Recent Advances in Radio Resource Management for Heterogeneous LTE/LTE-A Networks

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***Abstract*—As heterogeneous networks (HetNets) emerge as one of the most promising developments toward realizing the target specifications of Long Term Evolution (LTE) and LTE-Advanced (LTE-A) networks, radio resource management (RRM) research for such networks has, in recent times, been intensively pursued. Clearly, recent research mainly concentrates on the aspect of interference mitigation. Other RRM aspects, such as radio resource utilization, fairness, complexity, and QoS, have not been given much attention. In this paper, we aim to provide an overview of the key challenges arising from HetNets and highlight their importance. Subsequently, we present a comprehensive survey of the RRM schemes that have been studied in recent years for LTE/LTE-A HetNets, with a particular focus on those for femtocells and relay nodes. Furthermore, we classify these RRM schemes according to their underlying approaches. In addition, these RRM schemes are qualitatively analyzed and compared to each other. We also identify a number of potential research directions for future RRM development. Finally, we discuss the lack of current RRM research and the importance of multi-objective RRM studies.**

***Index Terms*—LTE, LTE-A, heterogeneous networks, femtocell, relay node, radio resource management.**

Glossary

3G	3rd Generation.
3GPP	3rd Generation Partnership Project.
4G	4th Generation.
ACK	Acknowledgement.
NAK	Negative-ACK.
AMBR	Aggregate Maximum Bit Rate.
AMC	Adaptive Modulation and Coding.
BS	Base Station.
CDMA	Code Division Multiple Access.
CoMP	Coordinated Multipoint Transmission.
CQI	Channel Quality Indicator.
CSI	Channel State Information.
CUE	CoMP User Equipment.
DCI	Downlink Control Information.
DeNB	Donor evolved NodeB.
DUE	Direct User Equipment.
EPC	Evolved Packet Core.
E-UTRAN	Evolved-Univ. Terrestrial Radio Access Network.
eNB	evolved NodeB.
FDD	Freq. Division Duplexing.
FFR	Fractional Freq. Reuse.
FMS	Femtocell Management System.
FPC	Fractional Power Control.
FUE	Femtocell User Equipment.
GBR	Guaranteed Bit Rate.
HeNB	Home evolved NodeB.
HetNet	Heterogeneous Network.
ID	Identity.
IP	Internet Protocol.
IMS	IP Multimedia Subsystem.
IMT	International Mobile Telecommunications.
MAC	Medium Access Control.
MBSFN	Multicast-Broadcast Single Freq. Network.
MUE	Macrocell User Equipment.
MME	Mobility Management Entity.
OFDMA	Orthogonal Freq. Division Multiple Access.
LTE	Long Term Evolution.
LTE-A	LTE-Advanced.
PRB	Physical Resource Block.
P-GW	Packet Data Network Gateway.
QoS	Quality of Service.
QCI	QoS Class Identifier.
RN	Relay Node.
RRM	Radio Resource Management.
RSRP	Reference Signal Received Power.
RUE	RN User Equipment.
SAE	System Architecture Evolution.
SC-FDMA	Single Carrier-Freq. Division Multiple Access.
SFR	Soft Frequency Reuse.
SINR	Signal-to-Interference and Noise Ratio.
S-GW	Serving Gateway.
TCP	Transmission Control Protocol.
TDD	Time Division Duplexing.
TTI	Transmission Time Interval.
UE	User Equipment.
VoIP	Voice over IP.

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I. Introduction

CONVENTIONAL cellular systems, e.g., the 3rd Generation (3G) Universal Mobile Telecommunication System, can no longer support the recent, rapidly growing demand for high-speed multimedia applications such as voice over Internet protocol (VoIP), video streaming, Internet surfing, online games, etc., due to their limited capacity and data rate. This drove the 3rd Generation Partnership Project (3GPP) to create the Long Term Evolution (LTE) [1] cellular system, to achieve higher data rates and capacity to support those multimedia applications. With the ambition of exceeding the performance specifications given by the International Mobile Telecommunications (IMT)-Advanced, LTE-Advanced (LTE-A) is seen as an enhanced version of LTE, which is more often referred to as the "True 4th Generation (4G)".

LTE is introduced as a fully packet-switched optimized system with an exclusively Internet Protocol (IP)-based architecture for the core and radio access networks, as specified in 3GPP specifications [2]. The key enabling technology of LTE systems is orthogonal frequency division multiple access (OFDMA), where the channel bandwidth is divided into small radio resources known as physical resource blocks (PRBs) [3]. OFDMA is resilient to intracell interference and frequency selective fading, hence it is superior to code division multiple access (CDMA), which is employed in 3G cellular systems in terms of achievable capacity. However, intercell interference can adversely affect OFDMA systems, hence the need for an efficient radio resource management (RRM). Moreover, the LTE network is expected to support numerous real-time applications such as voice and video services, which impose strict quality of service (QoS) constraints while guaranteeing a certain fairness level for low-priority services. In 3GPP Release 10 [4], LTE-A is introduced with the intention of outperforming the specifications set by IMT-Advanced, adding further challenges into the RRM design. Numerous studies ([5]–[21]) have been carried out to meet these challenges.

A recent trend has emerged with the heterogeneous deployment of low-power nodes within macrocells thus forming a new communication network paradigm known as heterogeneous networks (HetNets). The low-power nodes are generally known as small cells, e.g., microcells, picocells, femtocells and relay nodes (RNs). In particular, femtocells and RNs have recently attracted more interest from academia and industry compared to other types of small cells due to the following reasons.

1) Femtocells:

- *Improved indoor coverage*: It is predicted that approximately 50% of phone calls and 70% of data calls will originate from indoor environments in the near future [22]. Unfortunately, indoor environments usually suffer from high indoor building penetration losses. Consequently, the signal from the macrocell base station (BS) becomes weak or cannot be detected in these environments, which are known as *coverage holes* of the macrocell. Fig. 1 illustrates the coverage holes in a macrocell. The deployment of femtocells in indoor environments would provide better coverage due to the close proximity between indoor users and femtocells.
- *Traffic offload*: Femtocells can reduce traffic congestion at a macrocell BS by handling traffic that would otherwise be carried over indoor broadband wirelines [23].
- *Reduced costs*: The deployment of small cells is considered to be more cost-effective compared to that of macrocells, since macrocell deployment entails careful planning and high installation costs. The installation of femtocells is based on a simple "plug and play" method, and the cost of backhauling a femtocell could be reduced via an indoor broadband connection [23].
- *Reduced power consumption*: By deploying small cells, users can receive a stronger signal from the nearest small cell. As such, a lower transmission power is required [23].
- *Improved QoS satisfaction*: Since a femtocell typically serves a small number of mobile users, more resources can be received by each user, thus leading to better QoS [24].

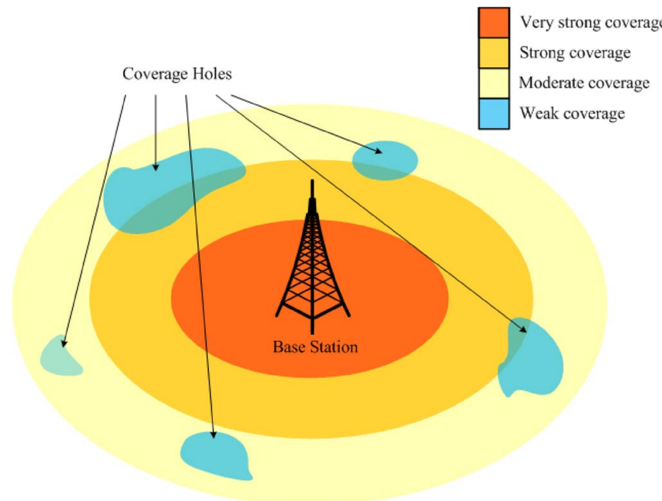


Fig. 1. Coverage holes in a macrocell.

2) Relay Nodes (RNs):

- *Improved cell-edge performance*: Generally, the signal strength of a macrocell BS at the cell-edge area is weak due to distance-dependent path losses and multipath fading. Therefore, deploying RNs at the cell-edge area would enhance the coverage and throughput performance [25], [26]. Besides, a more balanced load distribution between the cell-center and the cell-edge areas can be attained.
- *Reduced costs*: The cost of deploying RNs is relatively low in comparison to deploying eNBs [25].
- *Reduced power consumption*: Similar to femtocells, RNs can serve users with lower transmission power due to their close proximity.
- *Increased user capacity*: As RNs can improve the channel conditions (especially in the cell-edge area), a larger number of mobile users can be served [25], [26].

Although the HetNets technology is beneficial to LTE/LTE-A systems in many ways, several issues arise in terms of interference mitigation, radio resource utilization, fairness, complexity and QoS, all of which will be detailed in Section III. To realize the potential of the HetNets technology, intensive research has been carried out by both academia and industry to address these issues.

Several surveys and reviews [23], [27]–[30] related to the RRM for HetNets with femtocells and RNs have been published recently. In [27], the issues and approaches pertaining to interference management and resource allocation for OFDMA femtocell networks are briefly discussed. In addition to surveying the current issues and approaches, the survey in [23] provides a qualitative comparison in terms of interference mitigation, efficiency and complexity between the surveyed approaches. A more comprehensive survey of interference management and resource allocation techniques for OFDMA femtocell networks, with similar qualitative comparisons as in [23], is presented in [28]. The authors further classify the interference management and resource allocation techniques based on their underlying working principles or key enabling technologies. Another similar survey of interference management techniques for femtocells, including those for CDMA-based networks, is featured in [29]. However, unlike in [23] and [28], a classification and a qualitative comparison of interference management techniques are not provided in [29]. However, a survey of RRM schemes for relay-enhanced OFDMA-based networks is presented in [30]. Additionally, the authors provided a qualitative analysis of selected RRM schemes, with a primary focus on their complexity and fairness. It is worth mentioning that the existing surveys and reviews in [23] and [27]–[29] mainly focus on interference issues, with little attention being paid to other aspects such as fairness, resource utilization and QoS. Conversely, the survey in [30] provides neither an in-depth discussion nor an analysis in terms of interference mitigation, resource utilization and QoS. Moreover, the scope of the previous surveys is limited to general OFDMA-based cellular networks. As such, the discussion, with reference to the physical layer and RRM implementation constraints imposed by cellular systems such as LTE/LTE-A, is less in-depth.

In this paper, we aim to fill the research gaps found in the previous surveys by presenting a more comprehensive survey of the RRM schemes proposed in recent years for LTE/LTE-A HetNets. In particular, this survey mainly focuses on an in-depth technical review of the current challenges and of the existing RRM schemes that have been proposed in recent years for LTE/LTE-A femtocell and relay networks. That said, we focus more on the RRM schemes that perform spectrum allocation among small cells and packet scheduling among users, and less on other RRM functions such as admission control and handover.

In our survey, the more primitive existing RRM schemes are first reviewed, followed by the more intricate approaches, to reflect the knowledge advancement in the field to date. Additionally, a comprehensive qualitative assessment is carried out to compare existing RRM schemes in terms of interference mitigation, radio resource utilization, fairness, complexity and QoS. This assessment enables us to identify the strengths and weaknesses of existing RRM schemes. This assessment ultimately leads to the discussion of open issues and potential research directions for future RRM development. In this way, the contribution of this paper is fourfold with respect to previous surveys, as summarized below:

1) The importance of several challenges pertaining to RRM for LTE/LTE-A HetNets (interference mitigation, radio resource utilization, fairness, complexity and QoS) are highlighted and discussed.
2) A comprehensive survey of recently proposed RRM schemes for two-tier LTE/LTE-A femtocell networks is presented. The surveyed RRM schemes are classified according to their underlying approaches and how the mechanism of each approach addressed the technical challenges is examined. In addition, the RRM schemes are qualitatively analyzed and compared in terms of the aforementioned aspects of RRM.
3) A comprehensive survey of recently proposed RRM schemes for LTE/LTE-A relay networks is provided. Classifications and qualitative comparisons are also made across the surveyed RRM schemes.
4) A number of future RRM challenges and possible approaches that may be vital for further RRM development and improvement in LTE/LTE-A HetNets are identified. Lastly, conclusions are drawn to highlight the lack of current RRM research and to underline the importance of multi-objective RRM.

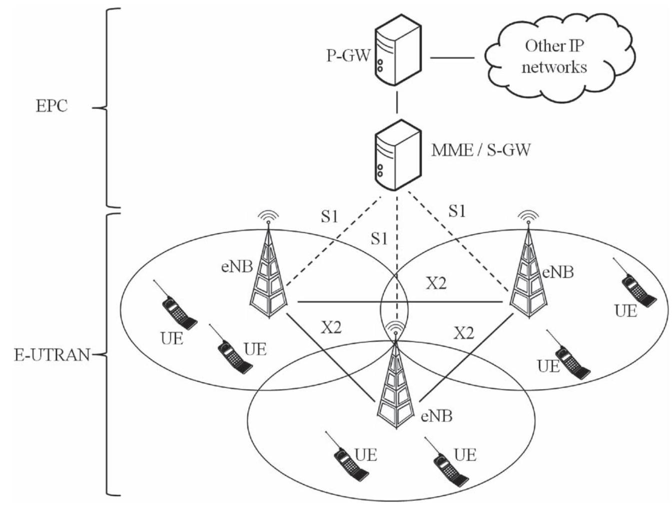


Fig. 2. LTE system architecture evolution.

The rest of this paper is organized as follows. Section II provides an overview of LTE/LTE-A networks. Section III describes the current technical issues and challenges arising from heterogeneous LTE/LTE-A networks. Section IV contains a comprehensive review of the existing RRM schemes for heterogeneous LTE/LTE-A networks with femtocells. A similar review for heterogeneous LTE-A networks with RNs is presented in Section V. Section VI discusses some potential future challenges and approaches. Lastly, Section VII concludes this survey and highlights some lessons learned.

II. Overview of Heterogeneous LTE/LTE-A Networks

This section provides an overview of the LTE/LTE-A architecture and the key aspects of RRM for LTE/LTE-A HetNets.

A. LTE/LTE-A Architecture

The LTE/LTE-A cellular system adopts System Architecture Evolution (SAE), which is an evolved network architecture that consists of a core network and a radio access network, as depicted in Fig. 2. The core network is known as the Evolved Packet Core (EPC), which is formed by the serving

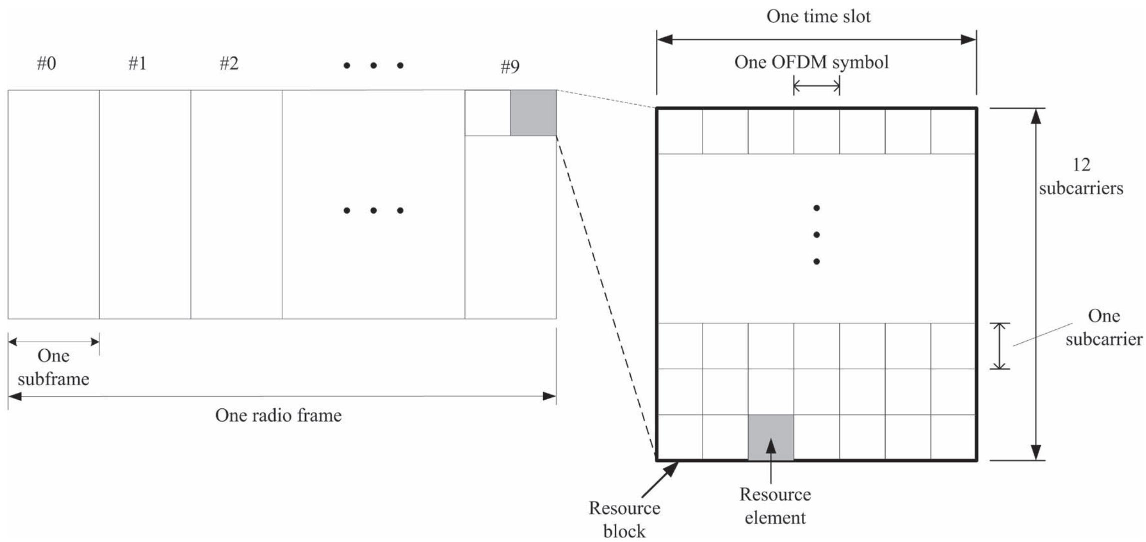


Fig. 3. LTE/LTE-A frame structure.

gateway (S-GW), the mobility management entity (MME) and the packet data network gateway (P-GW). The radio access network is known as the Evolved-Universal Terrestrial Radio Access Network (E-UTRAN), which comprises user equipment (UE) and macrocell BSs (macrocell BSs are known as evolved NodeBs [eNBs] in the context of LTE/LTE-A). Connections between the EPC and E-UTRAN are established through the S1 interface between the S-GW and eNBs. The X2 interface was introduced to allow interconnections among eNBs for direct signaling.

In the EPC, the S-GW serves as the local mobility anchor point for inter-eNB handover and inter-3GPP mobility, as well as for the handling of IP packet transfer between the EPC and the associated UEs. User mobility and connection management between LTE and other 3GPP technologies are handled by the MME. The MME also handles radio bearer management where a radio bearer is a data flow or logical channel established between an eNB and a UE [31], [32]. The P-GW serves as the medium between the EPC and other IP networks such as the Internet. It also performs IP address allocation for UEs and QoS enforcement. The eNB manages uplink and downlink transmissions among UEs and, unlike the traditional 3G radio access network, it also performs RRM functions and control signaling in the E-UTRAN for radio access.

In an LTE cellular system, a scalable system bandwidth of 1.4 MHz to 20 MHz is deployed; with carrier aggregation, a bandwidth of up to 100 MHz is achievable in LTE-A systems [2]. However, carrier aggregation does not form part of this study and, thus, will not be discussed further in this paper. In the physical layer of LTE/LTE-A systems, OFDMA is employed. The channel bandwidth is divided into small orthogonal PRBs [3], which is the smallest unit of radio resource to be allocated to UEs. Assuming a short cyclic prefix, each PRB consists of 12 consecutive subcarriers and seven orthogonal frequency division multiplexing symbols in which each PRB occupies a spectrum of 180 kHz and carries a time slot of 0.5 ms. With this multiple access scheme, the effect of frequency selective fading is reduced as a result of dividing the channel bandwidth into smaller frequency bands, with each exhibiting flat fading. On the other hand, the LTE/LTE-A uplink employs a linearly precoded OFDMA variant, namely the single carrier frequency division multiple access (SC-FDMA). The main reason to use SC-FDMA in the uplink is to reduce the peak-to-average power ratio of UEs, hence reducing their power consumption. In the downlink, the OFDMA allows the UE to be allocated multiple PRBs from any part of the channel bandwidth. However, unlike the downlink, the SC-FDMA imposes a constraint to the uplink, since only adjacent PRBs can be allocated to each UE.

In LTE/LTE-A systems, a radio frame consists of 10 subframes with each comprising two time slots of 0.5 ms. Thus, an LTE/LTE-A subframe has a period of 1 ms, which is one transmission time interval (TTI) and an LTE/LTE-A radio frame lasts 10 ms. Fig. 3 illustrates the structure of an LTE/LTE-A radio frame. Furthermore, there are two types of LTE/LTE-A frame structure that support frequency division duplexing (FDD) and time division duplexing (TDD) modes respectively. For further details about LTE/LTE-A frame structures, see [3].

When the UE is connected to an LTE/LTE-A network, a *default bearer* is set up for the UE, which is maintained throughout the connection lifetime. Additional bearers, namely the *dedicated bearers*, can be assigned to the connected UE for a new specific service. Radio bearers can be further classified into guaranteed bit rate (GBR) bearers and non-GBR bearers. The GBR is the bit rate expected to be achieved by a GBR bearer, while the aggregate maximum bit rate is the maximum bit rate achieved by each UE for all non-GBR bearers [33]. In fact, a default bearer belongs to a non-GBR bearer, while a dedicated bearer can be a GBR or a non-GBR bearer. Other QoS parameters for radio bearer management include allocation retention priority and QoS class identifier (QCI) [33]. The allocation retention priority is an important QoS parameter that decides whether to accept a bearer establishment or a modification request when resources are limited, especially during handover. The QCI is used as a scalar indicator to different classes of QoS requirements, as depicted in Table I [34].

TABLE I
MAPPING OF QCI SCALAR VALUE TO CLASSES OF DIFFERENT QOS REQUIREMENTS [34]

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2	GBR	4	150 ms	10^{-3}	Conversational Video (Live Streaming)
3	GBR	3	50 ms	10^{-3}	Real Time Gaming
4	GBR	5	300 ms	10^{-6}	Non-Conversational Video (Buffered Streaming)
5	Non-GBR	1	100 ms	10^{-6}	IP Multimedia Subsystem (IMS) Signalling
6	Non-GBR	6	300 ms	10^{-6}	Video (Buffered Streaming), Transmission Control Protocol (TCP)-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7	Non-GBR	7	100 ms	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
8	Non-GBR	8	300 ms	10^{-6}	Video (Buffered Streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9	Non-GBR	9	300 ms	10^{-6}	Video (Buffered Streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)

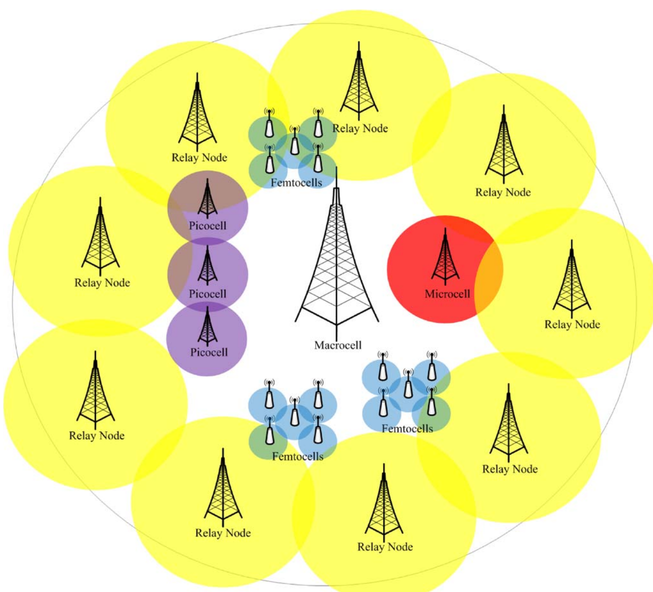


Fig. 4. Heterogeneous LTE/LTE-A networks.

B. Heterogeneous LTE/LTE-A Networks

An LTE/LTE-A network with a heterogeneous deployment of small cells such as microcells, picocells, femtocells and RNs is shown in Fig. 4. These small cells are usually deployed with the aim of filling the coverage holes within the macrocell and to increase capacity in densely populated areas. This results in saving the cost of deploying additional eNBs [25], [26], a process which requires careful network planning and optimization [35].

