

# Overview of 3GPP LTE-Advanced Carrier Aggregation for 4G Wireless Communications

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## ABSTRACT

To satisfy the ever increasing demand for higher throughput and data rates, wireless communication systems need to operate in wider bandwidths. 3GPP LTE-Advanced with carrier aggregation enables operators to maximally and optimally utilize their available spectrum resources for increased data rates and user experience while reducing their incurred OPEX and CAPEX. This article provides a tutorial overview of 3GPP LTE-Advanced with carrier aggregation as specified in Rel-10 including deployment scenarios of interest, main design features, PHY/MAC procedures, and potential enhancements for future standard releases.

## INTRODUCTION

In recent years the telecommunication industry witnessed a boom in packet-based data application services. Providing high quality of service for mobile applications in a cost-effective manner becomes increasingly important for operators to meet consumer needs. Toward this end, the International Telecommunication Union (ITU) initiated a global standard initiative, IMT-Advanced, for international mobile telecommunications in October 2007 [1]. IMT-Advanced systems include exciting new capabilities for providing a wide range of telecommunication services and applications, stressing improved quality of service and worldwide development. To support enhanced user and service demands, peak data rate targets of 100 Mb/s for high mobility and 1 Gb/s for low mobility are established for IMT-Advanced. In addition, IMT-Advanced strives for key features such as functional commonality, intersystem operability, global roaming, and user-friendly application.

In response to ITU's invitation of candidate proposals for IMT-Advanced, the Third Generation Partnership Project (3GPP) started Long Term Evolution (LTE)-Advanced in 2008 [2] which was ratified as an IMT-Advanced technology in November 2010. LTE-Advanced builds on the 3GPP Release 8/9 specification, known as LTE. LTE provides high spectral efficiency by a combination of advanced multi-antenna techniques, and orthogonal frequency-division multiple access (OFDMA) in the downlink (DL) and single-carrier frequency-division multiple access (SC-FDMA) in the uplink (UL) [3]. LTE supports scalable bandwidths of up to 20 MHz providing peak data rates of 300 Mb/s in the downlink (highest capability terminals) and 75 Mb/s in the uplink. LTE is also designed for reduced service latency, optimized packet transmission, simplified implementation complexity for cost reduction, and so on.

To satisfy the peak data rates required by IMT-Advanced, LTE-Advanced shall support wider bandwidths than LTE (e.g., up to 100 MHz). One approach is to simply extend the transmission bandwidth and use a single carrier. In practice, such a large portion of continuous spectrum is rarely available. Carrier aggregation [4–6], where multiple component carriers of smaller bandwidth are aggregated, is an attractive alternative to increase data rate. Additional advantages are offered by carrier aggregation in terms of spectrum efficiency, deployment flexibility, backward compatibility, and more. By aggregating non-contiguous carriers, fragmented spectrum can be more efficiently utilized. Various deployment scenarios for homogeneous and heterogeneous networks are supported by carrier aggregation with proper utilization of different carriers. With each component carrier being

LTE compatible, carrier aggregation allows operators to migrate from LTE to LTE-Advanced while continuing service to LTE users. Both implementation and specification efforts are minimized by reusing the LTE design on each of the component carriers.

## OVERVIEW OF LTE-ADVANCED CARRIER AGGREGATION

### DEPLOYMENT SCENARIOS

Generally, carrier aggregation systems are deployed to improve data rates for users within overlapped areas of cells. The following deployment scenarios [7] are considered during the design of LTE-Advanced carrier aggregation, exemplified with two component carriers at frequencies of F1 and F2 as shown in Fig. 1.

**Deployment scenario 1:** Cells with carrier frequencies F1 and F2 are collocated and overlaid with F1 and F2 in the same band. Nearly the same coverage is provided on both carriers due to the similar path loss within a same band. Mobility is supported on either carrier. Higher data rates are achievable throughout the cell by carrier aggregation.

**Deployment scenario 2:** Cells with carrier frequencies F1 and F2 are collocated and overlaid with F1 and F2 in different bands. Different coverage is provided on different carriers due to the larger path loss in the higher frequency band. Mobility is supported on the carrier in the lower frequency band providing sufficient coverage. The carrier in the higher frequency band is used to improve data rates and throughput.

**Deployment scenario 3:** Cells of carrier frequencies F1 and F2 are co-located with F1 and F2 in different bands. The antennas for cells of F2 are directed to the cell boundaries of F1 to improve the cell edge data rates and 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. Carrier aggregation is supported in areas with overlapping coverage.

**Deployment scenario 4:** Cells of carrier frequency F1 provide macro coverage, and remote radio heads (RRHs) of carrier frequency F2 are used to improve throughput at hot spots. Mobility is performed based on the cell coverage of frequency F1. In this deployment scenario the carrier frequencies F1 and F2 are usually of different bands. Carrier aggregation is applicable for users within the coverage of RRHs and the underlying macrocells.

