21}$$

where $\mathbb{E}[\cdot]$ denotes taking the expected value, $\sum_{i=1}^{t} R[i]$ is the partial sum of the discrete-time stationary and ergodic service process $\{R[i], i = 1, 2, \ldots\}$ and

$$\Lambda_c(\theta) = \lim_{t\to\infty} \frac{1}{t} \log\left(\mathbb{E}\left[e^{\theta\sum_{i=1}^{t} R[i]}\right]\right) \tag{22}$$

is a convex function differentiable for all real θ. To achieve the statistical delay guarantees, approaches to derive the effective bandwidth of real-time streams had been widely discussed (e.g., the effective bandwidth of the voice traffic can be obtained by the method proposed in [88]), and the effective capacity of interference avoidance schemes stated above can be analytically derived by [23]

$$\mathrm{E}^{l}_{\mathrm{C}}(\theta) = l\varpi^{l}\mathrm{E}^{1}_{\mathrm{C}}(l\varpi^{l}\theta), \tag{23}$$

where

$$\varpi^{l} = \frac{T_s - 1}{T_s} \cdot \left(1 - \frac{\sum_{g=0}^{\min(l,(1-\eta\varphi)\rho M)} g\mathrm{C}^{l}_{g}\mathrm{C}^{(1-\eta\varphi\rho)M-l}_{(1-\eta\varphi)\rho M-g}}{l \cdot \mathrm{C}^{(1-\eta\varphi\rho)M}_{(1-\eta\varphi)\rho M}}\right), \tag{24}$$

l is the number of unoccupied RBs utilized by a small cell.

With the facilitation of above foundations, the small cell BS can control the measurement period T_s and the RB allocation to achieve the required statistical delay guarantees for each UE by the following procedure.

1. The small cell BS calculates the effective bandwidth $\mathrm{E}_{\mathrm{B}}(\theta)$ of the real-time traffic.
2. To efficiently utilize the radio resources, T_s is initially set to a predetermined value.
3. The small cell BS first allocates $l = 1$ RB to the UE.
4. The small cell BS calculate the effective capacity.
5. Find the solution of θ such that

$$\mathrm{E}_{\mathrm{B}}(\theta) = \mathrm{E}^{l}_{\mathrm{C}}(\theta) = \delta. \tag{25}$$

6. Derive the delay violation probability by

$$\Pr\{\text{Delay} > d_{max}\} = e^{-\theta\delta d_{max}} \tag{26}$$

   a. If $e^{-\theta\delta d_{max}} > \varepsilon$, l is determined by

$$\min_{1 \le l \le L}\{l\}, \ s.t. \ e^{-\theta\delta d_{max}} \le \varepsilon \tag{27}$$

   b. If (27) is not satisfied, decrease T_s by one if $T_s > 2$ and repeat Step 4 to Step 6 to find the appropriate l and T_s such that (27) can be satisfied.

6. Conclusion

The introduction of small cells has the potential to significantly improve HetNet performance, benefiting from smaller transmission distance and better spatial reuse of spectrum. The dense and unplanned deployment of small cells will raise many challenges, which are discussed and summarized with the emphasis on interference mitigation in this paper. A novel taxonomy is proposed to classify the existing interference mitigation schemes by using the target of orthogonality achieved and types of information acquisition methods. By introducing CR in HetNet, small cells can exploit knowledge interpreted from the additional sensing information to design more effective and efficient interference mitigation schemes. By intensively discussing recent research efforts in CR-enabled interference mitigation schemes, we show that CR-enabled small cells can tackle the challenges and allow HetNet to reach its potential.

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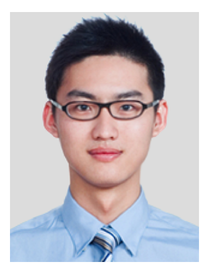

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