1) Femtocells: A femtocell, also known as the Home evolved NodeB (HeNB), serves as a short-range BS with low transmission power, mainly to be deployed in indoor environments [24]. The transmission power in femtocells typically ranges from 10 mW to 100 mW, while the coverage typically varies from 10 m to 30 m [23]. *Ad hoc* installation is one of the most attractive features of a femtocell. This "plug and play" feature enables mobile operators to save the backhaul cost as the traffic of the femtocell can be carried via subscribers' broadband communication links (such as the digital subscriber line [24], fiber optic and satellite links [36]) to the core network. Such backhaul links also help in offloading some of the traffic from the associated eNB, thus reducing traffic congestion at the eNB. Femtocells can be assigned by the mobile operator the licensed bands of the associated macrocell or distinct spectrum bands, [37] and can operate in different access modes, i.e., closed access, open access and hybrid access modes [38]. The closed access mode is an access control mode of femtocells, in which only registered members in the closed subscriber group of the femtocells are served. This access mode is suitable for residential areas. Open access femtocells allow all UEs to access them. In the hybrid access mode, all UEs are allowed to access the femtocells but a group of subscribers is prioritized.

TABLE II
CLASSIFICATION OF LTE-A RELAYS

Relay Type	Layer	Cell ID	Duplex Mode
Type-1	L3	Yes	Inband half-duplex mode
Type-1a	L3	Yes	Outband full-duplex mode
Type-1b	L3	Yes	Inband full-duplex mode
Type-2	L2	No	Inband half-duplex mode

2) Relay Nodes: The RN is defined in 3GPP Release 11 as one of the technologies supported by LTE-A systems [2]. In LTE-A systems, an RN is served by an eNB via a wireless backhaul link (eNB-RN). The serving eNB is referred as the *donor eNB* (DeNB) of the RN. An RN can operate in *inband* and *outband* relaying modes. In inband relaying, the relay backhaul link and the relay access (RN-UE) link share the same carrier frequency, whereas different carrier frequencies are employed for the backhaul and access links in outband relaying. In 3GPP Release 9, an RN is classified into Type-1 and Type-2 [4]. A Type-1 RN is an inband relay station that has its own physical cell identity (ID), and which appears as a distinct cell to UE. This type of RN is also called a Layer 3 relay, which comprises most of the RRM functions of a DeNB and supports self-backhauling. Two variants of Type-1 RN are further defined, namely Type-1a and Type-1b, in which the former operates in outband mode and the latter operates in inband mode. On the other hand, a Type-2 relay is a Layer 2 inband relay station that does not have a physical cell ID and supports only a few RRM functions. Table II provides a summary of the classification of LTE-A relays. In order to avoid the interference from an RN transmitter to its own receiver, the multicast-broadcast single-frequency network (MBSFN) subframe, which is used for multicast and broadcast applications, is configured to allow only backhaul transmissions between the RN and its associated DeNB. In an LTE frame, up to six subframes can be configured as MBSFN subframes [4].

C. Radio Resource Management

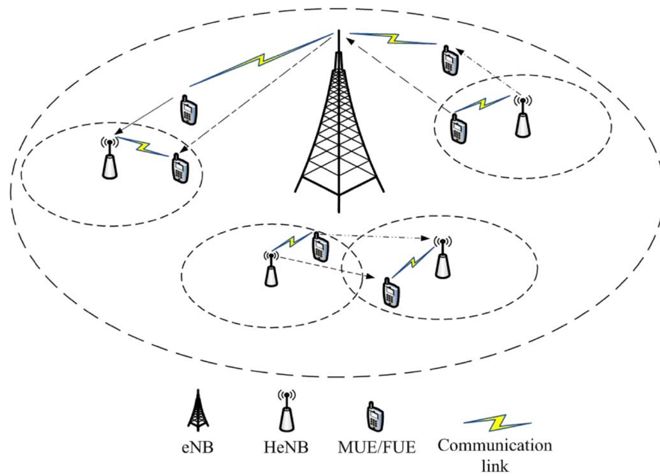
The main RRM functions in a heterogeneous LTE/LTE-A cellular system include: resource allocation/partitioning among macrocells and small cells, link adaptation, packet scheduling, radio admission control, handover management, etc.

1) Resource Allocation Among Macrocell and Small Cells: In HetNets, resource allocation/partitioning among macrocells and small cells may need to be performed, depending on which RRM approach is adopted. In a relay-based network, other considerations in resource partitioning include resource allocation between the backhaul link, the access link and the direct link (eNB-UE), depending on whether inband mode or outband mode is being operated. Factors to consider in resource allocation among the cells include: interference, resource demand, buffer size, number of users, etc. Resource allocation usually takes place at the eNB.

2) Packet Scheduling: Dynamic packet scheduling is one of the main RRM functions at the medium access control (MAC) layer of LTE/LTE-A systems, and it is carried out every single TTI to perform PRB allocation among UEs with the objective of maximizing the cell spectral efficiency and cell throughput. The scheduling decision may be based on the QoS requirement of each radio bearer of the UEs, the channel state information (CSI) or channel quality indicator (CQI) of the UEs, the interference level, etc. In heterogeneous LTE/LTE-A networks, the HeNB and the Type-1 RN can be equipped with packet scheduling to allocate PRBs to their associated UEs. Conventional scheduling methods that are widely used include proportional fair and round robin scheduling.

3) Link Adaptation: Link adaptation is another essential RRM function located at the MAC layer to achieve high user throughput performance with a given target block error rate [39]. Link adaptation functions include adaptive modulation and coding (AMC), and transmission power control. In AMC, a higher order modulation and coding scheme is assigned to UEs with better channel quality (as indicated by the CQI). The transmission power control usually operates jointly with AMC to further improve cell throughput. Additionally, the interference level can be controlled by means of such power control.

4) Radio Admission Control and Handover Management: The radio admission control entity is located at the radio resource control entity in Layer 3 of the LTE/LTE-A protocol stack, which decides whether a new radio-bearer admission request should be accepted. The decision is made according to the QoS requirements of the requesting radio bearer and the availability of radio resources such that the radio resource utilization can be maximized [2]. In order to admit a UE, the available radio resources must be sufficient to satisfy the QoS requirements of all the radio bearers associated with the UE. Decision-making can also be based on whether the UE is a new UE originating from the cell itself or a handover UE from a neighboring cell. Handover management is performed at the RRC layer, which handles user mobility and handover. In LTE/LTE-A systems, the handover procedure is network-controlled UE-assisted, i.e., the decision is made at the eNB, while signal strength measurements are obtained from the UE. Moreover, LTE/LTE-A systems only support hard handover, in which the radio resources are released by the serving eNB before new radio resources are assigned by the target eNB [2]. In addition, a random access procedure is evoked during the handover process for UEs to access the target BS. In LTE/LTE-A systems, contention-based and non-contention-based random access protocols are supported [2]. Both admission control and handover management can be implemented at the HeNB and Type-1 RN.



Interference	Direction	Source	Victim	Symbol
Cross-tier	Downlink	eNB	FUE	◄— — —
Cross-tier	Uplink	FUE	eNB	◄– – –
Cross-tier	Downlink	HeNB	MUE	◄-·-·-·
Cross-tier	Uplink	MUE	HeNB	◄———
Co-tier	Downlink	HeNB	FUE	◄- - - -
Co-tier	Uplink	FUE	HeNB	◄·-··-··

Fig. 5. Interference scenarios in two-tier femtocell networks.

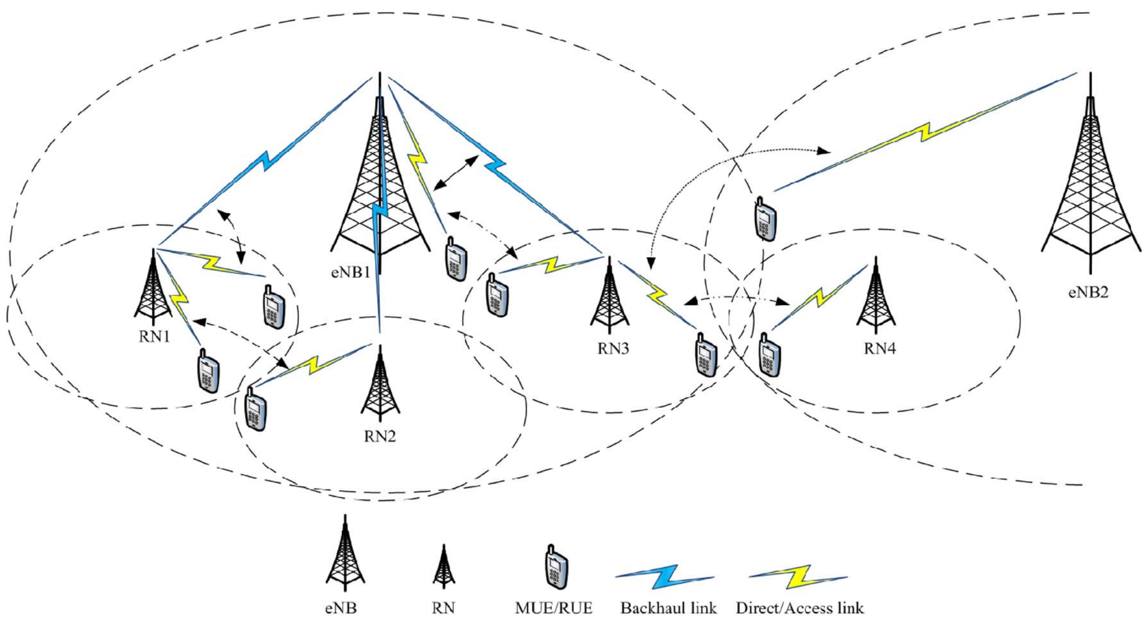
III. Issues and Challenges of RRM for HetNets

Although small-cell deployment benefits the LTE/LTE-A networks in many ways, several technical challenges and issues arise in RRM regarding aspects such as interference mitigation, radio resource utilization, fairness, QoS and RRM complexity.

A. Interference Management

In LTE/LTE-A HetNets, the overlaid small cells could either generate interference to an eNB or to other nearby small cells. In the literature, different terms are used to classify different types of interference in femtocells and RNs.

There are two types of interference in a two-tier femtocell network: *cross-tier interference* and *co-tier interference* [23]. Cross-tier interference is the co-channel interference generated between femtocells and macrocells. This interference occurs when both the femtocells and macrocells share the same set of PRBs. Fig. 5 depicts different cross-tier interference scenarios in both uplink and downlink. As femtocells are expected to be deployed in coverage holes, which suffer from the penetration losses of indoor environments [40], the interference between the eNB and femtocell UEs (FUEs) is virtually negligible. On the other hand, co-tier interference is the co-channel interference that occurs between femtocells. This happens when the femtocells are densely deployed within a macrocell, resulting in coverage overlaps among the femtocells. Some overlapping femtocells may reuse the same set of PRBs, causing interference in both uplink and downlink. Fig. 5 illustrates the possible co-tier interference scenarios in overlapping femtocells.



Interference	Interfering Links	Symbol
Intracell	eNB1 - RN3 eNB1 - MUE	←——→
Intracell	eNB1 – RN1 RN1 - RUE	←– –→
Intracell	eNB1 - MUE RN3 - RUE	←·–·→
Inter-RN	RN1 - RUE RN2 - RUE	←- - -→
Intercell	RN3 - RUE eNB2 - MUE	←·······→
Intercell/Inter-RN	RN3 - RUE RN4 - RUE	←··→

Fig. 6. Interference scenarios in relay-based networks.

In relay-based networks, also known as multihop networks [25], [26], interference can be categorized into *intracell interference*, *inter-RN interference* and *intercell interference*. Fig. 6 illustrates the possible interference scenarios in such networks. Intracell interference arises when the direct links, backhaul links and access links share the same set of PRBs. Inter-RN interference occurs when two adjacent RNs use the same set of PRBs. When an RN in a macrocell and a nearby macrocell UE (MUE) or an RN associated with a neighboring macrocell utilize the same set of PRBs, the interference generated is called intercell interference. The interference between two adjacent RNs associated with two different DeNBs respectively is also classified as inter-RN interference.

B. Radio Resource Utilization

One of the greatest challenges of LTE-A networks is to achieve the target downlink and uplink peak data rates of LTE-A, which are specified as 1 Gb/s and 500 Mb/s, respectively [40]. Given the current issues such as limited spectrum availability and low spectrum utilization, the efficient utilization of radio resources is crucial for achieving such high peak data rates. Intuitively, full frequency reuse, i.e., a frequency reuse factor of one is the best solution to achieve the aforementioned performance targets; but this introduces a tradeoff between radio resource utilization efficiency and interference management, where stronger interference is attributable to a higher reuse factor. Thus, an RRM scheme has to be designed in a way that minimizes interference as much as possible while maximizing the spectral efficiency. Designing the RRM scheme for HetNets is more difficult with a denser deployment of small cells, as this would generate stronger interference and complicate the radio resource allocation process. Therefore, the RRM scheme should be scalable and adaptive to the increasing number of small cells.

C. Fairness

Fairness is an important issue of RRM in many wireless networks. The traditional fairness problem in RRM is related to packet scheduling among UEs, where each UE should receive a fair amount of radio resources for wireless access. In HetNets, the fairness problem arises not only in scheduling but also in resource allocation among small cells. This issue is more complicated in multihop networks, as the fairness of resource partitioning between the direct link and the backhaul-access links has to be taken into consideration. Generally, the fairness issue in HetNets can be divided into *global fairness* and *local fairness* issues [41]. These terms have been introduced in [41] for LTE-A multihop networks, where the global fairness issue is related to resource allocation between the direct and the backhaul-access links, and the local fairness problem corresponds to packet scheduling among UEs. In the context of this paper, global fairness is generalized and defined as the fairness of resource allocation among small cells. In other words, if radio resources are allocated such that the resource demand of each small cell can be fully satisfied, the radio resource allocation is said to be "globally fair". On the other hand, if radio resources are allocated such that the lowest achievable rate among UEs or radio bearers is maximized, the allocation is said to be *max-min fair*. In other words, UEs or radio bearers with poor channel quality will receive more radio resources and those with good channel quality will receive a smaller amount of radio resources. As such, local fairness is said to be "high". To evaluate fairness, a performance metric known as Jain's fairness index [42] has been widely adopted.

D. QoS Management

Improved QoS experience can be achieved if the number of UEs served by a femtocell is small. However, some femtocells are expected to be deployed in public places such as airports and shopping malls, where the number of UEs could be large and the available radio resources may not be sufficient to fulfill the QoS requirements of each UE. Furthermore, QoS management becomes more challenging in heterogeneous LTE/LTE-A networks that have large numbers of small cells, where each small cell may have very limited frequency resources available after resource distribution from the eNBs. Therefore, fulfilling the QoS requirements of every UE requires a more sophisticated RRM solution, which must take into account the constraints of interference and limited radio resources. Moreover, designing a good QoS management that is compliant with LTE/LTE-A specifications (as shown in Table I) can be a difficult task.

E. Implementation and Computational Complexity

Complexity can be categorized into two types: 1) *computational complexity* and 2) *implementation complexity*. In this context, the implementation complexity of an RRM scheme refers to the amount of signaling overhead and information exchange between BSs required by the RRM scheme. On the other hand, the computational complexity of an RRM scheme refers to the processing time required by the RRM scheme to execute certain algorithms at the BS. As mass deployment of small cells is expected in LTE/LTE-A networks in the near future, traditional RRM schemes may not be feasible due to excessive signaling overhead between BSs, leading to prohibitive implementation complexity. In addition, since resource allocation among UEs is performed for every TTI in the LTE/LTE-A systems, this imposes a constraint on the maximum permissible computational time. Therefore, the computational time of an RRM algorithm must be kept within a TTI period. In summary, the need for joint consideration of both implementation complexity and computational complexity makes the RRM design more challenging.

IV. RRM in Heterogeneous LTE/LTE-A Networks With Femtocells

In this section, existing RRM schemes for LTE/LTE-A femtocell networks are reviewed. In general, these RRM schemes can be classified into centralized, decentralized and hybrid approaches.

In the centralized approach, each HetNet contains a single central entity that executes RRM functions. This central entity collects information such as channel quality and resource demand from both MUEs and FUEs, possibly via the serving BSs. Based on the information obtained, the central entity allocates the required amount of radio resources to each UE. This approach can provide optimal resource allocation for cellular networks, but the amount of signaling may be impractically large. Therefore, centralized schemes are only feasible for small-sized femtocell networks.

On the other hand, decentralized RRM schemes do not require a central entity and allow eNBs and HeNBs to determine by themselves the resource allocation among the associated MUEs and FUEs. This approach is attractive due to its low implementation complexity and low signaling overhead. However, optimal resource allocation among the UEs is difficult to achieve; this approach is more suitable for large-sized femtocell networks.

Although both centralized and decentralized approaches have their advantages and disadvantages, tradeoffs can actually be achieved between them. Such RRM schemes are said to be "hybrid" or "semi-centralized" or "partially decentralized." In these schemes, a central entity is used for performing certain global RRM functions, such as the gathering of channel and traffic information, while local RRM functions, such as packet scheduling, are decentralized to eNBs and HeNBs. Such schemes could be appropriate for moderately large networks.

Several RRM schemes share the same aim of achieving certain objectives but their working principles or technologies used can be very different. Therefore, a different classification can be made for RRM schemes based on the underlying working principles or the key enabling technologies. The key principles and technologies identified in the RRM schemes for LTE/LTE-A femtocell networks are: frequency scheduling, cooperative approaches, frequency reuse, femtocell-aware spectrum allocation, hybrid spectrum allocation, priority-based spectrum allocation, stochastic spectrum allocation, graph theory, femtocell clustering, cognitive radio, game theory, distributed learning and the power minimization approach. These principles and technologies are used to form the main features and capabilities of the RRM schemes. Thus, it provides useful insights to the reader about the characteristics of the RRM schemes and how well these approaches can perform in different aspects by understanding their underlying approaches. The following subsections will introduce the RRM approaches that are illustrated in Fig. 7 and will discuss in detail the recent RRM schemes under each of these approaches in addressing the RRM issues and challenges. The discussion and qualitative analysis of each of the surveyed RRM schemes are summarized in Tables III and IV.

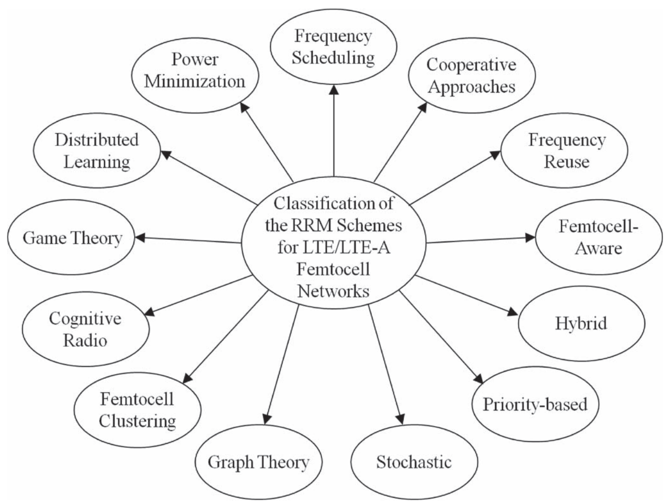


Fig. 7. Classification of RRM schemes for LTE/LTE-A femtocell networks based on the underlying working principles or key enabling technologies.

A. Frequency Scheduling Approaches

A simple RRM approach for LTE/LTE-A femtocell networks is to allocate PRBs to both MUEs and FUEs based on information such as the channel quality or the interference. This approach can be easily implemented in HetNets with either co-channel or orthogonal channel deployment. Some recently proposed RRM schemes that employ such a scheduling approach are discussed later in the paper.

In one of the earlier studies, Domenica and Strinati present a decentralized downlink frequency scheduling scheme for co-channel deployed self-organizing femtocell networks [43]. In order to reduce both cross-tier and co-tier interference, each HeNB first identifies the best PRBs based on the CSI of each FUE. Then, the HeNBs determine the best PRBs for all active FUEs according to their QoS and power constraints. In this scheme, the relevant QoS constraint is the outage probability, which is the probability of incorrect packet decoding. In addition, more PRBs, other than the assigned PRBs, are identified for each FUE until a target outage probability is satisfied. For fair packet scheduling among FUEs, the HeNBs employ the blind round robin scheduling scheme [44]. The authors also suggest using the matrix-based chunk allocation method [45] if the HeNBs are aware of their neighbors' presence and allocation strategy for better spectrum usage.

Clearly, the RRM scheme in [43] has low implementation and computational complexity since it is simple and decentralized while achieving efficient resource utilization. However, the round robin scheduler used is unfair in terms of user throughput, since it merely provides a fair time-sharing of resources among UEs, irrespective of the channel conditions and the amount of occupied resources [32]. On the other hand, the matrix-based chunk allocation method of [45] can guarantee proportional fairness. In fact, it is a proportional fair scheduling method that allows UEs with good channel conditions and low average past throughput to receive more PRBs. As such, a good tradeoff between max-min fairness and spectral efficiency can be achieved. Besides that, global fairness is not an issue since each HeNB can access the entire channel bandwidth. Another major concern is that the RRM scheme in [43] may still suffer from interference when an eNB and a HeNB, or two HeNBs use the same set of PRBs. This is most likely to occur when two BSs are adjacent to each other. However, this problem can be rectified if the eNB and HeNBs are aware of their adjacent interfering neighbors; a concept that has been investigated in [46].

In [46], the authors propose a centralized downlink proportional fair scheduling scheme for two-tier LTE femtocell networks that allows both MUEs and FUEs to be aware of their neighboring dominant interfering BSs. In this scheme, dominant interferers are identified based on the average received signal power at the UEs with respect to a predefined interference threshold. With this interference information, the PRBs allocated to a UE will not be scheduled to the UE's dominant interferers. In this way, cross-tier and co-tier interference can be alleviated. To implement the aforementioned RRM scheme in LTE femtocell networks, the authors leveraged the use of a central resource manager. In each scheduling interval, the central resource manager runs a proportional fair scheduler to allocate PRBs among UEs based on the interference and the CQI information obtained. As the central resource management operation is carried out at the eNB, the allocation information for FUEs is sent to the HeNBs via a femtocell backhaul. In addition, two power control schemes are proposed to reduce interference from nearby HeNBs to idle MUEs. The first power control scheme allows HeNBs to minimize their transmission power based on the transmission power level received from the eNB. The other scheme is based on user requests to reduce the transmission power of the interfering HeNBs.

Apparently, the scheme proposed in [46] is more refined in terms of interference management compared to that in [43], due to its interference-aware feature. However, the proportional fair scheduler used in [46] cannot guarantee QoS requirements [32]. Although the work in [43] does address this issue, the QoS constraint is only guaranteed per UE rather than per radio bearer. In LTE/LTE-A systems, each UE can hold more than one radio bearer and, thus, each UE may be imposed with more than one QoS constraint. Therefore, further studies on both [43] and [46] concerning QoS are required. On the other hand, the complexity of the RRM scheme in [46] is very high when large numbers of femtocells are deployed. Consequently, substantial signaling overhead will be incurred between the central resource manager and the HeNBs and the scheduling process will slow down with increasing user numbers.