**Deployment scenario 5:** Similar to deployment scenario 2, frequency selective repeaters are additionally deployed to extend the coverage for one of the carrier frequencies.

### DESIGN PRINCIPLES

To meet the various deployment needs, 3GPP LTE-Advanced aims to support intraband contiguous, intraband non-contiguous, and interband carrier aggregation. In addition, the design of 3GPP LTE-Advanced carrier aggregation further considers backward compatibility, specification impact, implementation complexity, and so on with the following design principles.

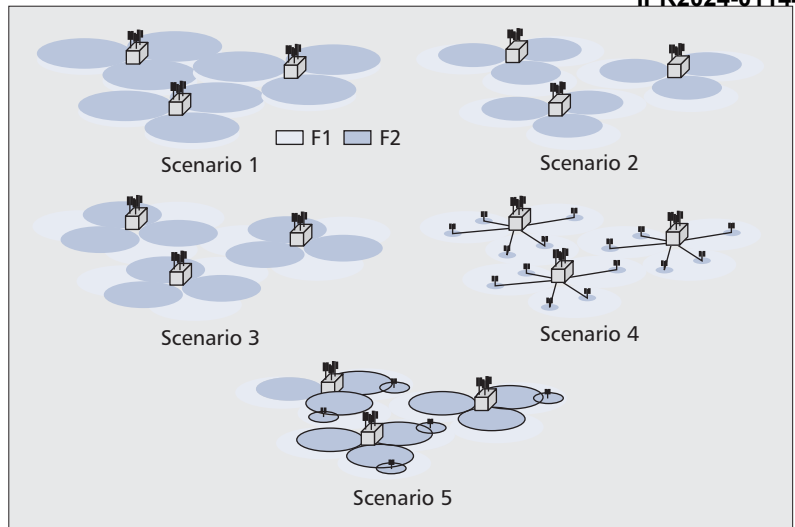


Figure 1. Carrier aggregation deployment scenarios ( $F2 > F1$ ) [7].

**Backward Compatibility** — Backward compatibility is essential for smooth system migration and maximal reuse of the LTE Release 8/9 design. Each component carrier in 3GPP LTE-Advanced is LTE Release 8/9 backward compatible, that is accessible by LTE Release 8/9 user equipment (UE). The complete set of LTE Release 8/9 downlink physical channels and signals are transmitted on each component carrier by the LTE Release 8/9 procedure, including system information, synchronization signals, reference signals, and control channels.

**Minimal Protocol Impact** — From the user plane protocol perspective, the component carriers are invisible to the Packet Data Convergence Protocol (PDCP) and radio link control (RLC) layers. The multiple component carriers are mere data transmission pipes managed by a single scheduling entity at the medium access control (MAC) layer. Each component carrier has its own hybrid automatic repeat request (HARQ) entity controlling a number of LTE Release 8/9 compatible HARQ processes for the physical (PHY) layer. Figure 2 [7] shows the layer 2 structure with carrier aggregation. The PHY and MAC design for 3GPP LTE-Advanced supports up to five component carriers and is agnostic to whether carrier aggregation is intraband contiguous, intraband non-contiguous, or interband.

**Limited Control Procedure Change** — Radio resource control (RRC) assigns the radio related information from the network to the UE. At a given point in time UE is in either RRC\_IDLE or RRC\_CONNECTED state. Only RRC\_CONNECTED UE can transmit/receive data to/from the network. There is no notion of carrier aggregation in RRC\_IDLE state. RRC\_IDLE UE shall transit to RRC\_CONNECTED state by establishing an RRC connection following the LTE Release 8/9 procedure before being able to operate on multiple component carriers. Hence, LTE-Advanced carrier aggregation does not impact the procedures of RRC\_IDLE UE; nor does it impact the procedure to establish an RRC connection.

*To facilitate mobility management as well as cell management in conjunction with carrier aggregation, UE shall perform various types of measurements as instructed by the network including intrafrequency measurement, interfrequency measurement, and inter-RAT measurements.*

## HIGHER LAYER ASPECTS

The services provided by higher layers are fulfilled by user plane and control plane functions. The user plane is responsible for data communication, and the control plane is responsible for maintaining the connection between the network and the UE. LTE-Advanced carrier aggregation inherits the LTE Release 8/9 user plane and control plane design to maintain backward compatibility. To efficiently utilize the multiple component carriers for data transmission, additional procedures, including cell management and cell activation/deactivation, are designed in LTE-Advanced carrier aggregation.

