CHAPTER

Carrier Aggregation

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LTE Rel-8/9 specified system bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz to meet different spectrum and deployment requirements. Support of wider bandwidths up to 100 MHz was one of the distinctive features of IMT-Advanced systems. The IMT-Advanced systems targeted peak data rates in excess of 1 Gbps for low mobility and 100 Mbps for high mobility scenarios [32,33]. In order to support wider transmission bandwidths, LTE Rel-10 introduced the carrier aggregation concept, where two or more component carriers with arbitrary bandwidths belonging to the same or different frequency bands could be aggregated. The support of system bandwidths up to 100 MHz would allow a substantial increase in link-level peak data rate, as well as in the system capacity and user throughput. Another advantage of carrier aggregation is to allow efficient use of fragmented spectrum in the form of a virtually wideband spectrum. The fragmented spectrum may belong to the same or different frequency bands and may be of different bandwidths. LTE Rel-11 further extended the advantages of carrier

LTE-Advanced.

aggregation by configuring extended carriers and carrier segments. Furthermore, carrier aggregation can be used to mitigate inter-cell interference in heterogeneous networks [30,31].

Using the carrier aggregation scheme, it would be possible to simultaneously schedule a user on multiple component carriers for downlink or uplink data transmission, resulting in some challenges in resource scheduling and load balancing across the network. In a non-contiguous inter-band carrier aggregation scenario, where the aggregated carriers belong to different frequency bands, the fading characteristics might be different between component carriers; as a result, the coverage may vary significantly from one carrier to another. At different locations in the cell, some users may only be scheduled on fewer carriers, while other users may have access to the entire carrier set, which may have a negative impact on sustained user throughput within the coverage area of an eNB.

To allow smooth network migration and upgrades to new releases, it was essential to ensure backward compatibility of LTE-Advanced with LTE Rel-8/9, as well as to support mixed operation of the legacy LTE systems and LTE Rel-10 on the same carrier in an operator's network. LTE Rel-10 carrier aggregation satisfied this requirement by configuring each component carrier in a backward compatible manner with LTE Rel-8/9, and by further supporting at least one of the bandwidths compatible with LTE Rel-8/9. The backward compatibility implies that the complete set of LTE Rel-8/9 downlink physical channels and signals are transmitted on each component carrier using LTE Rel-8/9 signaling procedures, including broadcast channel, synchronization signals, reference signals, and control channels. This would also allow reuse of the LTE Rel-8/9 RF designs and implementations at the eNB and the UE. Although we will primarily focus on carrier aggregation for FDD systems, carrier aggregation is fully supported in the TDD systems, as well.

In this chapter, we will take a pragmatic and systematic approach to describe carrier aggregation principles and its impact on different protocol layers. Various aspects of carrier aggregation including deployment scenarios, physical and MAC layer support, as well as higher-layer signaling and RF transceiver design challenges, will be discussed and examples will be provided.

13.1 Principles of carrier aggregation

In LTE-Advanced carrier aggregation terminology, a component carrier is often referred to as a serving cell, is assigned its own cell identifier, and is managed as a serving cell by the higher layers. Each individual RF carrier is known as a component carrier. A component carrier can be downlink and uplink or downlink only, but it cannot be an uplink-only RF carrier for obvious reasons. The number of downlink component carriers may be different than that of the

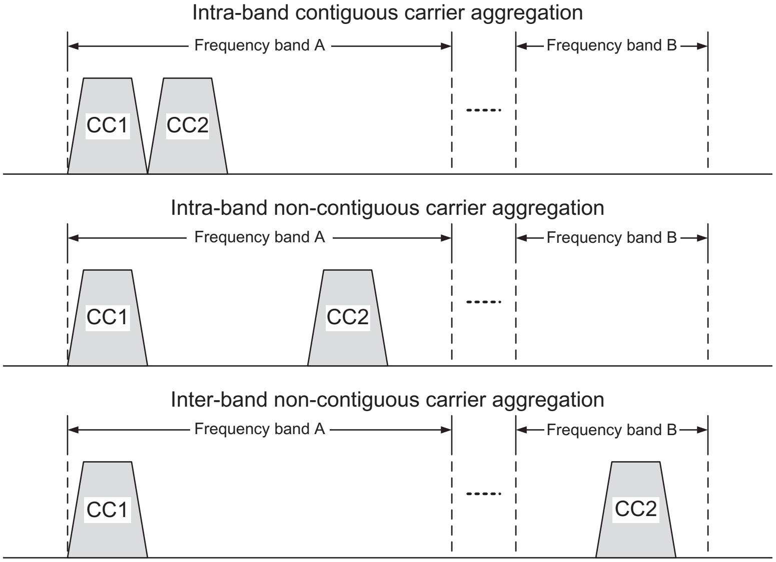

FIGURE 13.1

Carrier aggregation scenarios [16,18,20].

uplink. In general, a different number of component carriers can be aggregated for the downlink and uplink. The UE may support carrier aggregation only in the downlink or in both directions. Up to five component carriers, possibly each with different bandwidth can be aggregated, allowing transmission bandwidths of up to 100 MHz [12,14]. In FDD systems, a serving cell comprises a pair of different carrier frequencies for downlink and uplink transmissions, whereas for TDD, a serving cell is defined as a single-carrier frequency where downlink and uplink transmissions occur in different transmission time intervals. Given that component carriers do not have to be contiguous in frequency which enables utilization of fragmented spectrum, operators with a fragmented spectrum can provide high data-rate services based on the availability of a virtually wide bandwidth even though they do not own a single wideband spectrum allocation.

Each UE has a single serving cell that provides all necessary control information and functions, such as non-access stratum mobility information, security establishment, RRC connection establishment/reconfiguration, etc. This serving cell is referred to as the primary cell (PCell). Other auxiliary cells or component carriers are referred to as secondary cells (SCells).

As shown in Figure 13.1, there are three different carrier aggregation scenarios, as follows [11]:

1. Intra-band contiguous carrier aggregation: This type of carrier aggregation uses a single frequency band. It is the simplest form of carrier aggregation from an implementation point of view. In this scenario, the

carriers are contiguous and the frequency spacing between center frequencies of contiguously aggregated RF carriers is a multiple of 300 kHz in order to be compatible with the 100 kHz frequency raster of LTE Rel-8/9 and preserve orthogonality of the subcarriers with 15 kHz spacing.

2. Intra-band non-contiguous carrier aggregation: In this scenario, the aggregated carriers are not adjacent and the multi-carrier signal cannot be treated as a single signal; therefore, two transceivers may be required. This adds significant complexity particularly to the UE where form-factor, power consumption, and cost are the major concerns.
3. Inter-band non-contiguous: This type of carrier aggregation uses different frequency bands which might be appealing to network operators due to the possibility of using fragmented frequency bands. In this scenario, the UE may have to use multiple transceivers, having unavoidable impact on cost, performance, and power consumption. In addition, there are also further complexities resulting from the requirements to reduce intermodulation and cross-modulation impairments created by the transceivers. This type of carrier aggregation may improve mobility by exploiting radio propagation characteristics of different bands.

An enhanced carrier aggregation work item was approved for LTE Rel-11, where as part of that work item, new non-backward-compatible partially configured carrier types could be defined for LTE Rel-11 and beyond to address the ever-increasing demand for higher capacity and higher data rates in cellular networks [19]. The new carrier types are going to be useful in practical deployments where the size of the available frequency block does not match the provisioned bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz in LTE Rel-8/9. If the size of the frequency block is smaller than 5 MHz (corresponding to 25 resource blocks), the number of resources on the carrier segment or extension carrier may not be adequate to efficiently transmit user data and synchronization signals, broadcast and control channels. Although it is desirable to reduce the overhead of the new carrier types (i.e., extension carrier and carrier segment), in practical deployment scenarios, if the frequency gap between the reference carrier and the extension/segment carrier is excessively large, the time and frequency synchronization and slot/subframe alignment of the carriers in a carrier set may not be maintained without including synchronization signals on the extension carrier/carrier segments.

Any fully configured backward compatible carrier in a carrier set may be extended by an extension carrier or appended by segment carriers. The design of the new carrier types has been required to support the operation in the following scenarios, but not necessarily equally optimized for both cases:

- Synchronized carriers: The base carrier and the new carrier types are synchronized in time and frequency to the extent that no separate synchronization is needed in the receiver.

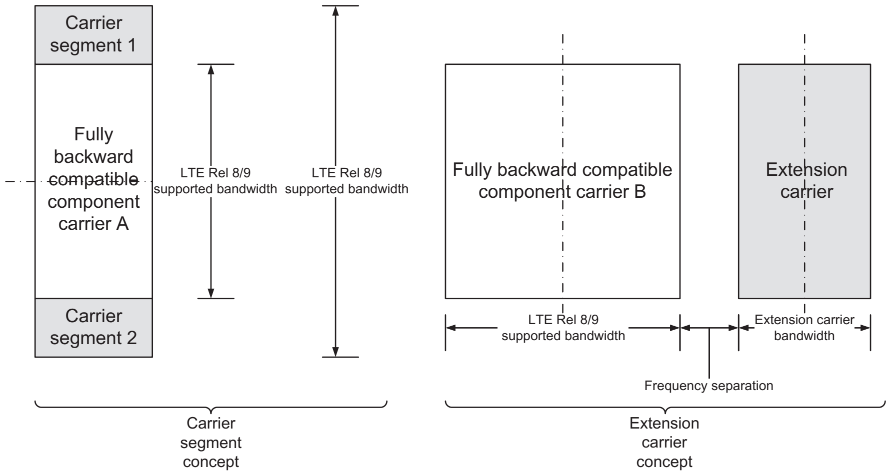

FIGURE 13.2

Illustration of the carrier segments and extension carriers [15].

- Unsynchronized carriers: The base carrier and the new carrier types are not synchronized with the same degree of accuracy as the synchronized carriers.

Note that synchronization is considered from the perspective of the UE receiver. Energy efficiency, flexible spectrum usage, heterogeneous network deployments, and machine type communications were identified as key objectives for the enhanced carrier aggregation project in 3GPP [19]. The considerations for the design of the additional carrier types that could assist in addressing the above goals mainly focused on operation with no cell-specific reference signals, enhanced control signaling with self-contained reference signals, and configurability of synchronization and other reference signal types when needed.

The new carrier types are defined as follows [15]:

- Carrier segment: The carrier segments are defined as the bandwidth extensions of an LTE Rel-8 compatible component carrier, provided that the total number of resource blocks is limited to 110. The combined RF carrier (i.e., LTE Rel-8 RF carrier + carrier segments as shown in Figure 13.2) utilizes the same backward compatible mechanisms of accessing the additional resources on the carrier segments as well as the base RF carrier. As an example, if two 2.5 MHz carrier segments are combined with a 5 MHz LTE Rel-8 RF carrier, the resulting 10 MHz RF carrier is going to be utilized as a 10 MHz LTE Rel-8 RF carrier. The use of carrier segments in the above manner would allow more efficient utilization of small fragments of spectrum without having to transmit additional overhead due to synchronization, broadcast, and control channels on the carrier segments. The notion of carrier segment allows for aggregation of additional resource blocks to a component carrier, while still retaining the backward compatibility of the original carrier, Note that carrier segments are always adjacent and linked to one component carrier and cannot be used as stand-alone. They do not provide synchronization signals, system information, or paging, and therefore cannot be used for random access or camping. They support the same HARQ process and transmission mode as the component carrier to which they are linked.

- Extension carrier: The extension carrier is a carrier that cannot be operated as a single stand-alone RF carrier and must be part of a component carrier set where at least one of the carriers in the set is a stand-alone backward compatible component carrier. Depending on whether the extension carriers are adjacent or non-adjacent to a component carrier carrying synchronization signals, the extension carrier may or may not be required to carry synchronization signals. If the extension carrier does not carry the synchronization signals, then it must be located close to a component carrier with synchronization signals for reliable synchronization. No legacy control channel PDCCH, PHICH, PCFICH, and no cell-specific reference signals is another possible configuration for the extension carriers which allows reduced overhead and more efficient use of radio resources on that carrier. The extension carrier supports a separate HARQ process, PDCCH, and transmission mode, which is configured from its linked component carrier.

13.2 Deployment scenarios

Carrier aggregation enables various network deployments. In general, carrier aggregation is used to improve data rates for users within overlapped areas of the cells (cell boundaries). However, carrier aggregation can also be used to mitigate inter-cell interference in heterogeneous networks (see Chapter 14). The following network deployment scenarios were considered during the development of LTE-Advanced. Although exemplified with two component carriers at frequencies f_{c_1} and f_{c_2} as shown in Figure 13.3, the concept can be generalized to any number of component carriers [7,22,23,29]:

- Deployment Scenario 1: In this case, cells with carrier frequencies f_{c_1} and f_{c_2} are (geographically) collocated, and their coverage is overlaid with f_{c_1} and f_{c_2} in the same frequency band. They provide approximately the same coverage due to similar path loss characteristics within the same band. This carrier aggregation scenario achieves higher data rates throughout the cell where both layers provide sufficient coverage and mobility. An example scenario is the case where $f_{c_1} = 2000$ MHz and $f_{c_2} = 800$ MHz are of the same band where aggregation is possible between the overlaid cells.

