Chapter 1
Future Radio Access, Wi-Fi-LTE, LTE-Advanced: The Path to 5G

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Abstract With the proliferation of IP-based bandwidth-intensive video services and smartphones, there has been an unprecedented exponential increase in mobile broadband data. This has resulted in increasing demand for additional wireless capacity. In order to increase the wireless capacity multifold, the next-generation radio access networks (RAN) boast of a number of sophisticated technologies, such as Carrier Aggregation (CA), Evolved-Multicast/Broadcast Multimedia Services (eMBMS) using Single-Frequency Networks (SFN), enhanced Inter-Cell Interference Coordination (eICIC) in self-organized Heterogeneous Networks (HetNets), Coordinated Multi-Point (CoMP) transmission in Multiple-Input–Multiple-Output (MIMO) systems using 2D/3D Beamforming, and full-duplex communication. Some of the above technologies are standardized in 3GPP Release 10+ systems like LTE-Advanced and are seen as a roadmap to 5G RANs. This chapter provides a comprehensive overview of each of these technologies and surveys the key open issues concerning them in terms of radio resource management (RRM) to facilitate maximum wireless capacity and provide Quality-of-Service (QoS) to the users. It also explores the synergies between these technologies towards developing holistic optimization techniques for the design of 4G+ and 5G systems.

1.1 Introduction

Recent proliferation of mobile broadband data is accelerated by the unprecedented increase in the subscription of next-generation bandwidth-intensive multimedia services by IP-based smartphone and tablet/computer users. 3GPP LTE, the latest 4G wireless broadband standard based on OFDMA, promises higher data rates than its predecessors from the legacy 3GPP systems. This is due to the independently modulated orthogonal and flat-fading sub-carriers that constitute a frequency-selective OFDM carrier. Furthermore, the multi-user diversity feature of OFDMA enables

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multiplexing different users with different requirements, by supporting different Modulation and Coding Scheme (MCS) rates on every sub-channel. However, the LTE operators face a significant challenge in satisfying the Quality-of-Service (QoS) demands of the multimedia services, such as HD video streaming/gaming and video broadcast, due to the limited and expensive resources of the licensed spectrum. This challenge is further compounded by the channel dynamics of the network due to factors such as user mobility, inter-cell interference, fading, and attenuation. Especially, the users close to the cell edges are significantly penalized. This is because of their poorer channel quality that they are not being allocated adequate radio resources to satisfy their QoS [1].

An effective Radio Resource Management (RRM), accounting for the dynamic channel characteristics and traffic demands of the user, is essential in meeting the QoS objectives of the services offered by the network operator, and in turn enhancing the Quality-of-Experience (QoE) of the subscriber. Hence, an efficient RRM strategy calls for continuous innovation in the state of art for network configuration, effective deployment, and utilization of the spectrum resources to improve the system performance. This chapter provides a comprehensive overview on the latest advancements in RRM techniques that serve as a roadmap to 5G telecommunication deployments. It also delineates the challenges and open issues associated with each of these techniques. The 3GPP Release 10+ standardizes some of the techniques detailed in this chapter.

LTE-A aims to meet the advanced requirements of International Mobile Telecommunications (IMT) to support high downlink data rates of up to 1 Gbps for low-speed mobile or stationary User Equipments (UE) or 100 Mbps for high-speed mobile UEs and peak uplink rates of up to 500 Mbps, for facilitating the next-generation telecommunication services. IMT requirements for LTE-A generally aimed at improving the average performance and spectral efficiency of cell-edge UEs, rather than enhancing the peak spectral efficiency of individual applications (such as VoIP) [1].

1.1.1 LTE Principles of Operation and Deployment

Each LTE mobile network operator is auctioned chunks of licensed frequency sub-bands. A licensed frequency sub-band deployed over each LTE base station, called Evolved Node B or alternatively, eNB, with scalable bandwidths ranging from 1.4 to 20 MHz (that includes 1.4, 3, 5, 10, 15, and 20 MHz), is called a Component Carrier (CC). Each CC consists of orthogonal, independently modulated and flat-fading sub-carriers (where a single distinct modulation scheme is used within the frequency domain of one sub-carrier), such that each sub-carrier has a phase shift of 90° with the adjacent ones [2, 3]. Each sub-carrier in LTE is 15 kHz in bandwidth. There are around 1200 sub-carriers in a 20-MHz CC. Each LTE frame consists of 10 sub-frames of 1 ms duration each. The minimum unit of radio resource allocation in the two-dimensional time–frequency domain is a Physical Resource Block (PRB) [4]. It consists of 12 OFDMA sub-carriers, pointing to a frequency sub-band chunk, from the frequency domain and 7 symbols or a half sub-frame (0.5 ms) from the time domain. The bandwidth of a PRB is 180 kHz. Considering the compromise in bandwidth due to the guard band interval between sub-carriers needed to preserve orthogonality, mitigate inter-symbol interference, and maintain significant cyclic prefixes, the number of PRBs in a 20-MHz CC is 100. Any User Equipment (UE), admitted for service by an LTE eNB, is allocated at least two PRBs. Each UE sends channel quality feedback to the eNB, which uses this information to choose an appropriate Modulation and Coding Scheme (MCS) rate, supported by the UE, for encoding the data signals to be transmitted to the UE. The encoded data rate is a function of the MCS, where a higher MCS rate indicates a higher amount of data delivered to the UE. The recent advancements in radio access technologies are broadly based on the following principles:

a. Bandwidth aggregation: This technique is employed to increase the bandwidth of the radio access network by aggregating spectrum resources, deployed in the form of Component Carriers (CC). It is one of the design techniques supported in LTE-Advanced systems from 3GPP Release 10 onwards, standardized by the term Carrier Aggregation (CA) [4, 5]. More than one CC, belonging to the same or different central band frequencies, are integrated as an aggregated carrier and deployed over the LTE eNBs. At most 5 different CCs can be aggregated and deployed over an LTE eNB, resulting in a maximum possible bandwidth of 100 MHz. Hence, a LTE-A eNB supporting CA can serve more than one cell, as shown in Fig. 1.1. Theoretically, CA facilitates peak downlink rates of up to 1 Gbps for stationary/low-speed mobile UEs and around 100 Mbps for high-mobile UEs [1].

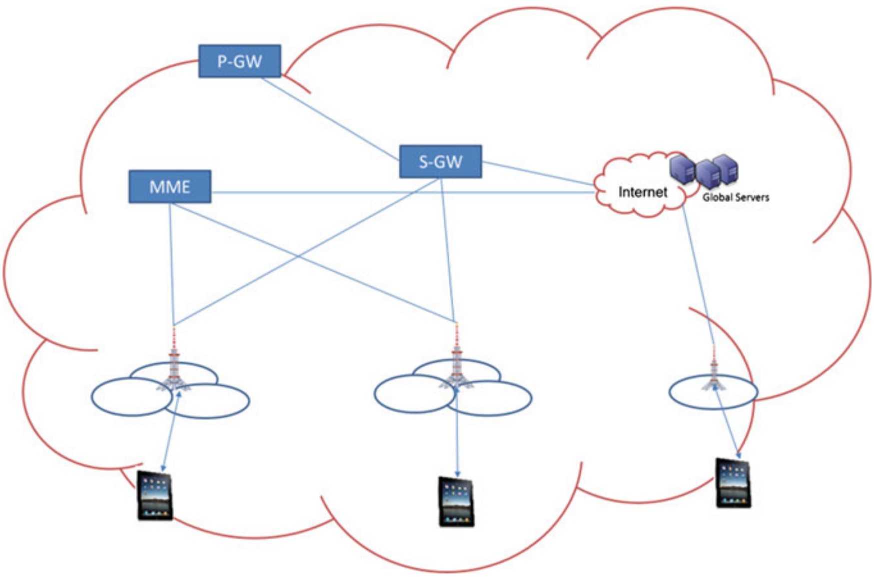


Fig. 1.1 Carrier aggregation serving more than one cell per eNB

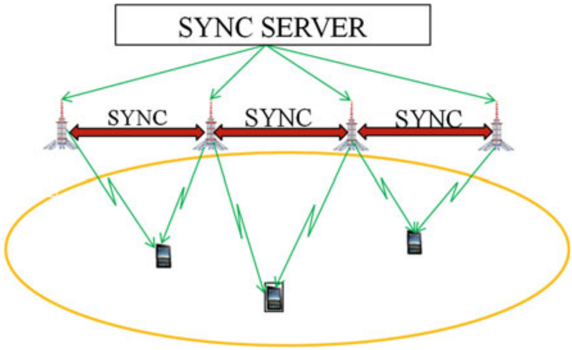


Fig. 1.2 Synchronized eNBs serving UEs

b. Transmission diversity: In this technique, the same information signals are transmitted from more than one eNB that are synchronized to jointly schedule the UEs, as shown in Fig. 1.2. The CCs deployed across the synchronized eNBs belong to the same central band frequency, forming a Single-Frequency Network (SFN) [6–9]. The eNBs coordinate with each other to schedule a common set of UEs on the same PRBs across the eNBs using the same MCS rates, based on the radio channel characteristics from each synchronized eNB. This results in constructive interference at the UE and causes diversity gains, due to a decrease in the number of interfering eNBs and (consequently) an increase in the number of signal-transmitting sources. This principle is used in Evolved-Multicast Broadcast Multimedia Services (eMBMS) feature of LTE [6], standardized in 3GPP Release 8, and in Coordinated Multi-Point transmission feature (CoMP), supported by LTE-Advanced [1]. While the former leverages the diversity gains to improve multicast performance, the latter enhances the performance of cell-edge UEs that otherwise have a higher cell-outage probability.

c. Network Heterogeneity: This design principle aims at enhancing the performance of LTE macrocell networks through small-cell deployments, as shown in Fig. 1.3. Small-cell eNBs are cheaper, lower power eNBs that are densely deployed within the coverage region of one or more LTE macro-eNBs [10, 11]. A dedicated set of radio resources are deployed in the form of CCs over the small-cell eNBs. This increases the network capacity, especially when the macro-cell eNBs face a shortage of residual resources in case of high data demand. Small-cell deployments also provide extended network coverage to macro-cell UEs, especially to the ones at the cell edges of the macro. LTE-Advanced small cells typically use CCs belonging to the same central band frequencies as the ones in the macrocell eNBs, resulting in higher frequency reuse. However, the deployment can lead to high co-channel interference, if resource sharing is not carefully planned. The UEs in the network have a larger degree of freedom in their cell association, as each of them could associate with either one of the small cells or an interfering macro.

d. Spatial diversity and multiplexing: Spatial diversity employs at the eNB multiple transmit antennae with identical design that are physically separated from each other, usually by at least a half-wavelength. In conventional single-stream

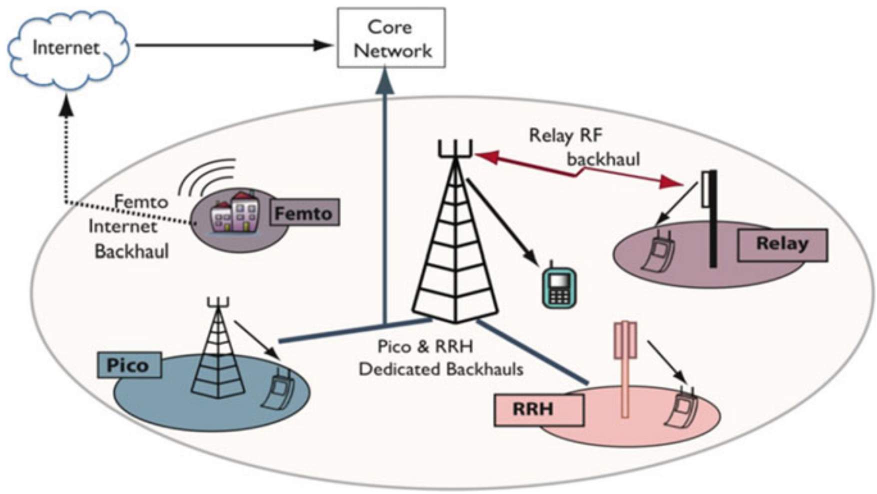


Fig. 1.3 Coexistence of heterogeneous transmission devices (macrocell, small cells)

beamforming, the same signal is transmitted from each transmit antenna in the array with appropriate weights, based on phase and channel gain, so as to maximize the throughput. Antenna arrays mitigate the destructive multi-path interference among the reflections of the transmitted signal by leveraging the different transmission and fading characteristics of each antenna with respect to the receiver, and combining them at the receiver. This improves the downlink channel quality at the UE. Spatial diversity is one of the operating principles used in Multiple-Input–Multiple-Output (MIMO) systems, shown in Fig. 1.4, where the downlink capacity is further enhanced by using multiple receiver antennae at the UE. In order to maximize the throughput of the UE equipped with multiple receiver antennae, a multi-stream transmission using spatial multiplexing is considered [12]. For a given sub-channel, a channel matrix is constructed for each eNB–UE pair from the channel quality value between each transmit–receive antenna pair. Multi-stream beamforming uses

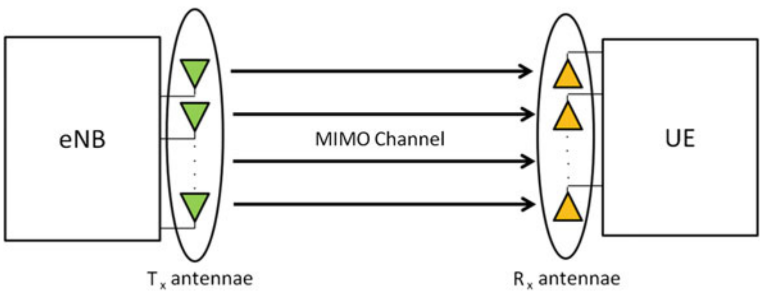


Fig. 1.4 Communication over a multi-antenna MIMO channel

this matrix to independently encode multiple data streams using a precoding vector and transmitting the information signals from each of the antennae in the array. This spatial multiplexing of different downlink data streams onto the MIMO channel exploits the additional degree-of-freedom gain, considering the varying channel characteristics between each transmit–receive antennae pair at the eNB and UE, respectively. Multiuser MIMO-OFDMA with 2D/3D-beamforming features is a recent sophistication, actively considered and tested in LTE-Advanced and 5G deployments.