In LTE-Advanced carrier aggregation, a component carrier is often referred to as a serving cell and is treated as such by the higher layer procedures. For frequency-division duplex (FDD), a serving cell comprises a pair of different carrier frequencies for downlink and uplink transmissions. For time-division duplex (TDD), a serving cell is defined for a single carrier frequency where downlink and uplink transmissions occur in different transmission time intervals which are referred to as subframes. Each UE unit has a single serving cell that provides all necessary control information and functions, such as non-access stratum (NAS) mobility information, security input, RRC connection maintenance, etc. This serving cell is referred to as the primary cell (PCell). Other serving cells are referred to as secondary cells (SCells). Table 1 summarizes the key differences between the PCell and an SCell in LTE-Advanced carrier aggregation.

### CELL MANAGEMENT

Cell management is the control procedure enabling the network to add/remove/change an SCell or to switch the PCell of UE. An RRC\_IDLE UE unit establishes an RRC connection toward a serving cell, which automatically becomes its PCell. Depending on the carrier where initial access is performed, different UE units in a carrier aggregation system may have different PCells. With the RRC connection on the PCell, the network can further configure one or more SCells for UE within the UE capability of carrier aggregation to meet traffic demands. The necessary information, including system information, of an SCell is conveyed to the UE via dedicated RRC signaling. Addition, removal, and reconfiguration of SCells to a UE unit are also performed via dedicated RRC signaling. The network can further change the PCell of a UE, for example, to improve the link quality of the PCell on which critical control information is sent or to provide load balancing among different SCells. PCell change in LTE-Advanced carrier aggregation can only be performed via the handover procedure. PCell change does not necessarily require UE to switch to single-carrier operation. Intra-LTE handover in LTE-Advanced allows the target PCell to configure one or more SCells for UE to use immediately after handover.

### MOBILITY MANAGEMENT

Mobility management plays an important role in mobile communication systems. To facilitate mobility management as well as cell manage-

ment in conjunction with carrier aggregation, UE shall perform various types of measurements as instructed by the network including intrafrequency measurement, interfrequency measurement, and inter-radio access technology (RAT) measurements. Intra- and interfrequency measurements are for LTE carriers while inter-RAT measurements are for carrier(s) with a RAT other than LTE. The network also configures the criterion under which UE shall send the measurement report and its reporting format. The following criteria for measurement reporting are defined by LTE-Advanced Release 10 [8]:

- Measurement event A1: Serving cell becomes better than threshold
- Measurement event A2: Serving cell becomes worse than threshold
- Measurement event A3: Neighbor cell becomes offset better than PCell
- Measurement event A4: Neighbor cell becomes better than threshold
- Measurement event A5: PCell becomes worse than threshold1 and neighbor cell becomes better than threshold2
- Measurement event A6: Neighbor cell becomes offset better than SCell
- Measurement event B1: Inter-RAT neighbor cell becomes better than threshold
- Measurement event B2: PCell becomes worse than threshold1 and inter-RAT neighbor cell becomes better than threshold2

Measurement event A6 is introduced for LTE-Advanced carrier aggregation to compare the channel quality of a neighboring cell relative to a reference SCell, thereby allowing fast reconfiguration of SCells. The other measurement events are also supported in LTE Release 8/9.

### CELL ACTIVATION/DEACTIVATION

Cell activation/deactivation is a mechanism aiming to reduce UE power consumption in LTE-Advanced carrier aggregation on top of discontinuous reception (DRX), which is already supported in LTE Release 8/9. DRX puts UE into power saving mode when the UE is not expected to receive data from the network. According to network configuration and ongoing HARQ processes, UE determines the DRX ON/OFF duration common to all serving cells. To further reduce UE battery consumption, an SCell in LTE-Advanced carrier aggregation can be activated or deactivated [9]. For a deactivated SCell, UE does not receive any downlink signal; nor does the UE transmit any uplink signal. Conversely, for an activated SCell, UE performs normal activities for downlink reception and uplink transmission. The SCell activation/deactivation is enabled by a combination of explicit and implicit means where the network can issue an activation/deactivation command in the form of a MAC control element (CE), or the UE autonomously deactivates a serving cell upon timer expiry. Serving cell activation/deactivation is performed independently for each SCell, allowing UE to be activated only on a necessary set of SCells. Activation/deactivation is not applicable for the PCell since the functions provided by the PCell require it to always remain

