# LTE-Advanced: Carrier Aggregation

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Toward IMT-Advanced

Cellular Evolution
Driven by ever-increasing demands for higher data rates, lower latency, and higher capacity, cellular radio access technology has advanced dramatically over the past decade or so. Since packet data connectivity was introduced in cellular's second generation, some of the more important advancements introduced include: adaptive modulation and coding (AMC), turbo coding, hybrid automatic repeat request (HARQ), multiple input/multiple output (MIMO) antenna systems, orthogonal frequency division multiple access (OFDMA), and ever-widening channel bandwidths.

The use of OFDMA in the 3GPP Long Term Evolution (LTE) technical specifications effectively institutionalized the concept of spectral scalability. Release 8 LTE permits channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz with no fundamental change in radio architecture. Wider channel bandwidths are particularly appealing because, in addition to permitting improved spectral efficiency (capacity), they are crucial in terms of increasing peak traffic channel data rates.

IMT-Advanced
The requirements incumbent upon third-generation (3G) cellular systems were laid out in the IMT-2000 specification published by the International Telecommunication Union (ITU). As 3G neared ubiquity, the ITU produced another set of requirements for the next generation of cellular. These requirements are known as IMT-Advanced. In the same way that IMT-2000 is synonymous with 3G, IMT-Advanced can be thought of as the definition of 4G.

IMT-Advanced defines, among other things, several performance levels to which compliant systems must rise. Selected IMT-Advanced performance targets are as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak downlink traffic channel data rate</td>
<td>1 gigabit/second</td>
</tr>
<tr>
<td>Peak uplink traffic channel data rate</td>
<td>500 megabits/second</td>
</tr>
<tr>
<td>Downlink peak spectral efficiency</td>
<td>15 bits/second/Hz</td>
</tr>
<tr>
<td>Uplink peak spectral efficiency</td>
<td>6.75 bits/second/Hz</td>
</tr>
</tbody>
</table>

IMT-Advanced also stipulates support for at least three different channel bandwidths, and a maximum channel bandwidth of at least 40 MHz.

In fact, Release 8 LTE already delivers on some of these requirements. LTE supports peak traffic channel data rates of up to 300 Mbps in the downlink and up to 75 Mbps in the uplink in a 20 MHz channel bandwidth. This is equivalent to 15 bits/second/Hz and 3.75 bits/second/Hz, respectively. Both the uplink efficiency and the peak traffic channel data rates in both directions fall well short of the IMT-Advanced requirements.

Given that the state-of-the-art in radio interface technology is already highly-leveraged to achieve these levels of performance, 3GPP determined that the most viable path to reach the IMT-Advanced requirements was to increase the channel bandwidth beyond 20 MHz. But increasing channel bandwidths to beyond 20 MHz is challenging in the context of cellular radio spectrum realities.
Cellular Radio Spectrum Realities

From its origins with the original “cellular” band at 850 MHz in North America, the radio spectrum available for use in cellular has been expanded greatly in the past 20 years. The Personal Communication Services (PCS) band at 1900 MHz was made available in the mid-1990s, followed by the Advanced Wireless Services (AWS) band at 2100/1700 MHz in the mid-2000s, and the “digital dividend” band at 700 MHz not long after. Though some North American carriers possess spectrum assets in the low-800 MHz or the 2.5 GHz bands, cellular radio spectrum essentially can be summarized as follows:

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectrum Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular (850 MHz)</td>
<td>2 blocks of 2x12.5 MHz (A, B)</td>
</tr>
<tr>
<td>PCS (1900 MHz)</td>
<td>3 blocks of 2x15 MHz (A, B, C)</td>
</tr>
<tr>
<td></td>
<td>3 blocks of 2x5 MHz (D, E, F)</td>
</tr>
<tr>
<td>AWS (1700/2100 MHz)</td>
<td>3 blocks of 2x10 MHz (A, B, F)</td>
</tr>
<tr>
<td></td>
<td>3 blocks of 2x5 MHz (C, D, E)</td>
</tr>
<tr>
<td>Digital Dividend (700 MHz)</td>
<td>2 blocks of 2x6 MHz (A, B)</td>
</tr>
<tr>
<td></td>
<td>1 block of 2x5 MHz (D)</td>
</tr>
<tr>
<td></td>
<td>1 block of 2x11 MHz (C)</td>
</tr>
<tr>
<td></td>
<td>1 block of 1x6 MHz (E)</td>
</tr>
</tbody>
</table>

Historically, spectrum licensing in North America has been regional, rather than national. The multiple rounds of spectrum allocation, along with multiple mergers and acquisitions, have produced a highly-variable radio spectrum ownership map, especially in the United States. A carrier providing a nationwide cellular service might own no spectrum at 700 MHz or 850 MHz, but might have significant holdings at 1900 MHz and AWS in one market, and simultaneously might own portions of all four bands in another market. Although ongoing mergers and acquisitions tend to bring some uniformity, there continues to be a great variability in terms of spectrum ownership for any particular carrier in any particular region.