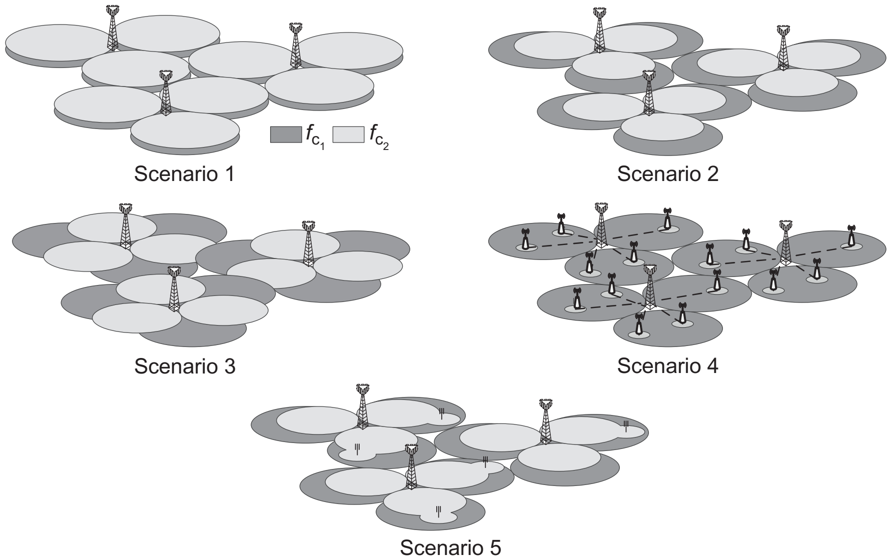

FIGURE 13.3

Carrier aggregation deployment scenarios [7].

- Deployment Scenario 2: In this case, the cells with carrier frequencies f_{c_1} and f_{c_2} are collocated and overlaid with f_{c_1} and f_{c_2} in different frequency bands. Different coverage is provided on different carriers due to the larger path loss in the higher frequency band. Mobility is typically supported on the carrier in the lower frequency band which further provides sufficient coverage. The carrier in the higher frequency band is used to improve data rates and throughput. The cells f_{c_1} and f_{c_2} are collocated and overlaid, but f_{c_2} has smaller coverage due to larger path loss. In other words, only f_{c_1} provides sufficient coverage and f_{c_2} is used to improve throughput. An example scenario would be the case where $f_{c_1} = \{800\ \text{MHz}, 2000\ \text{MHz}\}$ and $f_{c_2} = \{3500\ \text{MHz}\}$ where aggregation is possible between the overlaid cells.
- Deployment Scenario 3: In this case, the cells comprising carrier frequencies f_{c_1} and f_{c_2} are collocated with f_{c_1} and f_{c_2} in different frequency bands. The antennas for cells of f_{c_2} are directed to the cell boundaries of f_{c_1} to improve the cell-edge data rates and user throughput. Due to the larger path loss, coverage holes exist for cells in the higher frequency band on which mobility management is typically not performed. The carrier aggregation is supported in areas with overlapping coverage and the mobility is based on f_{c_1} coverage. An example would be the case where $f_{c_1} = \{800\ \text{MHz}, 2000\ \text{MHz}\}$ and $f_{c_2} = \{3500\ \text{MHz}\}$ in which aggregation is possible between the overlaid cells.

- Deployment Scenario 4: In this case the cells associated with carrier frequency f_{c_1} provide macro coverage and remote radio heads (RRHs) corresponding to carrier frequency f_{c_2} are used to improve throughput at hot spots. The mobility is performed based on the cell coverage of frequency f_{c_1}. In this deployment scenario, the carrier frequencies f_{c_1} and f_{c_2} are usually of different bands. The carrier aggregation is applicable to users within the coverage of RRHs and the underlying macro-cells. An example would be the case where $f_{c_1} = \{800\ \text{MHz}, 2000\ \text{MHz}\}$ corresponds to a larger cell and $f_{c_2} = \{3500\ \text{MHz}\}$ corresponds to smaller cell, in which aggregation is possible between the overlaid cells.
- Deployment Scenario 5: This case is similar to the second scenario where frequency-selective repeaters or distributed antenna systems are additionally deployed to extend the coverage for one of the carrier frequencies. It is expected that f_{c_1} and f_{c_2} cells of the same eNB can be aggregated where coverage overlaps.

13.3 Physical and MAC layer aspects of carrier aggregation

In this section, we discuss the physical and MAC layer aspects of carrier aggregation, and we will particularly focus on the impacts of carrier aggregation on the system operation at the lower protocol layers. Note that scheduling and use of the RF carriers are related to physical and MAC layers, and to a great extent are transparent to the upper layers.

13.3.1 Physical layer aspects

The physical layer is in charge of processing and transmission of data and control signaling between the radio access network and the user device. The LTE-Advanced carrier aggregation feature enables concurrent data transmission on multiple component carriers (up to five), where the transmission schemes are largely inherited from LTE Rel-8/9 data transmission procedures per component carrier, including the multiple access scheme; modulation and coding; and multi-antenna processing. Some additional UE functionalities beyond those of LTE Rel-8/9 are supported in LTE Rel-10, including data transmissions over two clusters of contiguous bandwidth on the same carrier where the data is precoded by a single DFT unit (see Chapter 10 for a description of clustered SC-FDMA), simultaneous transmission of a control channel and a data channel in the PCell (see Chapter 10 for simultaneous PUCCH and PUSCH transmission), and data transmissions from multiple antennas with spatial multiplexing [3–6]. Nevertheless, improving the downlink and uplink control signaling to efficiently support data transmission was the main challenge in the design of LTE-Advanced carrier aggregation [29].

The PDCCH provides information on resource allocation; modulation and coding scheme HARQ; and other parameters for downlink and uplink data transmission on the physical downlink/uplink shared channel. It is possible to configure each component carrier to transmit the PDCCH for scheduling PDSCH/PUSCH on the same carrier frequency and associated linked uplink carrier, where the linkage of the downlink and uplink carriers is conveyed in SIB2 [10]. In addition, the PDCCH on a component carrier can be configured to schedule PDSCH and PUSCH transmissions on other component carriers through a cross-carrier scheduling feature. Cross-carrier scheduling was primarily developed to support heterogeneous networks comprising a combination of macro-eNBs and low-power nodes (e.g., pico-cell, femto-cell, and RRHs) where significant intercell interference may arise when those networks are deployed on the same carrier [30,31]. Since the PDCCH is transmitted across the entire bandwidth of the respective carrier, interference coordination methods based on fractional frequency reuse may not be adequate in reducing the inter-cell interference on the PDCCH. Carrier aggregation can address this issue by configuring the UE connected to different network nodes to receive the PDCCH on different carriers, thereby reducing or even eliminating inter-cell interference on the PDCCH. With cross-carrier scheduling, only one component carrier needs to be protected for the PDCCH transmission, which can be used to allocate resources on other component carriers.

Cross-carrier scheduling enables a PDCCH on a component carrier to be configured in order to schedule PDSCH and PUSCH transmissions on another component carrier using a 3-bit carrier indicator field (CIF) which is inserted at the beginning of the downlink control information (DCI) messages. The carrier aggregation can reduce or even eliminate inter-cell interference on the PDCCH using cross-carrier scheduling. Figure 13.4 shows a hypothetical heterogeneous network scenario where a component carrier at f_1 is used by the macro-cell at full power and by the pico-cells at reduced power; whereas component carrier f_2 is used by the macro-cell at reduced power and by the pico-cells at nominally low power. In this case, cross-carrier scheduling from component carrier f_2 allows inter-cell interference mitigation among the macro- and pico-cells.

Cross-carrier scheduling is also an effective mechanism to schedule data transmissions on carriers of small bandwidth from a carrier with a larger bandwidth, considering that the PDCCH reliability targets are more challenging to achieve on carriers with small bandwidth due to limited frequency diversity gain. The PDCCH search space consists of a set of PDCCH candidates over which the UE performs blind decoding operations to determine whether there is any PDCCH addressed to it in a subframe. A common PDCCH search space is monitored by all UEs only in their respective PCells for receiving system information, paging, power control, and random access-related control information. Each UE also monitors a UE-specific PDCCH search space primarily carrying scheduling grants for downlink and uplink data transmissions. The start of the UE-specific PDCCH search space is a function of the UE's radio network temporary identifier (RNTI).

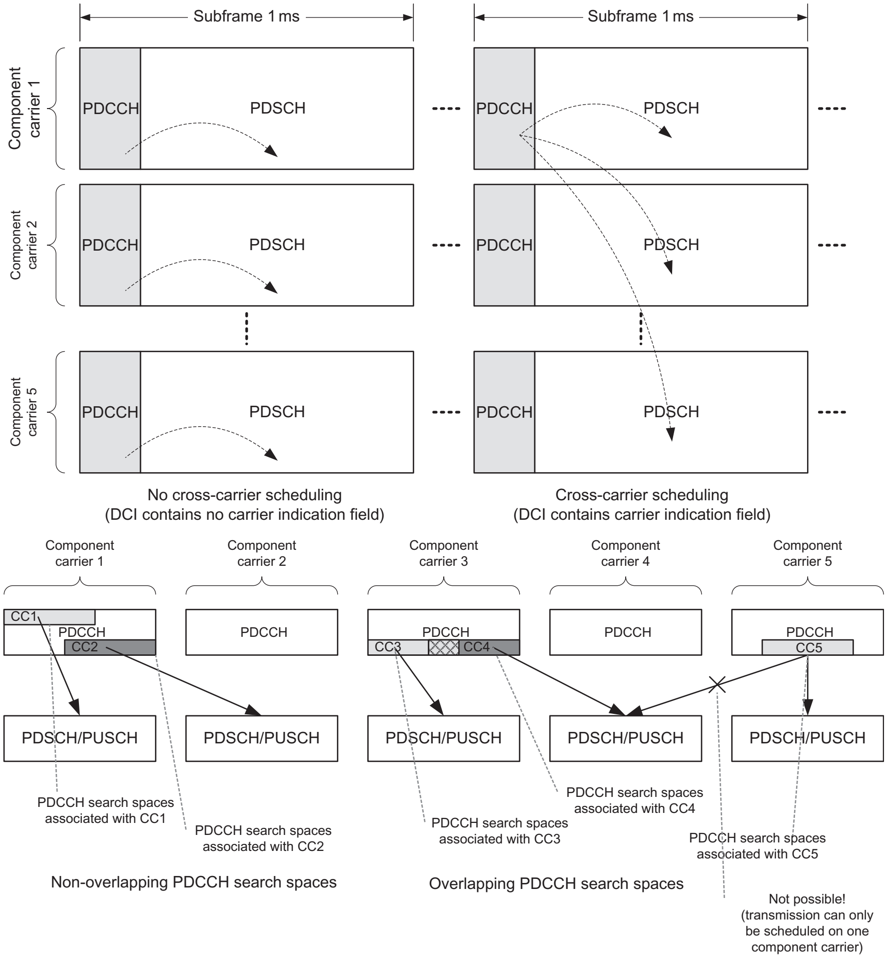

FIGURE 13.4

Illustration of the cross-carrier scheduling concept in carrier aggregation [13,14].

Since the same set of resources for PDCCH transmission is shared by all UEs, a PDCCH for a UE may not be transmitted due to partial overlapping with another PDCCH belonging to a different UE; this condition is referred to as PDCCH blocking. To maintain the PDCCH blocking probability at LTE Rel-8/9 level, an LTE Rel-10/11 UE monitors one UE-specific PDCCH search space for each activated component carrier. For a UE that is not configured with cross-carrier scheduling, the UE-specific PDCCH search space on each component carrier is the same as that in LTE Rel-8/9, whereas for a UE that is configured with cross-carrier scheduling, the UE-specific PDCCH search space is defined by a

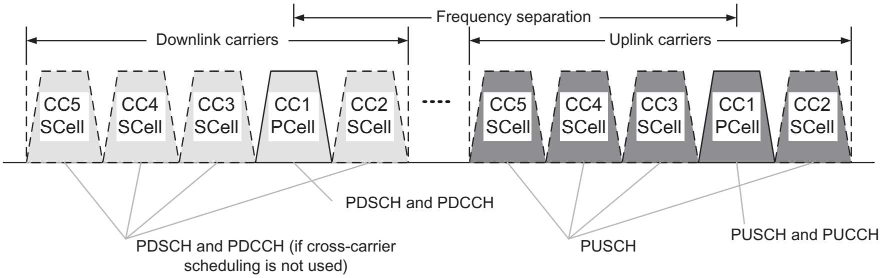

FIGURE 13.5

Symmetric carrier aggregation in the downlink and uplink (example) [16].

combination of the UE's RNTI and the serving cell index. The number of PDCCH blind decoding operations performed by a UE scales (approximately) linearly with the number of its activated component carriers [29]. If carrier aggregation is configured, the maximum number of blind decoding operations that a UE performs is 44 for the PCell plus 32 for each active downlink SCell. An additional 16 blind decodings are needed for each uplink component carrier that is configured for uplink MIMO operation. When cross-carrier scheduling is configured, CIF is only present in the PDCCH messages in the UE-specific search space and not in the common search space [13].

The PDSCH/PUSCH on a component carrier can only be scheduled from one component carrier. Therefore, for each PDSCH/PUSCH component carrier, there is an associated component carrier, configured via UE-specific RRC signaling, where the corresponding DCI can be transmitted. Figure 13.4 illustrates an example, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs transmitted on component carrier 1. In this case, since cross-carrier scheduling is not used, there is no carrier indicator in the corresponding DCI formats. The PDSCH/PUSCH transmissions on component carrier 2 are cross-carrier scheduled from PDCCHs transmitted on component carrier 1. Therefore, the DCI formats in the UE-specific search space for component carrier 2 include the CIF. Note that the transmissions on a component carrier can be scheduled by the PDCCHs on one component carrier; thus, component carrier 4 cannot be scheduled by PDCCHs on component carrier 5, given that there is a semi-static association between component carriers 3 and 4 for PDCCH transmission in this example [14].