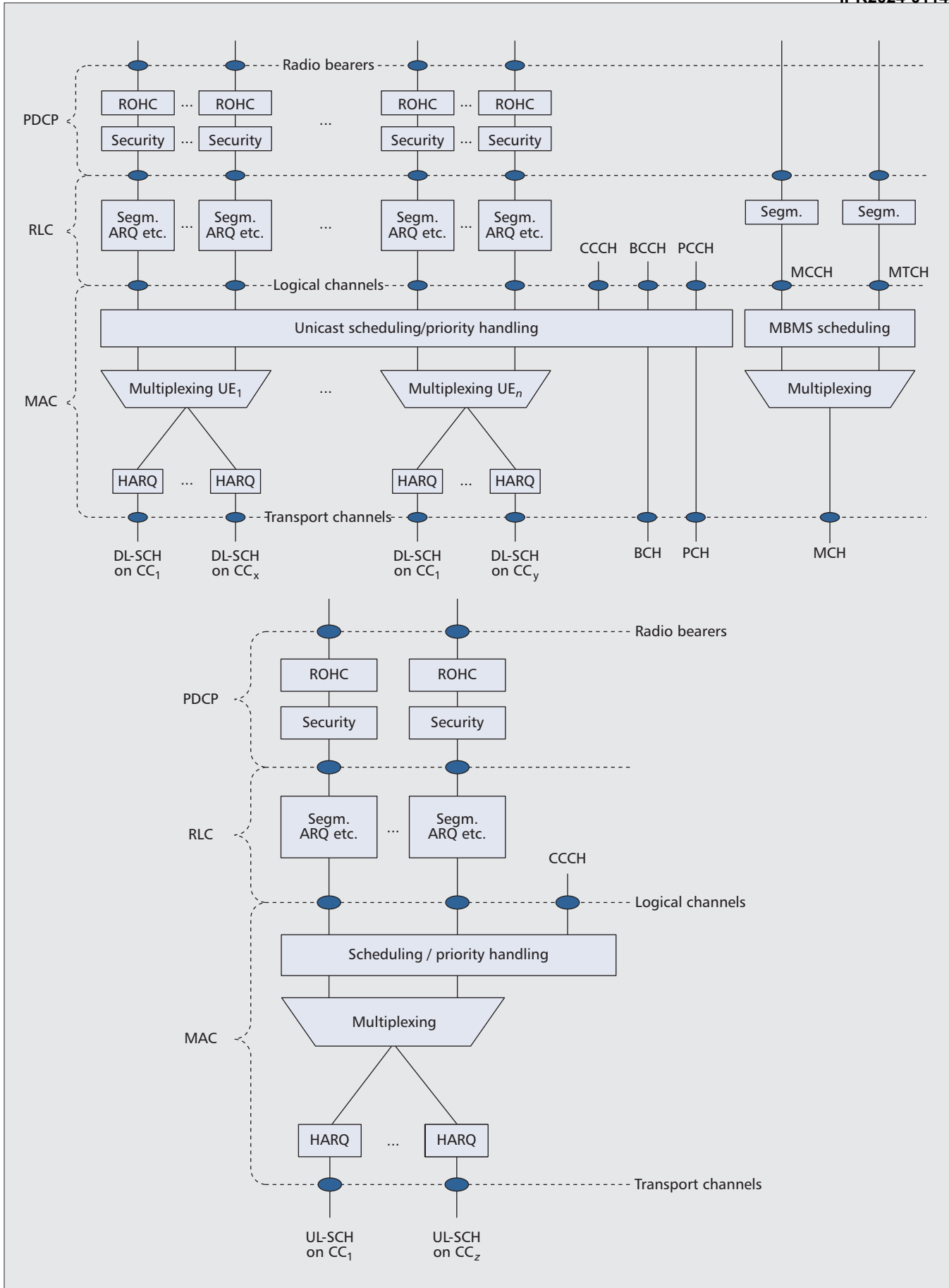


Figure 2. Layer 2 structure for DL and UL transmission with CA configured [7].

Cross-carrier scheduling is primarily motivated to support heterogeneous networks comprising a mixture of high- and low-power network nodes where significant intercell interference may arise if such networks are deployed on the same carrier.

|                                | PCell | SCell |
|--------------------------------|-------|-------|
| PUCCH configuration            | Yes   | No    |
| Radio link monitoring          | Yes   | No    |
| System information acquisition | Yes   | No    |
| NAS mobility information       | Yes   | No    |
| Security input                 | Yes   | No    |
| Random access procedure        | Yes   | No    |
| Semi-persistent scheduling     | Yes   | No    |
| Deactivated state              | No    | Yes   |
| Data transmission              | Yes   | Yes   |
| Sounding reference signal      | Yes   | Yes   |

**Table 1.** Difference between PCell and SCell.

activated when the UE has an RRC connection to the network.