The above principles are on the basis of LTE and will partake in shaping the 5G technology and, in turn, influence the backhaul infrastructure from the perspective of Fi-Wi convergence. This chapter discusses some of the open issues in each of the aforementioned radio access techniques from the perspectives of PHY and MAC layers. In the rest of this introductory section, we quickly introduce the main open issues at PHY and MAC layer that will be elaborated in the rest of the chapter.

PHY Layer: The challenges in the PHY layer are typically concerned with improving the channel quality of the users, e.g., increasing the Signal-to-Interference-plus-Noise Ratio (SINR) of the individual UEs. The factors that affect SINR include assignment of CCs to the UEs as the central band frequency of the CC impacts the path loss yielded to the UE, appropriate cell association based on its link quality with the UE, appropriate choice of precoding/beamforming vectors to manage the signal strength and inter-cell interference for the UEs multiplexed onto the MIMO channel, the number of eNBs synchronized in an SFN which impacts the diversity gain of the UEs served by the SFN, etc. The channel quality of the UEs helps in determining appropriate MCS rates chosen by the eNBs in serving the UEs and subsequently, the net system capacity. The crucial component in the net system performance is the channel quality of the cell-edge UEs. (e.g., in applications like eMBMS, the performance of a multicast/broadcast group is limited by the UEs, especially at the cell edges, who have minimum throughput).

MAC Layer: The issues in the MAC layer are centered on the allocation of frequency–time PRBs and scheduling them to the UEs. The key utility metrics in the MAC layer are throughput, fairness, and effective spectrum utilization. Throughput deals with achieving a higher net system capacity as a result of allocating PRBs and choosing appropriate MCS rates to serve the UEs, whereas fairness deals with allocating a fair share of PRBs to every UE in the network, accounting for its radio channel characteristics and traffic dynamics. Scheduling schemes like Proportional Fairness (PF) [13] balance the trade-off between throughput and fairness, where the related system utility function is seen as a logarithmic function of the throughput rates. Scheduling frequency–time PRBs to the UEs in the network impacts the Quality-of-Service (QoS) of the applications served by the eNBs and helps in evaluating related performance metrics, such as call/session admissibility.

Effective spectrum utilization is a measure of the fraction of the net deployed frequency–time PRBs that is scheduled to the UEs with appropriate MCS values. A higher value of this metric indicates that the licensed spectrum resources (in the form of PRBs) are being effectively deployed by allocating them appropriately to the UEs. Proportional Fair (PF) schedulers are also used to enhance the effective spectrum utilization of the eNB, as the sum of the logarithmic rates of the UEs would be higher if the eNB schedules a larger number of UEs with the best-possible MCS rates. The linear additive factor in the sum log rate helps in serving higher number of UEs and the log factor in the metric helps in ensuring fairness to each of them.

1.2 Carrier Aggregation

1.2.1 Definitions and Terminologies

3GPP LTE-Advanced (LTE-A) attempts to serve the next-generation telecommunication services, such as real-time high-definition video streaming, mobile HDTV, and high-quality video conferencing. LTE-A facilitates higher data rates in response to the requirements proposed by IMT-Advanced for providing higher QoS to mobile applications. LTE-A provides peak uplink and downlink data rates of 500 Mbps and 1 Gbps, respectively, for low-speed UEs and around 100 Mbps for fast-moving users [14, 15]. The bandwidths of LTE-A systems in both uplink and downlink can go up to 100 MHz, achieved by the aggregation of individual CCs through Carrier Aggregation (CA). Each CC corresponds to a cell or a coverage region and serves the UEs present in the region, which are associated with the cell. So, an LTE eNB supporting CA can serve more than one cell. An LTE-A Release 10+ UE can be scheduled on more than one CC, unlike an LTE Release 8/9 UE that can be scheduled on at most one CC. However, LTE-A UEs, supporting CA, are backward-compatible with LTE UEs, supporting operation on only one CC at the eNBs.

When an LTE-A UE attaches to an eNB and establishes or re-establishes a radio resource control connection with the eNB, only one cell corresponding to a CC is configured for the UE. This is termed as the primary cell. The CC corresponding to the primary cell is termed as primary CC. Then, depending on the serving traffic load on the primary CC and the Quality-of-Service (QoS) requirements of the UE, additional serving cells can be configured on the UE, termed as secondary cells [14]. The CCs corresponding to the secondary cells are called secondary CCs. Hence, an LTE-A UE can be associated with more than one cell. For every LTE-A UE, the primary cell is configured mandatorily, and the other configured secondary cells are based on the QoS requirements of the traffic profiles subscribed by the UE. The primary CCs across the LTE-A UEs need not be the same as in the aggregated carrier; they are UE-specific and can be different for different UEs served by the eNB. While both the primary and secondary CCs are involved in scheduling their PRBs to the UEs, the additional responsibility of the primary CC is to maintain the Radio Resource Control (RRC) connection of the corresponding UEs, which includes state information about location registration, connection establishment/re-establishment, termination, and handover. An LTE-A UE has only one RRC connection with the network. It establishes/re-establishes the RRC connection (using the random access procedure which registers the UE in the network) on the primary cell and uses additional RRC signaling to add, remove, or re-configure secondary cells. Hence, the primary CC for every UE cannot be changed dynamically as long as the UE is associated with an eNB, unlike the secondary CCs which can be dynamically configured and managed [5, 14, 15].

The PHY layer channel quality measurements taken by each UE are used to assist configuring, assigning, and managing CCs for the UE. The UE sends these channel quality values to the eNB using the uplink control channel on its primary CC. Although multiple cells are configured or assigned for an LTE-A UE, the UE is assigned a single-cell radio network temporary identifier, corresponding to the cell ID of the primary cell. This is used to uniquely identify the RRC connection of the UE for transmitting scheduling information on the downlink control channel corresponding to either the primary CC or the secondary CCs. The primary CC for a UE is selected through either a channel-aware or a traffic load-balancing technique. Typically, the former assigns the CC which yields the highest Reference Signal Received Power (RSRP, a measure of the received signal strength, discussed in Sect. 1.4.1) or conversely the lowest path loss to the UE, as the primary cell. Load-balancing can be used to designate the primary and secondary CCs. The CC with the highest number of residual PRBs, after serving the current traffic load, is selected as the primary CC for the UE. This is done to make sure that adequate PRBs are available to be allocated to the UE to satisfy its traffic demands. Additionally, this also helps in preventing resource exhaustion.

1.2.2 Types of Carrier Aggregation

The types of CA [16, 17] are as follows

a. **Intra-band contiguous CA** manages the aggregation of CCs in adjacent frequencies of contiguous bandwidths from the same frequency band [5]. It is the easiest to implement as the CCs are adjacent to each other. The aggregated carrier is considered as a single enlarged wideband channel from the RF standpoint and hence, the UE requires only one transceiver. Even with the aggregated increase in bandwidth, the power consumption and cost requirements are considerably less stringent allowing for greater flexibility in RF design due to the already-existent multi-carrier nature of OFDM-enabled eNBs. However, it is difficult for the operator to obtain a contiguous large chunk of aggregated bandwidth, say up to 100 MHz, during the auctioning process due to competitive bidders, limited availability, and expensive deployment of licensed spectrum resources.

b. **Intra-band non-contiguous CA** manages the aggregation of CCs from non-adjacent, non-contiguous sub-band frequencies belonging to the same frequency band [5]. This design is more complicated than intra-band contiguous CA,

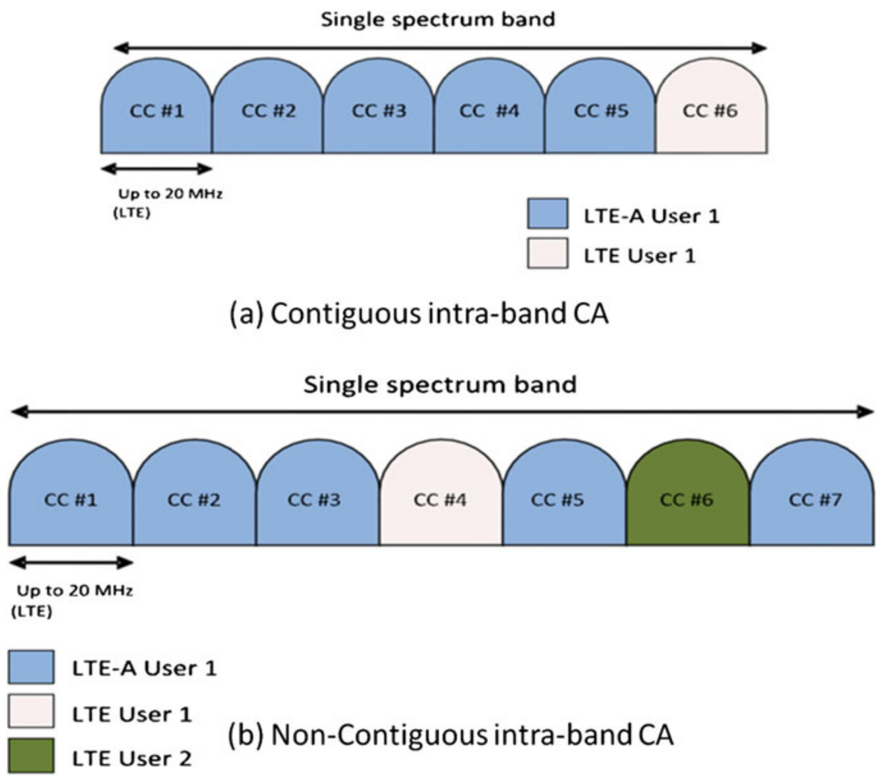


Fig. 1.5 Intra-band carrier aggregation

as the multi-carrier signals from non-adjacent sub-bands can no longer be treated as a single distinct signal, thus requiring two or more transceivers. This adds complexity to the RF design in terms of power consumption and cost. However, this addresses the challenge in allocating large chunks of aggregated bandwidth due to the non-contiguity nature in the auctioning and deployment of non-adjacent CCs to every bidding mobile operator.

Moreover, the radio channel characteristics yielded by the CCs from the intra-band non-contiguous CA to any UE are not drastically different from each other, except for the random slow and fast-fading attenuations and Doppler shifts, as the CCs correspond to the same frequency band. An illustration of intra-band contiguous and non-contiguous CA is shown in Fig. 1.5.

c. **Inter-band non-contiguous CA** manages the aggregation of non-adjacent CCs belonging to different frequency bands [5]. The fragmented frequency sub-band chunks that are aggregated as CCs at the eNB are of varying bandwidths. As network operators may not win adjacent spectrum slots, they also aggregate bandwidths that may be not contiguous. Moreover, since each CC corresponds to a different central band frequency, the transmission characteristics such as path loss,

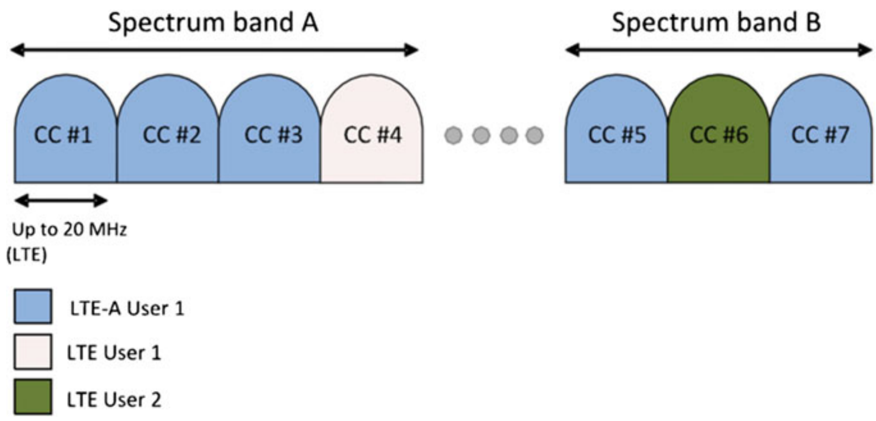


Fig. 1.6 Inter-band carrier aggregation

Doppler shifts, fading and attenuation, pertaining to each CC, are different from one another. This results in different received signal values from each CC, measured by the corresponding RSRP values, as shown in Sect. 1.4.1. Figure 1.6 shows aggregation of CCs from different frequency bands. Hence, the different combinations of one or more CCs yield varying multiplexing gains for any UE, while being assigned to it. The UE requires the use of multiple transceivers to transmit/receive signals to/from the different aggregated CCs, thereby introducing additional complexity to the RF design in power and cost, as in the case of intra-band non-contiguous CA.

Carrier Aggregation is possible in both uplink and downlink directions. While there are a good number of similarities between uplink [4, 18] and downlink CA, in the following we highlight the significant differences between these two forms of CA.