As mentioned earlier, there is one UE-specific search space per aggregation level and component carrier used for PDSCH/PUSCH. This is illustrated in Figure 13.4, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs transmitted on component carrier 1. There is no CIF in the UE-specific search space for component carrier 1 since cross-carrier scheduling is not used. For component carrier 2, on the other hand, a carrier indicator field exists in the UE-specific search space, given that component carrier 2 is cross-carrier scheduled from the PDCCHs transmitted on component carrier 1. Search spaces for different component carriers may overlap in some subframes. In Figure 13.4, this happens for the UE-specific search spaces for component carriers 3 and 4. The terminal can identify the two search spaces independently, assuming that a CIF is used for component carrier 4, but is not used for component carrier 3. If the UE-specific and common search spaces corresponding to different component carriers happen to overlap for some aggregation levels when cross-carrier scheduling is configured, the terminal only needs to monitor the common search space. The reason for this is to avoid ambiguities arising from this condition; if the component carriers have different bandwidths, a DCI format in the common search space may have the same payload size as another DCI format in the UE-specific search space corresponding to another component carrier [14].

The PCFICH is transmitted in each subframe and conveys a control format indicator (CFI) field, which indicates the number of OFDM symbols carrying control information in each subframe (up to three OFDM symbols per subframe). The UE derives the starting OFDM symbol used for the PDSCH transmission based on the decoded CFI value. For the PDSCH scheduled by PDCCH on the same component carrier, the UE is required to decode the PCFICH in order to determine the starting OFDM symbol used for the PDSCH. When cross-carrier scheduling is utilized, the starting OFDM symbol for the PDSCH transmission is configured by the network through higher layers, and the UE is not required to decode PCFICH on that component carrier.

The physical HARQ indicator channel carries HARQ feedback (ACK/NACK) information associated with a PUSCH transmission. The PHICH structure in LTE Rel-10/11 carrier aggregation is the same as that for LTE Rel-8/9. The PHICH corresponding to a PUSCH transmission is always transmitted on the component carrier where the PDCCH schedules the PUSCH transmission.

The uplink control information (UCI) includes HARQ feedback corresponding to one or more PDSCHs, channel state information, and scheduling request. Similar to LTE Rel-8/9, the UCI can be transmitted on the PUCCH, if there is no transmission on PUSCH in a subframe, or transmitted on PUSCH, if there is a scheduled transmission on PUSCH. LTE-Advanced further supports simultaneous PUCCH and PUSCH transmissions in a subframe (see Figure 13.6). This allows the eNB to flexibly control the performance of the PUCCH and PUSCH independently and to avoid the UCI overhead on PUSCH by utilizing existing PUCCH resources. The PUCCH can only be transmitted on the PCell, since it typically has more reliable link quality and coverage relative to the SCells (see Figure 13.5). When applicable, UCI is always transmitted on a single PUSCH.

HARQ feedback indicates whether a transport block is correctly received and decoded. LTE Rel-8/9 supports transmitting a maximum of two and four ACK/NACKs in an uplink subframe for FDD and TDD, respectively. Given independent HARQ processes per component carrier, the maximum number of HARQ feedback bits in a subframe in response to PDSCH transmissions can be 10 bits

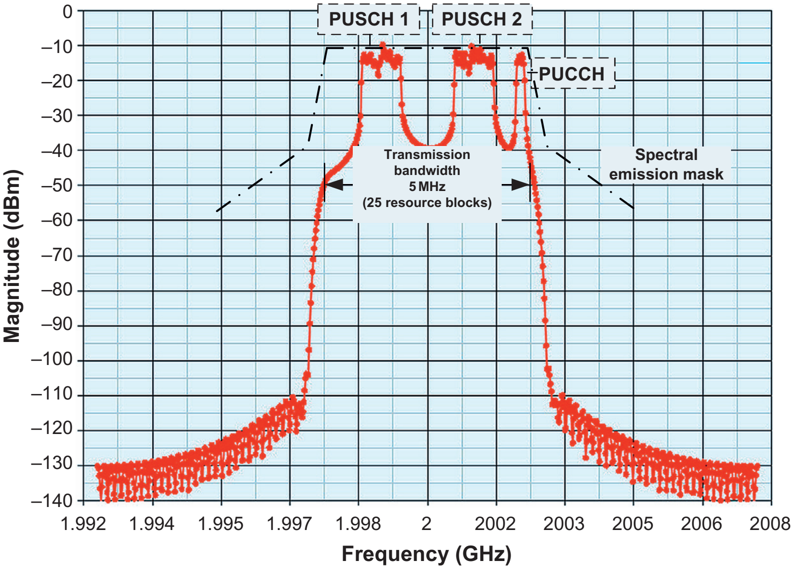

FIGURE 13.6

Snapshot of clustered SC-FDMA (simultaneous PUSCH and PUCCH transmission) in the uplink [17,18].

for FDD and up to 90 bits for TDD (assuming five component carriers with MIMO transmission modes per component carrier and TDD subframe configuration 5). Reliable transmission of large number of HARQ ACK/NACK bits in an uplink subframe requires a substantial amount of resources and sufficiently high signal to interference plus noise ratio. Therefore, HARQ feedback bundling/multiplexing schemes are designed for TDD systems to limit the maximum number of ACK/NACK bits in an uplink subframe to 20. Multiple HARQ feedback bits are bundled by a logical AND operation to produce one HARQ feedback bit per component carrier and per subframe for certain TDD subframe configurations. The PUCCH format 3 was introduced in LTE Rel-10 to support HARQ feedback for a UE configured with downlink carrier aggregation. The PUCCH format 3 uses a SC-FDMA waveform with five SC-FDMA symbols per slot carrying HARQ feedback information and one or two SC-FDMA symbols per slot (depending on the size of the cyclic prefix) for transmission of demodulation reference signals, to enable coherent demodulation of HARQ feedback (see Chapter 10 for more information on PUCCH format 3). An orthogonal cover code of length 5 is applied to the encoded HARQ feedback bits in the corresponding SC-FDMA symbols, allowing multiplexing of up to five UEs in one resource block. Assuming QPSK modulation, k HARQ feedback bits are encoded using the $(32, k)$ Reed−Muller code with circular rate matching into 48 encoded HARQ acknowledgment bits, which are transmitted in a subframe comprising two slots.

LTE-Advanced further supports the HARQ feedback multiplexing scheme for TDD, where two HARQ feedback bits are generated per component carrier, representing the number of consecutively correctly received PDSCHs on the component carrier. PUCCH format 1b can be used to carry four acknowledgments when channel selection is used, i.e., the PUCCH payload carries two acknowledgments and the selection of PUCCH resources carries the other two acknowledgments. The use of bundled acknowledgments in a single uplink subframe is not limited to the TDD duplex mode. The carrier aggregation in FDD with a different number of uplink and downlink component carriers encounters the same problem. In LTE Rel-10, there is only one PUCCH that is always transmitted on the primary component carrier. Hence, even in asymmetric carrier aggregation scenarios, the possibility to transmit more than two HARQ acknowledgment bits in the uplink must be supported. This is performed via resource selection or by using PUCCH format 3. The acknowledgments in response to PUSCH transmissions are transmitted using multiple PHICHs, where the PHICH is transmitted on the same downlink component carrier as the uplink scheduling grant which initiated the uplink transmission.

The channel-state information feedback enables the eNB to perform PDSCH scheduling including resource allocation, MCS selection, transmission rank adaptation, and the choice of precoding matrix. To accommodate different channel conditions and interference levels among different component carriers, CSI is fed back for each component carrier. Both periodic and aperiodic CSI feedbacks are supported in LTE Rel-10/11, where periodic CSI is transmitted on a set of semi-statically configured subframes, and aperiodic CSI is dynamically scheduled by the eNB via the PDCCH. Periodic CSI feedback is independently configured for each component carrier and transmitted on the PUCCH using PUCCH format 2. Since the payload size of PUCCH format 2 is limited, the periodic CSI for only one component carrier can be unconditionally transmitted in a subframe. A priority based on the periodic CSI reporting type determines the component carrier for which periodic CSI is reported in the event that periodic CSI feedback of multiple carriers collide in a subframe. If the collisions involve the same periodic CSI reporting type, the priority is according to ascending cell index. Aperiodic CSI feedback is transmitted on PUSCH and typically carries more CSI bits than periodic CSI feedback. LTE Rel-10/11 supports aperiodic CSI feedback for a single or multiple component carriers in a subframe so that the eNB can balance the CSI accuracy and feedback overhead [29].

Uplink power control is a mechanism to instruct the UEs to determine the PUSCH/PUCCH transmission power with the objective of ensuring that the target reception reliability of that channel is met. The uplink power control supported in LTE Rel-8/9/10 consists of an open-loop component adjusting for the path loss between the UE and its serving eNB, and of a closed-loop component based on transmission power control commands in the PDCCH. The uplink power control processes are independent among the respective activated cells and each process is the same as LTE Rel-8/9. The resulting transmission power for PUSCH or

PUCCH is referred to as nominal transmission power. The key differentiation with respect to the LTE Rel-8/9 uplink power control operation occurs when the sum of the nominal transmission powers from the UE exceeds the total maximum output power for which the UE is configured in a specific subframe. Depending on whether the UE is configured for simultaneous PUCCH and PUSCH transmissions, on the UCI types for transmission, and on the existence of any PUSCH transmission, the UE may transmit in a subframe one PUCCH, one PUSCH with UCI, one or more PUSCH transmissions without UCI, or any other combination. As control information is more important than data information and does not benefit from the use of HARQ, the UE transmission power is distributed by descending priority to the PUCCH, PUSCH with UCI, and PUSCH without UCI, where the nominal transmission power for a channel with higher priority is first guaranteed until the UE total maximum output power is reached. For one or more PUSCH transmissions without UCI, the UE scales each respective nominal PUSCH transmission power by the same factor, considering that the same quality of service for data transmission is required on all component carriers [29].

The eNB may not know the exact UE transmission power due to the possibility of missing power control commands, UE-specific implementation of maximum power reduction (MPR),[1] and additional maximum power reduction (A-MPR)[2] in order to meet regulatory requirements. To provide the eNB with more accurate information on the UEs transmission power, power headroom reporting was supported in LTE Rel-8/9. The UE may report type 1 and/or type 2 power headroom for an activated cell. The type 1 and type 2 power headroom reports indicate the amount of remaining the UEs transmission power beyond those already used for PUSCH, or PUSCH and PUCCH transmission in a subframe, respectively [29].

13.3.2 MAC layer aspects

From the MAC perspective, the carrier aggregation simply provides additional conduits, thus the MAC sublayer plays the role of a multiplexing entity for the aggregated component carriers. Figure 13.7 shows an overview of the downlink

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[1] The purpose of MPR is to allow the UE, in some configurations, to lower its maximum output power in order to meet the general requirements on signal quality and out-of-band (OOB) emissions. Note that MPR is an allowance and the UE is not required to use it [13].

[2] The eNB may inform the UE of the possibility of further lowering its maximum power by signaling an additional MPR (A-MPR). The need for an A-MPR occurs with certain combinations of E-UTRA bands, channel bandwidths, and transmission bandwidths for which the UE must meet additional (more stringent) requirements for spectrum emission mask and spurious emissions. As with MPR, the A-MPR is an allowance, not a requirement, and it applies in addition to MPR. Regardless of whether the UE makes use of the allowed MPR and A-MPR, the additional requirements for spectrum emission mask and spurious emissions that are signaled by the network always apply. The reason for the complex set of conditions for the relaxation is the expected intermodulation products which may fall into adjacent bands which have different levels of sensitivity (e.g., public safety bands) [13].

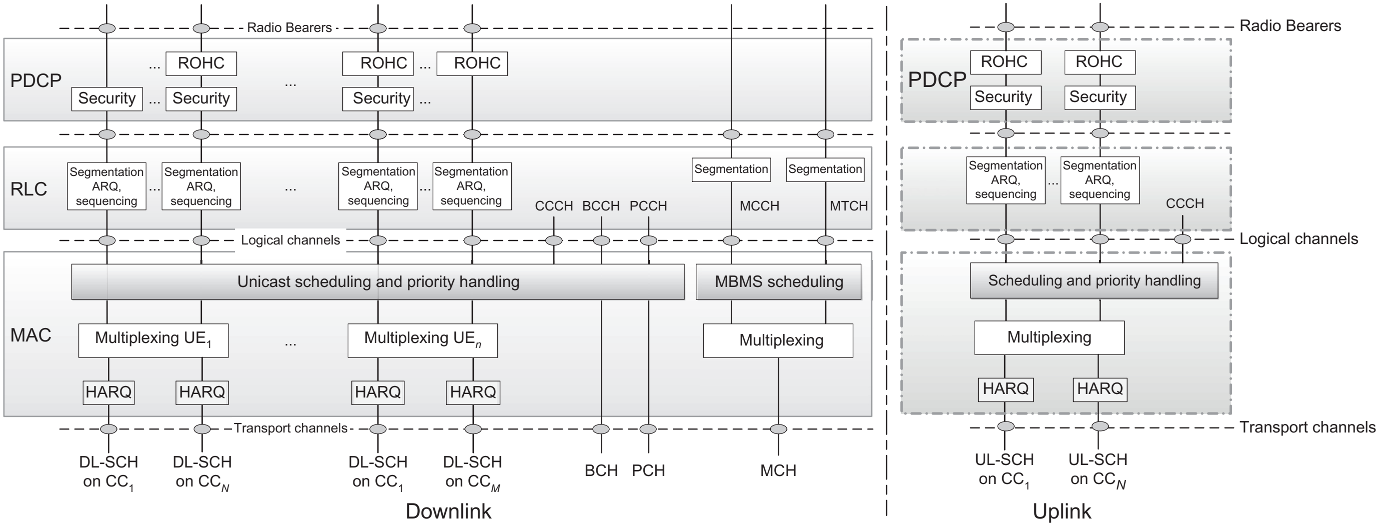

FIGURE 13.7

LTE-Advanced downlink/uplink layer 2 structure when carrier aggregation is configured [7].

user-plane protocol stack at the base station, as well as the corresponding mapping of the most essential radio resource management functionalities for carrier aggregation. Each user has at least one radio bearer which is referred to as the default radio bearer. The exact mapping of data to the default bearer is up to the operator policy and is configured via the traffic flow template. In addition to the default radio bearer, users may have additional bearers configured. There is one PDCP and RLC entity per radio bearer, including functionalities such as robust header compression, security, segmentation, and ARQ. As mentioned in the previous chapters, the interface between the RLC sublayer and MAC sublayer is referred to as the logical channel.