## PHYSICAL LAYER ASPECTS

The physical layer is responsible for the data and control information exchange between the network and the UE. By parallelizing the data transmission on multiple component carriers, LTE-Advanced carrier aggregation largely inherits the LTE Release 8/9 data transmission procedure per component carrier [3, 10, 11], including the multiple access scheme, modulation, and channel coding. Some additional UE functionalities beyond LTE Release 8/9 are supported in Release 10, including data transmissions over two clusters of contiguous bandwidth in the same carrier where the data is precoded by a single discrete Fourier transform (DFT) matrix, simultaneous transmission of a control channel and a data channel in the PCell, and data transmissions from multiple antennas with spatial multiplexing. Nevertheless, improving the downlink and uplink control design to efficiently support data transmission is the core physical layer design of 3GPP LTE-Advanced carrier aggregation.

### DOWNLINK CONTROL DESIGN

**Physical Downlink Control Channel** — The PDCCH provides information on resource allocation, modulation and coding scheme (MCS), HARQ, and other related parameters for downlink and uplink data transmission on a physical downlink shared channel (PDSCH) and a physical uplink shared channel (PUSCH), respectively. It is possible to configure each component carrier to transmit PDCCH scheduling a PDSCH on the same carrier frequency and PDCCH

scheduling a PUSCH on a linked UL carrier frequency where the linkage of the DL and UL carriers is conveyed as system information.

In addition, PDCCH on a component carrier can be configured to schedule PDSCH and PUSCH transmissions on other component carriers by means of cross-carrier scheduling. Cross-carrier scheduling is primarily motivated to support heterogeneous networks comprising a mixture of high- and low-power network nodes where significant intercell interference may arise if such networks are deployed on the same carrier. As PDCCH is transmitted across the whole bandwidth of the respective carrier, interference coordination methods based on fractional frequency reuse are not applicable to reduce the intercell interference on PDCCH. Carrier aggregation can address this issue for heterogeneous networks by configuring UE connected to different network nodes to receive PDCCH on different carriers, thereby reducing or even eliminating intercell interference on PDCCH. With cross-carrier scheduling, only one component carrier needs to be protected for transmission of PDCCH, which can schedule data resources on any component carrier and enable UE in heterogeneous networks to experience enhanced data rates. As illustrated in Fig. 3, component carrier at frequency F1 is used by macrocells at full power and picocells at their nominal power, whereas the component carrier at frequency F2 is used by macrocells at reduced power and picocells at their nominal power. In this case, cross-carrier scheduling from F2 is available. Cross-carrier scheduling is also an effective mechanism to schedule data transmissions in carriers of small bandwidth from a carrier of large bandwidth, where the PDCCH reliability targets are more challenging to achieve in carriers of small bandwidth due to the limited frequency diversity.

**PDCCH Search Space** — The PDCCH search space consists of a set of PDCCH candidates over which UE performs blind decoding operations to determine whether there is any PDCCH transmitted to it in a subframe. A common PDCCH search space is monitored by all UE units only in their respective PCells for receiving system, paging, power control, and random access related control information. Each UE unit also monitors a UE-specific PDCCH search space primarily carrying scheduling grants for downlink and uplink data transmissions. The UE-specific PDCCH search space is a function of the UE's radio network temporary identifier (RNTI). Since the same set of resources for PDCCH transmission is shared by all UE, a PDCCH to a UE unit may not be transmitted due to at least partial overlapping with a PDCCH to another UE unit, creating PDCCH blocking. To maintain a PDCCH blocking probability at a similar level as in LTE Release 8/9, LTE-Advanced UE monitors one UE-specific PDCCH search space for each activated component carrier. For a UE unit not configured with cross-carrier scheduling, the UE-specific PDCCH search space on each component carrier is the same as in LTE Release 8/9. For a UE unit configured with cross-carrier scheduling, the

UE-specific PDCCH search space is defined by a combination of the UE's RNTI and the serving cell index [11]. The number of PDCCH blind decoding operations required by a UE unit scales roughly linearly with the number of its activated component carriers.

#### Physical Control Format Indicator Channel

— 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 the subframe. UE derives the starting OFDM symbol used for PDSCH transmission based on the decoded CFI value. For PDSCH scheduled by PDCCH on the same component carrier, UE is required to decode the PCFICH in order to determine the starting OFDM symbol used for PDSCH. For PDSCH cross-carrier scheduled by PDCCH on another carrier, the starting OFDM symbol for PDSCH transmission is configured by the network through higher layers, and the UE is not required to decode the PCFICH on the component carrier of the PDSCH transmission.

**Physical HARQ Indicator Channel** — The PHICH carries the HARQ feedback information associated with a PUSCH transmission. The PHICH channelization in LTE-Advanced carrier aggregation follows the design of LTE Release 8/9 [3]. The PHICH for a corresponding PUSCH is always transmitted on the component carrier where the PDCCH schedules the PUSCH transmission.