B. Cooperative Approaches

In the cooperative approach, BSs exchange information to facilitate each other in performing resource allocation. Since the exchanged information is more reliable than self-estimation, a more effective and efficient resource allocation among BSs can be realized. Several ways of cooperation are discussed below.

In the RRM scheme proposed in [47], the eNB and the HeNBs cooperate with each other for downlink cross-tier interference mitigation. Within each scheduling interval, the MUEs first identify the potential interfering HeNBs in the downlink based on the reference signal received power (RSRP). They

TABLE III-PART I
SUMMARY OF RRM SCHEMES FOR LTE/LTE-A NETWORKS WITH FEMTOCELLS

Approach	Scheme	Working Principle
Frequency Scheduling	[43]	• PRB scheduling is based on the channel quality of each HeNB subject to outage probability and power constraints. • The resource allocation method in [45] is used if HeNBs are aware of their neighbors. Otherwise, the round robin scheduler is used.
	[46]	• Proportional fair coordinated scheduling based on identified dominant interferers and conditional CQIs.
Cooperative	[47]	• In the downlink, MUEs identify PRBs of poor quality and inform the HeNBs to cease transmission on the PRBs. • In the uplink, FUEs identify PRBs of poor quality and inform the eNB to cease transmission on the PRBs.
	[48]	• Each HeNB shares its own channel gain and traffic level information with other HeNBs. • Proportional fair scheduling and power allocation based on a Lagrangian method.
Frequency Reuse	[54]	• Frequency reuse is applied on femto tier. • The scheduler in [5] is used.
	[55]	• Some PRBs are reserved for MUEs. • Centralized proportional fair scheduling with PRB reuse.
	[58]	• Frequency bands are distributed across multiple macrocells based on the SFR technique. • Cell-edge FUEs can utilize the entire bandwidth while MUEs can utilize the whole cell edge bands. • Cell-center bands are divided into two portions based on a ratio with one serving FUEs and the other serving MUEs.
Femtocell-Aware	[59]	• Bandwidth is divided into two parts: macro dedicated spectrum and femto sharing spectrum. • Interfering MUEs are assigned PRBs from the macro dedicated spectrum while other UEs are assigned PRBs from the two spectra. • Proportional fair scheduling.
Hybrid	[60]	• MUEs can utilize the entire bandwidth. • A certain portion of the bandwidth, determined based on a splitting ratio, is reserved for FUEs.
	[61]	• Orthogonal resource preallocation between the eNB and HeNBs. • A shared factor is used to determine the amount of PRBs that can be shared by eNB to HeNBs and vice versa. • Round robin scheduling.
	[62]	• Inner femtocells operate in dedicated channel mode while outer femtocells operate in co-channel mode. • HeNB will be notified by the eNB if there are interfered MUEs nearby and the corresponding PRBs will be released.
Priority-based	[64]	• The channel bandwidth is divided to a number of chunks with each assigned to a distinct HeNB. • If additional PRBs are required, the HeNB will access other chunks with lower priority. • Round robin scheduling.
Stochastic	[65]	• System bandwidth is divided into a number of clusters. • FUEs are allocated from the PRB clusters based on the selection probabilities. • Indoor and outdoor MUEs are allocated first from clusters with the smallest and largest selection probabilities respectively.
	[66]	• System bandwidth are partitioned into two sets in which one serves the indoor MUEs and another serves the outdoor MUEs. • The FUEs are allocated from these two sets based on a stochastic rule.
	[67][68]	• PRB allocation among FUEs based on a likelihood metric that is determined using the obsolete DCI and ACK/NAK signaling.
Graph Theory	[69]	• Each HeNB estimates its own required PRBs. • PRB allocation among HeNBs based on an graph coloring method that minimizes the number of colors assigned. • Packet scheduling and power allocation among FUEs based on maximizing the minimum rate achievable by each FUE.
	[70]	• Link-conflict graph is used for representing the interference relationships among UEs. • PRB allocation among UEs based on a graph coloring approach that minimizes the number of colors assigned.
	[71]	• Resource allocation based on an interference graph coloring method that maximizes the PRB efficiency. • Admission control based on the QCI and the available PRBs in the HeNB is used to maintain QoS.
Femtocell Clustering	[75]	• Interfering femtocells is grouped in a cluster and a femtocell is selected as the cluster head for determining PRB allocation. • A feedback mechanism is used by FUEs to inform about collisions and remove the PRBs shared by other HeNBs/clusters. • Resource allocation among HeNBs is based on minimizing the gap between the numbers of PRBs required and allocated ones. • Round robin scheduling.
	[77]	• Similar to the first three points as in [75]. • Resource allocation among high-priority FUEs is based on maximizing the number of admitted high priority FUEs. • Resource allocation among best-effort FUEs is based on minimizing the gap between the numbers of PRBs required and allocated ones.
Cognitive Radio	[82]	• Cognitive radio is enabled in each HeNB to identify unoccupied PRBs. • Scheduling information from the eNB is compared with the sensing information from HeNBs to identify available PRBs.
	[83]	• Same as [82]. • Proportional fair scheduler.
	[84]	• Cognitive radio technology is enabled in each HeNB to identify unoccupied TV spectrum. • Unoccupied spectra are allocated among HeNBs in a frequency reuse manner. • Proportional fair scheduling.
	[85]	• Better transmission opportunities can be obtained if the HeNBs help to relay eNB's transmission. • Joint admission control and power allocation is based on Markov decision modeling and a Lyapunov optimization technique.
	[87]	• Cognitive radio is used to identify available unoccupied PRBs. • PRBs are allocated to FUEs such that the statistical QoS (transmission delay) requirement is guaranteed.
	[89]	• Spectrum sensing is performed to identify unoccupied PRBs. • Priority values are given to each UE based on types of traffic service classes. • PRBs, MCSs and transmit power are jointly allocated to each UE based on the assigned priority values.

TABLE III-PART II
(Continued.) SUMMARY OF RRM SCHEMES FOR LTE/LTE-A NETWORKS WITH FEMTOCELLS

Approach	Scheme	Working Principle
Game Theory	[90]	• Similar as in [85]. • A strategic game is used to share PRBs among collocated HeNBs.
	[81]	• Resource allocation problem among HeNBs is modeled as a correlated game. • An adaptive regret-matching algorithm is used to solve the game.
	[96]	• Resource allocation problem among UEs is modeled as a cooperative coalitional game. • A distributed coalition-formation algorithm is used to solve the game.
Distributed Learning	[97]	• Proportional fair scheduling. • Optimal power allocation among HeNBs based on Q-learning method.
Power Minimization	[101]	• PRBs, MCSs and power allocation among UEs based on minimizing the total transmission power subject to throughput demand constraints. • The optimization problem is solved based on an arbitrary MCS assignment, followed by a network simplex algorithm.

TABLE IV
QUALITATIVE COMPARISON BETWEEN DIFFERENT RRM APPROACHES FOR LTE/LTE-A NETWORKS WITH FEMTOCELLS

Approach	Scheme	Link Direction	Complexity	Interference		Spectral Efficiency	Fairness	QoS Guarantee
				Cross-tier	Co-tier			
Frequency Scheduling	[43]	Downlink	Low	Low	Low	High	Moderate / High	Moderate
	[46]	Downlink	High	Moderate	Moderate	Moderate	High	Low
Cooperative	[47]	Downlink	Moderate	High	-	High	-	-
	[48]	Downlink	Moderate	-	High	High	Moderate	Low
Frequency Reuse	[54]	Downlink	Moderate	-	High	High	Moderate	High
	[55]	Downlink	High	High	High	High	High	Low
	[58]	Downlink	Low	High	-	High	Low	-
Femtocell-Aware	[59]	Uplink and downlink	Moderate	Moderate	-	Moderate	Moderate	Low
Hybrid	[60]	Uplink and downlink	High	Low	Low	High	Moderate	Low
	[61]	Downlink	Low	High	-	High	Low	Low
	[62]	Uplink and downlink	Low	High	-	High	Low	Low
Priority-based	[64]	Downlink	Low	-	High	Moderate	Moderate	Low
Stochastic	[65]	Uplink	Low	Low	-	High	Low	Low
	[66]	Uplink and downlink	Low	Moderate	Low	High	Moderate	Low
	[67][68]	Downlink	Low	High	-	High	Low	Low
Graph Theory	[69]	Downlink	Moderate	-	High	Moderate	High	Low
	[70]	Uplink and downlink	Moderate	High	High	High	Moderate	Low
	[71]	Uplink and downlink	High	-	High	High	Low	High
Femtocell Clustering	[75]	Downlink	Moderate	High	High	Moderate	Moderate	Low
	[77]	Downlink	Moderate	High	High	High	Moderate	Moderate
Cognitive Radio	[82]	Uplink and downlink	Low	High	-	Moderate / High	-	-
	[83]	Uplink	Low	High	-	Moderate / High	Moderate	Low
	[84]	Uplink and downlink	High	High	Moderate	Low	Moderate	Low
	[85]	Uplink and downlink	Moderate	High	-	Moderate / High	-	-
	[87]	Uplink and downlink	Moderate	High	-	High	Moderate	Moderate
	[89]	Downlink	Moderate	High	Low	High	Low	High
Game Theory	[90]	Uplink and downlink	Moderate	High	High	High	Moderate	Moderate
	[81]	Downlink	Low	High	High	Moderate / High	Moderate	-
	[96]	Downlink	Moderate	High	High	Moderate / High	Moderate	Low
Distributed Learning	[97]	Downlink	Moderate	High	-	High	Moderate	Low
Power Minimization	[101]	Downlink	Moderate	-	High	High	Moderate	Moderate

then detect the PRBs that are of poor signal quality. After that, the eNB will forbid its associated HeNBs from using the PRBs. Such PRBs are determined based on the received signal-to-noise ratio (SINR) of the signals from the eNBs with respect to a predetermined threshold. Similarly, in the uplink, each FUE determines the PRBs that are of low SINR from the set of PRBs which are not prohibited by the eNB. Then, the HeNBs will forbid the eNB from using the low-SINR PRBs. The effectiveness of this cooperative approach in terms of throughput improvement over fixed shared and non-shared spectrum allocation has been demonstrated in [47].

Although the RRM scheme in [47] can mitigate downlink cross-tier interference, it does not address the co-tier interference problem. As affirmed in [47], it requires an additional power control scheme for co-tier interference mitigation. Also, it is unclear how eNBs and HeNBs exchange information. Moreover, fairness and QoS aspects are not addressed in [47]. Thus, it leaves plenty of room, including also the aspect of resource utilization, for further improvement.

In [48], the authors study a more sophisticated cooperative RRM scheme for downlink LTE femtocell networks. To enable information-sharing among HeNBs, a dedicated signaling channel is established via the X2 interface between HeNBs. The exchanged information includes the interference gain between HeNBs and the traffic load of each HeNB. With the interference and the traffic information, an optimization problem that maximizes the sum of the logarithmic rate of all FUEs is formulated. The optimal solution to such a problem is proportionally fair [49], [50]. However, the maximization problem is NP-hard. As such, the authors propose an enhanced version of the modified iterative water-filling algorithm [51] to approximate the optimal solution. In this algorithm, the resource allocation procedure is divided into two steps. In the first step, PRBs are allocated to FUEs using the proportional fair scheduling technique proposed in [52]. In the second step, power allocation is performed at each HeNB on each scheduled PRB. The allocated power for each scheduled PRB is computed by solving the Lagrangian of the maximization problem using the Karush–Kuhn–Tucker conditions [53]. The main implication of power allocation in a HeNB is that lower transmission powers are assigned on the PRBs to reduce co-tier interference to HeNBs which encounter heavier traffic or have relatively low achievable capacity.

Compared to [51], the simulation results in [48] demonstrated a notable improvement in terms of Jain's fairness index [42] but with a slight reduction in the average cell capacity. Furthermore, efficient resource-utilization is attained since all the PRBs are considered in the scheduling at each HeNB. However, the scheme proposed in [48] only guarantees local fairness. In addition, the issues of cross-tier interference and global fairness are not considered in the RRM framework.

Evidently, cooperation is an attractive approach. Both schemes proposed in [47] and [48] can efficiently address the interference problem by sharing and exploiting interference information. They introduce though, a non-negligible implementation complexity since information-sharing may require significant signaling overhead. Further studies concerning QoS issues are still needed, since the ones examined so far are suitable for medium-sized femtocell networks only.

C. Frequency Reuse Approaches

Frequency reuse has been an efficient and effective approach that can avoid interference and improve resource utilization in multicellular networks. In fact, frequency reuse can be applied in HetNets, since a HetNet can be viewed as a multicellular network. Some studies have explored the potential of this approach in LTE-A femtocell networks.

In [54], Capozzi *et al.* investigate the application of traditional frequency reuse techniques in LTE femtocells. Firstly, the channel bandwidth is divided into a number of frequency bands according to a predefined reuse factor. Next, the frequency bands are assigned to femtocells in such a way that any two non-adjacent femtocells can reuse the same frequency band. This technique is found to be very effective in reducing co-tier interference while efficiently reusing the radio resources. The scheduling strategy proposed in [5] is used for packet scheduling. This scheduling approach has an upper-level scheduler and a lower-level scheduler. The upper-level scheduler determines the amount of data required for transmission by each real-time data connection (such as a video flow) in the interval of an LTE frame, such that the delay constraint is fulfilled. On the other hand, the second scheduler allocates PRBs to each real-time data connection in a proportional fair manner, subject to the data amount determined by the first scheduler. The remaining available PRBs are allocated to non-real-time connections, such as to the best-effort flows using a proportional fair scheduler. This strategy gives high priority to real-time connections, thus guaranteeing low packet loss rates for real-time data transmissions. The outcome of the study in [54] indicates that a moderate reuse factor can optimize the achievable throughput and packet loss rate.

Traditional frequency reuse techniques work well with a QoS-aware fair scheduler, as shown in [54]. Resources are efficiently utilized and QoS guarantees are provided to real-time connections. Despite that, traditional frequency reuse techniques are not able to adapt to situations where HeNBs have diverse demands. To ensure global fairness, the frequency reuse techniques must be designed to be more dynamic; though this remains a challenging task in this area. Moreover, the study considered co-channel spectrum usage among macrocells and the associated femtocells and, hence, cross-tier interference.

In [55], Saha *et al.* propose a more dynamic downlink frequency reuse technique for two-tier LTE-A femtocell networks. In a similar fashion, the PRBs are reused in such a way that the FUEs from any two non-adjacent HeNBs can be allocated the same PRBs as in [54]. However, unlike [54], the PRBs are reused individually in [55] instead by dividing and reusing distinct frequency bands. In each scheduling interval, PRBs are allocated to both MUEs and FUEs using a conventional proportional fair scheduler subject to a PRB reuse strategy. In this strategy, the PRBs allocated to MUEs will not be reused in any tier; the PRBs allocated to FUEs can be reallocated to other FUEs from non-adjacent femtocells. As a result, both cross-tier and co-tier interference are avoided and efficient resource utilization is attained, while proportional fairness is guaranteed. Additionally, several PRBs are reserved and allocated to MUEs to ensure minimal performance in the macro tier.

The RRM scheme in [55] looks more promising compared to that in [54] in terms of global fairness, though several shortcomings can be observed; one major problem is that this RRM scheme can only be implemented in a centralized manner because it requires the HeNBs' location information, and the scheduling process involves both the MUEs and the FUEs. As such, a large amount of signaling overhead is needed. Further, QoS is not addressed.

On the other hand, an RRM scheme based on soft frequency reuse (SFR) [56], [57] for two-tier LTE femtocell networks is studied in [58]. In this scheme, the system bandwidth is partitioned into three frequency bands. The frequency bands are assigned using the SFR technique across multiple macrocells, as depicted in Fig. 8. The distance from the eNB to the boundary of the cell-center region is determined such that the estimated achievable throughput of the cell-edge MUEs approximates a predetermined threshold. In such a frequency reuse pattern, the cell-edge FUEs can exploit the entire bandwidth, since they are far away from the eNB. However, cell-center FUEs can still interfere with cell-center MUEs. Hence, a frequency band allocation ratio is used to obtain a portion

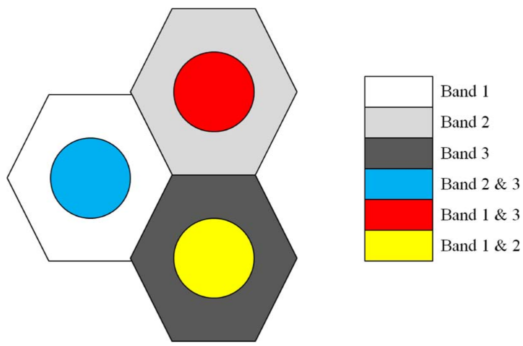


Fig. 8. SFR-based frequency band allocation in [58].

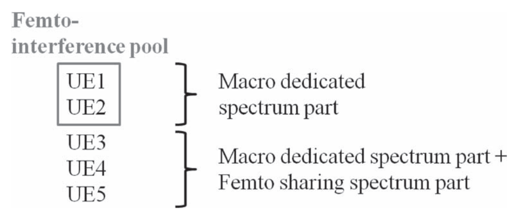


Fig. 9. Resource partitioning scheme in [59].

of each frequency band allocated to the cell-center region for serving the cell-center MUEs and the other portion serves the cell-center FUEs. An exhaustive search is required to find the optimal frequency band allocation ratio, such that the energy efficiency of the whole network is maximized. Additionally, MUEs can be allocated PRBs from the cell-edge band, aside from the portions allocated to the cell-center bands.

The RRM scheme in [58] can avoid cross-tier interference while guaranteeing efficient resource utilization. However, many aspects are not accounted for in the study, such as fairness and QoS. Also, co-tier interference is not mitigated by the scheme. However, it is feasible for practical implementation due to its low complexity.

D. *Femtocell-Aware Spectrum Allocation Approaches*

In one of the pioneering works, a static femtocell-aware spectrum allocation scheme for two-tier LTE networks is studied [59]. In this scheme, the available bandwidth is partitioned into two portions, namely a macro-dedicated spectrum and a femto-sharing spectrum. Additionally, a femto-interference pool, which is a list of MUEs that are potential interferers to nearby femtocells, is maintained by the eNB. The key idea is to allocate PRBs to members of the femto-interference pool from the macro-dedicated spectrum, while other MUEs and FUEs can be allocated PRBs from macro-dedicated and femto-sharing spectra. An example illustrating this resource partitioning scheme is shown in Fig. 9. In this fashion, less cross-tier interference is generated. The moving speed and the CQI information are exploited to identify interfering MUEs. MUEs with low moving speeds and high CQI values in the macro dedicated spectrum will be classified as interfering MUEs. Packet scheduling among UEs is performed using a proportional fair scheduler.

The complexity of the RRM scheme in [59] is deemed reasonable, even though some signaling overhead and computations are incurred. Nevertheless, the issues of co-tier interference and global fairness are not studied. As such, its suitability for densely deployed femtocell networks remains unknown.

E. *Hybrid Spectrum Allocation Approaches*

Two strategies are often investigated in spectrum allocation between the macro tier and the femto tier in LTE networks. The first strategy is known as orthogonal spectrum allocation where the available spectrum is divided into portions, with each serving a certain group of UEs (e.g., MUEs or FUEs). This strategy is beneficial in terms of interference mitigation but resource utilization is inefficient. The second strategy is referred to as co-channel spectrum allocation, where all UEs share the same spectrum. In contrast to orthogonal spectrum allocation, the network enjoys efficient spectrum usage but suffers from strong interference. In order to strike a good balance, several studies have developed hybrid spectrum allocation schemes by merging these two strategies.

In [60], a simple semi-static hybrid spectrum allocation scheme is developed for two-tier LTE femtocell networks where bandwidth is assigned to MUEs while a portion of it is assigned to FUEs. The size of the portion of the bandwidth assigned can be adjusted using a spectrum splitting ratio which can be defined by the operator. In addition, a max-min fair scheduler is used for each BS. To achieve a good tradeoff between fairness and spectral efficiency, the spectrum splitting ratio can be adjusted to an optimal value.

Although the scheme proposed in [60] provides flexibility to the operator for adjusting the spectrum-splitting ratio, it is still difficult to be calculated. As such, a brute-force approach may be required, which leads to high complexity and yet cross-tier interference could still remain. Nonetheless, local fairness is guaranteed by using the max-min fair scheduler but global fairness needs to be further investigated.

In [61], Yang *et al.* propose a semi-static downlink spectrum allocation technique for two-tier LTE-A femtocell networks. The primary objective is to achieve the best compromise between spectral efficiency and cross-tier interference mitigation. To meet this objective, a hybrid downlink spectrum assignment scheme that allows flexible resource utilization was designed. In this spectrum assignment scheme, the available channel bandwidth is prepartitioned into macro and femto spectra orthogonally. Depending on the location of each HeNB, the eNB can share a fraction of the macro spectrum with the HeNBs. The size of the fraction shared is determined by a partially shared factor, which is calculated based on the RSRP at the HeNB with respect to a cell-edge bound value. If a HeNB is located far away from the eNB, the factor becomes larger, and a larger fraction can be shared. Conversely, the femto spectrum can be shared with the eNB in a similar approach by considering its distance from the its nearest HeNB. In addition, each BS runs a round robin scheduler for packet scheduling.

The hybrid spectrum assignment scheme proposed in [61] can be tuned between fully orthogonal and fully shared spectrum assignment configurations. The former configuration corresponds to the partially shared factor value of one, whereas a zero value corresponds to the latter. This provides flexibility to mobile operators in deploying a desirable and efficient spectrum configuration. However, the fairness aspect needs further refinement. This drawback can be addressed by using a proportional fair scheduling strategy on top of the hybrid spectrum assignment scheme.

A different semi-static hybrid spectrum assignment scheme is presented in [62] for two-tier LTE femtocell networks. In this scheme, two spectrum usage modes are proposed, i.e., co-channel and dedicated modes. In the co-channel mode, both the MUEs and the FUEs share the same radio resources, whereas, in the dedicated modes, the spectrum is divided into two portions, one serving the MUEs and the other serving the FUEs. The femtocells underlaid within a macrocell are further categorized into inner and outer femtocells. The inner femtocells are those located near the eNB while the outer ones are located at a distance from the eNB. In order to avoid cross-tier interference, the inner femtocells operate in a dedicated mode and the outer femtocells operate in a co-channel mode. In this way, the cross-tier interference between the eNB and the inner femtocells is avoided, while radio resources are efficiently utilized in outer femtocells where cross-tier interference is negligible. In addition, a notification mechanism is implemented at the eNB to inform the HeNBs about the MUEs that are getting interference. Upon receiving this information, the corresponding PRBs are released by the interfering HeNBs to the MUEs that are getting interference. Also, fractional power control (FPC) [63] is used to reduce downlink cross-tier interference from the FUEs to the eNBs.

The hybrid spectrum arrangement scheme in [62] is simple and efficient for interference mitigation and resource utilization. Also, the overall implementation and computational complexity is relatively low. Nevertheless, several aspects including fairness are not studied in detail.