There is one MAC entity per user, which controls the multiplexing of data from all logical channels to the user, and further controls how this data is transmitted on the available component carriers. As illustrated in Figure 13.7, there is a separate HARQ entity per component carrier, which essentially means that if data transmission is on the *i*th component carrier, the HARQ retransmissions in case of erroneous reception must be performed on the *i*th component carrier. The interface between the MAC sublayer and the physical layer, which are referred to as transport channels, is also separate for each component carrier. The transport blocks sent on different component carriers can be transmitted with independent MCSs as well as different MIMO schemes. The latter allows data on one component carrier to be transmitted with open-loop transmit diversity (transmission mode 2), whereas data on another component carrier sent with dual-layer beamforming (transmission mode 8). There is independent link adaptation per component carrier in order to take advantage of more accurate link adaptation on different component carriers according to their respective propagation and radio channel conditions. Semi-persistent scheduling can only be configured for the PCell, and PDCCH allocations for the PCell can override the corresponding semi-persistent scheduling resource allocation.

The LTE Rel-8/9 control-plane protocol stack also applies to LTE-Advanced with multiple component carriers, meaning that there is one RRC per user, independent of the number of component carriers. Similarly, idle mode mobility procedures of LTE Rel-8/9 also apply in a network supporting carrier aggregation. It is also possible for a network to configure only a subset of component carriers for idle mode camping [26].

E-UTRA in general supports a synchronized uplink by means of un uplink timing advance (TA) adjustment procedure. The carrier aggregation in LTE Rel-10 only supports a single timing advance value which is applied to all component carriers. This means that the base station transceivers for different carriers should be at the same location to avoid different propagation delays. The use of RRHs, distributed antennas, and repeaters was limited. The signal should be received within the cyclic prefix length for a correct reception by a regular UE. The timing advance group (TAG) was introduced in LTE Rel-11 for supporting multiple timing advances typically encountered in inter-band carrier aggregation scenarios. A TAG includes one or more serving cells with the same uplink timing advance and the same downlink timing reference cell. If a TAG contains the PCell, it is referred to as the primary timing advance group (pTAG). If a TAG contains only SCell(s), it is denoted as the secondary timing advance group (sTAG). There is one timing reference cell and one time alignment timer (TAT) per TAG, and each TAT may be configured with a different value. For pTAG, the PCell is used as the timing reference cell, whereas for sTAG, the UE may use any activated SCell from the same sTAG as the timing reference cell. From an RF requirement point of view, the number of component carriers is limited to two for LTE Rel-11; thus, if the sTAG is configured, there is only one SCell in the sTAG [7].

The initial uplink timing alignment of the sTAG is obtained by an eNB initiated random access procedure similar to the pTAG. The SCell in a sTAG can be configured with random access channel resources, and the eNB may instruct the UE to perform random access on the SCell. The Msg2 (or random access response) in response to the SCell preamble is transmitted on the PCell using an RA-RNTI that conforms to the LTE Rel-8 RACH procedure. The grant in Msg2 is valid for the SCell in which the preamble was transmitted. The UE stops transmission of the random access preamble on the SCell when reaching the maximum number of transmissions. However, the UE will not indicate a random access problem to upper layers, if the maximum number of preamble transmissions is reached for the random access procedure on the SCell. The UE tracks the downlink frame timing change of the SCell and adjusts the uplink transmission timing following the timing advance commands from the eNB [7].

13.4 Protocol and signaling aspects of carrier aggregation

In order to enable mobility when supporting carrier aggregation, a UE handles a component carrier in the same way as it would deal with another carrier frequency in LTE Rel-8/9. The UE performs various measurements as instructed by the eNB including intra- and inter-frequency measurements which are used for selecting LTE carriers, as well as inter-RAT measurements which are meant for non-LTE RAT selection. As of LTE Rel-10/11, the following event-triggered reporting criteria are defined [10]:

- Event A1: Serving cell becomes better than absolute threshold.
- Event A2: Serving cell becomes worse than absolute threshold.
- Event A3: Neighbor cell becomes better than an offset relative to the serving cell.
- Event A4: Neighbor cell becomes better than absolute threshold.
- Event A5: Serving cell becomes worse than one absolute threshold and neighbor cell becomes better than another absolute threshold.
- Event A6: Intra-frequency neighbor becomes better than an offset relative to an SCell (LTE Rel-10/11 only).

For inter-RAT mobility, the following criteria for measurement reporting are defined [10]:

- Event B1. Neighbor cell becomes better than absolute threshold.
- Event B2. Serving cell becomes worse than one absolute threshold and neighbor cell becomes better than another absolute threshold.

The new measurement event A6 was introduced for LTE-Advanced carrier aggregation to compare the neighbor cells' component carriers to the current SCell, thus allowing reconfiguration of SCells.

The discontinuous reception (DRX) mode was defined in LTE Rel-8/9. If one or more SCells are configured for a UE in addition to the PCell, the same DRX mode is applied to all serving cells. According to network configuration and ongoing HARQ processes, the UE determines the DRX activity cycle which is common to all serving cells. This means that the active times for PDCCH monitoring are identical across all downlink component carriers (see Figure 13.8).

The SCell activation/deactivation is an efficient mechanism to reduce the UE power consumption in LTE Rel-10/11 carrier aggregation in addition to DRX. On a deactivated SCell, the UE neither receives downlink signals nor transmits any uplink signal. The UE is also not required to perform measurements on a deactivated SCell. Deactivated SCells can be used as a path loss reference for measurements in uplink power control. It is assumed that these measurements would be less frequent while the SCell is deactivated in order to conserve the UE power. On the other hand, for an activated SCell, the UE performs normal activities for downlink reception and uplink transmission. Activation and deactivation of SCells is controlled by the eNB. As shown in Figure 13.8, the SCell activation/deactivation is performed when the eNB sends an activation/deactivation command in the form of a MAC control element. A timer may also be used for automatic deactivation, if no data or PDCCH messages are received on an SCell for a certain period of time. This is the only case in which deactivation can be executed autonomously by the UE. Serving cell activation/deactivation is performed independently for each SCell, allowing the UE to be activated only on a particular set of SCells. Activation/deactivation is not applicable to the PCell because it is required to always remain activated when the UE has an RRC connection to the network [29].

As already mentioned, if the UE is configured with one or more SCells, the network may activate and deactivate the configured SCells. The PCell is always activated. The network activates and deactivates the SCell(s) by sending an activation/deactivation MAC control element as described in Chapter 8. Furthermore, the UE maintains an *sCellDeactivationTimer* per configured SCell and deactivates the associated SCell upon its expiration. The same initial timer value is applied to each instance of the *sCellDeactivationTimer* and it is configured by RRC signaling. The configured SCells are initially deactivated upon addition and after a handover [9].

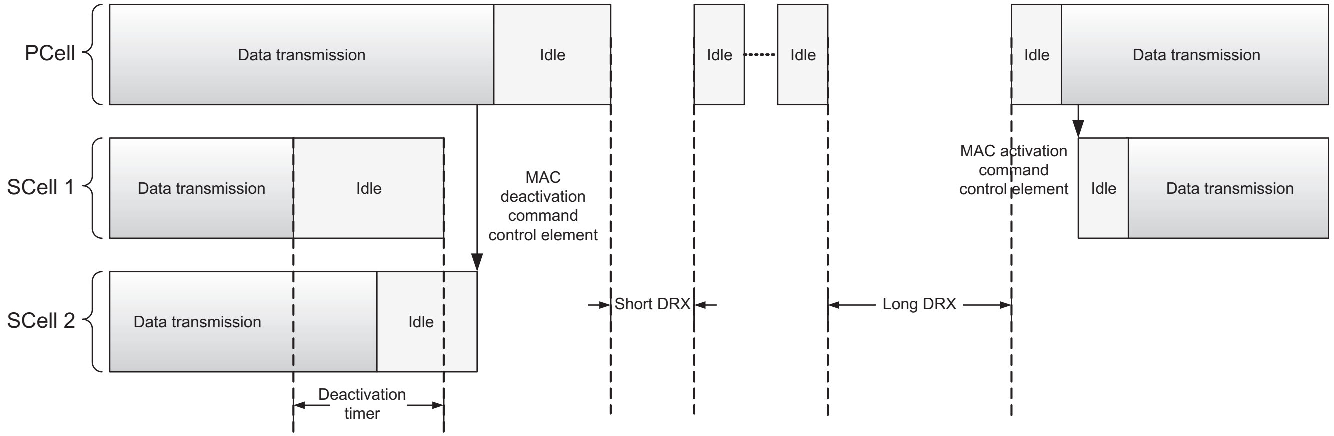

FIGURE 13.8

Illustration of SCell activation/deactivation procedure [20].

As mentioned earlier, the activation or deactivation of downlink component carriers are performed through a MAC control element. A command to activate a component carrier takes effect eight subframes after the receipt of the activation/deactivation command, i.e., if the MAC control element is received in subframe n, then the SCells are activated/deactivated starting from subframe $n + 8$. There is also a timer-based mechanism for deactivation such that a terminal may deactivate SCells after a configurable time with no activity. Note that the primary component carrier is always active. In the uplink, there is no explicit means of activation for uplink component carriers. However, whenever a downlink component carrier is activated or deactivated, the corresponding uplink component carrier is also activated or deactivated [14].

13.5 Radio resource management aspects of carrier aggregation

Cell management is the control procedure enabling the network to add, remove, or change SCells, or to switch the PCell of a UE. A UE in the RRC_IDLE state establishes RRC connection on a serving cell, which automatically becomes its PCell. Depending on the carrier where initial access is performed, different UEs in a network with carrier aggregation capability may have different PCells. With the RRC connection established on the PCell, the network can further configure one or more SCells for a carrier-aggregation-capable UE, considering the UEs capability [8] to meet the UE's data service requirements. The necessary information, including system information of an SCell is conveyed to the UE via dedicated RRC signaling. Addition, removal, or reconfiguration of SCells for a UE is performed via dedicated RRC signaling (see Figure 13.9). The network can further change the PCell of a UE to improve the link quality of the PCell on which critical control information is sent, or to provide load balancing among different SCells. The change of PCell in LTE Rel-10 carrier aggregation can only be performed via a handover procedure, and it does not necessarily require the UE to switch to single-carrier operation. Intra-LTE handover in LTE-Advanced allows the target PCell to configure one or more SCells for the UE to use immediately after handover [29].

The carrier aggregation additional SCells cannot be activated immediately at the time of RRC connection establishment, since there is no provision in the RRC connection setup procedure for SCells. SCells are added or removed from the set of serving cells through the RRC connection reconfiguration procedure. Note that, since intra-LTE handover is treated as an RRC connection reconfiguration, SCell handover is supported. The carrier aggregation-related information sent by the eNB pursuant to the RRC connection reconfiguration procedure can be summarized as follows [20]:

- Cross-carrier scheduling configuration: This indicates if scheduling for the referenced SCell is managed by that SCell or by another cell.

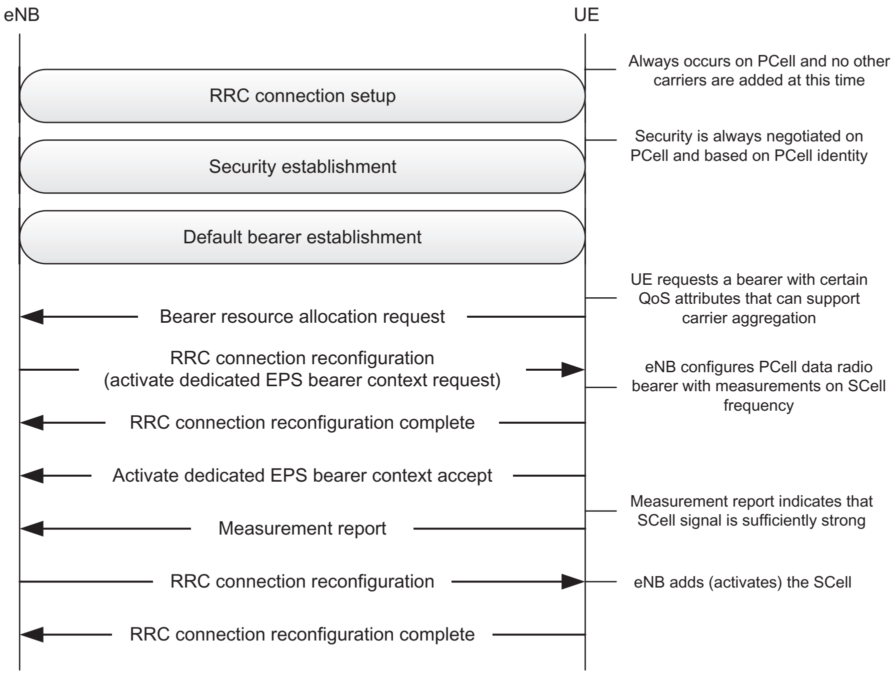

FIGURE 13.9

Summary of message exchange for addition of SCells [20].