Uplink CA: The performance of uplink CA is limited by the transmission power at the UEs. This limits the UEs from having high data rates yielded by the large bandwidths facilitated by CA. When LTE-A UEs transmit bandwidth-intensive multiple applications like HD videos in the uplink, they require being allocated larger PRBs and using higher modulation rates, in order to satisfy QoS and to make maximum usage of the allocated bandwidths, respectively. Both of these requirements increase the Peak-to-Average Power Ratio (PAPR) [19] at the UEs and hence, result in a higher consumption of battery life at the UEs. The expected transmission power (in dB) for UE u as a result of transmitting to eNB m on CC c, given by $P'_{u,m,c}$, is given in [4].

In order to reduce uplink power consumption, LTE uses Single-Carrier FDMA (SC-FDMA) [20] in the uplink, where the entire CC is available for the UE as a single channel, but the symbol time is of a much shorter duration, when compared to OFDMA. SC-FDMA requires allocation of contiguous PRBs across the deployed CC to each UE and this reduces the PAPR of the UE in the uplink. Moreover, the peak modulation rates availed by using SC-FDMA in the uplink are comparatively smaller than the ones obtained by using OFDMA in the downlink. Usage of higher MCS rates requires lower PRBs to be allocated to any UE for satisfying its QoS. But using higher rates increases the PAPR. On the other hand, using lower MCS rates requires using larger PRBs to be allocated to the UE. But, even larger PRBs increase the PAPR, as shown in [4]. However, a linear increase in PRBs only results in a logarithmic increase in the UE's transmission power. So, SC-FDMA manages this trade-off by using lower peak modulation rates and contiguous chunk of PRBs, for which a collective feedback is sent less frequently.

Downlink CA: The eNBs are not so limited by power in their downlink as the UEs, in the uplink. So, LTE uses OFDMA in the downlink that supports higher peak MCS rates, thereby resulting in an increased PAPR. In the downlink, OFDMA also supports allocation of non-contiguous independently modulated PRBs to the UEs so as to maximize the gains resulting from frequency diversity. While most of the issues pertaining to RRM and cell-edge user performance [4] are applicable to downlink CA, the exclusive aspects of downlink CA deal with Evolved-Multimedia Broadcast/Multicast Services (eMBMS) [21, 8] and MIMO features in LTE-A. For video multicast/broadcast, the eNB serves groups of UEs, who collectively subscribe to the same multimedia content called session, on a common set of PRBs using common MCS rates [6].

The performance of a multicast/broadcast session is limited by the UE with the poorest channel conditions (especially those around the cell edges), as the throughput of a session is defined as the minimum throughput achieved by any UE, who subscribes to the session. This UE with the poorest channel conditions is designated at the bottleneck UE for the session. So, the MCS rate allocated by an eNB to serve a session would be the lowest rate supported by any UE in the corresponding eMBMS group.

Especially, when both cell-center and cell-edge UEs are a part of an eMBMS group, the poorer channel conditions of the cell-edge UEs and the lower MCS rates supported by them would drastically bring down the performance of the cell-center UEs in the group that exist with much better channel conditions [22]. Now, when UEs with drastically different channel conditions are grouped together, the eNB needs to jointly account for the channel dynamics of each individual UE along with the QoS requirements of the entire session in allocating PRBs. Due to the above requirements, in video multicasting services over LTE-A systems supporting CA, a common set of one or more CCs should be assigned to serve each group using the PRBs that constitute the CC(s) [23, 24]. There should be one common primary CC to carry out RRC-related functionalities for the entire group, which is a major challenge, as each UE in the network may choose a different primary CC from the rest due to varying channel conditions, traffic and mobility patterns. Similarly, the other optional secondary CCs, if configured based on the QoS requirements for the session, must also be common for the entire group. However, the key difference here is that the choice of selection of secondary CCs, allocation of PRBs, and assignment of MCS values to the eMBMS groups for QoS need not be limited by

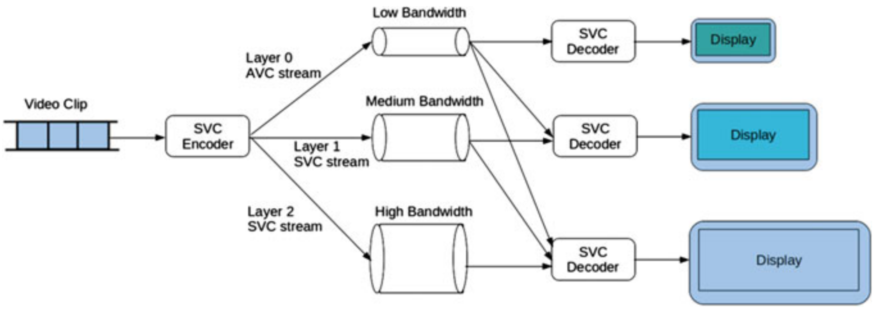


Fig. 1.7 Scalable video coding

the UE with the poorest channel conditions in each group. Let us understand this better via the following illustration (Fig. 1.7):

Illustration: We provide a simple illustration to discuss video multicast for downlink CA [25, 26] that downstreams a given source video into several independently encoded bit streams called layers with different resolution. The layer with the minimum resolution that can be supported by even lower underlying network bandwidths is called base layer, and the other layers are called enhancement layers. Now, to facilitate scalable video multicast over LTE-Advanced systems supporting CA, the mandatory base layer, which must be decoded by every UE in the eMBMS group, is scheduled over the primary CC, designated for the group. This selection of primary CC is, in turn, based on the channel dynamics of each UE present in the eMBMS group. As mentioned earlier, the primary CC is chosen based on either a channel-aware or a traffic load-balancing technique. Accordingly, the allocation of the primary CC should be such that it yields the required channel conditions and residual PRBs, adequate enough to provide the highest-possible data rates to the bottleneck UE for the session and/or satisfy its QoS requirements. In inter-band aggregated carrier, the primary CC for the group is usually considered as that CC corresponding to a lower central band frequency and that has a higher number of residual PRBs. A CC with a lower central band frequency yields a lower path loss value to the UEs of the group, especially crucial to those present around the cell edges. Hence, this results in the primary CC providing sufficient channel conditions required to decode the mandatory base layer of the HD video by all UEs (incl. the cell edge UEs) of the group that subscribe to the video. If the bandwidth offered by the primary CC is sufficient to serve the mandatory base layer specified by the Guaranteed Bit Rate (GBR), which is ensured by the operator to the session subscribers, then the optional enhancement layers are served to the group on the secondary CCs configured for the group [3, 22]. Now, the enhancement layers are not mandatory to be served; however, a higher number of enhancement layers served with best effort for the group subscription increases the overall session throughput, having as an upper bound the maximum bit rate (MBR) [3, 22]. So, the optional secondary CCs can schedule the enhancement layers, and the choice of

PRBs and MCS rates on the secondary CCs is not limited by the bottleneck UE of the eMBMS group subscribing to the session.

1.2.3 Radio Resource Management Framework for CA

The functionalities of the RRM framework for an LTE-A system supporting CA [27] are shown in Fig. 1.8. The eNB performs session admission control based on the QoS requirements and service class priorities of different UEs. A new RRM functionality, added to LTE-Advanced, is Layer-III CC Assignment and Configuration which configures and assigns a set of CCs for each UE. The other RRM functionality is Layer-II Packet Scheduling, which deals with the allocation of PRBs to the different UEs that are multiplexed on each CC assigned in the set.

Component Carrier Assignment and Configuration: The CC set is the collection of CCs where the UE may later-on be scheduled on its PRBs. The assignment and configuration of the CC set to the UEs is a Layer-III functionality in the LTE/LTE-A protocol stack for RRM and happens with RRC signaling to the UEs. The CC configuration functionality is important in optimizing throughput, fairness, power consumption, [4], etc. The QoS requirements, radio channel conditions, and UE capability like residual power, SNR, and antenna configuration are taken into account for assigning and configuring the CC set to the UEs.

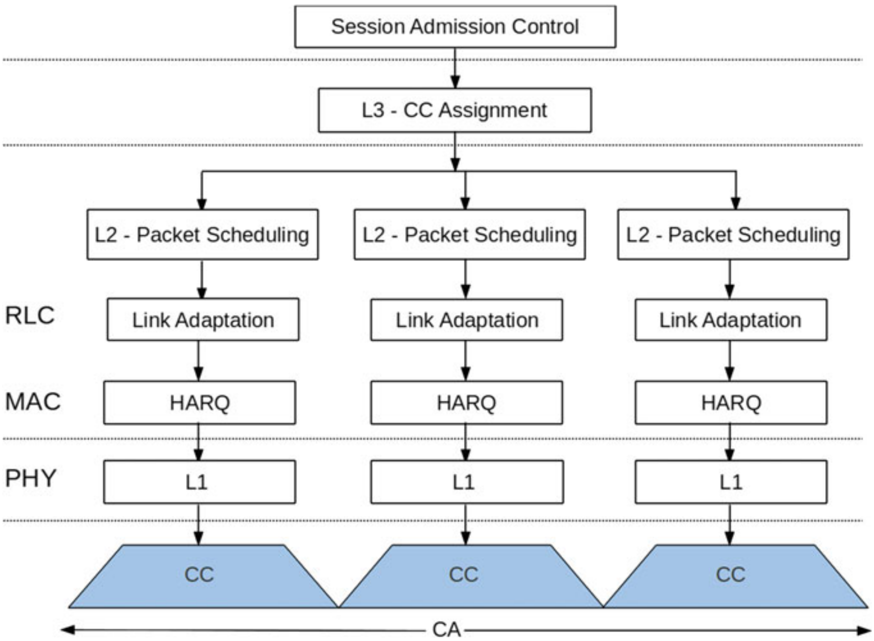


Fig. 1.8 Radio resource management framework for CA

The dedicated bearer established between the UE and the core network, corresponding to the traffic subscribed by the UE, communicates its QoS requirements in terms of the Guaranteed Bit Rate (GBR), Aggregate Maximum Bit Rate (AMBR), packet delay, loss rate tolerance, etc., indexed by the QoS class identifier [3]. Recalling the illustration above, the GBR traffic (corresponding to an SVC-encoded session's base layer), identified by a corresponding lower bound, can be assigned onto the primary CC and served for its QoS requirements to the UEs/eMBMS groups, subscribing to it. If the UEs/groups subscribe to a best-effort traffic, limited by an upper bound MBR/AMBR, then both the primary and the optional but dynamically (de-)activated secondary CCs can be invariably used to schedule the subscribed traffic (similar to serving the best-effort enhancement layers up to the MBR). The algorithms for CC assignment and configuration are open issues and are specific to eNB vendors; however, the assignment falls under the following categories:

- **Channel-blind CC Assignment**: Here, the assignment of the CCs to the UEs is agnostic of the radio channel characteristics of the UEs and is done based on balancing the traffic load served on all CCs in the set, such that each CC approximately serves equal amount of load. Some of the widely adopted techniques in a channel-blind assignment [27] include (i) Round-robin balancing, where a newly arriving UE is assigned to the CC that has the least number of UEs as the primary CC, thereby evenly distributing the load across all CCs, and (ii) Mobile hashing, where a hashing algorithm is used at the UE's end for choosing its primary CC and subsequently, establishing the RRC setup between the eNB and the UE. The output hash values are uniformly distributed among a finite set that maps on to the CC indices, thereby aiming to provide a balanced load across the CCs. The secondary CCs are similarly subsequently chosen for a UE based on its QoS specifications. Channel-blind CC assignment is mostly used for intra-band CA.
- **Channel-aware CC assignment**: The CC assignment is cognitive of the radio channel characteristics of the UEs and is widely used in inter-band CA. One of the standard techniques employed is a path loss-based CC assignment that accounts for the central band frequency of each CC in the set. Two techniques widely used in a channel-aware CC assignment include (i) throughput-based assignment [13, 28], where the UEs are sorted in decreasing order of their channel access probabilities and are assigned CCs which yield lower path loss values (usually, lower than a pre-defined threshold), and (ii) edge-prioritized CC assignment [4], which is usually done to increase the net system fairness. This sorts UEs in increasing order of their overall channel quality, with the UEs having poorer channel conditions preceding those having stronger channels. The assignment follows a similar path-based approach to UEs in the sorted order. Channel-aware CC assignment, however, needs further optimization, to evenly balance the load across the CCs.

Downlink Packet Scheduling: Packet scheduling is a dynamic Layer-II RRM functionality at the MAC layer of the LTE/LTE-A protocol stack and is responsible for scheduling UEs across their assigned, configured and activated CCs. It takes care of allocating the PRBs of the activated CCs, corresponding to the primary and secondary cells, to the UEs. In scheduling the PRBs to the UEs, this functionality leverages the multiuser diversity feature which supports multiplexing different UEs with different MCS values (based on the UEs' channel quality) on each independently modulated frequency sub-channel of the CC across sub-frames in the time domain. When two or more UEs are assigned onto a common CC, the individual PRBs must be scheduled to the different UEs, so as to avoid resource conflict and contention among UEs. The PRBs yield different rates to different UEs. Scheduling can be done in parallel across each individual CC in the set, including some coordination among CCs in the set to ensure optimal system performance and joint controlled signaling for UEs assigned onto multiple CCs. LTE-Advanced facilitates cross-CC scheduling which allows the eNB, supporting CA, to send scheduling grants for each UE for data transmissions corresponding to multiple CCs that are assigned to it, on the primary CC. Cross-CC scheduling allows more than one CC to jointly serve any UE, wherein the traffic subscribed by the UE can be scheduled on PRBs from more than one CC. Different types of scheduling techniques [13] include

- **Maximum Throughput Scheduling**: This scheduling technique is used to achieve the highest-possible spectral efficiency, which results in maximizing the system throughput. The operating principle is to schedule any PRB from any CC to the UE, which reports the largest possible instantaneous wideband achievable throughput on that CC. This scheduling scheme has benefits in terms of cell throughput and spectral efficiency, but comes at the cost of fairness. UEs with poorer channel conditions, especially at the cell edges, either are allocated lower number of PRBs or face resource exhaustion.
- **Blind Equal Throughput**: This heuristic attempts to yield the same throughput for all UEs, regardless of their channel quality. The operating principle is to schedule any PRB from any CC to the UE which reports the lowest past-achieved throughput on that CC. This scheduling scheme has benefits in terms of cell throughput and spectral efficiency, but comes at the cost of fairness. UEs with poorer channel conditions, especially at the cell edges, either are allocated lower number of PRBs or face resource exhaustion.
- **Proportional Fair (PF) Scheduling**: This scheduling technique handles the trade-off between the system throughput and fairness [29]. The operating principle is to schedule any PRB from any CC to the UE which reports the maximum value of the ratio of its instantaneous wideband achievable throughput to its past-achieved throughput on that CC. Different scheduling algorithms can be used across the individual CCs aggregated in the set, based on the QoS requirements of the traffic served on each CC. The RRM functionalities in the MAC layer and the PHY layer are specific to each individual CC in the set. LTE-A supports independent transport blocks, link adaptation, and HARQ on a per-CC basis and accordingly implements the scheduler for each CC.