Currently in North America, there is virtually no possibility of deploying a 2x20 MHz FDD LTE channel, and only limited opportunities to deploy 15 MHz LTE channels, especially given the commercial needs of legacy systems. Thus, there exists a need both to enable the full potential of LTE, and to achieve the requirements of IMT-Advanced. It is with this reality in mind that 3GPP has introduced carrier aggregation technology.
Carrier Aggregation in LTE-Advanced

Dual-Cell in HSPA

Synthesis of a wider-bandwidth channel by linking multiple, narrower-bandwidth channels is not a new concept, having existed in cellular industry since the 1990s. But this concept only made its first appearance in the 3GPP technical specifications with the introduction of “Dual-Cell” HSDPA (DC-HSDPA) in Release 8. With DC-HSDPA, two adjacent HSDPA channels are grouped together logically, permitting downlink transport blocks to be sent to the user equipment (UE) over both channels simultaneously. The peak downlink data rate for DC-HSDPA is 43.2 Mbps, slightly better than 42 Mbps that is achievable with a single 5 MHz channel and 2x2 MIMO. DC-HSDPA has been deployed in North America by a number of UMTS operators.

3GPP Release 8 permits Dual-Cell only in the downlink, i.e., only HSDPA is supported. Further, Release 8 Dual-Cell cannot be used in conjunction with MIMO. Recognizing the opportunity for significant increases in performance, 3GPP introduced important enhancements to Dual-Cell into Release 9, providing support both for E-DCH – and thus DC-HSPA – and for MIMO. Dual-Cell in conjunction with MIMO permits data rates as high as 86.4 Mbps (2x43.2 Mbps) in the downlink.

Release 9 also delivered another key advancement, namely, support for Dual-Cell with non-contiguous channels. Whereas in Release 8 the component channels are required to be immediately adjacent, Release 9 permits them to be non-contiguous – or even in another frequency band – which is a critical capability given the realities of the radio spectrum ownership in North America. Although the Dual-Band Dual-Cell HSPA concept is extensible to any frequency band, Release 9 focused on 2100/900 MHz, 2100/850 MHz, and North American 1900/1700 MHz (PCS/AWS) with support for 2100/1500 MHz and North American 1900/850 MHz frequency allocations arriving in Release 10.
Carrier Aggregation in LTE Advanced

System Aspects

In Release 10 of the 3GPP specifications, the groundwork laid in Release 8 and Release 9 by DC-HSPA was generalized and applied to LTE. This functionality – known as carrier aggregation (CA) – is a core capability of LTE-Advanced. CA permits LTE to achieve the goals mandated by IMT-Advanced while maintaining backward compatibility with Release 8 and 9 LTE.

Release 10 CA permits the LTE radio interface to be configured with any number (up to five) carriers, of any bandwidth, including differing bandwidths, in any frequency band. Further, the downlink and uplink can be configured completely independently, with only the limitation that the number of uplink carriers cannot exceed the number of downlink carriers. The carriers aggregated in the context of CA are referred to as component carriers (CCs). CC arrangements are described as intra-band contiguous, intra-band non-contiguous, and inter-band, referring to immediately adjacent CCs, non-adjacent CCs within the same operating band, and CCs in differing operating bands, respectively, as illustrated below:
The introduction of CA renders the previous conceptions of “frequency band” and “bandwidth” ambiguous. 3GPP therefore has introduced terminology and notation which serve to more clearly articulate the radio interface configuration. In the context of CA, the nominal, cumulative channel bandwidth is called the *aggregated channel bandwidth*. UEs are classified according to their *carrier aggregation bandwidth class*, which is an expression of the number of CCs and the aggregated channel bandwidth. The following table summarizes the currently-defined carrier aggregation bandwidth classes:

<table>
<thead>
<tr>
<th>Carrier Aggregation Bandwidth Class</th>
<th>Aggregated Channel Bandwidth</th>
<th>Maximum Number of Component Carriers per Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Up to 20 MHz</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>Up to 20 MHz</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>20+ MHz to 40 MHz</td>
<td>2</td>
</tr>
</tbody>
</table>

CA bandwidth classes D through F are, at the time of this writing, still under study.