- SCell PUSCH configuration: This indicates whether resource block group hopping is utilized on the SCell.
- SCell uplink power control configuration: This carries a number of primitives related to the SCell uplink transmit power command, including the path loss reference-linking parameter.
- SCell CQI reporting configuration: This carries a number of primitives related to CQI measurement reporting for SCells.

13.6 RF and implementation aspects of carrier aggregation

Although not considered a problem for the base station, carrier aggregation will undoubtedly pose major difficulties for the UE, which must handle multiple (simultaneously operating) transceivers. The addition of simultaneous non-contiguous transmitters creates a highly challenging radio environment in terms of spurious signal emissions and self-blocking. Carrier aggregation brings new technical challenges, especially for the LTE Rel-10/11 UE implementation. The complexity of the UE's RF front-end module can vary greatly, depending on which type(s) of carrier aggregation are supported, with contiguous carrier aggregation being the least complex scenario. In LTE Rel-10 devices, contiguous carrier aggregation will not exceed two component carriers or 40 MHz maximum bandwidth. It may be possible to support this configuration with a single wideband transceiver in the UE. For non-contiguous component carrier allocations, the UE will have to use multiple transceivers or a single, extremely wide wideband transceiver. Using multiple transceivers may be more realistic in the sense that such configuration requires only the addition of parallel paths to process each frequency band, as in existing multiband devices. However, using multiple transceivers also increases the size, cost, and power consumption of the mobile device [12–14].

In a wideband transceiver, a single transceiver must process the multi-band non-contiguous carrier aggregation using wideband RF components. There are two main issues with this approach. First, as the bandwidth increases, the effective noise bandwidth increases, thus resulting in increased noise power. Second, with a wider bandwidth, more unwanted signals are likely to be received from other sources. Therefore, for non-contiguous carrier aggregation, most proposals today are leaning toward the use of multiple transceivers instead of a single wideband approach. In addition to increasing the RF front-end complexity, using simultaneous non-contiguous transmitters creates a highly challenging radio environment in terms of spurious signal management and self-blocking. Because these challenges particularly impact UE design, more work needs to be done before interband carrier aggregation can be successfully introduced in the uplink [14].

Simultaneous transmit or receive with mandatory MIMO support would aggravate the challenge of antenna design. The frequency bands designated for the deployment of LTE are mostly the existing IMT-2000 bands, or the bands where the legacy systems, including UMTS and GSM, were deployed. The frequency bands in some regions are defined in a technology-neutral manner, which means that coexistence among different technologies is a necessity. In general, the requirements for LTE operation in different frequency bands do not impose any specific requirements on the radio-interface design. However, there are implications for the RF requirements and the way they are defined in order to support coexistence between operators in the same geographical area, collocation of base station equipment of different operators, and coexistence with services in adjacent frequency bands and across country borders [14].

Operators may deploy LTE or other IMT-2000 technologies such as HSPA or EDGE in their respective bands. Such coexistence requirements to a large extent are developed within 3GPP, but there may also be regional requirements defined by regulatory bodies in some frequency bands. There are in many cases limitations to where base station equipment can be deployed. The base station sites are often shared between operators, or an operator will deploy multiple technologies in one site. This imposes additional requirements on base station transceivers. The use of the RF spectrum is regulated through international agreements governed by ITU-R. As a result, there are requirements for coordination among operators in different countries, and for coexistence with services in adjacent frequency bands. Coexistence between operators of TDD systems in the same band is provided by inter-operator synchronization in order to avoid interference between downlink and uplink transmissions of different operators. Through the release-independent principle, it is possible to design terminals based on an early release of 3GPP specifications that support a frequency band added in a later release [14].

The requirements for carrier aggregation are defined for carrier aggregation configurations with associated bandwidth combination sets. For inter-band carrier aggregation, a *carrier aggregation configuration* is a combination of operating bands, each supporting a carrier aggregation bandwidth class. For intra-band contiguous carrier aggregation, a carrier aggregation configuration is a single operating band supporting a carrier aggregation bandwidth class. For each carrier aggregation configuration, requirements are specified for all bandwidth combinations contained in a *bandwidth combination set*, which is indicated per supported band combination in the UE radio access capability [8]. A UE can indicate support of several bandwidth combination sets per band combination [1].

13.6.1 Temporal/spectral masks and unwanted emissions

E-UTRA needs to ensure user orthogonality in the time-domain similar to UMTS systems. In UMTS, the requirements for user orthogonality were based on ON/OFF masks, which defined the allowable transmit power during the OFF and ON periods of transmission. In E-UTRA, similar requirements exist for the eNB for FDD and TDD operation modes. However, for the LTE UE, the requirements are considerably more complex than those for UMTS, due to the characteristics of the SC-FDMA scheme used for the uplink transmissions. Figure 13.10 shows the general ON/OFF mask in time which applies whenever the UE is required to switch on or off. Note that although the requirement is given in terms of a mask, it actually applies to the average power during the ON and OFF periods. In UMTS the transient period 20 μs is centered on the slot boundary, whereas in LTE, the transient period is in general shifted into the next subframe. Therefore, the first few SC-FDMA samples are more susceptible to corruption by insufficient transmit power or inter-UE interference, whereas the samples at the end of the subframe are protected. For PRACH, the transient periods are located outside the preamble in order to protect the entire random access preamble. The same principle applies to sounding reference signals to allow reliable uplink channel sounding without impairments arising from transient periods. This is also applicable to discontinuous transmission measurement gaps [1,13].

For TDD, where two sounding reference signals can be transmitted on adjacent symbols in the UpPTS field, the transient periods are located between the two sounding reference signals. The general temporal masks apply in the case of transitions into and out of the OFF power state. A general output power dynamic requirement also exists for continuous transmission at slot boundaries where frequency hopping occurs, and at subframe boundaries for either frequency hopping or power changes. In all these cases, the transient periods are symmetric around

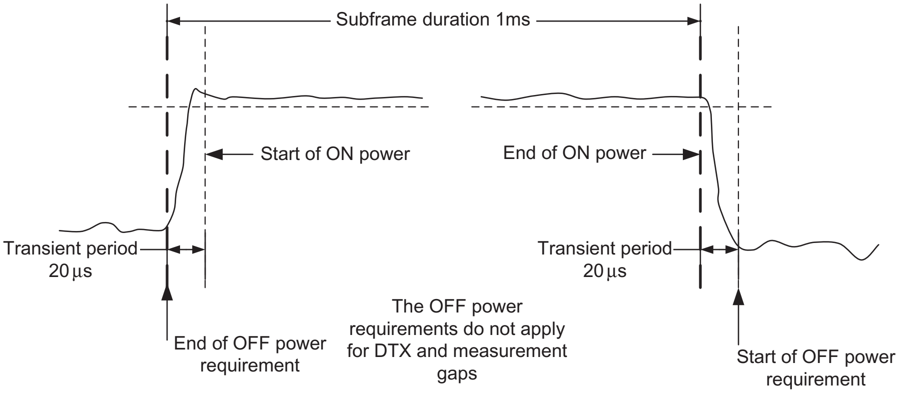

FIGURE 13.10

General ON/OFF temporal mask [1].

the slot or subframe boundaries. The transient power masks are applied in transition from the PUCCH/PUSCH to sounding reference signal with DTX after sounding reference signal, from the PUCCH/PUSCH to sounding reference signal to PUCCH/PUSCH, from DTX to sounding reference signal to PUSCH/PUCCH, or from PUCCH/PUSCH to DTX in a sounding reference signal symbol to PUCCH/PUSCH [1,13].

A radio transmitter is required not to transmit any signal outside its designated transmission band. However, in practice, all radio transmitters do transmit unwanted signals outside their designated transmission bands. The LTE specifications define two separate types of unwanted emissions: OOB emissions and spurious emissions. OOB emissions are unwanted emissions immediately outside the channel bandwidth resulting from the modulation process and non-linearity in the transmitter, but excluding spurious emissions. Spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emission, intermodulation products,[3] and frequency conversion products, but exclude OOB emissions. The OOB emissions requirement for the eNB transmitter is specified both in terms of adjacent channel leakage power ratio (ACLR) and operating band unwanted emissions. The operating band unwanted emissions define all unwanted emissions in the downlink operating band plus the frequency ranges 10 MHz above and 10 MHz below the band. Unwanted emissions outside of this frequency range are limited by a spurious emissions requirement. For an eNB supporting multi-carrier or intra-band contiguous carrier

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[3] Intermodulation or intermodulation distortion (IMD) is the amplitude modulation of signals containing two or more different frequencies in a system with non-linearities. The intermodulation between each frequency component will form additional signals at frequencies that are not just at harmonic frequencies (integer multiples) of either, but also at the sum and difference frequencies of the original frequencies, and at multiples of those sum and difference frequencies.

aggregation, the unwanted emission requirements apply to channel bandwidths of the outermost carrier larger than or equal to 5 MHz. The occupied bandwidth is the width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage $\beta/2$ of the total mean transmitted power. The value of $\beta/2$ is set to 0.5%. This requirement also applies during the transmitter ON period [1].

ACLR is the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency. The requirements apply outside of the edges of the RF bandwidth regardless of the type of transmitter considered, i.e., single carrier or multi-carrier. It applies to all transmission modes provisioned by the manufacturer's specification. In addition, for an eNB operating in non-contiguous spectrum, the ACLR applies to the first adjacent channel inside any sub-block gap with a sub-block gap size $W_{\text{gap}} \geq 15$ MHz. The ACLR requirement for the second adjacent channel applies inside any sub-block gap with a sub-block gap size $W_{\text{gap}} \geq 20$ MHz. This requirement is also applied during the transmitter ON period [1].

Since OOB emissions occur close to the desired signal transmission, increasing the power level of the desired signal will usually increase the level of the unwanted emissions. On the other hand, reducing the transmit power is usually an effective method for reducing the OOB emissions, thus providing one possible solution to network-signaled power-reduction requirements. The OOB emissions are an inevitable by-product of the modulation process, and are often caused by non-linearities in power amplifiers. In fixed-bandwidth radio systems, the OOB emission requirements were defined with respect to the center frequency of the transmission. Since E-UTRA supports variable bandwidth, it is more convenient to define OOB requirements with respect to the edge of the channel bandwidth rather than the center of the channel, as shown in Figure 13.11. In LTE, the OOB emissions are defined by means of spectrum emission masks and ACLR requirements.

The spectrum emission mask is a power attenuation function defined for out-of-channel emissions relative to the in-channel power spectrum. The spectrum emission mask of the UE applies to frequencies within Δf_{OOB} of the edge of the assigned LTE channel bandwidth, as shown in Figure 13.11. For intra-band contiguous carrier aggregation the spectrum emission mask of the UE applies to frequencies Δf_{OOB} starting from the $\pm$edge of the aggregated channel bandwidth (see Figure 13.11). For intra-band contiguous carrier aggregation and bandwidth class C, the power of any UE emissions are required not to exceed the levels specified in Table 13.1 within the specified channel bandwidth [1].

13.6.2 Operating bands for carrier aggregation

E-UTRA was designed to operate in the frequency bands defined in [1,2]. The requirements were defined for 1.4, 3, 5, 10, 15, and 20 MHz bandwidths with a specific configuration in terms of number of physical resource blocks. Using carrier

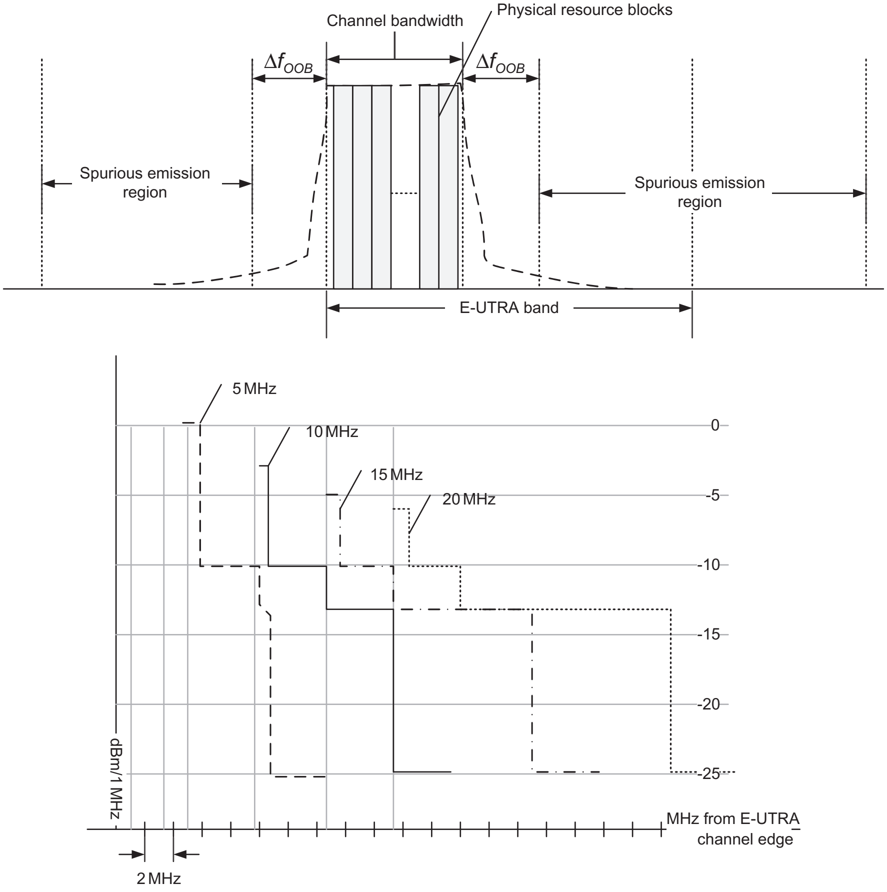


FIGURE 13.11

Transmitter RF spectrum and UE spectrum emission mask [1,13].

aggregation, a number of contiguous and/or non-contiguous frequency bands can be aggregated to create a virtually larger bandwidth. The channel raster is 100 kHz, which means the center frequency must be a multiple of 100 kHz [1]. To support transmission in paired and unpaired spectrums, two duplexing schemes are supported, i.e., FDD, allowing both full and half-duplex terminal operation, as well as TDD.