#### UPLINK CONTROL DESIGN

**Uplink Control Information** — UCI includes HARQ feedback corresponding to potentially multiple PDSCHs, channel state information (CSI), and scheduling request (SR). As in LTE Release 8/9, UCI can be transmitted on a physical uplink control channel (PUCCH) if there is no transmission on a PUSCH in a subframe, and transmitted on PUSCH otherwise. LTE-Advanced further supports, by network configuration, simultaneous PUCCH and PUSCH transmissions in a subframe. This allows the network to flexibly control the performance of PUCCH and PUSCH independently and avoids the UCI overhead on PUSCH by utilizing existing PUCCH resources. PUCCH can only be transmitted on the PCell since it typically has a better long term link quality than the SCells. When applicable, UCI is always transmitted on a single PUSCH.

**HARQ Feedback** — HARQ feedback indicates whether a transport block (TB) is correctly received. LTE Release 8/9 supports transmitting a maximum of 2 and 4 HARQ feedback bits in a UL subframe for FDD and TDD, respectively. With 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 for FDD and 90 bits for TDD, assuming 5 component carriers with MIMO transmission modes conveying up to 2 Tbytes per component carrier and TDD UL-DL configuration 5 with 9 DL subframes and 1 UL subframe per radio frame. Reliable

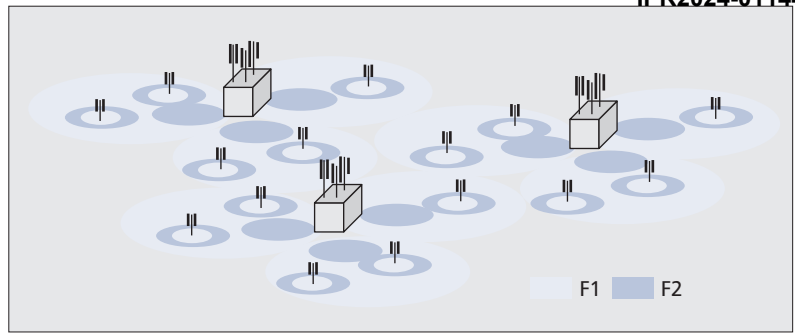


Figure 3. Illustration of carrier-aggregation-based heterogeneous network operation.

transmission of 90 HARQ feedback bits in a UL subframe requires substantial resources and an impractical signal-to-interference-plus-noise ratio (SINR). Hence, HARQ feedback compression schemes are designed for TDD to limit the maximum number of HARQ feedback bits in a UL subframe to 20. The multiple HARQ feedback bits are compressed by a logical AND operation to produce 1 HARQ feedback bit per component carrier and per subframe for certain TDD UL-DL configurations.

PUCCH format 3 [3] is introduced in LTE-Advanced to support HARQ feedback for UE configured with downlink carrier aggregation. PUCCH format 3 adopts an SC-FDMA waveform with five SC-FDMA symbols per slot carrying HARQ feedback information and one or two SC-FDMA symbols per slot for transmission of reference signals (RS), to enable coherent demodulation of the HARQ feedback information signal, as illustrated in Fig. 4. An orthogonal cover code (OCC) of length 5 is applied to the encoded HARQ feedback information in the respective SC-FDMA symbols, allowing multiplexing of up to 5 UE units in one resource block consisting of 12 subcarriers. With quadrature phase shift keying (QPSK), a payload of  $O$  HARQ feedback bits is encoded using the  $(32, O)$  Reed-Mueller code with circular rate matching into 48 encoded HARQ bits [10], which are transmitted in a subframe comprising two slots. The RS is based on a constant amplitude zero auto-correlation (CAZAC) sequence. Orthogonal RS multiplexing for different UE units is achieved through the use of different cyclic shifts for the assigned CAZAC sequence.

To further increase the uplink coverage, LTE-Advanced supports an additional HARQ compression scheme for TDD where 2 HARQ feedback bits are generated per component carrier representing the number of continuous correctly received PDSCHs on the component carrier [11]. PUCCH format 1b with channel selection is the corresponding transmission scheme as defined in LTE Release 8/9 [3, 11]. According to the HARQ feedback information, one of the multiple PUCCH format 1b resources is selected for transmission of a mapped QPSK symbol. To limit decoding complexity involving several PUCCH format 1b resources and reduce PUCCH overhead, at most 4 HARQ feedback bits can be conveyed by PUCCH format 1b with channel selection. Therefore, PUCCH format 1b

The uplink power control supported in LTE [11] consists of an open-loop component adjusting for the path loss between UE and its serving network node, and of a closed-loop component based on transmission power control (TPC) commands in PDCCH.