1.3 Transmission Diversity and Spatial Multiplexing

1.3.1 Transmit Diversity—Definition and Terminologies

Transmission diversity involves the simultaneous transmission of the same identically modulated information-bearing data signals to a UE or an eMBMS group of UEs, originating from two or more independent eNBs operating on the same central band frequency. This requires a tighter coordination among the eNBs, thereby allowing them to synchronously transmit the same data from the synchronized eNBs on the same set of PRBs using the same MCS value. This deployment of synchronized eNBs is called Single-Frequency Network (SFN) [7, 21].

The transmit diversity feature in an SFN addresses the problem of the variable transmission channel quality between the eNBs and the UE. Consider, e.g., a single transmit antenna at each eNB in the SFN and a single receive antenna at any intended UE served by the SFN. If a link between one of the eNBs and the UE/group undergoes a deep fade as a result of poorer channel conditions that affect the transmission, it is compensated by the combined effect of the links between other eNBs and the UE that may yield better received signal strength for the UE. The transmissions of the identical signals from multiple synchronized eNBs on the same PRBs yield a higher SINR as a result of this over-the-air combining effect. This is typically useful in improving the performance of cell-edge UEs in denser eNB deployments, whose channel conditions are marred by higher inter-cell interference. On the other hand, cascading the synchronization on data transmission and resource allocation across a higher number of eNBs would be detrimental if some of them do not contribute significantly to an increase in SINR for an average individual UE. This could amount to wastage of the deployed spectrum resources at such eNBs.

1.3.2 MIMO and Spatial Multiplexing—Definition and Terminologies

The Multiple-Input and Multi-Output (MIMO) technique requires the use of multiple antennae at both the transmitter eNB and receiver UE [30]. MIMO techniques such as beamforming, spatial multiplexing, and spatial diversity play a fundamental role in LTE-Advanced. Thus, in order to maximize the net downlink throughput for a multi-antenna receiver UE, MIMO leverages multi-stream beamforming, which sends multiple streams of UE-subscribed data signals with independent and appropriate precoded weights (based on phase and gain) over the multiple antennae equipped at the transmitter. Beamforming is a signal processing technique for directional transmission of signals by the eNB toward a particular direction in the cell or cell sector served by the eNB [12]. This steering of the beam toward a particular direction helps in increasing the received signal strength of the UEs present in that direction, thereby enhancing spatial selectivity. This is done by combining elements in a phased array such that the relative phase and gain (amplitude) of the signals are controlled at each transmitter antenna so as to enable a constructive interference of the signals at the receiver UE. Let us assume that the eNB has t transmit antennae and the UE has r receive antennae. So, there are t parallel data streams with independently coded phase and gain weights, representing a vector $\bar{x}$ of size t. If $\bar{y}$ is the received signal vector for the UE over the r antennae, then we have $\bar{y} = H\bar{x} + n$, where H is an $r \times t$ complex channel matrix, representing the channel gain values between the eNB and the UE accounting for the multiple antennae equipped at both the eNB and the UE, respectively, and n is the noise vector of size r at the UE. In this case, one of the widely used techniques to combine the received signal vector of size r at the receiver is Minimum Mean-Square error (MMSE) estimator [31].

MIMO-OFDMA: A linear MIMO-OFDM system is a system where the given frequency-selective channel in any CC is divided into a set of fixed parallel flat-fading, independently modulated sub-carriers. A group of 12 sub-carriers are combined to form a sub-channel, and these sub-channels are allocated to UEs for a pair of time slots, and the unit of frequency–time resources to be allocated to every UE is called PRB, as described earlier. This concept is called OFDMA, where different UEs can be simultaneously multiplexed on to the different sub-channels of the same CC with varying MCS rates. The flexibility of using different MCS rates for different UEs across sub-channels of the same CC during the same time is called multiuser (MU) diversity [32]. MIMO-OFDMA supports using different MIMO beamforming vectors simultaneously across sub-channels for scheduling UEs [16]. Figure 1.9 shows two different UEs with different beamforming vector weights from a single eNB, scheduled across 2 PRBs. MIMO-OFDMA is based on an extended version of space division multiple access (SDMA) [12] that allows multiple transmitters to send separate signals and multiple receivers to receive separate signals simultaneously in the same band.

1.3.3 Coordinated Multi-point Transmission

Coordinated multipoint (CoMP) transmission and reception techniques [33] utilize MIMO transmissions from multiple eNBs to enhance the received signal quality as well as decrease the received spatial interference. It is a framework that refers to a system where several geographically distributed antenna nodes on multiple synchronized eNBs cooperate with the aim of improving the performance of the users associated with the cells of the eNBs by choice of appropriate beamforming vectors. Figure 1.10 shows how two eNBs can choose appropriate beamforming vectors to serve the two UEs in the network, so as to address inter-cell interference. CoMP leverages both transmission diversity and spatial diversity to multiplex different UEs that support different data rates. It encompasses all required system designs to achieve tight coordination for transmission and reception. It serves two main

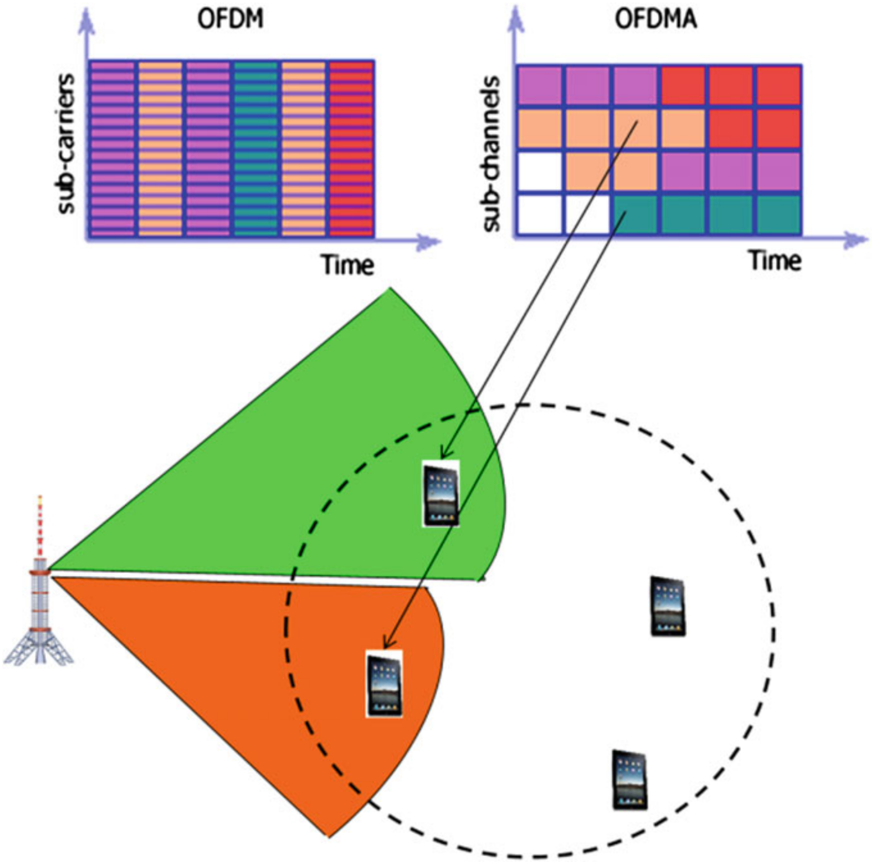


Fig. 1.9 Spatial multiplexing (MIMO OFDMA)

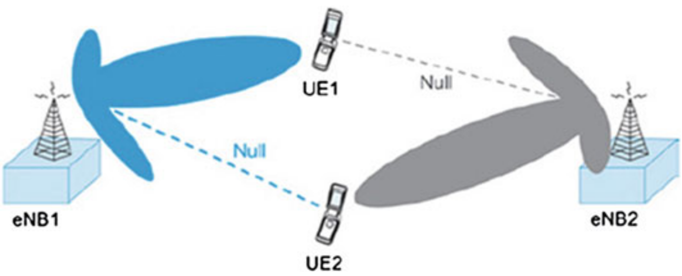


Fig. 1.10 Multi-cell beamforming

purposes: (i) increasing the received signal strength of UEs, and (ii) limiting the inter-cell interference among eNBs. Cooperation among eNBs is characterized by the need of an interconnection among the different nodes in the form of very high-speed dedicated links like optical fiber, wired backbone connection, highly directional wireless microwave links, and RAN controller [1]. These low-latency links are essential for the success of the cooperative communication, although their design is a very challenging issue due to the large amount of data that may need to be exchanged among the nodes. LTE-Advanced uses the standardized interface ×2 for these purposes. CoMP extends the concept of MIMO to multiple cells and hence, uses multi-cell beamforming [34] techniques to maximize performance. Therefore, CoMP works on the principle of Network MIMO. Network MIMO is particularly important for users who experience channel gains on the same order of magnitude from multiple base stations.

The applicability of CoMP depends on the backhaul characteristics (latency and capacity), communication among the eNBs over the X2 interface, which condition the type of CoMP processing and the associated performance. In order to account for the various possible network topologies and backhaul characteristics, the study of CoMP in 3GPP has focused on scenarios which talk about (i) coordination between the cell sectors controlled by the same macro-eNB, (ii) coordination among cells belonging to different radio sites from a macronetwork, (iii) coordination among macro- and small cells in a HetNet, etc. The techniques associated with CoMP include (a) coordinated beamforming/scheduling and (b) joint scheduling.

Coordinated beamforming/scheduling: Coordinated beamforming, otherwise called multi-cell beamforming, enables multiple coordinated eNBs to share their channel state information (CSI) for multiple UEs with each other over the X2 interface. It should be noted that each of the UEs is associated with a single distinct eNB, among the coordinated set. The associated eNB serves it for its subscribed data signals. However, coordination is required to choose appropriate beamforming vector weights and transmission powers [35, 36] across the multiple eNBs to limit the inter-cell interference arising from transmissions from other eNBs in the coordinated set. This coordination among multiple eNBs for the choice of optimal transmission powers and appropriate beamforming vectors is required to improve the net system performance in terms of throughput (subject to fairness constraints), even as each eNB takes independent scheduling decisions to serve its associated UEs.

Joint Processing: Joint processing has two implementation techniques, which include (i) joint scheduling and (ii) dynamic cell selection [1, 33]. Joint scheduling has been discussed earlier in the context of transmission diversity. Dynamic cell selection is a joint processing scheme where the transmission to the intended UE only takes place from one eNB at a given time slot (usually, a sub-frame). This eNB must be drawn from the CoMP cooperating set serving the same UE. The most frequent switching between cell association for a given UE can happen on a sub-frame-by-sub-frame basis, thus allowing for a dynamic change in the associated eNB that is associated with the UE. The related radio resource management, packet scheduling, and common channels are tasks always performed by the single serving cell. The fact that no more than one eNB transmits at the same time implies that there is no need for the eNBs to have a tight phase synchronization. Hence, dynamic cell selection can be implemented with relaxed RF performance requirements. Dynamic cell selection has also been used in the emerging deployments of Dynamic Single-Frequency Networks (DSFN) for multicast/broadcast transmission. In DSFN, the sets of synchronized eNBs that coordinate to serve a commonly subscribed multicast/broadcast traffic session keep changing within the given MBSFN area across time. Dynamic cell selection in DSFN helps in better multiplexing of PRBs across sessions and unicast traffic.