Figure 13.12 illustrates the relation between the channel bandwidth ($\mathrm{BW}_{\mathrm{Channel}}$) and the transmission bandwidth, i.e., the number of permissible physical resource blocks (N_{RB}). The channel edges are defined as the lowest and highest frequencies of the carrier separated by the channel bandwidth, i.e., $f_C \pm \frac{1}{2}\mathrm{BW}_{\mathrm{Channel}}$. In the case of carrier aggregation, the aggregated channel

Table 13.1 General E-UTRA Carrier Aggregation Spectrum Emission Mask for Bandwidth Class C [1]

	Spectrum Emission Limit (dBm/$BW_{\text{channel-CA}}$)				
Δf_{OOB}(MHz)	**50 RB +100 RB (29.9 MHz)**	**75 RB + 75 RB (30 MHz)**	**75 RB + 100 RB (34.85 MHz)**	**100 RB + 100 RB (39.8 MHz)**	**Measurement Bandwidth (MHz)**
± 0–1	−22.5	−22.5	−23.5	−24	0.030
± 1–5	−10	−10	−10	−10	1
± 5–29.9	−13	−13	−13	−13	1
± 29.9–30	−25	−13	−13	−13	1
± 30–34.85	−25	−25	−13	−13	1
± 34.85–34.9	−25	−25	−25	−13	1
± 34.9–35		−25	−25	−13	1
± 35–39.8			−25	−13	1
± 39.8–39.85			−25	−25	1
± 39.85–44.8				−25	1

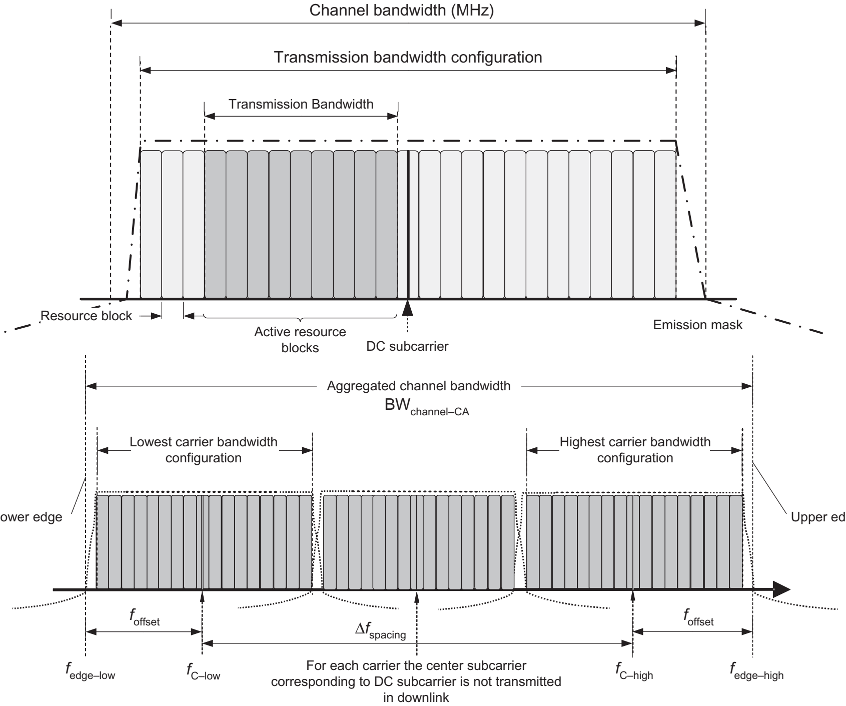


FIGURE 13.12

Relationship between channel bandwidth and transmission bandwidth in E-UTRA [2].

bandwidth $\mathrm{BW}_{\text{Channel-CA}}$ is defined as $\mathrm{BW}_{\text{Channel\_CA}} = f_{\text{edge-high}} - f_{\text{edge-low}}$ (see Figure 13.12). The lower band edge $f_{\text{edge-low}}$ and the upper band edge $f_{\text{edge-high}}$ of the aggregated channel bandwidth are used as the reference points in frequency for transmitter and receiver requirements, and are subsequently defined as follows: $f_{\text{edge-low}} = f_{C\text{-low}} - f_{\text{offset-low}}$ and $f_{\text{edge-high}} = f_{C\text{-high}} + f_{\text{offset-high}}$. The lower and upper frequency offsets depend on the transmission bandwidth configurations of the lowest and highest assigned edge component carriers, and are defined as $f_{\text{offset-low}} = 0.18N_{\text{RB-low}}/2 + BW_{\text{Guard-band}}$ and $f_{\text{offset-high}} = 0.18N_{\text{RB-high}}/2 + BW_{\text{Guard-band}}$ where $N_{\text{RB-low}}$ and $N_{\text{RB-high}}$ denote the transmission bandwidth configurations for the lowest and highest assigned component carrier, respectively, and $BW_{\text{Guard-band}}$ denotes the nominal guard band size. Note that the 0.18 multiplier in the equations is the bandwidth of a physical resource block in MHz. The aggregated transmission bandwidth is defined as the number of the aggregated resource blocks within the entire assigned aggregated channel bandwidth, and is defined per carrier aggregation band class.

As shown in Figure 13.12, the spacing between carriers depends on the deployment scenario and the size of the frequency block available to the network operator, as well as the channel bandwidth. The nominal channel spacing between two adjacent E-UTRA carriers is defined as $\Delta f_{\text{spacing}} = (BW_{\text{Channel(1)}} + BW_{\text{Channel(2)}})/2$ where $BW_{\text{Channel(1)}}$ and $BW_{\text{Channel(2)}}$ parameters are the channel bandwidths of the two respective E-UTRA carriers. The channel spacing can be adjusted to optimize performance in a particular deployment scenario. For intra-band contiguous carrier aggregation bandwidth, the nominal channel spacing between two adjacent E-UTRA component carriers is specified as follows [1,2]:

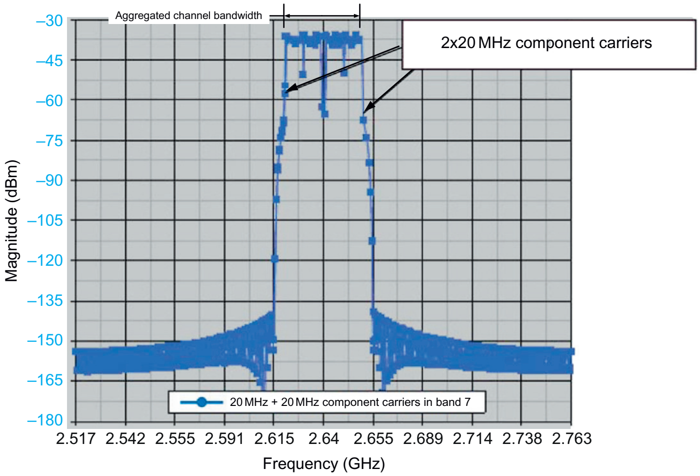
$$\Delta f_{\text{spacing-CA}}\,(\text{MHz}) = 0.3\left\lfloor \frac{BW_{\text{Channel(1)}} + BW_{\text{Channel(2)}} - 0.1\left|BW_{\text{Channel(1)}} - BW_{\text{Channel(2)}}\right|}{0.6} \right\rfloor$$

The channel spacing for intra-band contiguous carrier aggregation can be adjusted to any integer multiple of 300 kHz (less than the nominal channel spacing) to optimize performance in a particular deployment scenario. The E-UTRA channel raster (including the carrier aggregation scenarios) is 100 kHz for all bands, which means that the carrier center frequency must be an integer multiple of 100 kHz.

The carrier frequency in the downlink/uplink directions is designated by the E-UTRA absolute radio frequency channel number (EARFCN) in the range of 0–65,535. The relation between EARFCN and the downlink carrier frequency (in MHz) is given by $f_{\text{DL}} = f_{\text{DL-low}} + 0.1(N_{\text{DL}} - N_{\text{Offset-DL}})$, where $f_{\text{DL-low}}$, N_{DL}, and $N_{\text{Offset-DL}}$ parameters are given in [1,2]. Similarly, the relationship between EARFCN and the uplink carrier frequency (in MHz) for the uplink is defined as $f_{\text{UL}} = f_{\text{UL-low}} + 0.1(N_{\text{UL}} - N_{\text{Offset-UL}})$, where $f_{\text{UL-low}}, N_{\text{UL}}$, and $N_{\text{Offset-UL}}$ parameters are provided in [1,2]. Note that N_{DL} and N_{UL} in the latter equations are the downlink and uplink EARFCN, respectively. Figure 13.13 shows a snapshot of four adjacent 20 MHz component carriers chosen from the 3.5 GHz band that are aggregated with the adjacent center frequency spacing set to 20.1 MHz (a multiple of 300 kHz). This figure also shows the spectrum of two 20 MHz component carriers chosen from Band 7 in 2600 MHz that are aggregated with the center frequency spacing set to 20.1 MHz [18].

The channel numbers that designate carrier frequencies which are extremely close to the operating band edges are not used. This implies that the first 7, 15, 25, 50, 75, and 100 channel numbers at the lower operating band edge, and the last 6, 14, 24, 49, 74, and 99 channel numbers at the upper operating band edge are not utilized for channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz, respectively.

A sub-block is defined as one contiguous allocated block of spectrum for transmission and reception by the same eNB. There may be multiple instances of sub-blocks within an RF bandwidth. Sub-block bandwidth is defined as the bandwidth of one sub-block. The frequency gap between two consecutive sub-blocks within an RF bandwidth is referred to as sub-block gap, where the RF requirements in the gap are based on coexistence for uncoordinated operation. The lower sub-block edge of the sub-block bandwidth $BW_{\text{Channel-block}}$ is defined as $f_{\text{edge\_block\_low}} = f_{C\text{\_block\_low}} - f_{\text{offset}}$. The upper sub-block edge of the sub-block



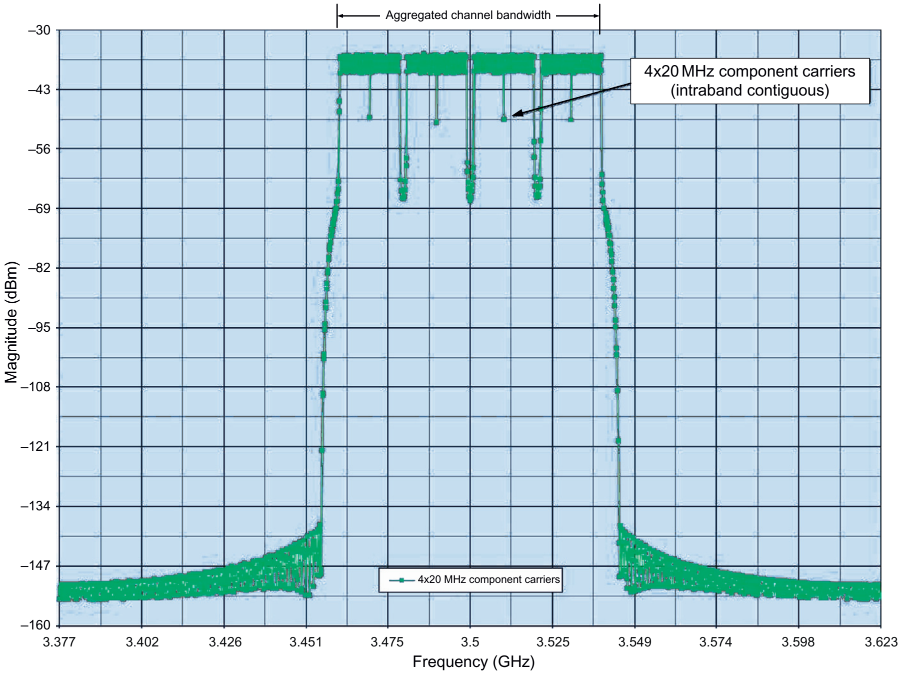


FIGURE 13.13

Snapshot of spectrum of two and four aggregated adjacent component carriers [17,18].

bandwidth is defined as $f_{\text{edge\_block\_high}} = f_{C\_\text{block\_high}} + f_{\text{offset}}$. The sub-block bandwidth $BW_{\text{Channel-block}}$ is alternatively defined as $BW_{\text{Channel\_block}} = f_{\text{edge\_block\_high}} - f_{\text{edge\_block\_low}}$ in MHz [2].

LTE Rel-10 specified the radio frequency aspects of inter-band carrier aggregation only for FDD, assuming aggregation of bands 1 and 5. However, network operators are interested in various band combinations, as shown in Table 13.2, depending on their available spectrum resources. Radio frequency properties of each band combination must be specified to comply with the regulations. In addition, inter-band carrier aggregation for TDD needs to be supported in future releases with the possibility of having different TDD uplink−downlink subframe configurations on different bands to coexist with the already deployed TDD systems in that band.