It is worth mentioning that hybrid spectrum allocation strategies only aim to address the spectrum-sharing issue between MUEs and FUEs. Therefore, an additional mechanism for co-tier interference mitigation is required in hybrid spectrum allocation strategies. Also, the QoS issue is not considered in these studies [60]–[62]. Nonetheless, the hybrid spectrum allocation approach can be further enhanced in the aforementioned aspects.

F. Priority-Based Spectrum Allocation Approaches

Instead of fully sharing the entire bandwidth, the HeNB may utilize a certain chunk with a certain priority level. This idea is first exploited in [64] to alleviate co-tier interference in the downlink of LTE-A femtocell networks. Initially, the channel bandwidth is divided into several equal-sized chunks according to the number of femtocells in the network. Then, each chunk is designated to a femtocell. The designated chunk is known as the *priority chunk* of the femtocell. In this configuration, the femtocells are always allowed to schedule PRBs from the designated chunk, but lower priorities are given to the priority chunks of other HeNBs. However, the femtocells schedule the PRBs only from their priority chunk if the amount of available PRBs is sufficient to support their traffic load. When additional PRBs are needed, the PRBs from low-priority chunks are selected based on the average SINR experienced by the FUEs belonging to the requesting HeNB. In this way, the resource demand of each femtocell can be satisfied, thus guaranteeing global fairness. After the required amount of PRBs is fulfilled, the FUEs are allocated PRBs in a round robin manner. However, when a femtocell utilizes the PRBs from low-priority chunks, the femtocell will interfere with other femtocells that use the chunks. As such, a power control mechanism is employed to limit the transmission power on additionally selected PRBs to minimize co-tier interference.

With the configuration proposed in [64], a minimal network performance guarantee can be maintained with low complexity. This configuration can be extended to address cross-tier interference, which is not studied in [64]. However, a drawback may be manifested when the number of active femtocells changes in each scheduling interval, thus requiring spectrum arrangement to be reconfigured in every scheduling interval, although the complexity can still be kept low. There is still room for improvement in this configuration [64], especially concerning resource utilization.

G. Stochastic Resource Allocation Approaches

In the literature, several studies have been conducted to manage interference in a probabilistic manner. In other words, radio resources are allocated to the UEs based on same probabilistic values that characterize the likelihood of getting interference from or interfering with, other UEs or BSs. Such resource allocation strategies are said to be stochastic.

A stochastic spectrum allocation approach is proposed in [65], which allocates PRBs to FUEs based on probabilities. In fact, the RRM scheme in [65] is quite similar to that of [64], in that they both divide the channel bandwidth into chunks. However, unlike the scheme in [64], each chunk is assigned a selection probability rather than a priority level. In this way, the FUEs will most likely be assigned the PRBs from the chunk with a high selection probability. Intuitively, the MUEs should avoid being allocated PRBs from the chunks with a high selection probability to avoid cross-tier interference. Therefore, the MUEs are allocated PRBs, starting from the chunks that are less likely to be occupied by FUEs.

The RRM scheme in [65] is implemented in an uplink two-tier LTE system with closed-access femtocells. The indoor and outdoor MUEs are further identified where the former are those interfering with by neighboring HeNBs and the latter are not. Both indoor and outdoor MUEs are identified based on the measurement reports received at the eNB. The uplink system bandwidth is divided into a fixed number of continuous PRB chunks of different sizes. Then, large-sized chunks are assigned high selection probabilities, while small-sized chunks are assigned low selection probabilities, as illustrated in Fig. 10. In each scheduling instant, each HeNB allocates PRBs to their associated FUEs from the chunks based on the assigned selection probability. On the other hand, the indoor MUEs are allocated PRBs that start sequentially from the end of the channel bandwidth that begins with a small-sized chunk. Since the outdoor MUEs are located far away from the HeNBs, the PRBs are allocated starting from the large-sized chunk

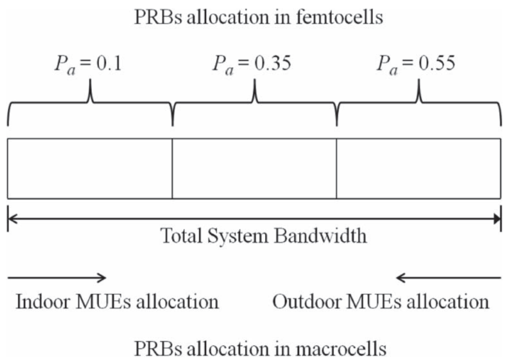


Fig. 10. Resource allocation scheme in [65].

at the end of the channel bandwidth. Although the outdoor MUEs could still generate some cross-tier interference, this shortcoming is tackled by tuning the path-loss compensation factor in the uplink FPC [63].

The probabilistic spectrum allocation and scheduling scheme in [65] has a low complexity because the scheduling function is decentralized to each HeNB and the information about the partitioned spectrum can be known *a priori*. The authors also proposed another variant of the probabilistic spectrum allocation approach in [66], which is more dynamic and takes into account fairness and co-tier interference.

In [66], the authors propose a decentralized dynamic spectrum allocation technique based on a stochastic resource-scheduling approach for both uplink and downlink LTE networks with closed-access femtocells. In the dynamic spectrum allocation technique, the channel bandwidth is partitioned into two sets of PRBs, in which one serves the indoor MUEs and the other serves the outdoor MUEs. The size of the two sets depends on the instantaneous indoor traffic load generated by indoor MUEs. The larger the indoor traffic load, the larger the indoor set and the smaller the outdoor set. Based on a stochastic rule, the FUEs are allocated PRBs iteratively, until their resource demand is satisfied. According to this rule, a PRB is selected and allocated to the corresponding FUE in every iteration from any of the two sets according to a certain probability. This probability is calculated based on the number of available PRBs in the two sets and on a bias parameter. Given a fixed bias-parameter value, if the number of available PRBs in the indoor set is large, the FUEs will most likely be allocated the corresponding PRB. A similar allocation approach is applied to the outdoor set. The setting of the bias parameter plays an important role. If the value of the bias parameter is large, the probability for the indoor set will be low, while that of the outdoor set will be high. As a result, it is less likely that the FUEs will be allocated from the indoor set, hence there is less cross-tier interference. On the other hand, as most of the FUEs will be allocated from the outdoor set, the FUEs from two different HeNBs might be using the same PRBs, thus resulting in stronger co-tier interference. The opposite implication will be observed with a small bias value. In practice, an appropriate value of the bias parameter can be determined by the cross-tier interference threshold that an indoor MUE can withstand from a neighboring HeNB. In the uplink, a similar approach is used, except that the allocation is consecutive, starting from the chosen PRB.

Similar to the scheme in [64], the complexity of the RRM scheme in [66] is relatively low, since it is a decentralized approach and only requires macrocell broadcast signaling. However, the scheme proposed in [66] may be inefficient when a large-sized femtocell network is considered. The interference problem will become more severe, since more FUEs will have a higher probability of transmitting on the same PRBs. This predicament can possibly be addressed by increasing the channel bandwidth, but this solution is impractical. In addition, local fairness can be further improved by a proportional fair scheduling strategy.

In [67] and [68], RRM schemes, based on exploiting the downlink control information (DCI) transmitted from the eNBs to HeNBs, are proposed for LTE femtocell networks. Due to the fact that the DCI is transmitted via a backhaul (e.g., DSL), a non-negligible delay may incur for the DCI to reach the target HeNBs, thus rendering the information in the DCI obsolete. The key idea of the RRM schemes is to find the PRBs that are occupied by MUEs, and which are of good channel quality to the FUEs by using the obsolete information. The HeNBs "chase the shadows" of eNBs for PRB allocation, hence the name "*shadow chasing*". The shadow chasing principle is first introduced in [67], to mitigate cross-tier interference in two-tier LTE femtocell networks. In this approach, the authors make use of the obsolete DCI from the eNBs to allow the HeNBs to learn the PRB allocation among the MUEs. In the context of [67], the MUEs are classified into indoor and outdoor MUEs. In addition, the acknowledgement (ACK) and negative-ACK (NAK) signals from the MUEs are exploited, in conjunction with the DCI, to determine the likelihood of each PRB not being used by indoor MUEs. The likelihood is determined as follows:

a) If some PRBs are allocated to a MUE but ACK/NAK signals from the MUE are not overheard by the HeNB, the likelihood will be very high.
b) If an ACK is overheard, an indoor MUE is probably near the HeNB but the PRBs still have good channel quality, the likelihood becomes lower than that of case a).
c) If a NAK is overheard, an indoor MUE is probably near the HeNB and the PRBs have poor channel quality, the likelihood is the lowest.

After estimating the likelihood of each PRB, the HeNBs will allocate the PRBs with the largest likelihood to their associated FUEs. In this way, the FUEs will be less likely to interfere with the indoor MUEs, thus inducing less cross-tier interference. The likelihood expression in [67] is derived from a heuristic. In [68], to estimate the likelihood in a more deterministic manner, a Markov chain model is used.

In summary, the shadow chasing approach avoids interference in a stochastic or probabilistic manner by allocating the PRBs to FUEs in such a way that the MUEs are less likely to be interfered with. It provides better resource-utilization, but several aspects, such as fairness and QoS, are in need of further investigation. Co-tier interference is considered and, since the RRM operations are decentralized to each HeNB, the overall complexity is fairly low.

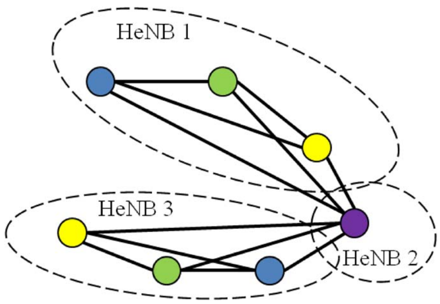


Fig. 11. Interference graph for representing the interference relationships between HeNB 1, HeNB 2 and HeNB 3, where HeNB 1 and HeNB 2 require three PRBs and HeNB 2 requires one PRB [69].

It is noteworthy that the aforementioned RRM schemes [65]–[68] cannot provide QoS provisioning to meet stringent QoS requirements such as those for video and VoIP services. Therefore, the QoS aspect needs further improvement before actual implementation in LTE/LTE-A systems.

H. Graph Theory Approaches

Considering a scenario where a multitude of femtocells are randomly deployed and located in an LTE/LTE-A network, the interference scenarios among the femtocells can become very complicated. Therefore, it is important to efficiently handle these complex interference issues between femtocells for resource allocation. In such a circumstance, a graph can be used to represent the interference relationships, and the resource allocation problem can be solved using graph theory. Several recently proposed schemes [69]–[71] based on the graph theory approach are discussed next.

In [69], a semi-centralized hierarchical RRM scheme is developed for downlink LTE femtocell networks, based on a graph theory approach. The hierarchical RRM process consists of three phases; in the first phase, the number of PRBs needed by each HeNB to guarantee a minimum data rate is estimated. The number of PRBs required by each HeNB is approximated according to the average channel gain experienced by each FUE in the femtocell across all PRBs using the Shannon's capacity formula. Then, in the next phase, resource allocation among the HeNBs is performed by a central server. The central server first constructs an interference graph that represents the interference relationship between every pair of HeNBs. The interference relationships are determined by the distance between each pair of HeNBs. If an HeNB is within the interfering range of another HeNB, and vice versa, then these two HeNBs are considered to be interfering with each other. After determining the interference relationships, an interference graph is drawn as follows: each HeNB is represented by a number of nodes (vertices) that equals the number of PRBs required. Two nodes are connected with a link (edge) if the two nodes are under the same HeNB, or if they are from two distinct HeNBs that are interfering with each other. An example of the interference graph is depicted in Fig. 11. After creating the interference graph, the resource allocation problem among HeNBs is solved by coloring the graph, where each node is assigned a PRB that is represented by a color. Any two linked nodes are colored with two different

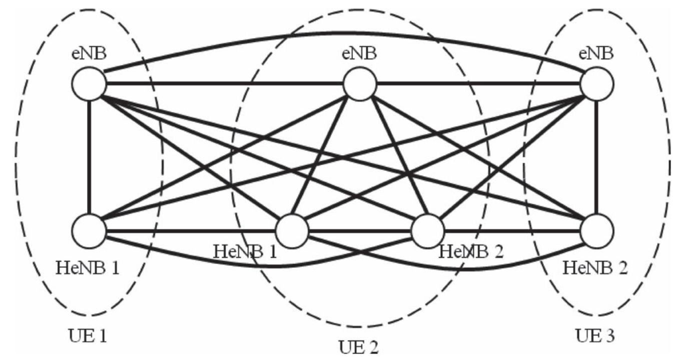


Fig. 12. Link–conflict graph for representing the interference relationships among UEs [70].

colors respectively, such that the two linked nodes do not share the same PRB. In this way, an interference-free environment is attained, while the resource demand of each HeNB is satisfied. Graph coloring is an NP-hard problem, which is solved using a heuristic proposed in [72] that minimizes the number of colors assigned. The colored graph is illustrated in Fig. 11. After performing the resource allocation among the HeNBs, each HeNB operates independently for PRB and power allocation as the final phase. The allocation is performed by solving a convex max-min fair optimization problem that maximizes the minimum rate achievable by each FUE, subject to the minimum requested data rate. The solution to this problem is obtained using a linear programming approach.

Co-tier interference is avoided in the RRM scheme proposed in [69]. This RRM scheme can be extended for cross-tier interference mitigation, but it has not been investigated in [69]. Also, the global and local fairness issues are addressed by satisfying the resource demand of each HeNB and giving more PRBs to FUEs with low achievable rates (i.e., poor channel quality), respectively. Moreover, the required signaling and computational loads are not heavy, since the packet scheduling function decentralized to each HeNB. Nonetheless, a deeper study on QoS requirements, such as packet loss rate and delay constraints, should be considered.

A study similar to [69] presents a graph theory-based resource allocation scheme with the aim of achieving max-min fairness [70]. The main difference between the schemes in [69] and [70] is that in [70] the interference graph is constructed as a link–conflict graph. In such a graph, each node represents a communication link between a UE and a BS. Since a UE may have more than one link, the nodes associated with the same UE will be grouped as a partition. As such, the number of partitions is equivalent to the number of UEs in the corresponding network. Fig. 12 shows an example of a link–conflict graph. Like in [69], a graph-coloring approach that minimizes the number of colors assigned is used. The graph is colored so that at least one node is colored in each partition. This is done by iteratively selecting a maximal independent set (i.e., a set of non-adjacent nodes that are not a part of other independent sets) and coloring all the nodes of the set with a particular color. After coloring, the graph is colored again by assigning colors to those nodes and their neighbors which have not been assigned colors. In addition, the minimum transmission power level that allows the

BSs to communicate with the corresponding UEs is selected to keep the interference to a minimum. In this way, a near max-min fair allocation can be achieved.

Practical implementation of the RRM scheme in [70] requires a central controller to initialize and execute graph coloring. Subsequently, each BS runs its own graph-coloring independently, by considering a local link–conflict graph that only involves the BS. If the BS cannot color all the corresponding partitions, the central controller will be called to perform coloring.

Though the scheme proposed in [70] can provide max-min fairness among UEs (i.e., local fairness is guaranteed), global fairness is not addressed because the actual resource demand of each HeNB or the eNB is not considered. Nevertheless, the interference problem is alleviated and radio resources are fully utilized. The implementation complexity is not high because the central controller will only be called on when needed. However, the computational complexity is not negligible.

In [71], a graph theory-based downlink RRM scheme, which is more refined compared to those in [69] and [70] in terms of QoS, is proposed. Unlike the schemes in [69] and [70], the interference graph is built so that each node represents an HeNB and each link indicates that the two connected nodes are interfering with each other. Also, the authors propose a different graph-coloring approach that maximizes the number of colors assigned for resource allocation. In the proposed graph-coloring approach, an optimization problem is formulated that maximizes the usage of each PRB (i.e., maximizes the number of colors assigned), subject to some interference and QoS constraints. The interference constraints are derived from the interference graph such that no two linked nodes are assigned the same color. On the other hand, the formulation of the QoS constraints is more thorough and compliant with the LTE standard. The QoS constraints allow each connection (radio bearer) to receive a certain amount of PRBs, depending on the QCI of the connections. If the QCI of a connection belongs to the GBR category, the connection will be satisfied with the number of PRBs required. Conversely, if the QCI belongs to the non-GBR category, at least one PRB will be allocated for the connection. Furthermore, the packet delay of every connection is guaranteed to be kept within a delay limit as specified in Table I from the LTE specification.

To implement the RRM scheme proposed in [71] in LTE femtocell networks, a centralized system implementation is suggested. Based on 3GPP specifications [2], a femtocell management system (FMS) connects to a group of femtocells within close proximity. As such, the FMS can be configured as a central controller for the femtocells. Therefore, the centralized implementation is compliant with the LTE femtocell architecture. In the RRM framework in [71], the FMS serves as the central controller for resource allocation among FUEs. In addition, each HeNB keeps a list that contains the cell ID of the interfering neighbors. The neighbor list is created as follows: Each HeNB periodically sends a notification to its neighboring HeNBs to announce its presence with a transmission power level that is double the regular level. If an HeNB receives the notification, the HeNB will add the sender to its "neighbor list." Then, the HeNB replies to the sender and the sender updates its list accordingly. Subsequently, the neighbor lists are sent to the FMS for interference-graph construction. During the resource allocation process, a "first-in, first-out"-based admission control mechanism is performed at the FMS to filter the connections that cannot be satisfied. The admission control mechanism is described as follows:

- If the HeNB has sufficient PRBs, the requesting FUE will be granted admission with all the requested PRBs granted.
- If the femtocell can only support partial PRBs, the GBR connections will be considered, i.e., the requesting FUEs will be granted sufficient PRBs for the GBR connections only.
- If the femtocell has insufficient PRBs, all connections requested by the FUE will be denied.

Consequently, a minimum QoS guarantee for the GBR connection can be provided to each FUE. After the admission control, the FMS performs the PRB allocation for the admitted connections. As stated earlier, the allocation is performed by using the proposed graph-coloring approach. The proposed resource allocation framework is shown to have a lower complexity than dynamic frequency planning [73] and adaptive fractional frequency reuse (FFR) [74], while achieving outstanding performance in terms of average throughput, rejection ratio of connection, average PRB efficiency and frame utilization.

It is worth noting that [71] has addressed the spectral efficiency and QoS aspects using the graph theory approach through simulation results. However, one of the major limitations is that the overall complexity is prohibitively high. The amount of overhead signaling needed is substantial as it is a centralized system. Moreover, the computational time may exceed a TTI if the number of FUEs or connections is large. Therefore, it is feasible only for HetNets with a small number of femtocells. Moreover, [71] does not consider fairness issues.

I. *Femtocell Clustering Approaches*

Femtocell clustering is a partially decentralized approach that involves the grouping of femtocells into clusters. Such clusters are formed by grouping femtocells that interfere with each other. Each cluster operates independently from the others for resource allocation among the femtocells. In this way, the co-tier interference can be effectively reduced. This approach is attractive because it is scalable to any network size, while the implementation complexity remains reasonable.

One of the first proposals based on femtocell clustering is known as the femtocell cluster-based resource allocation scheme [75]. In this scheme, the entire resource allocation process is divided into three stages; in the first stage, each HeNB creates a "one-hop" neighbor list, which contains the interfering neighboring femtocells, and this list is sent to all of its own one-hop neighbors. Then, each HeNB computes the interference degree, i.e., the number of interfering HeNBs of each of its one-hop neighbors. After that, each HeNB will decide by itself whether it should act as a cluster head or cluster member, based on the interference degree information. The HeNB with the highest interference degree in its neighborhood will be elected as the cluster head. The cluster members will attach to one of those cluster heads within their respective

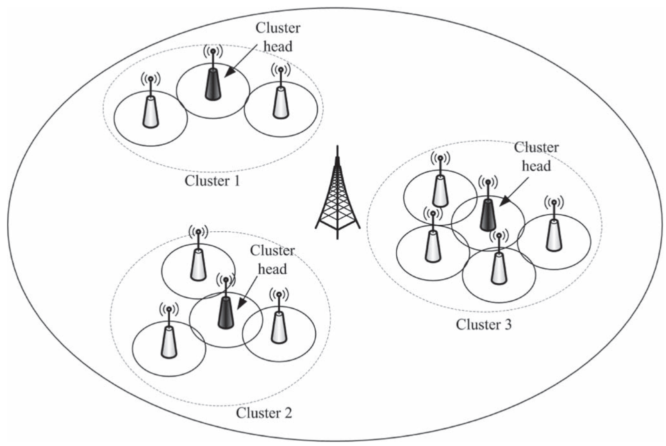


Fig. 13. Femtocell cluster-based resource allocation scheme [75].

neighborhood. If there is more than one cluster head in a HeNB's neighborhood, the one with the highest interference degree will be chosen. An example of cluster formation, as given in [75], is depicted in Fig. 13. In the second stage, the cluster head performs PRB allocation among its cluster members. To allocate PRBs within each cluster, an optimization problem is formulated with the objective of minimizing the largest difference between the number of allocated PRBs and the number of required PRBs in each femtocell. The problem is solved using the ILOG CPLEX solver [76]. As indicated by the authors, the optimizer provides a fast-convergence solution as the cluster size is likely to be small. For packet scheduling, PRBs are allocated to FUEs in a round robin manner. In the final stage, a feedback mechanism is enabled to allow each FUE to inform the serving HeNB about collisions and to remove the corresponding PRBs in cases where two adjacent femtocells (associated with two different clusters) are sharing the same PRBs. To avoid cross-tier interference, orthogonal spectrum allocation between macro and femto tiers is employed due to its simplicity and high spectral efficiency.

The RRM framework in [75] does not consider QoS issues. Therefore, an improved version is proposed in [77] that provides a QoS guarantee for HetNets that consist of hybrid access femtocells. The three-stage resource allocation process in [77] is similar to that in [75], except that a major modification is made at the second stage. In this modification, each femtocell cluster-head allocates PRBs among the FUEs within the cluster directly instead of among its cluster members. The PRB allocation is divided into two subproblems; in the first subproblem, the main purpose is to maximize the number of high-priority FUEs (subscribers of hybrid access femtocells) such that their resource demands are satisfied. To achieve this, a resource allocation and admission control mechanism is designed, using an elastic programming approach to remove high-priority FUEs that cannot be satisfied. The second subproblem aims to minimize the largest difference between the number of required PRBs and the number of PRBs allocated in each best-effort FUE (a non-subscriber of hybrid access femtocells), while avoiding interference with high-priority FUEs. Interference-avoidance is accomplished by stopping best-effort FUEs from using the PRBs assigned to the interfering high-priority FUEs. Similar to [75], the two subproblems are solved using the ILOG CPLEX solver.

The improved version in [77] brings drastic improvements in terms of overall fairness and QoS, by satisfying resource demands. Moreover, the variation in the complexity level of the improved version is insignificant. However, the QoS aspect can be further enhanced by considering packet loss rates and delay constraints. Moreover, in the context of LTE/LTE-A, the QoS requirements are guaranteed per radio-bearer instead of per UE. Nevertheless, this is one of the state-of-the-art femtocell clustering approaches.