1.3.4 Types of CoMP

Centralized CoMP: In a centralized approach [1], a central entity as shown in Fig. 1.11 is needed in order to gather the channel information from all the UEs in the area covered by the coordinating eNBs. This entity is also in charge of performing user scheduling and signal processing operations such as precoding. Furthermore, tight time synchronization among eNBs is needed and user data should be available at all collaborating nodes. On the downlink of frequency division duplexing (FDD) systems, the UE needs to estimate the channel and derive channel coherent or non-coherent indicators (CSI/CQI) to feed back to the eNB. In time division duplexing (TDD) systems, the channel information can be obtained by using channel reciprocity. In the case of FDD operation, terminals must first estimate the channel related to the set of cooperating eNBs. The information is fed back to a single cell, known as the anchor cell, which acts as the serving cell of the UE when coordination is being employed. Once the information is gathered, each

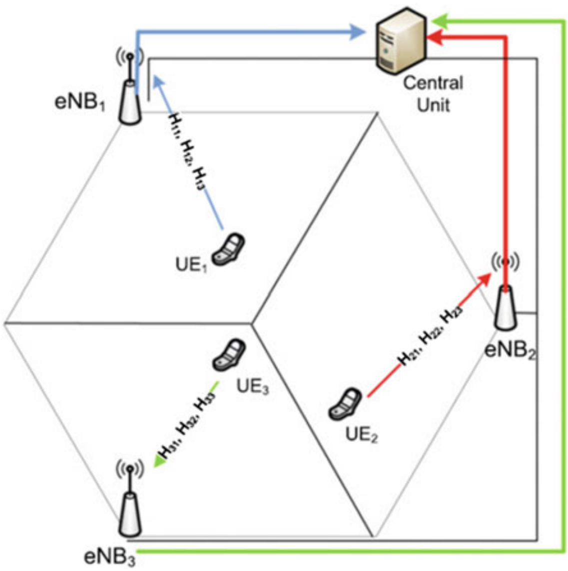
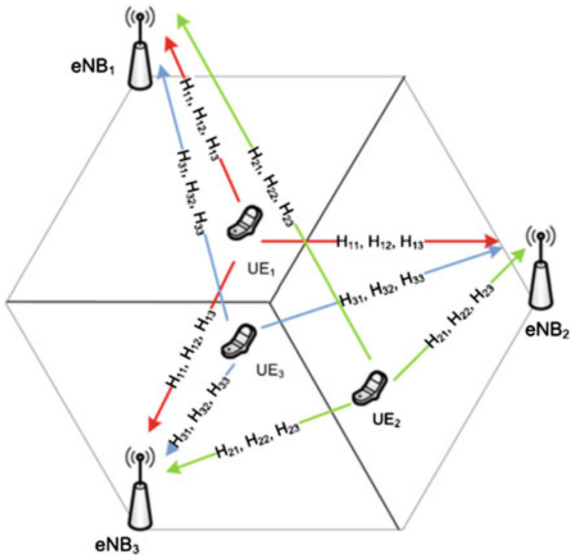


Fig. 1.11 Centralized CoMP

eNB forwards it to the central entity that is in charge of deciding the scheduling and the transmission parameters, and this new information is sent back to the eNBs. The main challenges of this architecture are related to the new associated communication links between the central entity and the eNBs. They must support very-low-latency data transmissions, and in addition, communication protocols for this information exchange must be designed. Fiber cables enable low-latency communication between eNBs.

Distributed CoMP: A distributed architecture [1] is another solution to perform coordination that alleviates the requirements of a centralized approach. Based on the assumption that schedulers in all eNBs are identical and channel information regarding the whole coordinating set can be available to all cooperating nodes, inter-eNB communication links are no longer necessary to perform cooperation. Thus, this architecture has the great advantage of minimizing the infrastructure and signaling protocol cost associated with these links and the central processing unit, so conventional systems need not undergo major changes. Furthermore, the radio feedback to several nodes could be achieved without additional overhead. The UE estimates the channel from all the coordinating eNBs in the very same way as in the centralized approach. The estimates are then sent back to all cooperating eNBs, and the scheduling is independently performed in each of them, as shown in Fig. 1.12. Identical schedulers are used across eNBs so as to limit the performance discrepancies among UEs, subject to coordinated scheduling. Similarly, transmission parameters are jointly selected according to a common design in the different nodes. This scheme presents some drawbacks: First, if different eNBs do not perform cooperation via a wired backhaul, the performance of the CoMP algorithms is less efficient. Furthermore, an obstacle associated with distributed transmission is the

Fig. 1.12 Distributed CoMP



handling of errors on the different feedback links. The same UE reports its channel conditions to all the eNBs in the set, but the wireless links to the different nodes might be very different and the impact of these errors on the system performance cannot be neglected.

1.3.5 Advancements: 3D Beamforming

Three-dimensional MIMO (3D MIMO) can be seen as an effective method to approach massive MIMO without requiring too many antennas on the transmitter or receiver [37, 38], as shown in Fig. 1.13. It introduces a vertical dimension in transmitting antennae by additionally accounting for the heights of the eNBs and the UEs. Vertical dimension is utilized in the antenna modeling, and down-tilt of the antennas becomes a significant channel parameter. For any eNB m and UE k, the respective channel coefficient matrix has three dimensions per PRB which are (i) the number of transmitting antennae on the eNB m at the corresponding CC c given by $N_{m,c}$, (ii) the number of receiver antennae on the UE k receiving signals corresponding to the CC c given by $N_{k,c}$, and (iii) the number of vertical antenna array elements N_a per transmit antenna that accounts for the height of the eNB m and UE k. The channel coefficients between eNB m and UE k over any PRB b from the bandwidth of the CC c are represented by a 3D matrix, given by the dimensions $N_{k,c} \times (N_{m,c} \times N_a)$. A 3D antenna requires the modeling of departure and arrival angles in the horizontal and vertical dimensions. Beamforming of linear array antenna elements merely in horizontal dimension does not give full free-space gain. This is due to the azimuth spread of the received signal as seen from the eNB.

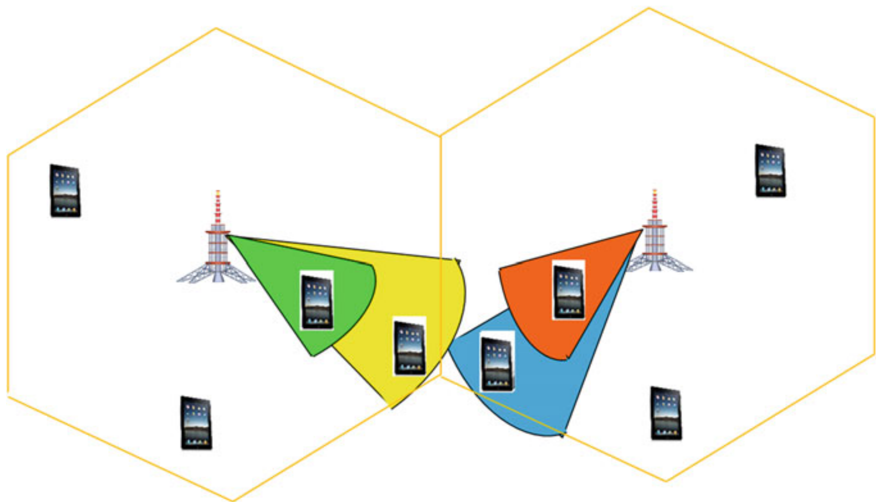


Fig. 1.13 3D beamforming

In conventional 2D MIMO scenarios, inter-cell interference is a serious problem affecting cell-edge UEs. Since the radio propagation from a transmission node to a UE is divided into the horizontal and vertical directions, the power of inter-cell interference can be reduced largely, which results in an enhancement of the SINR and hence, the net system performance.

1.3.6 Applications

eMBMS Services and MBSFN: LTE-A and evolving telecom standards are being increasingly deployed to carry commonly subscribed bandwidth-intensive broadcast sessions (such as HD video) to a larger set of subscribers. eMBMS, standardized in 3GPP Release 8, is a set of features in LTE to support over-the-air delivery of wireless content to a large audience, distributed over a wide geographical area. Applications of eMBMS are found in broadcasting live events (soccer matches, news flashes, etc.), live video at event venues (such as replays and video feeds), emergency broadcasts to the general public for safety, real-time software update over the air to a large set of mobile subscribers, etc. Multi-cell broadcast is facilitated in eMBMS by deploying an SFN and leveraging its transmit diversity feature, as shown in Fig. 1.2, where the session is subscribed by UEs, whose cell association spans across the multiple eNBs synchronized in the SFN. So, the same broadcast/multicast session is served by more than one eNB in the network managed by a mobile network operator. That is, every constituent eNB of the SFN serves the session, which is subscribed by at least one UE associated with the cell covered by the eNB (note that any UE is associated with the cell corresponding to exactly one eNB). Multi-cell eMBMS services schedule the same content over a common set of PRBs using the same MCS value across all the eNBs synchronized in the SFN. This feature of multi-cell broadcast across the SFN is called Multicast Broadcast SFN (or MBSFN). The eNBs constituting the MBSFN are collectively referred to as an MBSFN area. The diversity gain of the SFN helps in enhancing the performance of the wireless last hop of the session, which is otherwise marred by significant inter-cell interference.

Full-duplex communication: The basic idea here consists in using the same frequency–time radio resource for simultaneous uplink–downlink communication of independent data streams [39]. As shown in Fig. 1.14, full duplex in LTE uses the same PRBs for both uplink and downlink communication. The traditional half-duplex systems either use FDD or TDD to multiplex uplink and downlink data streams. The former consists in using separate frequency sub-bands in the deployed CC for uplink and downlink communication simultaneously, whereas the latter divides the LTE frame into independent sub-frames in the time domain, while using the entire frequency band in the CC, for uplink and downlink communication, respectively. As a result, full-duplex communication aims to double the radio system capacity, while carefully accounting for the same band self-interference due

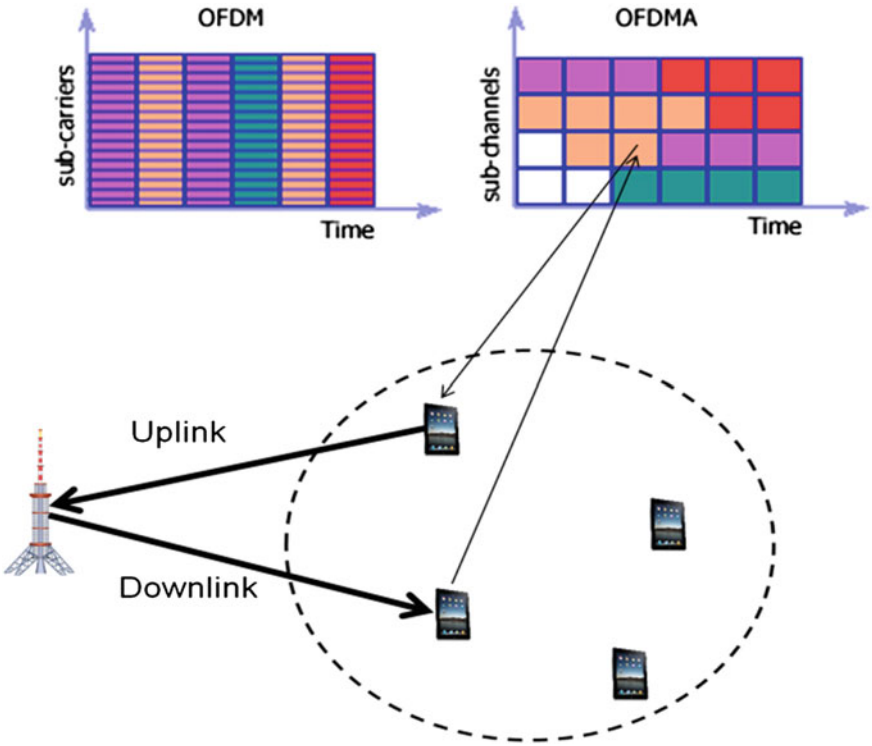


Fig. 1.14 Full-duplex LTE (simultaneous uplink–downlink on the same PRB)

to simultaneous bidirectional communication and spatially multiplexing UEs between uplink and downlink communication.

However, there are two important challenges in achieving this objective: (i) self-interference, (ii) uplink–downlink interference [39, 40]. Uplink–downlink (UL-DL) interference [39] is the interference caused at the UEs due to their simultaneous uplink–downlink communication on the same frequency resources (PRBs) resulting in intra-cell interference for the UEs. The scenario envisioned is a set of eNBs operating on the same frequency with a random distribution of UEs, each of which is associated with a distinct eNB. Some of the UEs subscribe to downlink traffic, whereas the remaining transmit data in the uplink from to their respective associated eNBs, simultaneously. A PRB on any CC deployed over an eNB has at most two UEs scheduled on it, one for uplink and the other for downlink. Techniques such as spatial multiplexing (MU-MIMO) and beamforming are employed to limit the UL-DL interference. Optimal mitigation of UL-DL interference requires appropriate selection of distinct sets of UEs for simultaneous uplink and downlink communication with appropriate choice of multi-cell beamforming vectors, as discussed in the previous section.

1.4 Wi-Fi-LTE, Unlicensed LTE

1.4.1 Definition and Terminologies

The exponential increase in mobile broadband traffic requires deployment of more spectrum resources for LTE to support higher data rates resulting from higher bandwidths. However, there are limited remaining spectrum resources that can be additionally deployed from the licensed frequency bands for LTE, such as 700–800 MHz, 2 GHz, [3]. Moreover, spectrum resources from licensed frequency bands are expensive. This results in increasing challenges for the mobile network operators to facilitate the soaring bandwidth-intensive traffic and provide QoS to subscribers. Hence, the operators are looking beyond licensed bands to deploy additional spectrum resources for LTE from unlicensed frequency bands like 5 GHz [41]. 5-GHz bands are being traditionally used for Wi-Fi systems such as IEEE 802.11n and 802.11ac. However, there are around 500 MHz of residual spectrum resources in the 5-GHz band, apart from those being used for Wi-Fi, for deploying different radio communication technologies [42]. LTE mobile operators are exploring to deploy additional frequency bands out of these residual resources. This radio access deployment of LTE CCs with scalable bandwidths ranging from 1.4 to 20 MHz from the residual spectrum resources in the 5-GHz unlicensed band is called Unlicensed LTE (LTE-U) [42, 43].