*Carrier aggregation configuration* refers to the CA operating bands and bandwidth classes that a UE can support. 3GPP has defined a compact notation used to express these capabilities, as follows:

\[
\text{CA}_{[\text{OB}_1][\text{CABC}_1]-[\text{OB}_2][\text{CABC}_2]-\cdots-[\text{OB}_n][\text{CABC}_m]}
\]

where \(\text{OB}_n\) refers to *operational band* \(n\), and \(\text{CABC}_m\) refers to *channel aggregation bandwidth configuration* \(m\). CA is indeed so flexible that 3GPP has limited the scope of work with regard to supportable carrier aggregation configurations in LTE Release 10. Release 10 focuses on CA_1C – 2x20+20 MHz in the 2100 MHz IMT-2000 band – and CA_1A-5CA – 2x10 MHz in each of the 2100 MHz and 850 MHz bands. The former satisfies the IMT-Advanced 40 MHz channel scalability requirement.
E-UTRAN Aspects

In support of CA, Release 10 introduces a distinction between a primary cell (PCell) and a secondary cell (SCell). The PCell is the main cell with which the UE communicates as defined as the cell with which RRC signaling messages are exchanged, or equivalently by the existence of the physical uplink control channel (PUCCH), of which there is exactly one. One PCell is always active in RRC_CONNECTED mode while one or more SCells may be active. All PCells and SCells are known collectively as serving cells. The component carriers on which the PCell and SCell are based are the primary component carrier (PCC) and secondary component carrier (SCC), respectively.

Each PCell is equipped with one physical downlink control channel (PDCCH) and one physical uplink control channel (PUCCH). An SCell could be equipped with a PDCCH or not, depending on UE capabilities. An SCell never has a PUCCH.

Transport (MAC) Layer Aspects

In terms of data transport, CA simply adds additional conduits – the shared channels (SCHs) – over which data may be transported to/from a given CA-enabled UE.
Architecturally:

becomes:

[Diagram showing network architecture with detailed components and labels]
Clearly, in order to take advantage of the aggregated bandwidth and produce the desired throughput increases, the base station’s MAC layer scheduler must have a purview which includes all active CCs. This differs from pre-Release 10 LTE schedulers, which need consider only one cell-carrier at a time.

In order for a CA-enabled base station’s MAC scheduler to sequence downlink allocations and uplink grants optimally, it must consider the downlink and uplink channel conditions across the entire aggregated bandwidth. This increases the complexity of the base station scheduler and could result in some unusual scheduling outcomes. For example, the scheduler could decide to send all of a given UE’s downlink transport blocks on CC$_1$, but to receive all of that UE’s uplink transport blocks on CC$_2$.

In the absence of MIMO, a CA-enabled scheduler allocates, at most, one transport block per SCH per TTI. The HARQ processes delivering the various transport blocks within a TTI (across SCHs) are independent.

**Physical Layer Aspects**

**Downlink Channel Quality**

Downlink channel quality, per LTE Release 8 and 9, is assessed at the UE and reported via the *channel state information* (CSI) *Information Element* (IE). In the absence of MIMO, CSI reduces to the familiar *channel quality indicator* (CQI). Release 10 does not change this paradigm, but the existence of multiple CCs means that CQI must be evaluated and reported for each CC individually when CA is active.

CQI – as well as downlink HARQ ACK/NACK indicators and other information – is reported to the base station via the *uplink control information* (UCI) IE. Since there is exactly one PUCCH (on the PCell) regardless of the number of CCs, UCI for each CC must be reported via the same PUCCH. Thus there is a need to distinguish the CC to which a given UCI pertains. This is accomplished through the *carrier indicator field* (CIF), which is header on the UCI.

Since it is possible to require the UE to report CQI periodically, and since UEs do not necessarily support simultaneous transmission of PUCCH and PUSCH, CQI also could be reported on the PUSCH, if the PUSCH happens to be active at the time of a periodic reporting instance. In the context of CA, this means that CQI could be transmitted on an SCell if an SCell uplink burst is ongoing while a PCell burst is not.