J. Cognitive Radio Approaches

Recently, cognitive radio has been gaining great attention from both academia and industry. As cognitive radio is envisioned as the key leveraging technology for next-generation wireless networks [78], [79], intense research is currently being carried out in this domain. In fact, cognitive radio provides a potential solution to the spectrum scarcity problem, which is becoming dire. The key idea of cognitive radio is to intelligently find and exploit unutilized or under-utilized spectrum (also known as *spectrum holes* in [80]) in occupied frequency bands. The intelligent functions that perform such detection and exploitation are called spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. For further details about these functions, readers may refer to [78] and [79]. Other capabilities of cognitive radio include load balancing, interference coordination, capacity and coverage optimization, etc. [81]. In cognitive radio frameworks, two types of networks are identified: *primary networks* and *secondary networks*. Primary networks are those that own some bands of frequencies. These owned frequency bands are referred as the licensed bands of the primary network. Users in the primary network, namely *primary users*, are allowed to access the licensed bands at all times. Secondary networks, however, do not own any frequency bands. Instead, *secondary users* detect, and transmit on, spectrum holes in the licensed bands using cognitive radio functions that do not interfere with the primary network. Since cognitive radio has received great interest, a large number of research papers on the applications of cognitive radio in various wireless networks can be found.

Evidently, the applications of cognitive radio in LTE/LTE-A HetNets with femtocells have been investigated. One of them is studied in [82], where the authors propose a cognitive radio-assisted frequency scheduling method to address cross-tier interference. In this scheme, each HeNB first receives scheduling information from the eNB, regarding the PRB allocation among the MUEs via a backhaul connection (or over the airwaves). Then, the HeNB performs spectrum-sensing, using an energy detection method to find PRBs occupied by nearby MUEs. By comparing the scheduling information and the sensing information obtained, the HeNB determines which PRBs are unoccupied. In the comparison process, the scheduling information is used to identify nearby MUEs and their PRBs, and then the sensing information is used to check whether these PRBs are unoccupied. In this way, the HeNB can avoid interfering with nearby MUEs. However, this approach cannot provide global

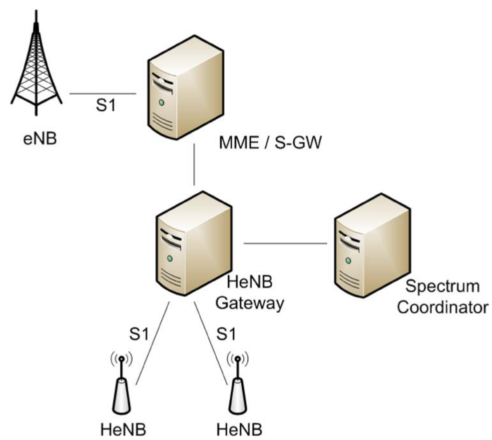


Fig. 14. LTE-A system architecture with a spectrum coordinator [84].

fairness, and the issues of co-tier interference, local fairness and QoS are not addressed. Nonetheless, the overall complexity is relatively low.

It is worth mentioning that the RRM scheme in [82] is also a cooperative approach, as the eNB cooperates by sharing its scheduling information with the HeNBs. However, it is only a one-sided cooperation, as the HeNBs do not share any information with the eNB and interference management relies more on the cognitive radio approach. Therefore, we consider this RRM scheme under the cognitive radio approach.

In [83], an RRM scheme which is slightly more refined compared to that of [82] is based on a centralized approach for uplink LTE femtocell networks. Like [82], unoccupied PRBs are identified for femtocells through a comparison between spectrum sensing and scheduling results. However, the main difference is that the comparison is done at the eNB instead of at the HeNBs, thus achieving more reliable identification. After determining the unoccupied PRBs, each HeNB runs a proportional fair scheduler independently for PRB allocation among its associated FUEs. In this way, the RRM scheme in [83] shows an improvement on local fairness over that in [82].

Another study in [84] applied cognitive radio to find additional spectrum for femtocells from TV bands in LTE-A networks. In the context of cognitive radio, TV broadcast networks are primary networks, while femtocell networks are secondary networks. The RRM architecture in [84] consists of HeNBs equipped with cognitive radio technology (which are also referred as cognitive HeNBs), and an additional spectrum coordinator, as illustrated in Fig. 14. When a cognitive HeNB is connected to the spectrum coordinator, the latter informs the former about the frequency subbands from the TV bands that are to be monitored. Then, the cognitive HeNB will perform spectrum sensing to identify the interference level in the subbands. Subsequently, the interference information is sent back to the spectrum coordinator. The decision concerning subband allocation among HeNBs is made by the spectrum coordinator, according to the interference level experienced by each HeNB on each subband. The subbands are allocated, as in a frequency reuse pattern, such that no two adjacent HeNBs share the same subbands but that a subband can be reused in two non-adjacent HeNBs. Additionally, the spectrum coordinator performs PRB *stealing* on some HeNBs to satisfy other HeNBs with heavier traffic demands. The signaling process between the cognitive HeNBs and the spectrum coordinator is based on the IEEE 802.21 media-independent handover signaling method. After receiving some subbands, each HeNB will run proportional fair scheduling to allocate PRBs among FUEs.

In [84], by targeting the TV bands, cross-tier interference is completely prevented. Also, co-tier interference is reduced by means of a frequency-reuse technique. Local fairness is addressed by using a proportional fair scheduler, but the scheduler provides no QoS guarantee. On global fairness, the scheme proposed in [84] may not fully satisfy the resource demands of each HeNB, because only under-utilized PRBs can be stolen from the targeted subbands. The implementation complexity is comparatively high, due to significant signaling exchanges between the HeNBs and the spectrum coordinator.

In [85], Urgaonkar and Neely introduced two cooperative resource-allocation models for cognitive femtocell networks. It is noted that, in contrast to [84], the target primary networks are macrocell networks. The first cooperative model is known as the cooperative relay model, which makes use of opportunistic cooperation to allow FUEs to act as relay stations for relaying MUE transmissions. In return, more transmission opportunities will be created for FUEs for their own transmission as the primary spectrum band's occupancy period would be smaller after the cooperative relaying takes place. In this way, the probability of an HeNB interfering with MUEs is reduced. The second model, which is known as the interference model, allows femtocells to defer transmissions during the busy periods of primary users. Again, in return, better transmission can be obtained by the secondary users. In particular, the interference model allows concurrent transmissions by both primary and secondary users. Following these models, a joint admission control and power allocation policy is designed to stabilize the secondary user's queue and to maximize the throughput, with some power and scheduling constraints imposed. In the admission control policy, if the packet queue of a secondary user does not exceed a predefined threshold, new packets will be admitted to the queue. Power allocation is performed in such a way that a certain power level is allocated to the secondary user to relay the primary user's packet in the cooperative relay model, or its own transmission in both cooperative relay and interference models. The power allocation problem is formulated as a constrained Markov decision problem [86], and is solved using an adaptive algorithm based on a Lyapunov optimization technique.

It is obvious that the scheme proposed in [85] can only address cross-tier interference problems. Other aspects, such as co-tier interference, fairness and QoS are neglected. Like the scheme in [82], it can be considered as a cooperative RRM scheme and the reason for it being classified as a cognitive radio approach is the same as that of the scheme in [82].

With the objective of addressing the challenge in QoS, the authors in [87] propose a cognitive RRM scheme for LTE femtocell networks. Akin to [85], the macrocell network is the target primary network in [87]. In this cognitive RRM scheme, a sensing period, which comprises a sensing frame and a number of data frames is defined. It is noteworthy that each frame in the context of [87] corresponds to an LTE subframe. During each sensing frame, each HeNB performs spectrum sensing to identify the occupied PRBs in the macrocell, using a threshold-based comparison method. After performing spectrum sensing, the sensing data is further processed to extract information that characterizes PRB allocation in the macrocell, which will be used for PRB allocation among the FUEs. In the data frames, the HeNB allocates PRBs to its associated FUEs in a manner that guarantees QoS, using the *effective capacity* theory [88]. The effective capacity theory provides a formulation based on statistical QoS requirements, where the probability of a packet delay exceeding a specific delay limit can be approximated as an exponential function of the delay limit which is a constant determined by the arrival rate, the service rate, and a QoS exponent. With the information acquired during the sensing frame, this probability can be calculated. Then, PRBs are iteratively allocated one-by-one, until the probability is kept below an acceptable threshold. Before that, the sensing period is set to a relatively large value. If the PRB allocation cannot satisfy the delay requirement under the given sensing period, the sensing period will be decreased and the PRB allocation is performed again. A similar procedure is repeated until the delay requirement is met. The reason for decreasing the sensing period is that the initial sensing period may be too large, thus causing large estimation errors and leading to a higher probability of inducing cross-tier interference. Therefore, the shortening of the sensing period will reduce the estimation error as the channels are more frequently sensed.

Compared to [85], the cognitive RRM scheme in [87] has better tackled the QoS issue. Although the co-tier interference problem is not addressed, it is studied in an extended work using game theory which will be discussed in the next subsection. Additionally, local fairness is not assured as the PRB allocation does not prioritize the UEs with poor channel quality.

Another recent RRM scheme is proposed in [89] to address the QoS aspect with a more in-depth consideration (compared to that in [87]) of cognitive femtocells in LTE networks. In [89], three QoS classes are considered: real-time, non-real-time and best-effort services. For real-time services, the QoS requirements considered are: packet delay, packet loss ratio and bit error rate. The minimum transmission rate and bit error rate correspond to non-real-time services. For best-effort services, only the bit error rate is considered. To meet the QoS constraints of each service class, an optimization problem that maximizes the data rate over all allocated PRBs for all UEs subject to QoS constraints is formulated. The optimization problem is solved in three steps; in the first step, spectrum sensing is performed to identify unoccupied PRBs in subsequent LTE subframes after the sensing time. Secondly, each UE is assigned a priority value depending on the service class. If the service class is real-time, the priority value is assigned based on the current delay. If the current delay approaches the maximum delay budget, the priority assigned becomes higher. For non-real-time services, the priority value is assigned according to the transmission rate. Best effort services are assigned a zero priority value. In addition, FUEs are given a higher priority compared to MUEs. Then, the minimum required number of transmission bits are allocated to each UE according to the priority value. In the final step, PRBs, MCSs and transmission power are jointly allocated to each UE, based on the priority value and the required SINR to transmit the minimum allocated bits.

It is evident that the QoS aspect is more compliant with LTE specifications in [89], compared to that in [87]. However, the RRM scheme in [89] is inferior to [87] in terms of co-tier interference mitigation. Co-tier interference still exists, since all HeNBs may sense and share the same set of occupied PRBs. The issue of fairness is neglected in [89].

As cognitive radio provides efficient resource utilization, the schemes proposed in [82], [83], [85], [87], and [89] can achieve high spectral efficiency, but not in [84]. This is because the scheme proposed in [84] does not reuse the available system bandwidth. Additionally, these schemes have low implementation complexity because no (or negligible) signaling overhead is required. Some of them may have high computational complexity due to the spectrum sensing function, but the overall complexity is reasonable.

In fact, many RRM schemes based on cognitive radio frameworks for LTE/LTE-A femtocell networks have been proposed. However, some of them were investigated from the perspective of game theory. Since the development of cognitive radio frameworks is based on game theory, these schemes will be classified separately under the game theory approach in the next subsection.

K. Game Theory Approaches

As stated earlier, several RRM schemes have been designed using game theory in addition to the cognitive radio approach. In fact, game theory has been widely investigated in cognitive radio networks and a tremendous amount of research has been done on it. On the other hand, game theory is a mathematical modeling tool, which is useful to study the interaction of multiple decision-makers. In particular, it helps to achieve equilibrium among decision-makers by assigning a strategy such that each decision-maker cannot increase the payoff by changing his or her strategy while others maintain theirs. Such a tool is powerful for solving resource allocation problems. In this context, decision-makers are the BSs and the strategies correspond to resource management. We review several game theory-based RRM schemes next.

In [90], the authors extend their previous work in [87] to address co-tier interference using game theory. Considering a scenario where femtocells are collocated, the cognitive RRM scheme in [87] may allow the HeNBs to identify the same set of unoccupied PRBs. However, the cognitive RRM scheme cannot configure the HeNBs such that the PRBs are shared in an interference-free manner. Therefore, the authors propose a strategic game-based RRM scheme for co-tier interference management as a supplement to the RRM framework in [87]. In the strategic game-based RRM scheme, collocated HeNBs are modeled using a strategic game. Each collocated HeNB has a strategy profile, where each strategy corresponds to a set of probabilities. In this set, each probability represents the likelihood of a specific number of PRBs being used among the unoccupied PRBs that are sensed. The payoff is the expected number of PRBs that do not experience co-tier interference. In addition, the HeNBs employ the same strategy, where the strategy would be known commonly among the HeNBs. In this game, the authors exploit the solution concept called the *Nash equilibrium* [91]. To achieve Nash equilibrium, a strategy profile must be such that:

1) The payoff of each HeNB is identical for all the specific numbers of PRBs that correspond to nonzero probability.
2) No other strategy profiles can yield a better payoff than the current strategy for all the specific numbers of PRBs that correspond to nonzero probability and all other numbers of PRBs that correspond to zero probability.

It is worth mentioning that there could be multiple Nash equilibria. In this case, the best equilibrium is chosen where the expected number of PRBs used for each femtocell is the largest. After each collocated HeNB determines the number of PRBs, PRB allocation is done in a similar manner as in [87]. Since the scheme proposed in [90] is inherited from that in [87], the strengths and weaknesses of the former is, in various ways, similar to the latter apart from the aspect of co-tier interference mitigation.

On the other hand, Huang *et al.* [81] introduce a decentralized PRB access scheme based on correlated game theory for cognitive LTE femtocell networks. Like [85], [87], [90], the macrocell and femtocells correspond to the primary and secondary networks respectively. In this scheme, a global utility function for the overall network is formulated as the satisfaction level of the worst-off HeNBs in terms of achievable data rates. The main goal of this scheme is to maximize the global utility function by means of PRB allocation. However, this cannot be achieved in a decentralized RRM architecture. Therefore, each HeNB will use and maximize a local utility function such that the global utility function is maximized. The local utility function comprises three components; the first component corresponds to the rate demand satisfaction level of the HeNB. The second component corresponds to fairness, which prevents HeNBs from behaving selfishly by consuming more PRBs. The third component corresponds to co-tier interference mitigation, which serves the purpose of minimizing transmission power. To optimize PRB allocation, the correlated equilibrium approach [92], [93] is used, which provides a strategy profile such that no other strategies could achieve a better utility for a decision-maker, apart from the strategy profile. In fact, correlated equilibrium is a generalization of the Nash equilibrium. Details of the correlated and Nash equilibria can be found in [94]. In order to achieve correlated equilibrium, the authors suggest an adaptive variant of the regret-matching algorithm in [95], where each HeNB reacts (transmits or does not transmit on a specific PRB) based on previous actions and the regret matrix, which represents the average gain in utility values of the HeNB after performing a certain action.

The scheme proposed in [81] can maintain good global fairness and efficient resource utilization. Moreover, both the co-tier and cross-tier interference problems are addressed. Cross-tier interference is avoided because a spectrum overlay approach is used where spectra are orthogonally allocated among the macrocell and femtocells. On the other hand, since PRB allocation among the UEs is not considered, the issues of local fairness and QoS issues are left untreated.

In [96], an RRM scheme based on the cooperative game theory approach is designed for cognitive LTE networks with closed access femtocells. In this scheme, collaborative coalitions that consist of a number of UEs are formed, with each coalition associated with a BS (i.e., eNB or HeNB). The coalitions are formed in such a way that the total network throughput is maximized, while a degree of fairness is guaranteed. To achieve this, a utility function that corresponds to a coalition is formulated as a linear function proportional to the throughput achieved by all the UEs belonging to the coalition. A payoff, defined as the increment of the utility function, is received by a UE when it joins a coalition. Then, an optimization problem can be formulated as the maximization of the average payoffs achieved over all the coalitions. Four constraints are imposed on the above-mentioned optimization problem, one of which is to ensure that the sum of payoffs for a coalition is equal to the total revenue achievable in that coalition. The second constraint is to ensure that the UE in a coalition is a subscriber to the closed access femtocells. In the third constraint, each UE must receive a predefined amount of payoff before joining any coalition. If this constraint cannot be fulfilled, the UE will form a singleton coalition that does not associate with any BS. Finally, a fair resource allocation is guaranteed such that there are no other possible resource allocations that can result in better payoffs for all UEs by joining another coalition. To solve this constrained optimization problem, a cooperative coalition-formation game is used. In this game, the UEs are the players that seek to join the best coalition to achieve optimal payoff allocation. Optimal payoff allocation is known as the *core*, when no other players can obtain a better payoff through another payoff allocation. The core is reached when the sum of all the payoffs equals the maximum of the sum of the revenue over all possible coalitions and the sum of the payoffs for a coalition is equal to, or larger than, the total revenue in the coalition. To reach the core of the game, a distributed coalition formation algorithm is proposed to iteratively obtain the PRB allocation that constitutes the best payoff allocation.

It is certain that the achievable spectral efficiency is high, since cognitive radio technology is leveraged in [96]. Also, almost all UEs are guaranteed an equal minimum payoff, hence it is moderately fair for all UEs. The authors have made an assumption that cognitive radio can effectively detect interference-free radio resources. Additionally, UEs receive low payoffs if the corresponding radio resources are of poor quality, which in turn discourages the UEs from joining the corresponding coalitions, thereby reducing both cross-tier and co-tier interference. The implementation complexity is relatively low, since the RRM scheme is decentralized to each BS, but the computational complexity could still be high due to the slow convergence of the algorithm in reaching the core.

L. Distributed Learning Approaches

One appealing RRM approach is to allow cellular systems to learn their wireless environment. The learned information may aid the RRM decision-making to achieve optimal resource allocation. This approach has been investigated in [97], where the authors employ a reinforcement learning technique [98] to develop a decentralized downlink power and PRB allocation scheme for femtocell networks, with the aim of mitigating cross-tier interference. Firstly, a proportional fair scheduling method is used by each HeNB to allocate PRBs among FUEs. Subsequently, the transmission power is allocated to each HeNB on the assigned PRBs, using a famous variant of reinforcement learning, namely the Q-learning approach [99]. In the Q-learning approach, the HeNBs are the learning agents and each agent has a set of actions. In the context of [97], the set of actions is a set of power levels that can be assigned. Also, a set of states is defined for each agent, where a state of an HeNB corresponds to the current power level, the data rate of the associated eNB, and the femtocell's capacity. A cost function is defined for evaluation of an action taken in a given state. If an action taken causes the cost function to increase, it means that the selected power level has exceeded the allowable threshold, or the macrocell capacity has dropped below the minimum limit. During the Q-learning process, each HeNB estimates a set of Q-values, where the Q-value is defined as the expected discounted sum of future costs. When an action is taken in a given state, a cost value results, which is used to estimate the corresponding Q-value. As such, a set of Q-values with each Q-value corresponding to an action and a state can be learned. After learning all the Q-values, the optimal power allocation for any state can be attained by taking the action that gives the smallest Q-value for the corresponding state. To obtain the state information from the macrocell, the authors exploit the X2 interface to convey the information from the eNB to the HeNBs. Simulation results show that this scheme outperforms the smart power control technique studied in [100].

In summary, the RRM scheme proposed in [97] can effectively mitigate cross-tier interference and guarantee local fairness for all the FUEs. A similar learning approach may be extended to mitigate co-tier interference, but such an approach is not studied in [97]. Nevertheless, other aspects such as global fairness and QoS need further attention.

M. Power Minimization Approaches

Reducing the transmission power of a BS will naturally reduce the potential interference that may be caused to other BSs. Radio resources can be reused more efficiently, as the interference is minimal. This approach is investigated in [101] where the authors study a power minimization-based RRM scheme for LTE femtocell networks, with the main aim of mitigating co-tier interference. The key idea is to jointly allocate PRBs, transmission powers and MCSs to the UEs so that the required transmission power of the corresponding HeNB is minimized. To realize this idea, the joint allocation is formulated as an optimization problem, in which each UE can transmit on different PRBs with differing power levels and be assigned one MCS only. In particular, a constraint is imposed by the optimization problem where the assigned MCS and PRBs must satisfy the required throughput demand for each UE. In addition, an interference constraint is enforced such that the transmission power of each HeNB is limited to keep the SINR experienced by each UE within a tolerable level. The maximum transmission power of an HeNB is determined by the HeNBs that receive interference. Estimation of the maximum transmission power is achieved by dividing the maximum interference power by the number of interfering HeNBs of the HeNBs that are being interfered with. Thereafter, the HeNBs being interfered with send the estimated transmission power to their interfering HeNBs via the X2 interface. Since an HeNB may receive multiple estimated maximum transmission powers, the one with the lowest value will be selected as the interference constraint. In order to solve the aforementioned optimization problem, the authors suggest a smart search technique, where an MCS is assigned to each UE arbitrarily. As a result, the optimization problem is narrowed down to a PRB and power-allocation problem, which can be solved using a network simplex algorithm. The MCS assignment that leads to the lowest transmission power will be selected, as the MCS solution and the allocation of PRBs and power can be obtained using the network simplex algorithm.

It is worth noting that the RRM scheme proposed in [101] runs independently at each HeNB, hence its low implementation complexity. Although some signaling overhead is required for maximum transmission power estimation, the estimated information is only transmitted when the new maximum transmission power deviates significantly from the old maximum. Additionally, the computational complexity is reasonable. Since solving the optimization problem satisfies the throughput demand of each UE, the issue of global fairness is addressed. However, local fairness can be further enhanced as the RRM scheme does not guarantee that UEs with low achievable rates will receive more PRBs; or that UEs with high achievable rates will receive fewer PRBs. Nevertheless, the RRM scheme can efficiently utilize radio resources and minimize co-tier interference. The same approach can possibly also be applied to the eNBs to mitigate cross-tier interference—something that is not considered in [101]. Nonetheless, the QoS aspect needs further improvement, since the delay and packet loss rate constraints are not addressed.

N. Summary and Comparison Between RRM Approaches for LTE/LTE-A Networks With Femtocells

Table III summarizes the working principles of all the RRM approaches discussed here for LTE/LTE-A networks with femtocells.