Figure 1.15 shows the availability of 5-GHz unlicensed spectrum for the purposes of deploying frequency sub-bands as LTE CCs. However, due to the lower transmission power (23–30 dBm) imposed by regulations on transmissions in unlicensed spectrum and higher path loss resulting from the high central band frequency and sharing of the 5-GHz spectrum resources with other Wi-Fi technologies, the network coverage of an eNB that operates on U-LTE is comparatively smaller. Hence, the eNBs that operate on LTE-U are typically small cells with

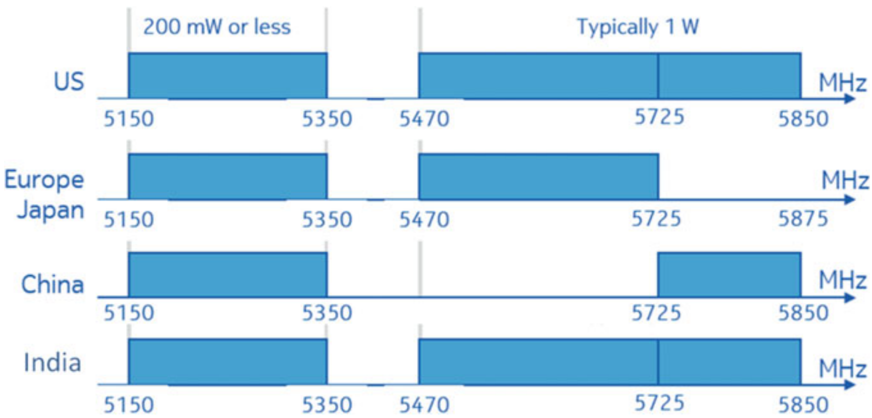


Fig. 1.15 5-GHz unlicensed spectrum availability

shorter radio coverage and comparatively lower transmission power [42]. The coexistence of Wi-Fi and LTE systems has not yielded expected performance benefits due to the lack of good coordination between the different lower layer designs of Wi-Fi and LTE technologies, such as Wi-Fi's OFDM versus LTE's OFDMA and Wi-Fi's asynchronous transmission versus LTE's synchronous transmission. The above-discussed design principles of LTE-Advanced in this chapter that are applicable for LTE-U deployment include [42, 43]:

- **Carrier aggregation**, which is used to integrate LTE-U CCs from unlicensed bands, along with LTE CCs from licensed bands. This requires distinguishing primary and secondary cells between licensed and unlicensed LTE CCs.
- **Wi-Fi-LTE interference management**, which is used to manage co-channel interference between Wi-Fi and LTE systems, deployed in unlicensed frequency bands. LTE-U uses opportunistic channel access, which takes into account the spectrum resources shared by Wi-Fi systems and other radio access technologies from the same frequency band.

In addition to serving higher traffic volumes due to the larger available bandwidth offered by the 5-GHz unlicensed spectrum, the reasons for aggregating LTE-U include (i) high data rates and high spectral efficiency, (ii) a solution that is well integrated to the operator's existing radio network setup, avoiding multiple solutions for network management, (iii) higher data rates with better QoS, upon aggregating with LTE-licensed bands, and (iv) satisfying regulatory requirements for the LTE-U band by allowing coexistence with other technologies such as Wi-Fi, operating on the same frequency band.

1.4.2 CA of LTE-Licensed and LTE-U CCs

Here, we discuss the strategies for integration of LTE-U CCs with LTE-licensed CCs in the form of the distinction between primary and secondary CCs, as in Sect. 1.2, and the deployment strategies for the coexistence of LTE-licensed CCs with unlicensed CCs over LTE-A eNBs [44]. This CA of LTE-U and licensed CCs is supported in 3GPP Releases 12 and 13.

Primary and Secondary CCs: The shorter network coverage range due to lower transmission power, higher coverage holes due to higher path loss, and opportunistic channel access over non-contiguous frequency resources due to spectrum sharing with other Wi-Fi systems render the transmission of information over common control and data channels of LTE-U CCs unreliable. Recall that, since transmission of common control information is important for radio resource control management, information signaling to maintain user-state information is a reserved functionality on the CC deployed over an LTE eNB to serve its associated UEs. So, to compensate for this unreliable nature of transmission over LTE-U, one of the recommended deployment strategies in LTE-Advanced is to aggregate a

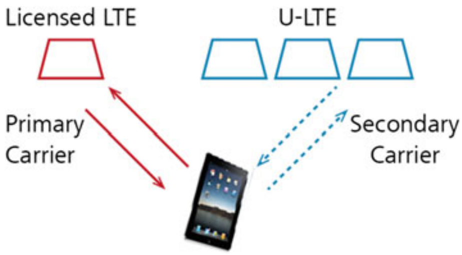


Fig. 1.16 CA of LTE-licensed and LTE-U CCs as primary and secondary carriers

LTE-U CC with a licensed LTE CC and designate the licensed CC as the primary CC for the UE. Since transmission over a licensed LTE CC is more reliable due to a higher transmission power, lower path loss, and orthogonal spectrum access that support higher modulation rates, the licensed CC can be designated as the primary CC for any UE. LTE-U can be used only for scheduling functionalities dealing with allocation of PRBs to UEs. Moreover, for the above distinct features between an LTE-licensed CC and an LTE-U CC, the former can be used to schedule traffic subscriptions with moderate lower bound GBR and lower latency requirements for QoS, and the latter can be used for serving best-effort traffic associated with upper bound maximum bit rate requirements. State information about UE mobility is handled by the licensed primary CC, while joint scheduling between LTE-licensed and LTE-unlicensed CCs is managed at the centralized eNB for smooth load balancing and choice of MCS values for rate adaptation. Figure 1.16 shows the CA of licensed LTE CC as the primary carrier and the LTE-U CC as the secondary CC.

Deployment strategies: One of the widely followed access techniques for LTE-U deployment is TDD [43]. Due to spectrum sharing with other Wi-Fi radio access technologies in unlicensed spectrum bands and opportunistic non-contiguous channel access nature of LTE-U, the support for FD-LTE results in spectrum inefficiency and ineffective spectrum utilization. By resorting to TD-LTE, the limited spectrum resources can be fully used for uplink and downlink communication, multiplexed across different sub-frames. 3GPP Release 13 supports TDD operation of LTE CC only in the downlink, whereas from 3GPP Release 14 onwards, the full bidirectional operation of the LTE CC is supported in TDD. There are two strategies for the deployment of an aggregated carrier of LTE-licensed and LTE-U CCs. One way to do it is the colocated deployment of aggregated LTE CCs from licensed and unlicensed bands over a single small-cell eNB. Since LTE-U does not support a larger coverage region, the aggregated carrier is deployed over the small-cell eNBs. This enables any UE, associated with a small-cell eNB, to be jointly scheduled on both the licensed and unlicensed CCs. Another strategy is a non-colocated deployment where a licensed CC is deployed over the LTE macrocell eNB and an unlicensed CC is deployed over the small cells, deployed within the coverage region of the macrocell. However, with this deployment, the association of UEs is split between the macrocell and the small cells such that each UE has a distinct cell association. So, a UE can be scheduled on either a licensed

CC or an unlicensed CC. The use of LTE-U is considered for indoor cells and outdoor hot spots, generally in places where there is coverage from licensed LTE bands, but where additional capacity would benefit system performance and traffic requirements. LTE-U is also deployed in corporate environments that benefit from the dedicated capacity in the unlicensed CC.

1.5 Network Heterogeneity: Self-organizing HetNets

1.5.1 Definition and Terminologies

The exponential increase in mobile broadband traffic requires making the available radio spectrum as spectrally efficient as possible. One of the promising solutions to serve the high data demand of the mobile broadband traffic is the enhancement of the LTE macrocell networks with small-cell deployments. Small cells are LTE eNBs covering a relatively shorter range but deployed with dedicated radio resource bandwidth from the same licensed frequency bands as the macrocells. Small cells are low-powered, low-cost radio access nodes that operate at a transmission power of around 23 dBm, resulting in a coverage radius of around 10 to 300 m. The collective deployment of macro- and small cells transmitting simultaneously on the same frequency channels to their respective user equipment (UE) clients is referred to as Heterogeneous Networks (HetNets) [10, 11]. Small cells are generally used to fix the coverage holes in the macrocell network and provide dedicated capacity to UEs that cannot be allocated adequate spectrum resources by the macrocell eNBs. The kind of UEs usually benefitting by deploying small cells includes (i) macro-cell-edge UEs, due to their poor received signal and higher inter-cell interference causing both coverage and capacity issues, (ii) UEs in locations with high subscriber density (such as office buildings, apartment complexes, shopping malls) where the broadband traffic density is high, thereby causing capacity issues.

Illustration: Figure 1.17 shows a macrocell eNB and a set of small cells within the coverage of the macrocell. A couple of UEs at the cell edges of the macrocell are subscribing to high bandwidth traffic, such as video conferencing and video gaming. These UEs are seen to be having poorer channel conditions (indicated by the number of green vertical bars). Since their subscription to bandwidth-intensive traffic is further compounded by poorer channel conditions, these UEs are likely to suffer from exhaustion of resources. Hence, deployment of small cells around such UEs helps overcome this issue. Since the small cells offer stronger link stabilities and dedicated bandwidths to such UEs, the macrocell-edge UEs are served with adequate resources with better QoS.

Small cells is a general term used to refer to femtocells and picocells, whose usage is restricted to closed subscriber and open subscriber groups, respectively. The former are typically used for indoor communication up to a few tens of meters, whereas the latter cover a wider range up to a few hundred meters. Picocells are

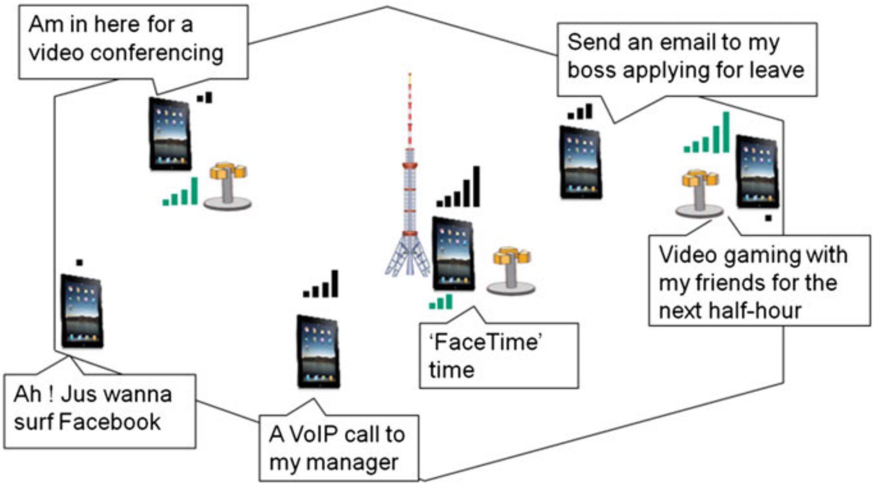


Fig. 1.17 Coverage and capacity issues addressed in HetNets

typically installed in wireless hot spot areas such as malls and near office buildings and provide access to all UEs [11]. Such heterogeneous deployments, caused by the densification of the network using small cells, are expected to dominate the broadband market in providing next-generation 4G+ and 5G telecommunication services. LTE small cells typically share the same frequency carriers with nearby macrocells; as a result, their deployment can lead to a higher co-channel interference if resource sharing is not carefully planned. This requires designing Enhanced Inter-cell Interference Coordination (eICIC) techniques for higher spectral efficiency and effective frequency reuse [45]. HetNets are standardized as part of 3GPP Release 10, and the communication among the different cells in a HetNet topology is enabled by a centralized authority such as a self-organized network (SoN) server and/or in a distributed manner via backhaul communication protocols between the macro- and the small cells, leveraging the X2 interface.