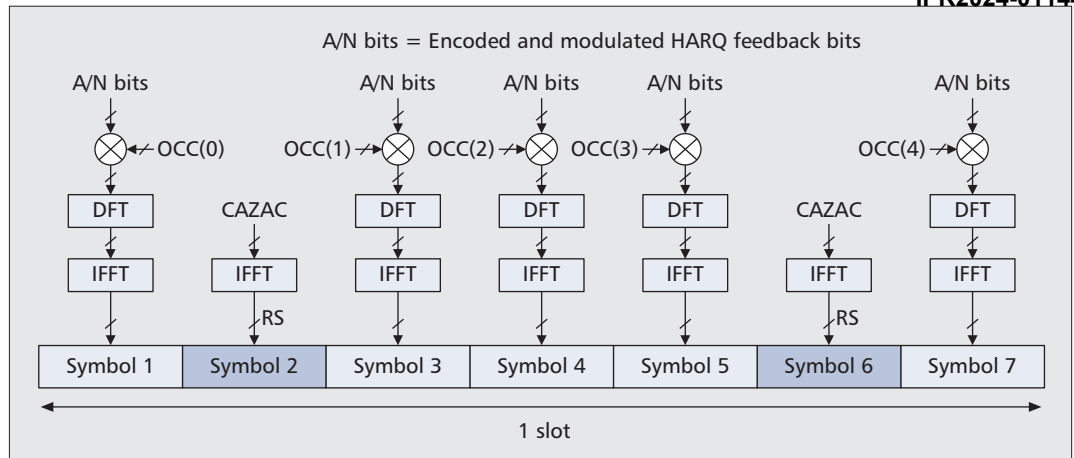


Figure 4. PUCCH Format 3 transmission structure.

with channel selection is not applicable for UE configured with more than two component carriers for both FDD and TDD.

**CSI Feedback** — CSI feedback facilitates the network to perform PDSCH scheduling, including resource selection, MCS selection, transmission rank adaptation, and precoding matrix determination. To accommodate the different channel conditions and interference levels among different component carriers, CSI is fed back for each component carrier. Both periodic CSI and aperiodic CSI feedback are supported in LTE-Advanced, where periodic CSI is transmitted on a set of semi-statically configured subframes, and aperiodic CSI is dynamically triggered by the network via PDCCH. Periodic CSI feedback is independently configured for each component carrier and transmitted on PUCCH using PUCCH format 2 [3]. The payload size of PUCCH format 2 is limited (e.g., up to about 11 information bits can be reliably transmitted before the coding rate becomes notably larger than 0.5). Hence, 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 shall be fed back in the event that periodic CSI feedback of multiple carriers collide in a subframe. In case 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 than periodic CSI feedback. LTE-Advanced supports aperiodic CSI feedback for a single or multiple component carrier(s) in a subframe in order for the network to balance the CSI accuracy and feedback overhead.

#### UPLINK POWER CONTROL

Uplink power control is the mechanism with which UE determines a PUSCH transmission power or a PUCCH transmission power with the objective to ensure that the respective reception reliability targets are achieved. The uplink power control supported in LTE [11] consists of an open-loop component adjusting for the path loss between a UE unit and its serving network node,

and of a closed-loop component based on transmission power control (TPC) commands in PDCCH.

The uplink power control processes are independent among the respective activated cells, and each process is the same as in LTE Release 8/9. The resulting transmission power, for either the PUSCH or the PUCCH, will be referred to as nominal transmission power. The key differentiation with respect to the LTE Release 8/9 uplink power control operation occurs when the sum of the nominal transmission powers from UE exceeds the total maximum output power for which the UE is configured at the respective 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, UE may transmit in a subframe one PUCCH, one PUSCH with UCI, one or more PUSCHs without UCI, or any combination thereof. 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.

The network may not know the exact UE transmission power, due to, say, TPC commands missed by the UE, UE-specific implementation of maximum power reduction (MPR), and additional MPR (A-MPR) to meet regulatory requirements. To provide the network with more accurate information on UE transmission power, power headroom reporting (PHR) is supported in LTE. The UE may report a type 1 and a type 2 PHR for an activated cell. The type 1 and type 2 PHR indicate the amount of remaining UE transmission power beyond those used for PUSCH, or used for PUSCH and PUCCH transmission in a subframe, respectively.

## FUTURE ENHANCEMENTS

LTE-Advanced in Release 10 developed the radio frequency aspects of interband carrier aggregation only for FDD, assuming aggregation of bands 1 and 5. Operators are interested in various band combinations, as shown in Table 2, depending on their available spectrum resources. Radio frequency properties of each band combination shall be specified to comply with the regulations. In addition, interband carrier aggregation for TDD needs to be supported in future releases with the possibility of having different TDD UL-DL configurations on different bands to coexist with the already deployed TDD systems in the respective band.