A carrier aggregation bandwidth class is defined by the aggregated transmission bandwidth configuration and the maximum number of component carriers supported by a UE. Table 13.3 shows supported bandwidth classes for LTE Rel-11 UE as defined in [1]. Figure 13.14 illustrates the standard notation used by the UE to indicate its support of carrier aggregation for a particular frequency band or band combination to the network. The example shows that in order to indicate support for intra-band, non-contiguous carrier aggregation in band 5 based on bandwidth class A, the notation would be CA_5A_5A. It informs the network that this device is able to receive (or transmit) two separate carriers in frequency band 5, each with a maximum bandwidth of 100 resource blocks, i.e., 20 MHz. Another example is CA_1C which indicates that the UE can operate with two contiguous component carriers with a maximum of 200 resource blocks which can be in the form of 15 + 15 or 20 + 20 MHz. Note that there might be different bandwidth combinations for each E-UTRA carrier aggregation configuration [1]. Table 13.4 summarizes some important parameters associated with UE categories as of LTE Rel-11.

13.6.3 Transmitter characteristics for carrier aggregation

The transmitter characteristics not only define RF requirements for the desired signal transmitted from the UE and the eNB, but also for the unavoidable unwanted emissions outside the transmission bandwidth. These requirements are fundamentally categorized as follows: (1) output power-level requirements set the limits for the maximum permissible transmitted power corresponding to dynamic variation of the power level during transmission; (2) transmitted signal quality requirements define the cleanliness of the transmitted signal and also the relationship between multiple transmitter branches; and (3) unwanted emissions requirements set the limits for all emissions outside of the transmitted carrier(s) operating band which are tightly coupled to regulatory requirements and coexistence with other systems. The following is a list of major UE and eNB transmitter attributes [14]:

- eNB: Output power level (maximum output power, output power dynamics, and on/off power for TDD), transmitted signal quality (frequency error, error vector magnitude (EVM), and time alignment between transmitter branches),

Table 13.2 Carrier Aggregation Bands and Band Aggregation as of LTE Rel-11 [1]

Band Combination	**Carrier Aggregation Scenario**	**Uplink Frequency Range (MHz)** $f_{\text{UL-low}} - f_{\text{UL-high}}$	**Downlink Frequency Range (MHz)** $f_{\text{DL-low}} - f_{\text{DL-high}}$	**Duplex Mode**
1	Intra-band contiguous	1920–1980	2110–2170	FDD
7		2500–2570	2620–2690	FDD
40		2300–2400	2300–2400	TDD
41		2496–2690	2496–2690	TDD
1 and 5	Inter-band	1920–1980 824–849	2110–2170 869–894	FDD
1 and 18		1920–1980 815–830	2110–2170 860–875	FDD
1 and 19		1920–1980 830–845	2110–2170 875–890	FDD
1 and 21		1920–1980 1447.9–1462.9	2110–2170 1495.9–1510.9	FDD
2 and 17		1850–1910 704–716	1930–1990 734–746	FDD
2 and 29		1850–1910 N/A (downlink only SCell)	1930–1990 717–728	FDD
3 and 5		1710–1785 824–849	1805–1880 869–894	FDD
3 and 7		1710–1785 2500–2570	1805–1880 2620–2690	FDD
3 and 8		1710–1785 880–915	1805–1880 925–960	FDD
3 and 20		1710–1785 832–862	1805–1880 791–821	FDD
4 and 5		1710–1755 824–849	2110–2155 869–894	FDD
4 and 7		1710–1755 2500–2570	2110–2155 2620–2690	FDD
4 and 12		1710–1755 699–716	2110–2155 729–746	FDD
4 and 13		1710–1755 777–787	2110–2155 746–756	FDD
4 and 17		1710–1755 704–716	2110–2155 734–746	FDD
4 and 29		1710–1755	2110–2155 717–728	FDD

(*Continued*)

Table 13.2 (Continued)

Band Combination	Carrier Aggregation Scenario	Uplink Frequency Range (MHz) $f_{\text{UL-low}} - f_{\text{UL-high}}$	Downlink Frequency Range (MHz) $f_{\text{DL-low}} - f_{\text{DL-high}}$	Duplex Mode
		N/A (downlink only SCell)		
5 and 12		824–849	869–894	FDD
		699–716	729–746	
5 and 17		824–849	869–894	FDD
		704–716	734–746	
7 and 20		2500–2570	2620–2690	FDD
		832–862	791–821	
8 and 20		880–915	925–960	FDD
		832–862	791–821	
11 and 18		1427.9–1447.9	1475.9–1495.9	FDD
		815–830	860–875	

unwanted emissions (operating band unwanted emissions, ACLR, spurious emissions, occupied bandwidth, and transmitter intermodulation).

- UE: Output power level (transmit power, output power dynamics, and power control), transmitted signal quality (frequency error and transmit modulation quality), unwanted emissions (spectrum emission mask, ACLR, spurious emissions, occupied bandwidth, and transmit intermodulation).

The ACLR is directly related to the operating point of the power amplifier. In general, leakage into adjacent channels increases abruptly as the power amplifier is driven into its non-linear operating region at the highest output power levels due to the intermodulation products. As a result, it is important that the peak output power of the UE does not drive the power amplifier too far into its non-linear region. On the other hand, most power amplifiers are designed to operate efficiently only in a small region at the top of the linear operating region. This corresponds to the rated output power of the power amplifier below which the efficiency drops abruptly. Since high efficiency is crucial to ensuring a long battery life for the UE, it is also desirable to maintain the power amplifier operating as close as possible to the top of the linear operating region. If the ACLR and spectrum mask requirements cannot be met, typically the UE output power must be reduced to bring the leakage to acceptable levels. This can be achieved without excessive loss of efficiency by reducing the peak output power of the power amplifier, a process known as derating. The amount of derating required is highly dependent on the peak to average power ratio (PAPR) and bandwidth of the transmitted signal. In general, for any given channel bandwidth and power amplifier, transmissions with a larger occupied bandwidth create more OOB emissions,

Table 13.3 Carrier Aggregation Bandwidth Classes and Corresponding Nominal Guard Bands [1]

Carrier Aggregation Bandwidth Class	Aggregated Transmission Bandwidth Configuration	Maximum Number of Component Carriers	Nominal Guard Band $BW_{\text{Guard Band}}$
A	$N_{\text{RB-Aggregated}} \leq 100$	1	$0.05BW_{\text{Channel-1}}$
B	$N_{\text{RB-Aggregated}} \leq 100$	2	–
C	$100 < N_{\text{RB-Aggregated}} \leq 200$	2	$0.05\max(BW_{\text{Channel-1}}, BW_{\text{Channel-2}})$
D	$200 < N_{\text{RB-Aggregated}} \leq 300$	–	–
E	$300 < N_{\text{RB-Aggregated}} \leq 400$	–	–
F	$400 < N_{\text{RB-Aggregated}} \leq 500$	–	–

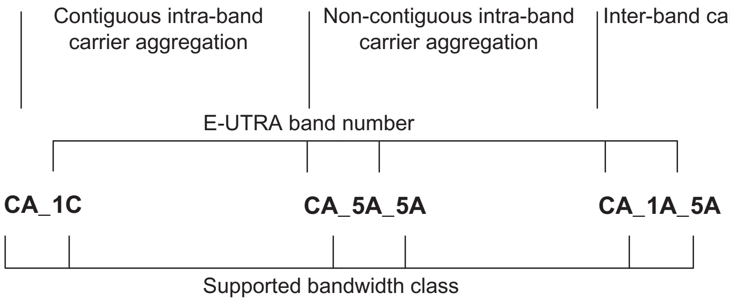


FIGURE 13.14

Standard notation for carrier aggregation support (type, frequency band, and bandwidth) [1,16].

resulting in larger adjacent channel leakage than transmissions with lower occupied bandwidth. The increase in OOB emissions from the larger occupied bandwidth of the LTE signal is mainly due to increased adjacent channel occupancy by third and fifth order intermodulation products (see Figure 13.15). For an LTE uplink transmitted signal, certain combinations of resource block allocations and modulation schemes create more OOB emissions than others [13].

For low-bandwidth applications such as VoIP, which typically use QPSK modulation, no power derating is required from the normal-rated maximum UE output power, ensuring broad coverage for such applications, since full output power of the power amplifier can be used to counter the path loss effect at the cell-edge. Moreover, the structure of the LTE uplink signal, with control information being usually positioned at the channel edge and high-bandwidth data transmissions toward the middle of the band, helps to improve OOB emissions and reduce ACLR. Taking the above considerations into account, the total power

Table 13.4 UE Categories as of LTE Rel-11 [8]

UE Category	Peak Data Rate Downlink/ Uplink (Mbps)	Maximum Number of DL-SCH Transport Block Bits Received within a TTI	Maximum Number of Bits of a DL-SCH Transport Block Received within a TTI	Total Number of Soft Channel Bits in the Downlink	Maximum Number of Supported Layers for Spatial Multiplexing in the Downlink	Maximum Number of UL-SCH Transport Block Bits Transmitted within a TTI	Maximum Number of Bits of a UL-SCH Transport Block Transmitted within a TTI	Support for 64QAM in Uplink	Total Layer 2 Buffer Size (Bytes)	Maximum Number of Bits of an MCH Transport Block Received within a TTI
Category 1	10/5	10,296	10,296	250,368	1	5160	5160	No	150,000	10,296
Category 2	50/25	51,024	51,024	1,237,248	2	25,456	25,456	No	700,000	51,024
Category 3	100/50	102,048	75,376	1,237,248	2	51,024	51,024	No	1,400,000	75,376
Category 4	150/50	150,752	75,376	1,827,072	2	51,024	51,024	No	1,900,000	75,376
Category 5	300/75	299,552	149,776	3,667,200	4	75,376	75,376	Yes	3,500,000	75,376
Category 6	300/50	301,504	149,776 (4 layers) 75,376 (2 layers)	3,654,144	2 or 4	51,024	51,024	No	3,300,000	(75,376)
Category 7	300/150	301,504	149,776 (4 layers) 75,376 (2 layers)	3,654,144	2 or 4	102,048	51,024	No	3,800,000	(75,376)
Category 8	1200/600	2,998,560	299,856	35,982,720	8	1,497,760	149,776	Yes	4,220,0000	(75,376)

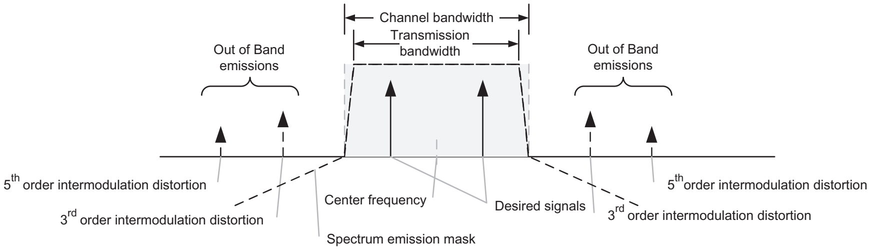


FIGURE 13.15

Illustration of the IMD components [20].

derating required to meet a target ACLR value can be decomposed into a term corresponding to the occupied bandwidth as a proportion of the channel bandwidth, and a term corresponding to the waveform of the transmitted signal. Small resource assignments at the edges of the band behave as tones and hence may produce highly concentrated IMD products [14]. Therefore, for simultaneous PUSCH and PUCCH transmission, the spectral emission mask is expected to be the limiting requirement, as it is for LTE Rel-8 with full resource allocation (see Figure 13.6).

As mentioned earlier, the ACLR metric defines the ratio of the power transmitted in the assigned channel bandwidth to the power of the unwanted emissions transmitted in an adjacent channel. There is a corresponding receiver requirement known as adjacent channel selectivity (ACS), which defines a receiver's ability to suppress a signal in an adjacent channel. Therefore, from the receiver's point of view, the unwanted emissions as a result of transmissions in the adjacent bands in the desired signal's receiver bandwidth are represented by ACLR, and the ability of the receiver to suppress the interfering signal in the adjacent channel is defined by ACS. The two parameters when combined define the total leakage between two transmissions on adjacent channels. That ratio is called the adjacent channel interference ratio (ACIR), and is defined as the ratio of the power transmitted on one channel to the total interference received by a receiver on the adjacent channel due to both transmitter RF filter imperfection (ACLR) and receiver RF filter imperfection (ACS) [14].

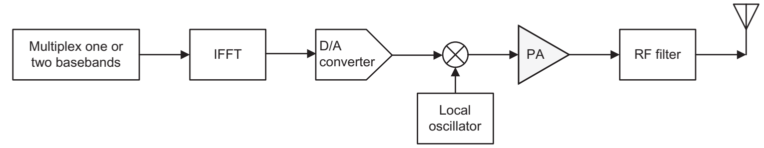
In LTE, the EVM is required to be less than 17.5% for QPSK, 12.5% for 16QAM and 8% for 64QAM (applicable to the downlink only). The EVM values are designed to correspond to no more than 5% loss in average and cell-edge throughputs in typical deployment scenarios. At the link level, EVM is equivalent to signal to noise ratio loss [13]. The occupied bandwidth is defined as the bandwidth containing 99% of the total integrated mean power of the transmitted spectrum on the assigned channel. The occupied bandwidth for all transmission bandwidth configurations (resource blocks) must be less than the channel bandwidth. For intra-band contiguous carrier aggregation the occupied bandwidth is a measure of the bandwidth containing 99% of the total integrated power of the transmitted spectrum. The occupied bandwidth must be less than the aggregated channel bandwidth [1].

The output power dynamics are impacted by the UE transmitter architecture, which may be based on single or multiple power amplifiers. Figure 13.16 illustrates various options for UE transmitter architecture which can be used to support different carrier aggregation scenarios. As shown in Figure 13.16 for alternative 1, if two component carriers are contiguous, then a single IFFT module can be used to generate both OFDM signals. A single RF mixer can be used to convert the baseband signal frequency to RF frequency followed by a single power amplifier to amplify the power of the transmitted signal. If two component carriers are non-contiguous but within the same frequency band, then alternatives 2 or 3 shown in Figure 13.16 may be used as a general transmitter architecture. However, for non-contiguous component carriers in different frequency bands, separate IFFT modules, mixers, and power amplifiers would be required to process the OFDM signals, unless a multi-band power amplifier is utilized.