1.5.2 Background on Inter-cell Interference Coordination (ICIC)

A. Macrocell ICIC

Fractional Frequency Reuse (FFR): FFR is an inter-cell interference mitigation mechanism for radio resource management (RRM) in cellular networks [46], as shown in Fig. 1.18. The synchronous operation of downlink and uplink transmissions across cells requires transmissions to be intelligently scheduled to manage interference. FFR partitions the licensed frequency bands of the operator into chunks of non-overlapping sub-bands and deploys them over the adjacent eNBs, while reusing a fraction of the sub-bands commonly over all the eNBs. The reused frequency resources are meant for serving the UEs at the cell center that normally get reduced interference from adjacent eNBs and stronger links from their respective serving eNBs to which they are associated. On the other hand, the non-overlapping frequency sub-bands are used to serve UEs at the cell edges. The interference for such cell-edge UEs is mitigated due to the deployment of non-overlapping frequency resources over adjacent eNBs such that their transmissions do not interfere with each other. Hence, the interference caused by cell-center users is reduced while using more total spectrum than conventional spectrum reuse. The use of FFR in cellular networks leads to natural trade-offs between improvement in rate and coverage for cell-edge users, thereby addressing the trade-off between network throughput and spectral efficiency. In the popular 1-3 FFR scheme for macrocell networks, the spectrum is divided into four fixed-size bands, as shown in Fig. 1.18. One band is used by all the cell-interior clients (in each cell), who do not see interference due to the close proximity to their BS, while the other three bands are used (by cell-exterior clients) in an orthogonal manner among the three sectors of a cell to mitigate interference with sectors of adjacent cells. Thus, while the band used by cell-interior clients is reused in each cell, the reuse of the other three bands is subject to the spatial reuse. Recently, dynamic FFR [47] approaches have been proposed specifically for small cells, and determine the number and size of bands to be used by each small cell based on the aggregate traffic demand from its cell-interior and cell-exterior clients. This allows for better spectral utilization and does not rely on planned sectorization (unlike macrocells). However, the denser deployment of small cells within the coverage region of an interfering macro poses significant challenges in splitting the licensed frequency sub-bands among the interfering cells. Note that the FFR schemes only determine

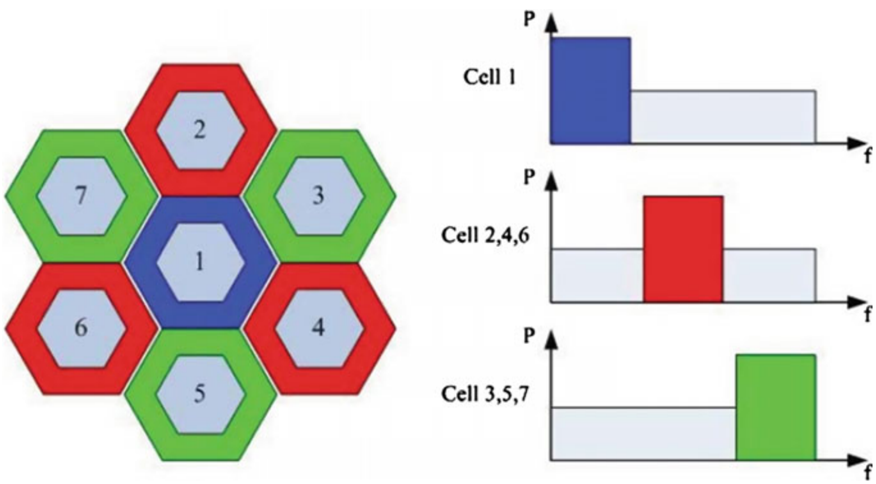


Fig. 1.18 1–3 fractional frequency reuse

the set of spectral resources assigned to cells—scheduling of clients within these resources is done by each cell locally (based on per-client feedback) to leverage multiuser diversity.

Soft Frequency Reuse (SFR): The term soft reuse is due to the fact that effective reuse of the spectrum can be accomplished by the division of powers between the frequencies used in the center and edge bands [48]. SFR makes use of the concept of zone-based reuse factors in the cell-center and cell-edge areas; however, frequency and power used in these zones are restricted. In particular, a frequency reuse factor of 1 is employed in the central region of a cell, while frequency reuse factor greater than 1 at the outer region of the cell close to the cell edge. In fact, when the mobile station is near the antenna of the base station, the received power of the wanted user signal is strong, and the interference from other cells is weak. So, at the inner part of the cell, all the sub-carriers can be used to achieve high data rate communication. For example, considering the 3-sector cell sites, the cell-edge band uses 1/3 of the available spectrum which is orthogonal to those in the neighboring cells and forms a structure of cluster size 3. The cell-center band in any sector is composed of the frequencies used in the outer zone of neighboring sectors. The benefits of the soft frequency reuse scheme include improved bit rate at cell edge, high bit rate at the cell center, decreased interference at the cell edge, so the procedures of channel estimation, synchronization, cell selection, and reselection are relatively easier.

B. Macrocell and small-cell ICIC

The details of ICIC techniques between the macrocells and the small cells in a HetNet deployment are discussed in [49]. The *dedicated frequency band* allocation is the case where the same frequency band is shared by all the femtocells, and a different non-overlapping frequency band is allocated to the macrocells. This scheme is not suitable to support dense femtocells deployment, as the use of the same frequencies by the densely located femtocells would cause severe inter small cell interference. Moreover, due to the non-overlapping split of frequency bands among the small cells and the macrocells, this scheme results in inefficient spectrum utilization. In the *shared frequency band* allocation scheme, the frequencies from the same spectrum can be allocated for the femtocells and the macrocells. This scheme results in high-frequency reuse; however, it causes high interference among the small-cell and macrocell deployments. In the *static frequency reuse* scheme, the set of all cellular frequencies is divided into three equal bands and each one of the three macrocells in a macrocellular cluster uses one of these three different frequency bands. If a macrocell uses a particular frequency band, then the femtocells within that macrocell use the other two frequency bands. The *dynamic frequency reuse* scheme is similar to the static scheme; however, for each femtocell, one band is used in the center of the femtocell, while the other band is used at the edge of the femtocell. The frequency band used in the center of all femtocells of the same macrocell is the same, but the frequency bands used in the edges of the various femtocells are, in general, different, to avoid interference.

1.5.3 Enhanced Inter-cell Interference Coordination (EICIC)

The transmission power of the macrocell eNB is significantly higher than that of a small-cell eNB. The higher power macrocell eNBs are deployed for blanket coverage of urban, suburban, or rural areas, and the picocell eNBs with small RF coverage areas complement the macronetwork for filling the holes in macrocoverage and providing dedicated resources for enhancing throughput. Hence, the association of UEs to either a small or a macrocell based on the maximum transmission power would be unfair for the small cell, as it operates at lower transmission power. Lower user association to the small cells under-utilizes their licensed spectrum resources and defeats the purpose of their deployment. Moreover, users associated with the small cell are marred by interference from the adjacent macro, resulting in poorer SINR. This does not contribute to an effective reuse of the licensed frequency bands at the small cells, resulting in wastage of limited and expensive spectrum resources. Such unfairness for the small cell is compensated by the usage of an additive cell selection bias (CSB) [10] value (in dB) that is broadcast by the small cell, and the simultaneous support by adjacent macrocell(s) via blanking transmission for a certain number of time slots [10]. The additive CSB value, along with the Reference Signal Received Power (RSRP) of the UE from the small cell, can bias the decision of the UE to attach to the small cell over the macro. Moreover, such offloading of UEs to the small cell reduces the traffic load bottleneck for the macro, as a result of which, the macro can serve more incoming traffic for QoS. The geographical region comprising UEs that attach to the small cell, only upon adding the broadcast CSB value, is called the Cell-Range Expansion (CRE) region [10, 45, 50]. The UEs in the CRE region are considered to be the edge users for the small cell, and are affected by the interference from the adjacent macrocells. Therefore, an eICIC technique is required to achieve effective spectrum utilization and a better Quality-of-Service (QoS) for the small cells by facilitating higher data rates. Macro blanking is one such technique that stops the macrocell from transmitting data signals on the frequency channels for a predetermined number of time slots per LTE frame, called Almost Blank Subframes (ABS) [10, 51]. The number of ABS per LTE frame in any CC deployed over the macrocell eNB is defined as the ABS length of the CC. The reason why the blanked sub-frames are called “almost” blank is because the macro can still transmit some broadcast signals and control signals over these subframes. Since these broadcast signals only occupy a small fraction of the OFDMA PRBs, the overall interference caused by the macro to the small cells is much less during these ABS periods.

1.5.4 Defining the CRE Region

This section analytically profiles the CRE region of the small cell as a function of its CSB with relevant illustrations. The deployment of small cells is considered in topologies with (i) a single interfering single-carrier macro and (ii) multiple-interfering single-carrier macros. These use-cases offer insights on pertinent real-world LTE topology configurations such as FFR and SFN, respectively. FFR limits the inter-cell interference between adjacent macro-eNBs by splitting the licensed frequency band of the telecom operator into sub-bands across the adjacent eNBs. Hence, any small cell observes significant interference only from a single adjacent macrocell within whose coverage, it is deployed. However, in SFNs, since all the macrocells operate on the same frequency band, any small cell observes interference from the adjacent as well as neighboring macrocell eNBs.

A. Single macrocell interferer for FFR:

Consider any UE indexed u at any point in coordinate space, a macrocell m, and a small cell s. Without loss of generality, we assume that the macrocell is located at the origin (0, 0) and the small cell is located at (R, 0). Let $r_{s,u}$ and $r_{m,u}$ denote the distances from the UE u to s and to m, respectively, that also accounts for the difference between the eNB and UE heights. Let $\mathrm{rsrp}_s(u)$ be the Reference Signal Received Power (RSRP) value at UE u with respect to s. This is given by:

$$rsrp_s(u) \triangleq \frac{p_s \cdot \gamma . e^{-|h_{s,u}|}}{r_{s,u}^{\rho_s}}$$

where $P_s = P_s^{[\mathrm{T}]}/f_c^{\alpha s}, P_s^{[\mathrm{T}]}$ is the transmission power at the small-cell antenna, P_s is the power transmitted from s along the frequency band f_c of any CC C_c, α_s is the frequency-dependent path loss exponent for s, γ is the fraction of the transmission power available for the Cell-specific Reference Signal (CRS) [3], and $h_{s,r}$ indicates the shadow fading of the link between the small-cell eNB s and the UE u. Usually, $h_{s,u}$ is an independent and identically distributed Gaussian random variable, and ρ_s is the path loss exponent in terms of the distance. Similarly, the RSRP at UE indexed u w.r.t the fixed macrocell m is given by:

$$rsrp_m(u) \triangleq \frac{p_m \cdot \gamma . e^{-|h_{m,u}|}}{r_{m,u}^{\rho_m}}$$

where $P_m = P_m^{[T]}/f_c^{\alpha_m}$ is the transmission power of the macrocell over CC C_c; similarly, $h_{m,u}$ is the i.i.d Gaussian shadow fading between the macrocell eNB m and UE u. Assuming equal path loss exponents for the macro- and small cells, i.e., $\rho_s = \rho_m = \rho$, if a CSB value $cb_{s,c}$ (in linear scale) is associated with small cell s on CC C_c and if the UE indexed u is inside the CRE region, the following conditions are satisfied [10, 11]: $(i)\ rsrp_s(u) < rsrp_m(u),\ and\ (ii)\ rsrp_s(u).cb_{s,c} > rsrp_m(u).$

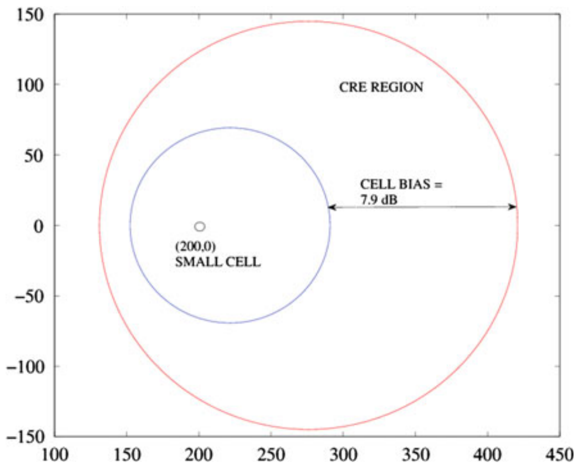


Fig. 1.19 CRE region with CSB 7.9 dB when macrocell to small-cell distance is 200 m

Figures 1.19 and 1.20 indicate the CRE regions of the small cell, when it is present at 200 and 400 m distance from the interfering macro. The CRE regions correspond to maximum possible CSBs that can be used in the case of a dense distribution of UEs in a HetNet scenario, such that each UE is guaranteed at least a pair of PRBs upon being served by the small cell.

B. Multiple macrocell Interferers for SFN:

In the presence of multiple-interfering macrocells, the small cell effective service region is the region where the RSRP of the small cell is greater than the sum of the RSRPs of the interfering macrocells. Hence, now the net CRE region is defined as the area where (a) the RSRP of the small cell is less than the sum of the RSRPs from the interfering macrocells; and (b) the product of the RSRP of the small cell and the CSB is greater than the sum of the RSRPs of the interfering macrocells.

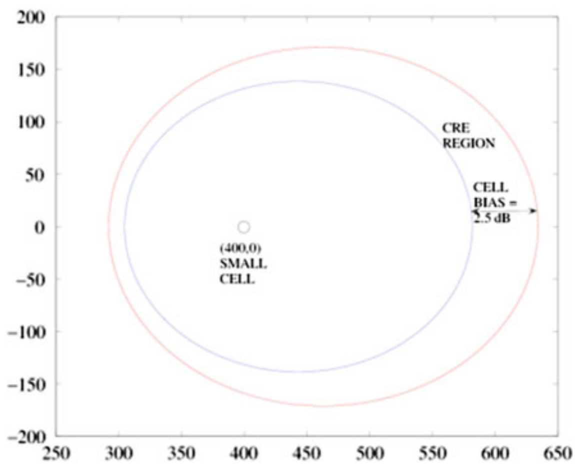


Fig. 1.20 CRE region with CSB 2.5 dB when macrocell to small-cell distance is 400 m

Different UEs need different sets of macrocells to blank, in order to get a better service from the small cells. In this case, at least one macrocell needs to blank, such that the UEs in the CRE region expanded by the CSB get a higher RSRP from the small cell. In the presence of multiple-interfering macrocells, we have:

$$\frac{p_s.\gamma.e^{-|h_{s,u}|}}{r_{s,u}^{\rho_s}} < \max_{m \in M} \frac{p_m.\gamma.e^{-|h_{m,u}|}}{r_{m,u}^{\rho_m}}$$

1.5.5 Enhancements: eICIC with CA

Inter-band CA (discussed in Sect. 1.4.1) enables the small cell to transmit and receive on multiple CCs and hence, there would be more than one CRE region, corresponding to each CC. As the CCs in an inter-band CA belong to different non-adjacent central band frequencies, they yield different radio channel conditions (such as path loss) to their UEs. These channel dynamics, along with the instantaneous traffic load on each CC, affect the assignment of CCs to UEs and thereby their QoS. Accordingly, a channel- and traffic-aware CC assignment to UEs that uses distinct CSB values across CCs is required. Hence, the corresponding CRE regions across CCs need not be identical; each CC may serve a different number of cell-edge UEs.