Table IV provides a qualitative evaluation and comparison of the different RRM approaches. The aspects considered include complexity, interference management, achievable spectral efficiency (corresponds to resource allocation), fairness and QoS guarantees. Generally, these aspects are evaluated based on the following criteria:

1) *Complexity*
   - Implementation complexity
     a) Amount of information exchanged between HeNBs
     b) Amount of information exchanged between the eNB and the HeNBs
     c) Amount of information exchanged between the eNB/HeNB and the central entity

- d) Amount of information exchanged between the eNB/HeNB and the MUEs/FUEs
- e) Formation of femtocell clusters
- Computational complexity

2) *Interference Mitigation*
- Effectiveness in mitigating cross-tier interference
- Effectiveness in mitigating co-tier interference

3) *Achievable Spectral Efficiency*
- PRB allocation approach (orthogonal/co-channel/reuse)
- Achievable throughput
- Length of sensing interval (applicable to the cognitive radio approach only)

4) *Fairness*
- Ability to guarantee global fairness (among BSs)
- Ability to guarantee local fairness (among users)

5) *QoS Guarantees*
- Satisfaction level of QoS constraints
- Consideration of LTE-compliant QoS requirements

Some aspects were not considered in the development of some RRM schemes. For these RRM schemes, the evaluation results for the relevant aspects are marked as "-" in Table IV. On the other hand, several RRM schemes, which are based on the cognitive radio approach, are evaluated as "Moderate/High" under the spectral efficiency aspect. This happens because their sensing interval is not specified, as a long sensing interval leads to a lower spectral efficiency and vice versa. Conversely, the fairness of the RRM scheme in [43] is evaluated as "Moderate/High" as the authors employ two scheduling approaches; the first approach (round robin method in [44]) results in moderate fairness, while the other one (matrix chunk allocation method in [45]) gives high fairness. Additionally, whether or not the RRM schemes are applicable to uplink or downlink is indicated in Table IV.

From Table VIII, we can observe that the RRM schemes in [77] and [90] are generally the best, as all aspects are almost entirely addressed. However, the QoS aspect needs further attention. This is because the QoS management in these RRM schemes may not be compliant with the LTE specifications because the QoS requirements are defined per radio bearer instead of per user. The RRM schemes in [54], [71], and [89] do provide good LTE-compliant QoS management. However, these RRM schemes need major improvement on interference-mitigation and fairness.

V. RRM in Heterogeneous LTE/LTE-A Networks With Relay Nodes

In LTE/LTE-A multihop networks, RNs relay packets transmitted from their DeNB to UEs that are located in a remote region. Such a packet-relaying process involves two independent transmissions, one in the backhaul link and the other is in the access link. This makes the RRM design more complicated, as radio resources need to be allocated for both transmissions. In this section, a survey of such RRM schemes for LTE/LTE-A multihop networks is presented. Similar to Section IV, a classification of RRM approaches based on the working principle or key enabling technology for LTE/LTE-A multihop networks is provided. The principles/technologies identified are: static resource allocation, user-proportional resource allocation, buffer-based, frequency reuse, proportional fair approach, QoS-aware, game theory, evolutionary approaches and the Lyapunov optimization approach. Classification of RRM schemes for LTE/LTE-A multihop networks is illustrated in Fig. 15. In the following discussion, we refer to the UEs served by RNs and their DeNB as relay-UEs (RUEs); while those served directly by the eNBs are referred as MUEs. Also, we refer to RNs as Type-1 RNs, unless they are specified as Type-2 RNs. The discussion and qualitative analysis of each surveyed RRM scheme are summarized in Tables V and VI.

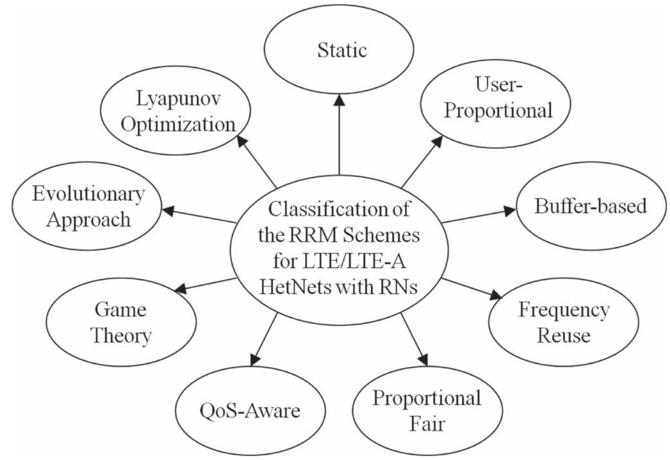


Fig. 15. Classification of RRM schemes for LTE/LTE-A multihop networks based on the underlying working principles or key enabling technologies.

A. *Static Resource Allocation Approaches*

One of the conventional RRM approaches for LTE-A multihop networks assigns radio resources among RNs statically. This approach has been investigated in [102] and [103].

In [102], the authors propose a downlink RRM scheme for LTE-A multihop networks, where the core idea is to assign fixed numbers of subframes for backhaul and access links in each LTE-A frame. Such assignment allows all PRBs from the assigned subframes to be fully allocated to the RNs and UEs for backhaul and access transmission respectively. In particular, the authors in [102] assign the numbers of subframes based on a ratio of x%–y%. In this ratio, x% represents the percentage of subframes in an LTE-A frame that is scheduled for backhaul transmission, while y% is the percentage scheduled for access transmission. It is noteworthy that $y\% = (100 - x)\%$. In addition, each BS (i.e., eNB or RN) runs a packet scheduler independently to allocate PRBs among UEs. Proportional fair and round robin schedulers are both investigated. Performance evaluation is carried out by the authors, using two ratios, namely 20%–80% and 40%–60%. Results show that 40%–60% is superior to 20%–80% in terms of throughput, which implies that a higher throughput performance can be achieved with more radio resources allocated for backhaul transmission.

The RRM scheme in [102] is simple and straightforward, but some issues have not been addressed. For instance, when RNs are densely deployed, inter-RN interference occurs, as all RNs transmit on the same allocated PRBs. Also, intracell

TABLE V
SUMMARY OF RRM SCHEMES FOR LTE/LTE-A MULTIHOP NETWORKS

Approach	Scheme	Working Principle
Static	[102]	• Fixed assignment of the number of backhaul and access subframes. • Traditional scheduling methods, such as proportional fair and round robin, are applied.
	[103]	• Soft and hard time/frequency/power coordination schemes as in Fig. 16(a) and (b). • Range expansion-based association scheme is applied.
User-proportional	[104]	• PRBs are allocated to each RN based on the number of RUEs served for backhaul links during the backhaul subframes. • Max-min fair scheduling for access links during access subframes.
	[105]	• Same as [104]. • Direct transmissions are allowed during backhaul subframes.
	[109]	• PRBs are allocated to the backhaul and to the access links of each RN based on the number of RUEs served. • Round robin scheduling. • Backhaul, access and direct transmissions are carried out in different time slots as in Fig. 17.
	[110]	• PRBs are allocated among RNs and MUEs for transmissions during backhaul subframes until (1) is satisfied. • Proportional fair scheduling.
	[114]	• PRBs are allocated among RUEs based on the number of UEs served by each eNB for each shared RN. • Proportional fair scheduling
Buffer-based	[115]	• PRBs are allocated to each RN based on the buffer size at the RN and the eNB. • Proportional fair scheduling.
	[116]	• Bandwidth is divided into two chunks for MUEs and RNs respectively, where the size of the chunks is determined based on the total cumulative buffer length of all RNs. • PRB allocation among RNs based on their cumulative buffer length for transmissions during backhaul subframes. • PRB allocation among RUEs based on the buffer size and channel quality for transmissions during access subframes.
Frequency Reuse	[118]	• The SFR scheme is applied during backhaul transmissions for both MUEs and RUEs, and the available resources are allocated to each RN based on the number of RUEs associated. • The conventional frequency reuse scheme is applied for access transmissions for both MUEs and RUE, and the available resources are allocated to each cell-edge area (belonging to different eNBs) based on the number of RUEs. • Round robin scheduling.
	[119]	• The FFR scheme is applied. • The backhaul and access links are allocated cell-edge bands. • A modified round robin scheduling is applied where the cell-edge UEs with the highest channel degradation from the eNB, and the cell-center UEs with the highest channel degradation from the RN, share the same PRBs.
Proportional fair	[41]	• Resource-partitioning between backhaul, access and direct links based on a proportional fair manner. • Proportional fair scheduling.
	[121]	• A proportional fair resource and subframe allocation problem is formulated for all the UEs as an optimization problem that maximizes the sum of all the logarithmic rates. • The gradient-based scheduling algorithm in [122][123] is used. • Range expansion-based association scheme is applied.
QoS-aware	[124]	• The two-level scheduler of [5] is used for backhaul and access transmissions. • Static frequency reuse is applied among multiple macrocells.
	[126]	• Relay selection and resource allocation is formulated as an optimization problem that maximizes the overall network throughput subject to minimum GBR rate constraints. • The optimization problem is solved using a dual decomposition technique.
	[127]	• The resource allocation among the backhaul links and the access links for transmissions during the backhaul subframes is the same as in [110]. • Data flows that are of same QCI are grouped as a single super-flow at the eNB. • A metric is proposed for packet scheduling, where flows with large delays and minimum rates are prioritized. • The proposed metric is used in both backhaul and access scheduling.
Game Theoretic	[128]	• Fixed-resource partitioning between the eNB and RNs. • A utility function is formulated as the achievable capacity of each player node. • A repeated game is used to model the PRB allocation problem among BSs (e.g., eNB and RN). • A Nash equilibrium is achieved by encouraging the players to cooperate.
Evolutionary	[130]	• The resource allocation problem is formulated as an optimization problem that maximizes throughput, subject to the minimum throughput constraint. • A genetic algorithm is used to solve the problem.
Lyapunov Optimization	[131]	• The joint subframe, PRB and power allocation problem is formulated as an optimization problem. • The Lyapunov conditional drift-plus-penalty function is derived from the optimization problem. • The joint resource allocation problem is solved by minimizing certain components of the function, using convex programming, linear programming and dual decomposition methods.

interference between direct and backhaul links may arise if both the RNs and the MUEs communicate with the eNB simultaneously. Other issues, such as global fairness, and QoS are not considered in this study. As such, this RRM scheme may not be feasible for LTE-A multihop networks. Nonetheless, it provides a valuable insight into the throughput performance of RUEs, given the radio resources allocated for the backhaul links.

Hu *et al.* [103] propose more refined static downlink RRM schemes for LTE multihop networks. Specifically, two downlink resource coordination schemes are developed, as shown in Fig. 16, which illustrates both the soft and the hard time/frequency/power coordination schemes. In the soft time/frequency/power coordination scheme, the channel bandwidth is partitioned into two frequency bands. During each backhaul

TABLE VI
QUALITATIVE COMPARISON OF RRM SCHEMES FOR LTE-A MULTIHOP NETWORK

Approach	Scheme	Link Direction	Complexity	Interference Mitigation			Spectral Efficiency	Fairness	QoS Guarantee
				Intracell	Inter-RN	Intercell			
Static	[102]	Downlink	Low	Low	-	-	Low	Low/Moderate	Low
	[103]	Downlink	Low	Moderate	-	-	High	-	-
User-proportional	[104]	Uplink	Low	Moderate	High	-	Low	Moderate	Low
	[105]	Uplink	Low	Moderate	High	-	Moderate	Moderate	Low
	[109]	Downlink	Low	Moderate	High	-	Moderate	Low	Low
	[110]	Downlink	Low	Moderate	High	-	Moderate	Moderate	Low
	[114]	Downlink	Low	High	High	High	Low	Moderate	Low
Buffer-based	[115]	Downlink	Low	Moderate	High	-	Moderate	High	Low
	[116]	Uplink	Low	Moderate	High	-	Low	High	Low
Frequency reuse	[118]	Downlink	High	High	High	High	High	Low	Low
	[119]	Downlink	Moderate	High	High	High	High	Low	Low
Proportional fair	[41]	Downlink	Moderate	High	High	-	Moderate	High	Low
	[121]	Downlink	High	High	High	-	Moderate	High	Low
QoS-aware	[124]	Downlink	Low	Moderate	High	High	Low	High	High
	[126]	Uplink	High	High	High	-	Low	Moderate	Moderate
	[127]	Downlink	Low	Moderate	Moderate	-	Moderate	High	High
Game theory	[128]	Downlink	Moderate	High	High	-	Moderate	-	-
Evolutionary	[129]	Uplink and downlink	High	Moderate	Moderate	Moderate	Moderate	Moderate	-
Lyapunov Optimization	[131]	Downlink	High	High	High	-	High	High	Low

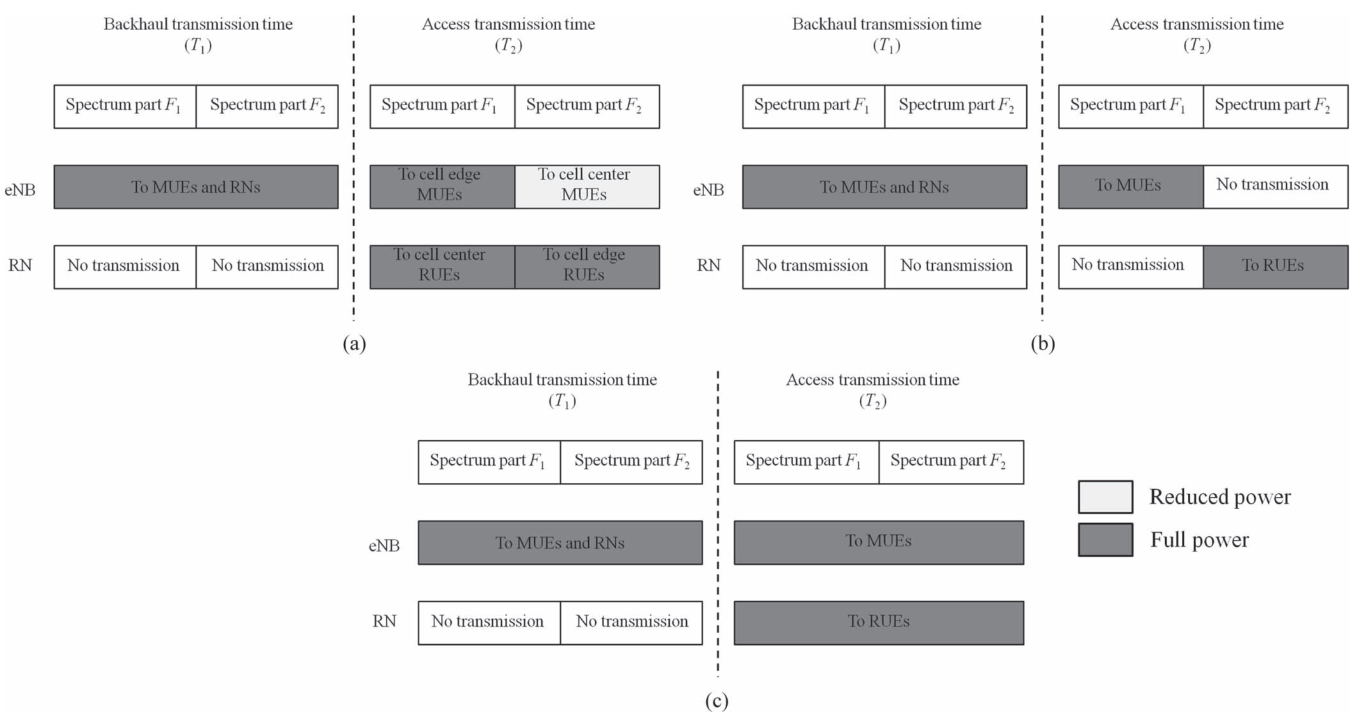


Fig. 16. (a) Soft time/frequency/power coordination, (b) hard time/frequency/power coordination, and (c) no frequency/power coordination [103].

subframe T_1, the eNBs transmit packets on the entire channel bandwidth to the associated MUEs and RNs, while the RNs are kept silent. Conversely, during each access subframe T_2, the eNBs serve the cell-edge and the cell-center MUEs, using the first and second frequency bands respectively. The cell-center MUEs transmit on the second frequency bands with a lower power. Meanwhile, the RNs serve their associated cell-center and cell-edge RUE, using the first and second frequency bands respectively. Thus, the intracell interference between MUEs and RUEs can be reduced since they utilize different frequency bands in different regions. However, interference may exist when a cell-edge MUE is located near the cell-center region of an RN. In addition, a range expansion-based association scheme is employed to enable more UEs to select RNs as their serving cells, so as to achieve a higher cell-splitting gain. On the other hand, the hard time/frequency/power coordination scheme is similar to the soft scheme, except that the first frequency band is reserved for MUEs and the second frequency band is reserved for RUEs during the access subframe T_2. The authors further compare the two schemes against that without coordination [Fig. 16(c)]. Simulation results indicate that the soft scheme achieves better spectral efficiency compared to the hard scheme, though the hard scheme achieves better SINR distributions among the UEs. This is to be expected, since the soft scheme still generates interference, while the hard scheme has completely eliminated interference. However, it is unclear which scheduling method is used in the soft and hard schemes, and QoS issues are not considered in this study.

Evidently, the scheme proposed in [103] is more effective than that in [104] in terms of intracell interference mitigation. However, like the scheme in [104], the RRM scheme in [103] is also limited by its inability to mitigate inter-RN and inter-cell interference, and the lack of consideration of fairness and QoS aspects. Nevertheless, the current complexity level of the schemes in [103] and [104] is relatively low, thus a more sophisticated enhancement can be incorporated.

B. User-Proportional Resource Allocation Approaches

The static resource allocation approaches are simple and easy to implement. However, they cannot satisfy numerous RNs, each with their own diverse demands. Hence, they are impractical and globally unfair to the RNs. Therefore, it is necessary for an RRM scheme to be able to allocate a proper amount of radio resources to an RN with respect to its resource demand. However, this requires an indicator that represents the resource demand of the RN for determining the required amount of radio resources to be allocated. A simple solution to this problem is to use the number of RUEs served by the RN as the indicator—something that has been proposed in several studies.

In [104], the authors suggest allocating PRBs among RNs according to the number of RUEs currently served by the RNs. This idea is implemented as a two-step resource-sharing scheme, with power control in the uplink of the LTE-A multihop networks. In the first step, the FPC [63] scheme is enabled in the UEs and RNs to mitigate the vulnerability of the SC-FDMA signals to the loss of orthogonality. In the second step, the optimal number of backhaul subframes is determined, followed by resource allocation among RNs and UEs. In the backhaul resource allocation process, the available PRBs are divided orthogonally to each RN in proportion to the number of RUEs served. For access resource allocation, the PRBs, which are of the same frequencies as the PRBs allocated in the backhaul link for each RN, are used for packet scheduling. A max-min fair scheduler is used by each RN to allocate PRBs among the RUEs. As such, it guarantees local fairness. Additionally, the MUEs are allocated PRBs from the entire bandwidth within the access subframe.

It is worth mentioning that the RRM scheme proposed in [104] does not allow direct transmissions between eNBs and their associated MUEs within the backhaul subframe. Consequently, a shortcoming can be observed, i.e., when the number of backhaul subframes is large, the achievable overall throughput decreases, due to the small number of access subframes. One solution to this problem is to allow transmission from the eNBs to the MUEs within the backhaul subframe. This approach is implemented in addition to the RRM scheme proposed in [104] and it is investigated in [105]. During the backhaul subframe, the available PRBs are assigned to the RNs and the MUEs in proportion to the total number of RUEs and MUEs respectively. Simulation results demonstrate a substantial increment for the overall network throughput. Furthermore, the scheme proposed in [105] is enhanced with relay-cell extension as proposed in [106] and [107] and it is investigated in [108].

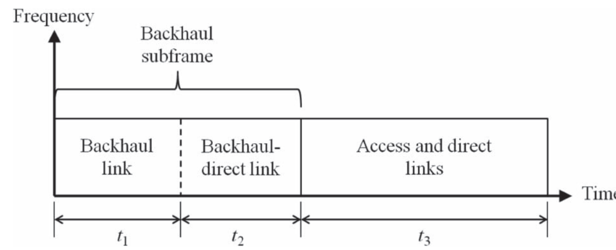


Fig. 17. Resource allocation pattern model in [109].

Although the RRM scheme proposed in [105] improves the overall throughput performance, it does not optimize the radio-resource utilization. To address this issue, the authors in [109] suggest a resource allocation model for downlink LTE-A multihop networks, as illustrated in Fig. 17 where the backhaul subframe is divided into two time slots. The backhaul link time slot is used for backhaul transmission, whereas the backhaul-direct link timeslot is used for direct transmission. The optimal time slot intervals, as depicted in Fig. 17, i.e., t_1, t_2 and t_3, are found by maximizing the minimum achievable throughput of the worst UEs, using linear programming. After determining the time slot intervals, radio resources are allocated within the time slots in a round robin manner.

The *fair-throughput* RRM scheme is proposed in [110] for downlink LTE-A multihop networks. In this scheme, the available PRBs are continuously allocated to the backhaul and to the direct links for transmission during the backhaul subframe, until the following condition is satisfied:

$$\frac{N_R}{TP_B} \approx \frac{N_M}{TP_M} \tag{1}$$

where N_R is the number of RUEs served, N_M is the number of MUEs served, TP_B is the aggregate backhaul throughput and TP_M is the aggregate MUE throughput. It can be observed that if TP_M is large, the inequality in (1) will not hold, hence the PRBs will still be allocated to the backhaul link until (1) holds true. After resource allocation between the backhaul and the direct links is completed, the eNB runs a two-stage proportional fair scheduler [111] to allocate PRBs among the RNs and the MUEs for backhaul and direct transmission during the backhaul subframe. The backhaul flows are prioritized at the eNB by being put on top of the list for scheduling. For transmission during the access subframe, both the eNB and RNs run the two-stage scheduler for PRB allocation among the MUEs and the RUEs respectively. Simulation results show that a major improvement is attained by the fair-throughput scheme over the RRM scheme proposed in [112] in terms of throughput distribution among the RUEs. Following the work in [110], the fair-throughput scheme is further investigated in outband relaying LTE-A networks with carrier aggregation capability enabled in [113]. It is noted that the study in [110] does not consider resource allocation for transmission during the access

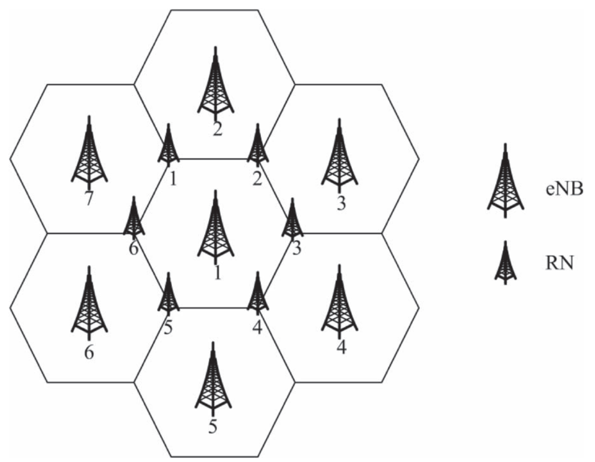


Fig. 18. Shared relay cellular network.

subframe; this is because both the eNB and RNs reuse parts of the entire bandwidth during the access subframe.