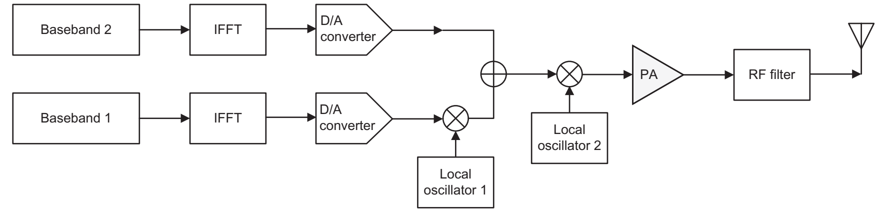
13.6.4 Receiver characteristics for carrier aggregation

Although the requirements for LTE receivers are similar to those defined for UMTS, they are defined differently due to the flexible bandwidth properties of LTE. The receiver RF requirements are primarily divided into three categories: (1) sensitivity and dynamic range requirements for receiving the desired signal; (2) receiver susceptibility to interfering signals defining receiver's vulnerability to different types of interfering signals at different frequency offsets; and (3) unwanted emission limits. The following is a list of attributes for the UE and eNB receivers [14]:

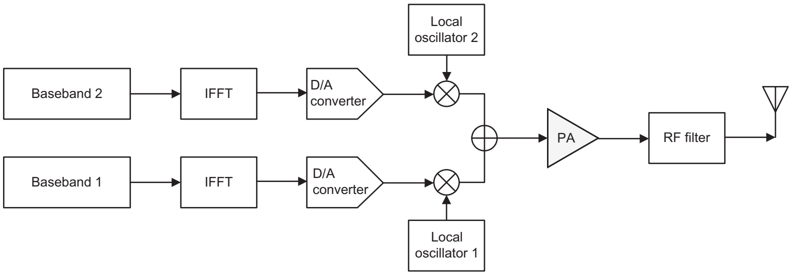
- eNB: Sensitivity and dynamic range (reference sensitivity, dynamic range, and in-channel selectivity), receiver susceptibility to interfering signals (OOB blocking, in-band blocking, narrowband blocking, ACS, and receiver intermodulation), and unwanted emissions from the receiver (receiver spurious emissions). The spurious emissions power is the power of emissions generated or amplified in a receiver that appear at the eNB receiver antenna connector. The requirements apply to all eNBs with separate receive and transmit antenna ports. The test for the FDD eNB must be performed when transmitter and receiver are on, with the transmit port properly terminated. For the TDD eNB with a common receive and transmit antenna port, the requirement applies during the transmitter OFF period. The blocking characteristic is a measure of the receiver's ability to receive a desired signal at its assigned channel in the presence of an unwanted interferer. Narrowband blocking is similar to ACS, but with interfering signals consisting of only one resource block.
- UE: Sensitivity and dynamic range (reference sensitivity power level and maximum input level), receiver susceptibility to interfering signals (OOB blocking,



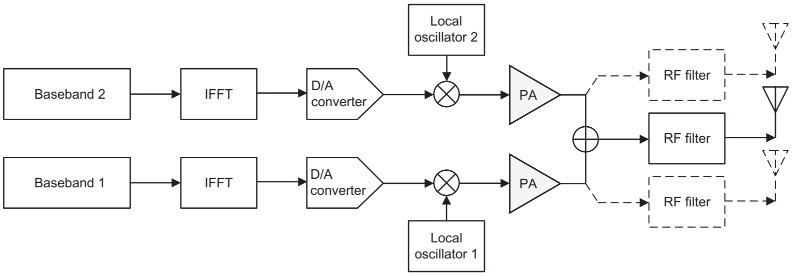
Alternative 1: Single (Baseband + IFFT + D/A converter + mixer + PA)



Alternative 2: Multiple (Baseband + IFFT + D/A converter) + Single (Stage-1 IF Mixer + IF Combiner + Stage-2 RF Mixer + PA)



Alternative 3: Multiple (Baseband + IFFT + D/A converter + Mixer) + Low-power RF Combiner + Single PA



Alternative 4: Multiple (Baseband + IFFT + D/A converter + Mixer + PA) + High-power RF Combiner + Single or Multiple Antennas

FIGURE 13.16

Example transmitter implementation for intra-band/inter-band carrier aggregation [11].

spurious response, in-band blocking, narrowband blocking, ACS, and intermodulation characteristics), and unwanted emissions from the receiver (receiver spurious emissions). Third and higher order mixing of the two interfering RF signals can produce an interfering signal in the band of the desired channel. Intermodulation response rejection is a measure of the capability of the receiver to receive a wanted signal on its assigned channel frequency in the presence of two interfering signals (a continuous wave and E-UTRA signals).

The LTE RF receiver requirements were partly derived from UMTS. This was meant to ensure that the implementation of an LTE RF receiver is not going to be more complex than that of UMTS in order to reduce redesigning efforts. The main differences between the LTE and UMTS RF receiver requirements arise from the variable channel bandwidth and the different multiple access schemes. The receiver RF requirements are based on a number of specific assumptions for testing purposes including integrated antennas with 0 dBi gain; two antenna ports; test signals of equal power level applied to each antenna port; and use of a maximal ratio combining to combine the signals. It is assumed that the signals are received from independent AWGN channels, thus signal addition would provide 3 dB diversity gain.

LTE supports different MCSs; however, the RF receiver specifications are defined for only two MCSs, referred to as reference channels, which are at the extremes of the available range, in order to reduce the number of conformance tests which have to be performed. The low-SNR reference channel uses QPSK with a code rate of 1/3, while the high SNR reference channel uses 64QAM with a code rate of 3/4. For each of the reference channels, the SINR requirements, at which 95% throughput is achieved, are specified.

When the LTE receiver is tested in full-duplex FDD mode, the transmitter must also be operating so that signal leakage from the transmitter to the receiver due to insufficient isolation of the duplexer is taken into consideration. This condition does not apply to half-duplex FDD or TDD operation. In practice, the transmitted signal leakage interferes with the receiver not only because of the power of the fundamental components, but also because of the OOB phase noise of the transmitted signal when it falls into the receiver band. In LTE, the spurious emissions from the UE transmitter in its own receive band are required to be −47 dBm or less, measured in a 1 MHz bandwidth. This corresponds to −107 dBm/Hz. The maximum transmit power for an LTE mobile device is +23 dBm for power class 3, thus the spurious emissions requirement is −130 dBc/Hz. The LTE receiver sensitivity is measured with the transmitter operating at the full power for its class. In order to allow the transmitter to degrade the receiver sensitivity by no more than 0.5 dB, the transmitter noise needs to be 9 dB below the noise floor at the antenna connector. If we assume that the spurious emissions of the transmitter in the corresponding receiver band are just at the limit of the specifications, it can be shown that the duplexer isolation needs to be at least 78 dB for the LTE FDD mode. However, making duplexers smaller and cheaper is often achieved at the expense of compromised isolation, and typical duplexers might provide just 45−55 dB isolation [14]. Therefore, the transmit signal could substantially desensitize the receiver. This is not acceptable, thus the LTE transmitter has to achieve spurious emissions about 20 dB lower than the transmitter requirements within the receiver band. The transmit power at the input to the low-noise amplifier is equal to the transmit power at the antenna plus the duplexer attenuation from transmit port to antenna (about 2 dB) minus the duplexer transmit-to-receiver isolation (~50 dB). Therefore, at the maximum LTE UE output power of +23 dBm, the mean transmitter power leakage to the low-noise amplifier is −25 dBm [13].

This value is calculated based on the average transmit power, but the transmitted signal contains amplitude modulation, and therefore the peak signal will be higher. The transmitter leakage problem presents a particularly challenging requirement, if applied to RF bands with a small frequency separation. In FDD systems, when performing a selectivity or blocking test with a single interfering signal in one of the adjacent channels, the receiver is also exposed to its own transmitted signal as a second interferer, which, in the worst case scenario, can cause intermodulation, in which the interferers are mixed together to generate in-band IMD products.

The maximum input level is the maximum mean received signal strength, measured at each antenna port, at which there is sufficient SINR for a specified modulation scheme to meet a minimum throughput requirement. In LTE, the maximum input level is only specified for the high SINR reference channel, assuming that the high SINR reference channel is about 4 dB higher due to the PAPR of the signal. The downlink requirement is for a maximum average input level of −25 dBm at any channel bandwidth with full resource block allocation. In FDD systems, the requirement must be met when the transmitter is set at 4 dB below the maximum output power. If PAPR is measured on a bitwise basis and plotted as a complementary cumulative probability distribution, then for the LTE downlink it reaches a value of around 11 dB for QPSK and 11.5 dB for 64QAM, over a window of 106 bits. In OFDM, the PAPR is dominated by the multi-carrier nature of the signal, and therefore does not vary much with modulation [13].

The primary purpose of the reference sensitivity requirement is to verify the receiver noise figure, which is a measure of how much the receiver's RF signal chain degrades the SNR of the received signal. For this reason, a low-SNR transmission scheme using QPSK is chosen as a reference channel for the reference sensitivity test. The reference sensitivity is defined at a receiver input level where the throughput is 95% of the maximum throughput for the reference channel. For the base station, reference sensitivity could potentially be defined for a single resource block up to a group covering all resource blocks. Considering the complexity, a maximum granularity of 25 resource blocks has been chosen, which means that for channel bandwidths larger than 5 MHz, sensitivity is verified over multiple adjacent 5 MHz blocks, while it is only defined over the full channel for smaller channel bandwidths. For the UE, reference sensitivity is defined for the full channel bandwidth signals and with all resource blocks allocated to the desired signal. For channel bandwidths greater than 5 MHz in some operating bands, the nominal reference sensitivity needs to be met with a minimum number of allocated resource blocks [14]. In other words, the reference sensitivity level is the minimum mean received signal strength applied to both antenna ports (assuming two receive antennas) at which there is sufficient SINR for the specified modulation scheme to meet a minimum throughput requirement of 95% of the maximum possible value. It is measured with the transmitter at full power. The reference sensitivity is a range of values that can be calculated as $P_{\text{Reference\_Sensitivity}} = 10\log(kT_0B) + NF + SINR + L_{\text{Implementation\_Margin}} - 3$ (dBm), where kT_0B is the thermal noise power in dBm, B is the noise equivalent bandwidth (~system bandwidth), NF is the maximum receiver noise figure, $SINR$ is the minimum SINR for the chosen MCS, $L_{\text{Implementation\_Margin}}$ is the implementation margin, and −3 represents the receive diversity gain [13]. Note that the noise floor for any receiver is defined as $Noise\_Floor = 10\log(kT_0B) + NF = -174 + NF + 10\log B$ (dBm), where $NF = SNR_{\text{in}} - SNR_{\text{out}}$ (in dB) is a measure of SINR degradation by the components in the RF signal path, including the RF filters and low-noise amplifier. The thermal noise power density $kT_0 = -174$ dBm/Hz is measured at typical room temperature of $290°K$. The LTE specifications require $NF \leq 9$ dB for the UE and $NF \leq 5$ dB for the eNB, nevertheless, commercial RF components and UE receivers can achieve lower than these limits [13].

The UE receiver dynamic range requirement is meant to ensure that the receiver can operate at received signal levels considerably higher than the reference sensitivity. The base station dynamic range testing assumes the presence of increased interference and corresponding higher signal levels, thereby testing the effects of different receiver impairments. In order to drive the receiver to the worst condition, a higher SNR transmission scheme using 16QAM is applied for the test. In order to further drive the receiver to processing higher signal levels, an interfering AWGN signal at 20 dB above the assumed noise floor is added to the received signal. The dynamic range requirement for the UE is specified as a maximum signal level at which the throughput requirement is met.

Blocking corresponds to the scenario when strong interfering signals received outside the operating band (OOB blocking) or inside the operating band (in-band blocking), but not adjacent to the desired signal. In-band blocking includes interferers in the first 20 MHz outside the band for the base station and the first 15 MHz for the UE. The scenarios are modeled with a continuous wave signal for the OOB case and an E-UTRA signal for the in-band case. There are additional base station's blocking requirements for the scenario when the base station is collocated with another base station in a different operating band. For the UE, a fixed number of exceptions are allowed from the OOB blocking requirement, for each assigned frequency channel and at the respective spurious response frequencies. At those frequencies, the UE must comply with the more relaxed spurious response requirement. Note that these effects and satisfaction of the requirements become more challenging when carrier aggregation is supported.

ACS is the case when there is a strong signal in the channel adjacent to the desired signal, and is closely related to the corresponding ACLR requirement. For the UE, the ACS is specified for two cases with a lower and a higher signal level. In-channel selectivity is the case when there are multiple received signals of different received power levels inside the channel bandwidth, where the performance of the weaker desired signal is verified in the presence of the stronger interfering signal. In-channel selectivity is only specified for the base station. Narrowband blocking is an adjacent strong narrowband interferer, which in the requirement is modeled as a single resource block LTE signal for the base station and a continuous wave signal for the UE. Receiver intermodulation occurs when there are two interfering signals in the spectral proximity of the desired signal, where the interferers are one continuous wave and one LTE signal. The interferers are placed in frequency in such a way that the main intermodulation product falls within the desired signal's channel bandwidth. There is also a narrowband intermodulation requirement for the base station where the continuous wave signal is very close to the wanted signal, and the LTE interferer is a single resource block signal. For all requirements except in-channel selectivity, the wanted signal uses the same reference channel as in the corresponding reference sensitivity requirement. When the interference is added, the same 95% relative throughput is met as for the reference channel, but at a desensitized higher desired signal level [14].

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