While being backward compatible offers simplified design and development for carrier aggregation systems in LTE-Advanced, it also incurs irreducible overhead on each component carrier for transmission of broadcast information, common reference signals, synchronization signals, and downlink control signals. The percentage of such overhead is relatively high for a component carrier with small transmission bandwidth. Non-backward-compatible carriers on which the above mentioned signals are not transmitted can further improve the spectrum efficiency, especially for scenarios aggregating fragmented and small pieces of transmission bandwidths and for energy-efficient network implementations. Non-backward-compatible carriers shall only be used in association with a backward-compatible carrier where the necessary control signals are transmitted.

Enhancements on the physical control channel design are also envisioned for LTE-Advanced carrier aggregation in later releases. Examples include supporting compressed HARQ feedback for more than two component carriers to improve the uplink coverage, periodic CSI feedback of multiple component carriers in a sub-frame to reduce feedback latency and avoid excessive drops of CSI feedback due to collisions, joint transmission of CSI and HARQ feedback for UE configured with downlink carrier aggregation, extension of downlink control channels in the PDSCH region to increase capacity and allow for interference coordination in the frequency domain, and so on.

The network controls the UE uplink transmission timing so that signals from UE in a cell arrive at the network node roughly at the same time to reduce intersymbol interference. LTE-Advanced carrier aggregation in Release 10 only allows the same UE uplink transmission timing on all component carriers, addressing deployment scenarios with similar propagation delays on multiple component carriers. For deployment scenarios involving different propagation delays (e.g., the deployment scenario 5 in Fig. 1 with frequency selective repeaters), possible mechanisms to allow different UE uplink transmission timings on different component carriers shall be studied.

## CONCLUSIONS

This tutorial article provides an overview of LTE-Advanced carrier aggregation. Apart from the benefit of data rate increase, carrier aggregation enables efficient spectrum resource utilization in various deployment scenarios.

| CA band or band combination | Operator    | 3GPP E-UTRA bands                                                                                            | Duplex mode |
|-----------------------------|-------------|--------------------------------------------------------------------------------------------------------------|-------------|
| Band 4 + band 17            | AT&T        | Band 4: 1710 – 1785 MHz (UL)<br>2110 – 2155 MHz (DL)<br>Band 17: 704 – 716 MHz (UL)<br>734 – 746 MHz (DL)    | FDD         |
| Band 2 + band 17            | AT&T        | Band 2: 1850 – 1910 MHz (UL)<br>1930 – 1990 MHz (DL)<br>Band 17: 704 – 716 MHz (UL)<br>734 – 746 MHz (DL)    | FDD         |
| Band 4 + band 5             | AT&T        | Band 4: 1710 – 1785 MHz (UL)<br>2110 – 2155 MHz (DL)<br>Band 5: 824 – 849 MHz (UL)<br>869 – 894 MHz (DL)     | FDD         |
| Band 5 + band 17            | AT&T        | Band 5: 824 – 849 MHz (UL)<br>869 – 894 MHz (DL)<br>Band 17: 704 – 716 MHz (UL)<br>734 – 746 MHz (DL)        | FDD         |
| Band 41                     | Clearwire   | Band 41: 2496 – 2690 MHz                                                                                     | TDD         |
| Band 38                     | CMCC        | Band 38: 2570 – 2620 MHz                                                                                     | TDD         |
| Band 20 + band 7            | Orange      | Band 20: 832 – 862 MHz (UL)<br>791 – 821 MHz (DL)<br>Band 7: 2500 – 2570 MHz (UL)<br>2620 – 2690 MHz (DL)    | FDD         |
| Band 3 + band 7             | TeliaSonera | Band 3: 1710 – 1785 MHz (UL)<br>1805 – 1880 MHz (DL)<br>Band 7: 2500 – 2570 MHz (UL)<br>2620 – 2690 MHz (DL) | FDD         |
| Band 4 + band 12            | US Cellular | Band 4: 1710 – 1785 MHz (UL)<br>2110 – 2155 MHz (DL)<br>Band 12: 699 – 716 MHz (UL)<br>729 – 746 MHz (DL)    | FDD         |
| Band 5 + band 12            | US Cellular | Band 5: 824 – 849 MHz (UL)<br>869 – 894 MHz (DL)<br>Band 12: 699 – 716 MHz (UL)<br>729 – 746 MHz (DL)        | FDD         |
| Band 4 + band 13            | Verizon     | Band 4: 1710 – 1785 MHz (UL)<br>2110 – 2155 MHz (DL)<br>Band 13: 777 – 787 MHz (UL)<br>746 – 756 MHz (DL)    | FDD         |

**Table 2.** CA band or band combination.

LTE-Advanced carrier aggregation inherits the key designs of LTE Release 8/9 per component carrier, thereby maintaining the advantages of LTE Release 8/9, and reducing the specification and implementation efforts for faster product availability and system deployment. As spectrum resources become scarcer, carrier aggregation will continue to be an important technique in future communication systems and evolve with appropriate enhancements.

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