In [114], the RRM for a typical multihop network architecture known as *shared relay networks* is studied. In such networks, each RN is associated with two or more eNBs. An example is illustrated in Fig. 18, with RN 1 shared by eNBs 1, 2, and 7. In [114], Type-2 RNs are considered. On the other hand, the proposed RRM framework for such networks is designed so that the RNs only relay packets to UEs (supposedly within the coverage of the RNs) when the UEs do not receive the intended packets from the eNB. When an RN overhears an NAK signaling from a UE to an eNB, the RN helps retransmit the packet to the UE. Since each RN is shared by more than one eNB and the frequency reuse factor of one is applied across all macrocells, the RNs allocate resources among UEs from the system bandwidth based on the number of UEs associated with each eNB, to avoid intercell interference. After that, the allocation information is sent to each eNB. Then, each eNB runs a proportional fair scheduler to allocate PRBs among the RNs for transmission from the RNs to the UEs based on the allocation information. After PRB allocation among the RNs, the remaining UEs are again allocated PRBs using the proportional fair scheduler.

It is worth mentioning that the user-proportional RRM schemes discussed above are advantageous in some respects. First of all, they do not require heavy signaling and computation. This is due to the fact that the resource calculation is straightforward and additional signaling is not needed. Besides this, these RRM schemes are also free from inter-RN interference within a macrocell, as PRBs are assigned orthogonally among RNs. However, intracell interference is not completely avoided in the schemes, as studied in [104], [105], [109], and [110]. This is because radio resources are not separated for both MUEs and RUEs. Moreover, the aforementioned RRM schemes may not be able to tackle intercell interference when the RNs exploit the same radio resources with their neighboring macrocells or their associated RNs. Conversely, more efficient radio resource utilization can be achieved by the RRM schemes in [105], [109], and [110]. The RRM schemes in [104], [105], [110], and [114] perform well in terms of global and local fairness because the RNs with more RUEs receive more PRBs. However, the number of UEs served by a BS does not actually reflect the actual demand required by the BS. A more accurate indicator of resource demand will be presented in the next subsection. Despite that, the RRM scheme in [110] only guarantees global fairness during the backhaul subframe. Another limitation of all the user-proportional RRM schemes reviewed is that they could not provide QoS guarantees to each UE since QoS-unaware schedulers are used.

C. *Buffer-Based Resource Allocation Approaches*

The number of RUEs associated with each RN might not reflect the actual traffic demand from the corresponding RN, as each RUE may have a different amount of data to be transmitted in each TTI. Consequently, user-proportional RRM schemes may still be globally unfair. Instead of the number of RUEs, the resource demand of each RN can be determined by its buffer size. The buffer size of an RN can serve as an indicator of the channel quality or the number of resources required, depending on whether the resource allocation is for the downlink or the uplink.

In [115], a buffer-based backhaul resource allocation scheme is proposed for downlink LTE-A multihop networks. The main idea of this scheme is to exploit the buffer size at the eNB for transmission to a particular RN. The buffer size of the eNB is used as an indicator of the resource demand of the RN and the buffer size of the RN is used as the indicator of the channel quality at the RN with respect to the associated RUEs. The scheme proposed in [115] is implemented in two steps. In the first step, the eNB determines the resource demand of each RN. The estimation of the resource demand depends on the buffer size at the RN and the eNB for transmission to the RN. If the buffer size at the RN is large, this corresponds to low channel quality and the resource demand of the RN is set at a lower value. On the other hand, if the buffer size of the eNB is large, more packets need to be transmitted to the RUEs that are served by the RN, hence the resource demand becomes larger. In the second step, a minimum number of PRBs is allocated to fulfil the resource demand of each RN for backhaul transmission. The leftover PRBs are allocated to the MUEs using a proportional fair scheduler. Consequently, the two-step mechanism allows the RNs with large buffer sizes to receive fewer PRBs. In a similar manner, RNs with small buffer sizes receive more PRBs. In this way, a proportional fair end-to-end throughput (from the backhaul links to the access links) distribution can be achieved among all the RNs. During the access subframe, each BS (i.e., eNB or RN) performs proportional fair scheduling among the UEs (i.e., the MUEs and RUEs). As in [110], the eNB and RNs reuse parts of the entire bandwidth during the access subframe.

The mechanism proposed in [115] is able to improve resource utilization efficiency, while maintaining a certain level of global fairness. In spite of that, buffer overflow may still occur at the eNB because some packets have to remain in the buffer at the eNB to avoid buffer overflow at the RN. Meanwhile, intracell interference may occur during the access subframes, since the MUEs and the RUEs may utilize the same PRBs. Since a proportional fair scheduling strategy is employed in the RRM scheme in [115], local fairness is guaranteed among the UEs.

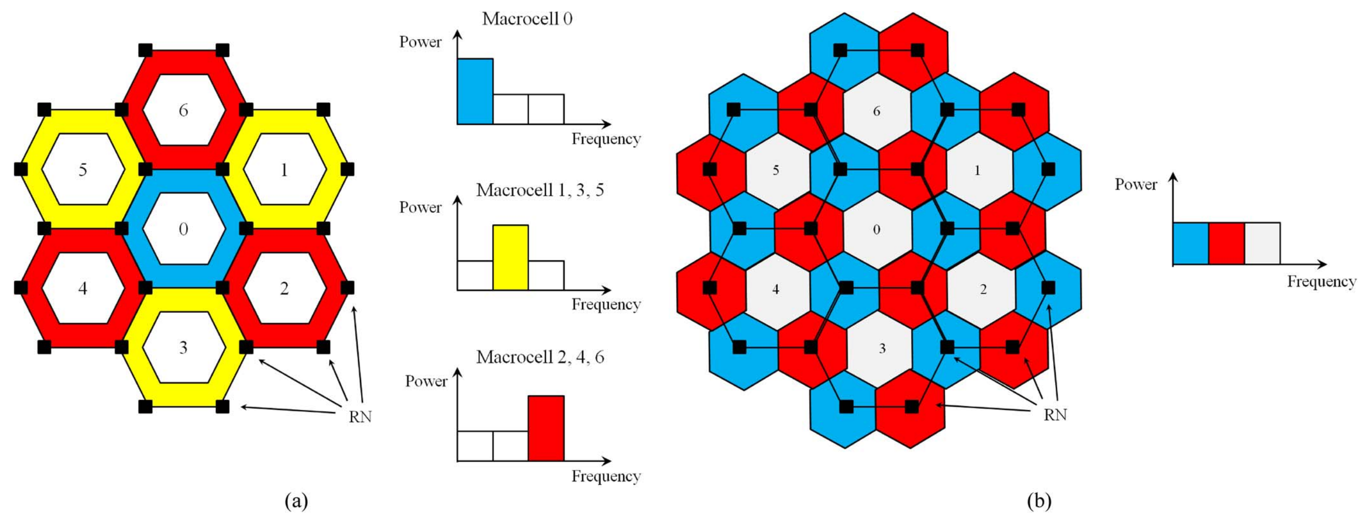


Fig. 19. Frequency reuse approach in [118], where (a) SFR is applied for transmissions during backhaul subframes and (b) traditional frequency reuse is applied for transmission during access subframes.

On the other hand, Mehta *et al.* [116] propose a buffer-based scheduling scheme for the uplink of LTE-A multihop networks. In this scheme, the channel conditions of the RUEs are considered in the scheduling decisions, in addition to the buffer size. In the uplink, packets are buffered at the UEs or at the RNs of which the buffer size information can be delivered to the eNB via buffer-status reporting [117]. The operations of the RRM scheme consist of the following three phases:

- *Phase I*: The available PRBs are divided into two resource chunks, where one is reserved for the MUEs and the other for the RNs. The division is based on the cumulative buffer length of the MUEs and RUEs. In other words, if the cumulative buffer length of the MUEs is longer than that of the RUEs, a larger resource chunk will be reserved for the MUEs and vice versa.
- *Phase II*: The available resource chunk for the RNs will be allocated to each RN according to its cumulative buffer length.
- *Phase III*: Packet scheduling among UEs is carried out according to the buffer length and the channel quality of the UEs. In other words, the UEs with longer buffer lengths and better channel quality will be assigned more PRBs.

In addition to the buffer-based channel-dependent scheduler, a buffer-based resource partitioning strategy is used for allocating PRBs among RNs for both backhaul and access transmission. The proposed RRM scheme exhibits superior performance in terms of average resource utilization efficiency, fairness and packet dropping probability compared to pure buffer-based, round robin and opportunistic schedulers.

Clearly, the RRM scheme proposed in [116] is more appealing than that in [115] in terms of fairness and interference mitigation. Global and local fairness are effectively addressed through allocating radio resources to the RNs and UEs in proportion to their resource demand. However, unlike [115], [46] does not consider simultaneous transmissions with direct links. Nevertheless, both schemes share common features such as non-negligible complexity and reasonable resource utilization efficiency.

D. Frequency Reuse Approaches

The frequency reuse approach has also been employed in designing RRM schemes for LTE/LTE-A multihop networks besides those for femtocell networks. In fact, the frequency reuse approach could be more practical for multihop networks than for femtocell networks. This is because the RNs are deployed in fixed locations in cell-edge areas and stay active at all times. As such, frequency planning and interference coordination techniques such as frequency reuse can be readily implemented. However, femtocells may not stay active constantly, hence the need for frequent frequency reconfigurations, which may entail high implementation complexity. In the following, several frequency reuse approaches for LTE/LTE-A multihop networks are reviewed.

In [118], a frequency reuse-based RRM scheme is proposed for LTE-A shared relay networks. The shared relay network considered is similar to that featured in Fig. 18. For shared relay networks, a downlink RRM scheme is developed based on traditional frequency reuse and SFR techniques. In this scheme, the SFR technique proposed in [56] and [57] is adopted to allocate radio resources to the backhaul link and to the direct link for transmission during the backhaul subframe. In implementing the SFR, the bandwidth is divided into three frequency bands and distributed in a reuse pattern, as shown in Fig. 19(a). In particular, cell-edge UEs can only utilize the cell-edge bands with higher transmission power, while cell-center UEs can use both cell-center and cell-edge bands with lower transmission power. Moreover, each RN can utilize three different cell-edge bands for backhaul communications with three different eNBs respectively. In addition, the eNBs apply user-proportional resource partitioning for each RN, according to the number of RUEs served in the respective cell-edge areas. On the other hand, a traditional frequency reuse technique is applied across all the RNs, as depicted in Fig. 19(b), for transmission during access subframes. In this way, the RNs will

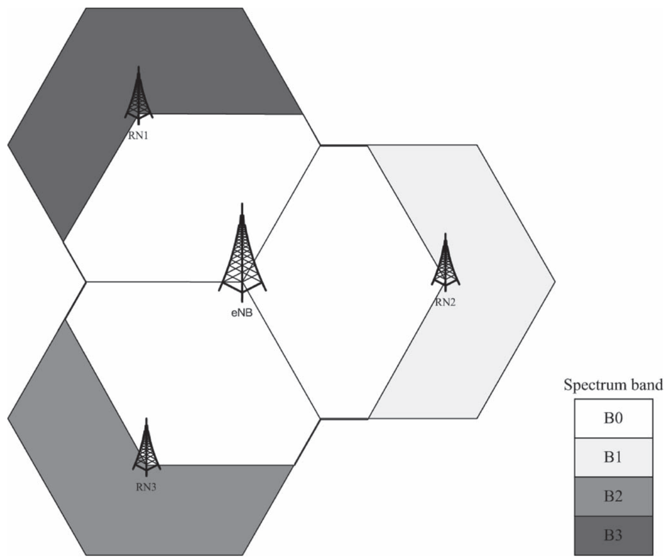


Fig. 20. FFR-based LTE-A with RN network.

serve the cell-edge UEs associated with different eNBs by using the respective cell-edge bands, and the eNBs will serve the cell-center UEs by using the cell-center bands. In addition, each RN applies user-proportional resource partitioning among the three different cell-edge areas belonging to different eNBs. For PRB allocation among UEs, a round robin scheduling method is employed.

The sophisticated frequency reuse approach proposed in [118] significantly enhances its interference mitigation capability. All interference is alleviated by means of frequency reuse and user-proportional resource partitioning. Furthermore, frequency reuse allows for efficient resource utilization across all the RNs and eNBs. However, the implementation complexity can be high due to the complicated architecture of the shared relay networks. Since each RN associates with a number of eNBs, additional signaling may be involved between them for many purposes, such as for differentiating UEs that are served by different eNBs. As discussed earlier, user-proportional resource partitioning schemes may not be globally fair and the round robin scheduling method used cannot guarantee local fairness. Nonetheless, the proposed RRM scheme is an appealing one.

Another frequency reuse-based RRM scheme is presented in [119] for LTE-A networks with Type-2 RNs. In this RRM scheme, each RN serves the RUEs (which are also cell-edge UEs) using the cell-edge bands allocated using the FFR technique [120], as depicted in Fig. 20. It is worth noting that the scheduling at the RNs is performed at the eNB since Type-2 RNs are incorporated. During the backhaul subframes, the RNs transmit using the PRBs from the cell-edge bands allocated by the FFR technique. Besides that, the MUEs (who are cell-center UEs) are assigned PRBs using a round robin scheduler. During the access subframes, the eNB performs a modified round robin scheduling to allocate PRBs among the RUEs and the MUEs. In the modified round robin scheduling, the RUEs with the highest channel degradation with respect to the eNB (as well as the MUEs with the highest channel degradation with respect to the serving RNs) are selected to share the same PRBs from the cell-edge bands. Other UEs are allocated PRBs using a normal round robin scheduling. In addition, a typical call setup signaling procedure is employed, as shown in Fig. 21. Note that when a UE discovers that the CQI of the cell-edge bands is higher than that of the cell-center bands, only the CQI of the cell-edge band will be sent back to the eNB and not the CQIs of both the cell-edge and cell-center bands. This feedback mechanism helps reduce the energy consumption of the UEs.

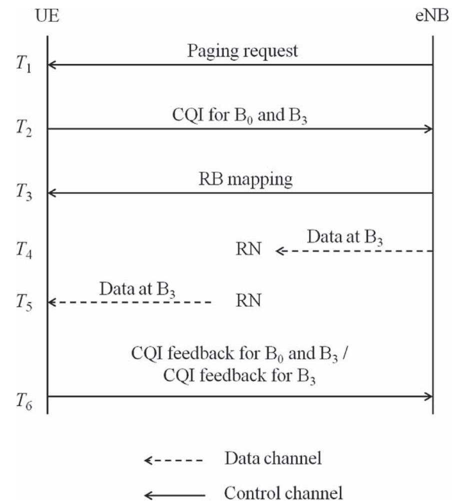


Fig. 21. Call setup signaling process in [119].

The RRM scheme in [119] can effectively minimize intracell interference by means of the FFR scheme, while attaining a notable improvement on spectral efficiency through the modified round robin scheduling. In the deployment scenario depicted in Fig. 20, inter-RN and intercell interference could be avoided. However, like in [118], fairness and QoS aspects are not addressed, as round robin scheduling is unfair in terms of user throughput and it is not QoS-aware. These two aspects need to be further studied.

E. Proportional Fair Approaches

Some of the RRM schemes we have reviewed so far employ proportional fair scheduling methods to guarantee proportional fairness and achieve a good trade-off between max-min fairness and spectral efficiency. Since the scheduling methods are implemented at the BSs for PRB allocation among the UEs, the trade-off can only be achieved locally in each BS. In view of this, some studies [41], [121] develop a complete RRM framework so that proportional fairness can be attained both globally and locally.

One of the aforementioned studies presents a proportional fair downlink resource allocation framework for LTE-A multihop networks [41]. The main objective of this RRM framework is to attain complete proportional fairness among all the UEs (i.e., for all the MUEs and all the RUEs). To achieve this, a maximization problem is formulated as the sum of the achievable logarithmic rate of all the UEs. As proven in [49] and [50], solving this problem will yield proportional fairness. However, the problem is NP-hard and may require prohibitive implementation complexity as it requires heavy signaling to collect information from every UE. Therefore, the authors propose a two-step solution to simplify the problem and allows

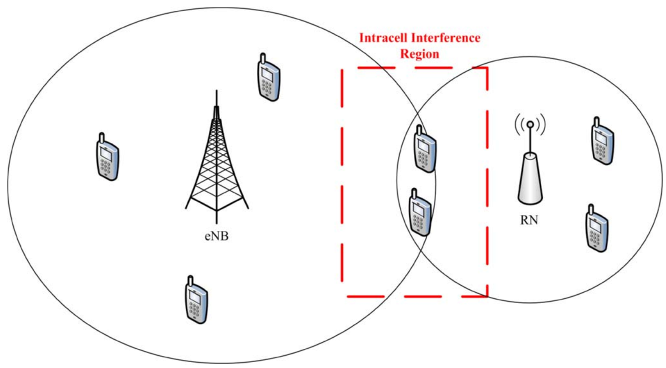


Fig. 22. A heterogeneous network with RNs and intracell CoMP.

its implementation at a lower complexity. In the first step, proportional fair resource partitioning between the backhaul, access and direct links is carried out. Several assumptions are made, one of which is to equate the achievable backhaul rate to the achievable access rate. Another assumption is made by approximating the achievable rate as a linear function of the SINR. By having these assumptions, the maximization problem can be simplified and solved using a Lagrange multiplier method. In the second step, two scheduling methods are employed for PRB allocation among the RNs and the UEs. For transmission during the backhaul subframe, the eNB performs buffer-based scheduling to allocate PRBs to each RN. The scheduling mechanism is similar to that in [115], which was discussed earlier in Section VI-C. It is worth noting that direct transmission between the eNB and the MUEs is not allowed during the backhaul subframe. Conversely, for transmission during the access subframe, proportional fair scheduling is used by both the eNB and RNs to allocate PRBs among the MUEs and RUEs respectively.

The framework proposed in [41] scores highly in terms of global and local fairness, while achieving satisfactory spectral efficiency. The overall throughput performance can be further improved by allowing a direct transmission during the backhaul subframe. Intracell and inter-RN interference are also avoided as buffer-based resource scheduling is used for partitioning resources to each RN.

Another proportional fair downlink resource allocation framework is developed for LTE-A multihop networks with cooperative RNs [121]. The intracell coordinated multipoint (CoMP) transmission capability is enabled such that the UEs can be served jointly by the eNB and its associated RNs. The main intention of enabling such a capability is to alleviate the intracell interference between the eNB and its associated RNs, as depicted in Fig. 22. In addition, a range-expansion-based association scheme is employed to balance the traffic load between the eNB and its associated RNs. In each scheduling interval, an RUE with: 1) the SINR received from the serving RN that is lower than a predetermined threshold, and 2) a signal power received from the DeNB that is higher than a predetermined interference threshold, will be categorized as a CoMP UE (CUE). Note that the categorization of a CUE is made separately for each allocated PRB. Then, to allocate PRBs among all UEs, a proportional fair resource allocation is formulated as an optimization problem that maximizes the sum of the achievable logarithmic rate of all the UEs, subject to the resource constraints of the eNBs and RNs. The resource constraints ensure that each PRB is allocated to a UE or to an RN for all the direct, backhaul and access links. To solve this problem, the gradient-based scheduling algorithm proposed in [122] and [123] is used, which determines the sets of allocated PRBs for the direct, backhaul and access links. In addition, after determining the sets of allocated PRBs, the numbers of backhaul and access subframes required can be determined.

Like in [41], the RRM scheme proposed in [121] can achieve high fairness both globally and locally, while achieving high throughput performance. Even more remarkably, intracell and inter-RN interference is effectively mitigated. This thanks to the capability of the CoMP and the aforementioned resource constraints, which increases the received SINR significantly and ensure orthogonal PRB allocation. However, it appears that the RRM scheme is implemented at the eNB. In other words, each eNB behaves as a central controller to decide the PRB allocation among its RNs and UEs for direct, backhaul and access transmissions. Thus, the implementation complexity can be high.

The throughput performance of both the RRM schemes in [41] and [121] can be further improved by allowing direct transmission during the backhaul subframe. Nevertheless, neither scheme provides any QoS guarantee. Thus, further improvement is needed in terms of QoS management.

F. QoS-Aware Resource Allocation Approaches

As the existing RRM schemes for LTE/LTE-A multihop networks are not able to provide strict QoS limits for real-time applications, Piro *et al.* [124] bridge this gap by implementing the two-level scheduler proposed in [5] at the eNB and at its associated RNs. The two-level scheduler uses the upper-level scheduler to determine the amount of data required to be transmitted by each radio bearer to satisfy its delay constraint during an LTE-A frame interval; while the lower-level scheduler is used to allocate PRBs to each radio bearer using a proportional fair scheduling method subject to the data quota determined. Furthermore, the two-level scheduler prioritizes the PRB allocation for real-time traffic; the leftover resources will then be allocated to best-effort applications in a proportional fair manner. The two-level scheduler is implemented at both the DeNB and at its associated RNs for both backhaul and access transmissions. A static frequency reuse strategy is applied across all eNBs and RNs. The authors evaluate the performance of the scheme using their LTE-Sim simulator [125], and an excellent performance in terms of packet loss rate and throughput for real-time traffic (such as video and VoIP) is achieved.

The RRM scheme in [124] is well suited to address fairness and QoS issues. Since a static frequency reuse strategy and a two-level scheduler are employed, all possible interference is virtually avoided, albeit at the cost of less efficient resource utilization. A downside can be observed during the access subframe, because the direct links may interfere with the access links. This scheme does not provide any mechanism to handle such interference, hence the need for further improvement in terms of intracell interference mitigation. Nevertheless, the overall complexity is relatively low.

In [126], a QoS-aware resource allocation scheme is developed for uplink LTE-A multihop networks. Typically, the network allows cooperative relaying, i.e., both the UEs and the RNs can transmit the same packet to the eNB jointly. In fact, this is similar to the intracell-CoMP feature of [121], which was discussed in Section VI-E. However, the cooperative relaying is implemented in a different way: In a time slot, the transmission between a UE and the eNB is overheard by a selected RN, which helps forward the received transmission from the UE to the eNB using a regenerate-and-forward protocol in the next time slot. The transmissions received from the UE and the RN are then combined at the eNB, using maximal ratio combining. In the proposed resource allocation scheme, relay selection, as well as PRB and power allocation, are incorporated. The allocation problem is formulated as an optimization problem that maximizes the overall network throughput, subject to a QoS constraint. This QoS constraint ensures that the UEs with traffic flows of GBR class achieve a minimum rate. The problem is tackled using a dual decomposition method, where the optimal power allocation is first solved using the Karush-Kuhn-Tucker conditions [53], assuming that the RNs are selected and the PRBs are allocated in a certain manner. After that, the joint optimal relay selection and PRB allocation problem is solved using a subgradient method.

The RRM scheme in [126] performs generally well in terms of QoS guarantee. However, a number of limitations can be observed: First, fairness is only guaranteed for those UEs with GBR traffic flows. Other UEs suffer unfair resource allocation, as UEs with good channel quality are favored for PRB allocation. Secondly, the scheme may lead to a significant signaling exchange between eNBs and RNs, in order to gather channel information about UEs and RNs. The implementation complexity makes such RRM schemes nearly impractical, a situation which is worsened by the computational complexity at the eNBs.