This results in varying user association and traffic load on each CC. Subsequently, the small cell requests the interfering macro for different ABS lengths across its aggregated CCs. Moreover, when there is resource exhaustion on one of the CCs, the small-cell eNB should decide between (i) deflection of the UE to another CC aggregated in the small cell and (ii) deflection of the UE to an appropriate CC in the macro. This subsequently requires the macro to support different ABS lengths across CCs based on the varying net QoS requirements of the UEs belonging to each distinct CRE region. This suggests that the application of one technique (CA/eICIC) may impede the performance of another (eICIC/CA), upon being agnostic of the inter-dependencies between the two. Considering two inter-band CCs C_c and C_c', a UE present in the CRE region corresponding to C_c can be scheduled in the PRBs of any CC C_c' upon availability of sufficient residual bandwidth, if and only if the central band frequency of C_c given by f_c is higher than the central band frequency of C_c', given by f_c'. This is because if $f_c > f_c'$, then transmission on C_c yields a higher path loss when compared to C_c'. So, the UEs at the CRE region corresponding to C_c need not necessarily be at the CRE region corresponding to C_c'. This shows how an efficient interference mitigation mechanism should jointly account for the inter-dependencies between the applications of CA and eICIC. Figure 1.21 shows an illustration of using eICIC along with CA with different CRE regions for the small cells corresponding to different CCs and varying ABS lengths for the interfering macrocell across the CCs.

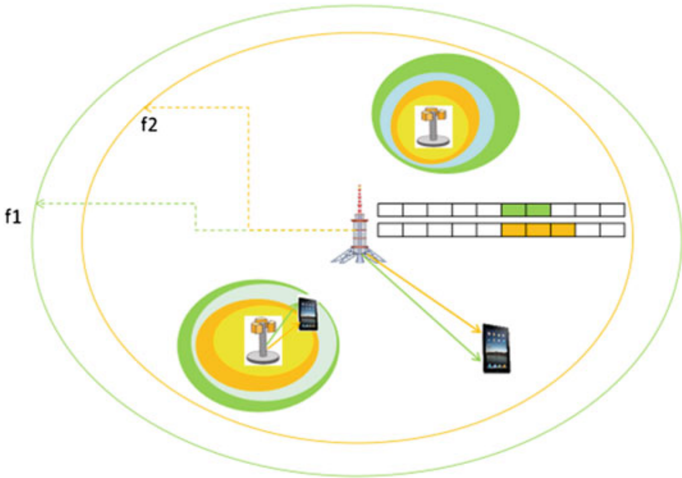


Fig. 1.21 eICIC enhancement with CA

1.6 Conclusion

This chapter introduces the reader comprehensively to the foundational concepts of the design principles used in the radio access of next-generation telecommunication systems such as LTE-A. They provide a roadmap to the 5G centralized radio access technologies. The design principles are based on bandwidth aggregation, transmission diversity, interference management, MIMO spatial diversity, etc. It specifically emphasizes upon the recent advancements in 5G radio access technologies, such as the aggregation of LTE-licensed and unlicensed bands, and full-duplex communication, based on the aforementioned design principles. It highlights some of the key PHY and MAC layer issues pertinent to the design techniques. In traditional legacy 3GPP systems, the end-to-end performance was limited by the coverage and capacity bottlenecks of the wireless medium. However, the aforementioned techniques have significantly enhanced the performance of the radio access medium.

In terms of meeting 5G requirements, these radio access techniques achieve very high data rates, up to 1 Gbps downlink and 500 Mbps uplink capacity in the case of Carrier Aggregation, up to 2× speeds in the case of full-duplex communication (e.g., facilitating HD 1080p videos in the case of downlink eMBMS traffic), up to 10× speeds in the case of HetNets using small cells, and up to 2×/4×/8× speeds in the case of 2×2, 4×4, 8×8 MIMO enhanced with independently precoded multi-stream beamforming.

References

1. Akyildiz IF, Estevez DMG, Reyes EC (2010) The evolution to 4G cellular systems: LTE-Advanced. Elsevier Phys Commun 3
2. Astely D, Dahlman E, Furuskar A, Jading Y, Lindstrom M, Parkvall S (2009) LTE: the evolution of mobile broadband. IEEE Commun Mag 47(4)
3. Holma H, Toskala A (2009) LTE for UMTS: OFDMA and SC-FDMA based radio access. Wiley
4. Sivaraj R, Pande A, Zeng K, Govindan K, Mohapatra P (2012) Edge-prioritized channel- and traffic-aware uplink carrier aggregation in LTE-advanced systems. In: Proceedings of 13th IEEE WoWMoM
5. Iwamura M, Etemad K, Fong M-H, Nory R, Love R (2010) Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update]. IEEE Commun Mag 48(08)
6. Lu S, Cai Y, Zhang L, Li J, Skov P, Wang C, He Z (2009) Channel-aware frequency domain packet scheduling for MBMS in LTE. In: Proceedings of IEEE VTC
7. Chen J, Chiang M, Erman JJ, Li G, Ramakrishnan KK, Sinha R (2015) Fair and optimal resource allocation for LTE multicast (eMBMS): group partitioning and dynamics. In: Proceedings of IEEE INFOCOM
8. Monserrat J, Calabuig J, Fernandez-Aguilella A, Barquero DG (2012) Joint delivery of unicast and eMBMS services in LTE networks. IEEE Trans Broadcast 58(2)
9. Nguyen ND, Knopp R, Nikaein N, Bonnet C (2013) Implementation and validation of multimedia broadcast multicast service for LTE/LTE-advanced in openairinterface platform. In: IEEE LCN workshop
10. Deb S, Monogioudis P, Miernik J, Seymour P (2013) Algorithms for enhanced inter cell interference coordination (eICIC) in LTE HetNets. IEEE/ACM Trans Netw 22(1):137–150
11. Vasudevan S, Pupala RN, Sivanesan K (2013) Dynamic eICIC—A proactive strategy for improving spectral efficiencies of heterogeneous LTE cellular networks by leveraging user mobility and traffic dynamics. IEEE Trans Wirel Commun 12(10)
12. Bjornson E, Jorswieck E (2012) Optimal resource allocation in coordinated multi-cell systems. Found Trends Comm Info Theory 9(2–3)
13. Kela P, Puttonen J, Kolehmainen N, Ristaniemi T, Henttonen T, Moisio M (2008) Dynamic packet scheduling performance in UTRA long term evolution downlink. In: Proceedings of International symposium wireless pervasive computing (ISWPC)
14. Pedersen KI, Frederiksen F, Rosa C, Nguyen H, Garcia LGU, Wang Y (2011) Carrier aggregation for LTE-advanced : functionality and performance aspects. IEEE Commun Mag 49(06)
15. Wang H, Rosa C, Pedersen KI (2011) Performance analysis of downlink inter-band carrier aggregation. In: Proceedings of IEEE ICC
16. Dahrouj H, Yu W (2010) Coordinated beamforming for the multicell multi-antenna wireless systems. IEEE Trans Wirel Comm 9(5)
17. Yuan G, Zhang X, Wang W, Yang Y (2010) Carrier aggregation for LTE-advanced mobile communication systems. IEEE Comm Mag 48(2):88–93
18. Wang H, Rosa C, Pedersen KI (2010) Performance of uplink carrier aggregation in LTE-advanced systems. In: IEEE VTC
19. Sundaresan K, Rangarajan S (2013) Energy efficient carrier aggregation algorithms for next generation cellular networks. In: Proceedings of IEEE ICNP
20. Dahlman E, Parkvall S, Skold J (2011) 4G: LTE/LTE-advanced for mobile broadband: LTE/LTE-advanced for mobile broadband. Academic Press, 1st edn
21. 3GPP, "TR 36.814 E-UTRA; Further Advancements for E-UTRA Physical Layer Aspects," Rel. 9
22. Sivaraj R, Pande A, Mohapatra P (2013) Spectrum-aware radio resource management for scalable video multicast in LTE-advanced systems. In: Proceedings of IFIP Networking

23. Yoon J, Zhang H, Banerjee S, Rangarajan S (2012) Muvi: a multicast video delivery scheme for 4G cellular networks. In: Proceedings of ACM Mobicom
24. Suh C, Mo J (2008) Resource allocation for multicast services in multicarrier wireless communications. IEEE Trans Wirel Comm 7(1)
25. Li P, Zhang H, Zhao B, Rangarajan S (2009) Scalable video multicast in multi-carrier wireless data systems. In: Proceedings of IEEE ICNP
26. Sharangi S, Krishnamurthi R, Hefeeda M (2011) Energy-efficient multicasting of scalable video streams over WiMAX networks. IEEE Trans Multimedia 13(1)
27. Wang Y, Pedersen KI, Sorensen TB, Mogensen PE (2010) Carrier load balancing and packet scheduling for multi-carrier systems. IEEE Commun Mag 48(08)
28. Songsong S, Chunyan F, Caili G (2009) A resource scheduling algorithm based on user grouping for LTE-advanced systems with carrier aggregation. In: Proceedings of symposium computer networking and multimedia technology
29. Jalali A, Padovani R, Pankaj R (2000) Data throughput of CDMA-HDR, a high e_ciency-high data rate personal communication wireless system. In: Proceedings of IEEE VTC
30. Goldsmith A, Jafar S, Jindal N, Vishwanath S (2003) Capacity limits of MIMO channels. IEEE J Sel Areas Commun 21(5)
31. Jagannatham AK. Electronics-advanced 3G & 4G wireless mobile communications, national programme on technology enhanced learning, Government of India, https://www.youtube.com/watch?v=zm0tKvOA3sQ
32. Shi S, Schubert M, Boche H (2012) Weighted sum-rate optimization for multiuser mimo systems. In: Proceedings of IEEE CISS
33. Lee D, Seo H, Clerckx B, Hardouin E, Mazazarese D, Nagata S, Sayana K (2012) Coordinated multipoint transmission and reception in lte-advanced: deployment scenarios and operational challenges. IEEE Commun Mag 50(02)
34. Venturino L, Prasad N, Wang X (2010) Coordinated linear beamforming in downlink multi-cell wireless networks. IEEE Trans Wirel Commun 9(4)
35. Farrokhi FR, Liu KJR, Tassiulas L (1998) Transmit beamforming and power control for cellular wireless systems. IEEE J Sel Areas Commun 16(8):1437–1450
36. Sivaraj R, Broustis I, Shankaranarayanan NK, Aggarwal V, Mohapatra P (2015) Mitigating macro-cell outage in LTE-advanced deployments. In: Proceedings of IEEE INFOCOM
37. Li Y, Ji X, Liang D, Li Y (2013) Dynamic beamforming for three-dimensional MIMO technique in LTE-advanced networks. Hindawi J Antennas Propag 2013(764507)
38. Eckhardt H, Klein S, Gruber M (2011) Vertical antenna tilt optimization for LTE base stations. In: Proceedings IEEE 73rd VTC Spring
39. Khojastepour M, Sundaresan K, Rangarajan S, Tehrani MF (2015) Scaling wireless full-duplex in multi-cell networks. In: Proceedings of IEEE INFOCOM
40. Aryafar E, Khojastepour MA, Sundaresan K, Rangarajan S, Chiang M (2012) Midu: enabling MIMO full duplex, 2. In: Proceedings of ACM Mobicom
41. The Prospect of LTE and Wi-Fi sharing Unlicensed Spectrum, http://www.signalsresearch.com
42. Nokia Networks White paper, Nokia LTE for Unlicensed spectrum, http://networks.nokia.com
43. Huawei White Paper, U-LTE: Unlicensed Spectrum Utilization of LTE, http://huawei.com/ilink/en/download/hw327803
44. Cavalcante A, Almeida E, Vieira R, Chaves F, Abinader F, Choudhury S, Tuomaala E, Doppler K (2013) Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands. IEEE Veh Technol
45. Lindbom L, Love R, Krishnamurthy S, Yao C, Miki N, Chandrasekhar V. Enhanced inter-cell interference coordination for heterogeneous networks in LTE-advanced: a survey. http://arxiv.org/abs/1112.1344
46. Sundaresan K, Arslan MY, Singh S, Rangarajan S, Krishnamurthy SV (2013) FluidNet: a flexible cloud-based radio access network for small cells. In: Proceedings of ACM MobiCom

47. Stolyar AL, Viswanathan H (2008) Self-organizing dynamic fractional frequency reuse in OFDMA systems. In: Proceedings of IEEE INFOCOM
48. Mao X, Maaref A, Teo KH (2008) Adaptive soft frequency reuse for inter-cell interference coordination in SC-FDMA based 3GPP LTE uplinks. In: Proceedings of IEEE Globecom
49. Chowdhury MZ, Jang YM, Haas ZJ. Cost-effective frequency planning for capacity enhancement of femtocellular networks, http://arxiv.org/ftp/arxiv/papers/1412/1412.3639.pdf
50. Deb S, Monogioudis P, Miernik J, Seymour P (2013) Algorithms for enhanced inter cell interference coordination (eICIC) in LTE HetNets. IEEE/ACM Trans Netw 22(1):137–150
51. Prez DL, Gven I, de la Roche G, Kountouris M, Quek TQS, Zhang J. Enhanced inter-cell interference coordination challenges in heterogeneous networks. http://arxiv.org/abs/1112.1597
52. Lee H, Sohn I, Kim D, Lee KB (2011) Generalized MMSE beamforming for downlink MIMO systems. In: Proceedings of IEEE ICC
53. 3GPP, “TR 36.808 Evolved Universal Terrestrial Radio Access (E-UTRA); Carrier Aggregation; Base Station (BS) Radio Transmission and Reception; Rel. 12.”