Another QoS-aware downlink RRM scheme is proposed in [127] for LTE-A multihop networks. This scheme is an enhanced version of that in [110]. The backhaul and access resource partitioning in [127] are the same as that in [110], except for the packet scheduling. In [110], a two-stage proportional fair scheduler is used for PRB allocation among the RUEs and MUEs. However, the scheduler is incapable of guaranteeing delay and rate constraints for real-time GBR-type data flows such as video and VoIP services. To address the aforementioned QoS issue in the backhaul, the authors suggest grouping data flows of the same QCI number as a single backhaul flow, also known as a *super flow*, at the eNB. Thus, the minimum rate of each super flow is equivalent to the sum of all the data flows grouped, and the maximum allowable delay is reduced to that divided by the number of data flows grouped. Then, these super flows are scheduled using a QoS scheduling metric. This metric is used to weigh each link based on its current delay and minimum rate requirement. If a link has a delay that approaches the maximum value and the required minimum rate is high, the link will receive a large metric value and hence more PRBs. Similarly, the scheduling metric can be used for access resource allocation.

As a result of the enhancement proposed in [127], a substantial improvement is achieved in the aspects of global fairness and QoS. Although non-negligible computational complexity is incurred, the overall complexity is still deemed reasonable.

G. Game Theory Approaches

As discussed earlier in Section IV-K, game theory is a mathematical tool for modeling the interaction of multiple decision-makers. A game is said to be "in equilibrium" when each decision maker cannot improve its payoff by deviating from its given strategy while others maintain their strategies. The game theory RRM approach has been studied in femtocell networks, though its potential has been also explored in multihop networks.

In [128], an RRM scheme is proposed based on a repeated game theory approach for LTE-A multihop networks. In this RRM scheme, the available PRBs are partitioned statically among the BSs (i.e., eNBs and RNs). After that, the PRBs with good channel quality are reassigned to each BS from the PRBs partitioned for other BSs. In this way, resource utilization can be maximized and the required throughput can be attained without generating excessive mutual interference. In order to solve the reassignment problem, a repeated game is employed. In this game, each player node is a BS and each strategy chooses whether or not to cooperate with other players. In addition, a utility function is formulated as the capacity of each player node. The objective of the game is to maximize the utility function by maximizing the number of PRBs allocated to each player node. Therefore, the game encourages each player to cooperate by letting other players use some of their PRBs, which are of good channel quality. As the game is repeated for multiple rounds, each player node receives a final payoff that is the sum of the individual payoffs (achieved utility values) discounted over time. Based on Folk theorem [94], the game will eventually reach the Nash equilibrium [91]. Additionally, a penalty mechanism exists to encourage players to cooperate. In the penalty mechanism, non-cooperating players will be penalized by reducing the achieved throughput, thus forcing the game into a cooperation state more rapidly.

Although [128] presents an interesting approach for LTE-A multihop networks, several aspects such as fairness and QoS are not addressed. Nonetheless, the radio resources are efficiently utilized while intracell and inter-RN interference are kept within an acceptable level.

H. Evolutionary Approaches

Evolutionary algorithms are optimization algorithms inspired by natural evolutionary phenomena. One of the popular evolutionary algorithms is known as the genetic algorithm [129], which is inspired from the genetic evolution of mankind. The genetic algorithm has been an effective technique for solving numerous computationally complex problems.

In [130], the authors propose a genetic algorithm-based resource allocation scheme for LTE-A multihop networks. The objective of this scheme is to maximize throughput and fairness, while attaining load-balancing between the RNs and their associated DeNBs. To achieve this, a genetic algorithm is used to search for the optimal set of channel gains for the MUEs or the RUEs, and to achieve optimal PRB allocation such that the system throughput is maximized. To implement the genetic algorithm, an optimization problem that maximizes the system throughput is formulated, subject to the minimum throughput constraints. This formulation is accomplished by modeling the LTE-A multihop network as a weighted bipartite graph, where the vertices represent the DeNBs, the RNs or the UEs and the edges signify the channel quality between the vertices. In the optimization mechanism of the genetic algorithm, the population that contains a set of solutions (i.e., the channel gain and the PRB allocation) is first randomly initialized. Then, crossover operations are performed over the set, followed by mutation operations. Such operations are repeated until certain termination criteria are fulfilled.

The genetic algorithm is a promising technique for complicated RRM problems, but the convergence time remains a critical issue for such an evolutionary approach. Since the channel conditions and resource demands of each BS may vary rapidly over time, the performance of genetic algorithms may vary accordingly. Furthermore, the implementation of the genetic algorithm proposed in [130] requires a centralized processor, thus creating substantial complexity. Nevertheless, genetic algorithms generally can achieve satisfactory fairness, resource utilization and interference mitigation.

I. Lyapunov Optimization Approaches

In [131], a Lyapunov optimization approach is used to jointly allocate subframes, PRBs and power to LTE-A multihop networks. The joint resource allocation problem is formulated as an optimization problem that maximizes the sum of all the logarithmic average rates achieved by the UEs, subject to a number of constraints. The constraints include: 1) guarantee queue stability at the eNB and RNs, 2) ensure that the instantaneous and average powers do not exceed predefined thresholds, 3) limit the number of admitted packets, 4) ensure that each PRB is assigned to one UE only, and 5) avoid concurrent transmissions between backhaul and access links in the same subframe. To solve the problem, along with the constraints, an auxiliary variable is introduced for each UE and a set of auxiliary constraints is added. Then, a Lyapunov function is defined in terms of the length of the packet queues at the eNB and RNs, the power queues for the eNB and RNs, and the virtual queues that are constructed to satisfy the auxiliary constraints. Subsequently, the Lyapunov conditional drift-plus-penalty function can be derived. Minimizing certain components of the function will yield the optimal subframe, PRB and power allocation with all the constraints satisfied. The component for auxiliary variables is minimized using a standard differentiation technique, as it is a convex problem. The component that limits the number of admitted packets is minimized using a linear programming approach. Finally, the components that jointly allocate subframes, PRBs and powers are minimized using a dual decomposition method. It is worth noting that the implementation complexity can be further reduced by having the RNs find suboptimal solutions for the decision variables that correspond to the access links. Then, these solutions can be reused at the eNB to complete the entire resource allocation.

Evidently, the resource allocation problem for LTE-A multihop networks is entirely addressed in [131]. Remarkably, the joint allocation mechanism enables effective intracell and inter-RN interference mitigation by allowing only one PRB for one UE and by preventing concurrent transmissions between the backhaul and the access links. Moreover, radio resources are reused between the direct and the access links, hence higher spectral efficiency. Global and local fairness are guaranteed, since the solution to the optimization problem gives proportional fairness for the entire network. However, the implementation complexity of this RRM scheme remains high, even though an attempt is made to reduce it. In addition, a major improvement is required in terms of QoS.

J. Summary and Comparison Between RRM Schemes in LTE/LTE-A Multihop Networks

The key working principles of all the aforementioned RRM schemes are summarized in Table V.

In a similar way to those for femtocells, the different RRM schemes proposed for HetNets with RNs are evaluated and compared qualitatively in terms of: complexity, interference management, spectral efficiency, fairness and QoS satisfaction (See Table VI). As in Section IV-N, these aspects are evaluated according to the following criteria:

1) *Complexity*
   - Implementation complexity
     a) Amount of information exchanged between the eNBs and the RNs
     b) Amount of information exchanged between the RNs and the central entity
     c) Amount of information exchanged between the eNBs/RNs and the MUEs/RUEs
   - Computational complexity
2) *Interference Mitigation*
   - Effectiveness in mitigating intracell interference
   - Effectiveness in mitigating inter-RN interference
   - Effectiveness in mitigating intercell interference
3) *Achievable Spectral Efficiency*
   - PRB allocation approach (orthogonal/co-channel/reuse)
   - Achievable throughput
4) *Fairness*
   - Ability to guarantee global fairness (among BSs)
   - Ability to guarantee local fairness (among UEs)
5) *QoS Guarantee*
   - Satisfaction level of QoS constraints
   - Consideration of LTE-compliant QoS requirements

Some factors are not considered in the development of several of the RRM schemes. These factors are marked as "-" in the corresponding column in Table VI. Since the RRM scheme in [102] is evaluated using both the round robin and the proportional fair scheduling methods, the assessment outcomes of fairness are "Low/Moderate."

Overall, we can observe from Table VI that none of the RRM schemes has addressed all the aspects satisfactorily. The majority of them neglect intercell interference issues, which are essential in multihop networks. Although the RRM schemes in [114], [118], [119], and [124] do consider all aspects, some of them are not adequately addressed. For instance, the RRM schemes in [114] and [124] have low spectral efficiency because the PRBs are allocated in a fully orthogonal manner. Conversely, the RRM schemes in [118] and [119] do not score well in terms of fairness and QoS issues. In fact, most of the RRM schemes do not provide a QoS guarantee.

The RRM scheme in [124] appears to be a promising one, as most of the aspects except spectral efficiency are properly addressed. However, the scheduling mechanism used in [124] is sophisticated and is designed for PRB orthogonal allocation. Thus, it could be difficult to promote PRB reuse using the scheduling mechanism without some modification.

On the other hand, the frequency reuse-based RRM schemes in [118] and [119] look more appealing compared to that in [124]. Since frequency reuse schemes are deployed, efficient resource utilization and interference mitigation are achieved across all the macrocells. Although the schemes in [118] and [119] do not perform well in terms of fairness and QoS, improvements to these aspects are feasible without major modification. In this way, resource partitioning and scheduling can be integrated easily with frequency reuse schemes. However, frequency reuse-based RRM schemes such as the one proposed in [118] can entail high implementation complexity, and the complexity reduction of such schemes can be challenging.

VI. Future Challenges and Potential Approaches

In this section, several open issues and potential future directions for heterogeneous LTE/LTE-A networks are highlighted.

A. *Low-Complexity Resource Allocation Among Femtocells*

A number of RRM schemes [55], [77], [81], [90], [96] can perform well in terms of interference mitigation, resource utilization and global fairness. However, most of them entail high complexity in terms of implementation and computation. For instance, RRM schemes such as that in [55] may require large amounts of signaling and computation due to their centralized framework. The RRM scheme in [77] is an appealing one, as its femtocell clustering mechanism can significantly relieve implementation complexity, especially for large networks. However, there is a major concern about whether the cluster head has sufficient processing capability to manage resource allocation among the FUEs within its cluster. As an HeNB is a small BS, its processing capability may be relatively low compared to an eNB, hence the RRM scheme in [77] is unlikely to be implemented at the HeNB. The RRM schemes in [90] and [96] have reasonable complexity, but further improvements in the aspects of fairness and QoS may involve substantial complexity. The RRM scheme in [81], however, can be further improved in terms of fairness and QoS without a significant complexity increase, thus making more sophisticated enhancements possible. In summary, the complexity issue must be carefully addressed, considering the limited processing capability of an HeNB, the amount of signaling overhead and the possibility of further improvements without incurring higher complexity.

B. *Efficient and Fair Resource Allocation Among RNs*

As demonstrated in the qualitative evaluation in Section V-K, most of the RRM schemes cannot achieve high resource-utilization efficiency. The frequency reuse approach in [118] and [119] appears to be able to achieve high spectral efficiency with good interference mitigation. However, neither scheme provides a satisfactory level of global fairness. In addition, the RRM scheme in [118] entails a prohibitive implementation complexity. Since the RRM scheme in [118] is designed for shared relay networks, complexity reduction is possible by adapting it to the conventional LTE/LTE-A multihop network. To date, it remains a challenging task to design resource allocation schemes for LTE/LTE-A multihop networks with low complexity, while simultaneously excelling in aspects such as interference mitigation, resource utilization and global fairness.

C. *Scheduling in Small Cells*

Employed in many of the proposed RRM schemes, conventional scheduling such as the proportional fair and the round robin schedulers are both fairness-aware and channel-aware, but they are not QoS-aware. As a result, throughput degradation occurs, especially for the traffic class with high QoS constraints such as video and VoIP. It is important for packet schedulers to be able to differentiate traffic classes and prioritize the radio resource allocation for GBR bearers, while guaranteeing an acceptable level of fairness to non-GBR bearers. Although several RRM schemes [54], [71], [89], [124], [127] employ a QoS-aware scheduler that can satisfy various QoS constraints that are compliant with LTE/LTE-A specifications, some outstanding issues still remain. For instance, the scheduler used in [54], [89], [124], and [127] is designed for downlink PRB allocation only. As such, it cannot be applied directly without major modification for uplink PRB allocation, due to a SC-FDMA constraint that allows only consecutive PRB allocation for each UE. In [71], the resource-scheduling scheme lacks fairness consideration. Conversely, the scheduler in [89] assumes each UE holds one radio bearer only. Therefore, it is unclear how the multiple radio bearers of the different QCI classes for each UE are handled. In addition, the RRM scheme in [127] is able to manage multiple radio bearers for each UE and guarantee proportional fairness, but only two LTE/LTE-A compliant QoS constraints are considered, namely the minimum rate and the delay constraints. The packet loss constraint should be considered as well, since it is correlated to the delay constraints. In summary, the design of a packet scheduling method should be aware of fairness and QoS (in addition to the channel conditions of UEs) as well as being implementable in both the uplink and the downlink. Several channel-aware/QoS-aware scheduling methods that may be applicable can be found in [32].

D. Consideration of SC-FDMA Constraints

Although several RRM schemes are seemingly applicable to the uplink, these schemes do not actually address the uplink SC-FDMA constraints in the RRM design for LTE/LTE-A systems. This issue has been addressed in [66] and [126] for femtocell and multihop networks respectively, but other aspects such as interference, fairness and QoS are not adequately addressed. This presents a challenge in the design of RRM schemes for the uplink, since there are multiple objectives (e.g., interference mitigation, fairness and QoS) to be achieved while handling the uplink SC-FDMA constraint.

E. Admission Control and Handover in Small Cells

It is forecast that future cellular networks will be overlaid with densely deployed small cells, thus the frequency of UEs traveling across many small cells will be very high, especially for high-mobility UEs. This may in turn lead to large numbers of unnecessary handovers, known as the "ping-pong effect," which may degrade the QoS. In order to guarantee QoS satisfaction, the handover mechanism needs to determine whether each incoming UE should be accepted to a target small cell or remain served by the current small cell with the objective of reducing unnecessary handovers. Such a mechanism is called radio admission control, which is part of the handover process. The design of radio admission control schemes should consider several parameters such as PRB availability, load conditions and the QoS requirements of the radio bearers. Several related studies of radio admission control in HetNets have been carried out in [71], [77], and [132]–[136]. However, [133]–[136] concentrate on radio admission control in OFDMA-based cellular networks, instead of LTE/LTE-A networks. In [71], the proposed admission control scheme is based on a centralized approach, where the admission decision is made by a central entity located at the eNB, and the decision is relayed to the HeNBs. As such, a significant amount of signaling overhead is required. Meanwhile, the schemes in [77] and [132] consider only single-bearer admission control, instead of multiple radio bearers. In short, a distributed admission control scheme that considers multiple radio bearers with low complexity is required for LTE/LTE-A HetNets.

On the other hand, random access plays an important role in the handover performance of HetNets. In LTE/LTE-A systems, a random access procedure is evoked when the UEs attempt to access a target eNB during a handover process. An efficient completion of the random access process would guarantee several important QoS constraints, such as low packet loss and low delay for the UEs. Therefore, the design of random access protocols may impact the network performance, especially for densely populated small-cell networks. However, the design of a random access protocol can be a very challenging task. In general, the design parameters of random access protocols (which include the contention window, the backoff period and the number of retransmission limits) must be carefully considered and analyzed. Such an analysis can be very difficult and challenging. Several studies [137], [138] have investigated such design parameters in LTE/LTE-A systems by providing a good mathematical analysis on the parameters, which is useful in facilitating the design of random access protocols for HetNets.

F. Load Balancing Between Macrocell and Small Cells

As mentioned previously, one of the advantages of HetNets is that they can offload some traffic from the eNBs to their associated HeNBs. However, an uneven traffic-load distribution problem may arise when the region covered by the eNBs has more users or is encountering heavier traffic than that in their associated HeNBs. As a result, the benefit of traffic offload is negated and the available resources at the HeNBs may not be fully utilized; the same problem may arise in LTE-A multihop networks. In this case, a load-balancing mechanism is required. For example, the MUEs that are in close proximity to a small cell can perform handover from the serving eNB to the small cell. Several load-balancing techniques have been investigated for LTE/LTE-A HetNets such as: power control [48], mobile association/cell selection [107], [121], [139], resource allocation [129], [140] and virtual range adjustment [141]. Moreover, the combination of a virtual range-adjustment scheme and a power control scheme using a fuzzy rule-based RL for load balancing is investigated in [142]. However, there is still room for further improvement in the design of load balancing techniques, where aspects such as interference mitigation, resource utilization, fairness in terms of load distribution, and complexity should be jointly considered.

G. Incorporating Random Access Into RRM for HetNets

The dense deployment of small cells would certainly be able to support a large number of users within the underlaid macrocell network. A large number of users may result in network congestion, so dynamic resource allocation and scheduling methods may be inefficient as they may introduce substantial control signaling overheads, especially when scheduling multimedia traffic flows with small and periodic packets such as VoIP packets [143]. In such a case, random access-based RRM schemes may be a promising approach. In fact, several studies [143]–[145] have proven that random access-based RRM schemes can provide QoS guarantees to multimedia flows such as VoIP flows. As such, the same outcome could be attained by applying them to LTE/LTE-A HetNets. This is possible because LTE/LTE-A systems support random access protocols, and several physical and logical channels are defined in LTE/LTE-A specifications for the purpose of random access [2]. However, several technical challenges may arise when incorporating random access protocols into the RRM design for HetNets, such as the design of the contention window, the backoff period and the number of retransmission limits. As these design parameters may bring significant impact to various users or traffic flows, a careful and detailed analysis on the network performance with respect to the design parameters must be carried out. Several studies [137], [138], [143]–[146] have analyzed the behavior of random access protocols and their stability in various scenarios with regard to the design parameters, which may provide useful insights into developing random access-based RRM schemes for HetNets. In addition, one may refer to [147], which discusses other important challenges of random access protocols in small cell networks.

H. Enabling Cognitive Radio in Multihop Networks

Cognitive radio has been adopted in many RRM schemes, particularly for femtocell networks. However, there have been few attempts to leverage cognitive radio into RNs in LTE/LTE-A networks [148]. Such networks can be referred as the *cognitive multihop networks*. There are many ways to incorporate cognitive radio into RNs to perform radio resource allocation. For instance, the RN can be equipped with spectrum-sensing capability to identify unoccupied radio resources for access transmission, while the backhaul resources are allocated by the eNB—studied in [149] for general cellular networks. The RN can also identify unoccupied radio resources for both the backhaul and the access links, but the computational cost and energy consumption of the RN can be very high. Nevertheless, this could further improve the spectral efficiency while reducing the computational costs at the eNB for resource scheduling. However, many technical challenges remain; for example, the sensing period has to be sufficiently short as resource scheduling occurs every TTI, with a typical time span of 1 ms.

I. Toward Self-Organizing HetNets

It is envisaged that the next generation cellular network will be able to self-organize autonomously without manual intervention, leading to a new form of cellular networks known as *self-organization networks*. From the perspective of RRM, the eNB and the small cells should be able to perform self-optimization for radio resource allocation, load balancing, interference coordination, etc. This requires that all the BSs be aware of their surrounding environments and system conditions, which poses a great challenge for the network operator to implement such networks with low complexity. Such networks enjoy numerous advantages such as: reduced energy consumption, efficient resource allocation, cost saving, and seamless communications. The authors in [71] apply self-organizing functionalities to facilitate their proposed RRM schemes, but a self-organizing network relies on a central entity, the complexity of which could be prohibitive. In summary, technical challenges remain in this area and further research is required. For further reading about self-organization networks, a comprehensive survey of self-organization cellular networks can be found in [150].

J. HetNets With Different Small Cells

Since it is foreseen that future cellular networks may comprise numerous small cells such as femtocells and RNs, the design of RRM should address the problems that may arise between different types of small cells that are adjacent to each other. Hence, resource partitioning, scheduling, admission control, handover, etc. may all have to be redesigned. Some studies [140], [141] have considered LTE/LTE-A HetNets that consist of different types of small cells. However, issues such as interference and resource allocation are still not addressed in depth. For example, the HeNB needs to be aware of its surrounding small cells, such as the RNs and the other HeNBs, so that interference can be avoided or tackled. This awareness may include information about the radio resources used in the backhaul link and the access link of the RNs.

VII. Conclusion and Lessons Learned

The architectural structure of the LTE/LTE-A networks has gradually evolved into the form of HetNets. Such an evolution brings about the fulfillment of the need for high-speed wireless communications. However, several RRM challenges in the form of interference mitigation, fairness, complexity, resource utilization and QoS have become major obstacles to the continued evolution of these networks. This has given rise to various RRM approaches—some of which have been introduced in this paper—with the ambition of overcoming these challenges. The current development of RRM approaches ranges from primitive approaches, such as simple scheduling and frequency reuse, to those that are more dynamic and intelligent, such as cognitive radio and game theory approaches.

Due to the architectural differences between femtocells and RNs, the developed RRM frameworks for these two types of small cells are different. Unlike femtocells, the RRM frameworks for RNs have to accommodate backhaul issues. However, both these small cells face similar challenges in terms of interference mitigation, fairness, etc. Therefore, the RRM schemes developed for these small cells share the same objective of overcoming these challenges. As such, they share common quality measures in a network performance evaluation.

From our review, we found that the recent developments of the RRM schemes for LTE/LTE-A femtocell networks resulted in effective interference mitigation, while attempting to provide a fair and efficient resource-utilization with a reasonable complexity and QoS guarantee. Similar advancements are found in LTE/LTE-A multihop networks. Despite such advancements, our qualitative comparison indicated that the RRM schemes did not fully satisfy all these aspects, especially the QoS. A major reason for this is that the existing schemes were designed in such a way as to give high priority to certain aspects such as interference mitigation, at the expense of some other aspects such as QoS; multi-objective techniques are one promising approach for maximizing the satisfaction level of all the aspects.

The design of RRM schemes can be formulated as a multi-objective problem. The best solution to such a problem achieves the objectives in the most satisfactory manner. Therefore, studies of multi-objective RRM seem vital to the future research and development of RRM. Given the complicated architecture of LTE/LTE-A HetNets, the solution may need to be developed with combinations of several approaches. In fact, this design method has become popular in the research of RRM in LTE/LTE-A femtocell networks. For instance, the game theory-based RRM schemes used in the femtocell networks are built upon the cognitive radio approach. Such a way of designing an RRM scheme is very interesting, and could prove very effective in satisfying multiple aspects jointly.

Finally, it can be concluded that the research area of RRM for LTE/LTE-A HetNets is still subject to many challenges, some of which have been highlighted in this paper. Meeting these challenges will make the evolution of LTE/LTE-A networks into HetNets a success and, thus, make these networks able to support numerous high-speed multimedia applications.

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