**Uplink Channel Quality**

Uplink channel quality, again per LTE Release 8 and 9, is assessed at the base station via *sounding reference symbols* (SRS) transmitted by the UE. CA implies that channel sounding could be required on multiple CCs. Release 10 introduces enhancements to permit the base station to request periodic SRS transmission on SCells in addition to PCells, though this function is optional at the UE.
Uplink Transmit Power Control

Uplink transmit power control (TPC) commands are transported to the UE via the downlink control information (DCI) IE. The one PUCCH and one or more PUSCHs can be power controlled independently. TPC commands for the PUCCH are always received on the PCell's PDCCH. But the TPC commands for the SCells could be received either through the SCell's PDCCH, or through the PCell's PDCCH. Again, carrier distinction is accomplished through the presence of the a CIF in the DCI IE.

Downlink Radio Link Monitoring

When operating in CA mode, the UE evaluates radio link health – and declares radio link failure – only through the PCell. This is intuitive as the SCell represents only additional traffic channel bandwidth rather than a conduit for critical control information. Thus, it could be strategically advantageous – due to superior propagation characteristics – to deem the lower-frequency cells as PCells and the higher-frequency cells as SCells, particularly in the context of inter-band CA.

Timing and Synchronization

The PCell and the SCell(s) are deemed to be transmitted by the same base station. The electrical path length between the base station and the UE therefore is deemed to be the same for all carriers. This is the case regardless of frequency band. Thus, there is a single timing advance value applied to all uplink transmissions, regardless of whether they occur on the PCell or an SCell.

Cross-carrier Scheduling

As stated previously, SCells might or might not be equipped with a PDCCH. In the former case, the UE assumes that the scheduling information is carried by the SCell's PDCCH. In the latter case, scheduling information for the SCell must be delivered via another cell's PDCCH. In Release 10, this is referred to as cross-carrier scheduling.

As with other functionality described above, the carrier responsible for the delivering scheduling information in the context of cross-carrier scheduling is indicated by the CIF. Cross-carrier scheduling support is optional for the UE.
Radio Resource Control (RRC) Aspects

UE Capability Transfer
Given the flexibility of CA, the E-UTRAN must be informed of the details of the UE’s support for CA. This is accomplished via the RRC UE Capability Transfer procedure. The CA-related information sent by the UE pursuant to this procedure is summarized below:

**UE category** – CA support¹ is implied by UE categories 6, 7, and 8

**Cross-carrier scheduling support** – Indicates that the UE can receive scheduling orders regarding SCells from the PCell

**Simultaneous PUCCH and PUSCH transmission support** – For CA-capable UEs, implies that the UE can support simultaneous PUCCH and PUSCH transmission on different CCs (not merely the same CC)

**Multi-cluster PUSCH within a CC support** – Indicates baseband (non-band-specific) support for multi-cluster PUSCH transmission within CCs

**Non-contiguous uplink resource allocation within a CC support** – Indicates RF (band-specific) support for non-contiguous uplink resource allocations within CCs

**Supported band combinations** – Indicates the specific frequency band and channel bandwidth configurations that the UE can utilize in support of CA

**Event A6 reporting support** – Indicates that the UE is able to report Event A6, which occurs when a neighbor PCell becomes stronger than a serving SCell by an offset

**SCell addition during handover to E-UTRA support** – Indicates that the UE can support E-UTRAN inbound inter-radio access technology (IRAT) handover directly into CA mode

**Periodic SRS transmission on all CCs support** – Indicates that the UE can transmit periodic SRSs on all SCells

¹ Note that UE category does not imply support for a particular carrier aggregation configuration, which is signaled separately.
SCell Addition and Removal

SCells cannot be activated immediately at the time of RRC establishment. Thus, there is no provision in the RRC Connection Setup procedure for SCells. SCells are added and 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 (see below). The CA-related information sent by the base station pursuant to this the RRC Connection Reconfiguration procedure is summarized below.

**Cross-carrier scheduling configuration** – Indicates, among other things, whether scheduling for the referenced SCell is handled by that SCell or by another cell

**SCell PUSCH configuration** – Indicates, among other things, whether resource block group hopping is utilized on the SCell

**SCell uplink power control configuration** – Carries a number of primitives related to SCell uplink TPC, including the path loss reference linking parameter

**SCell CQI reporting configuration** – Carries a number of primitives related to CQI measurements reporting for SCells

Handover

Handover processing for LTE in Release 10 is largely the same as Releases 8 and 9, except that clarifications are made to refer to PCell in the measurement-related RRC signaling messages. Release 10 does introduce one new measurement event: Event A6. As indicated above, Event A6 occurs when a neighboring cell’s strength becomes better than an SCell’s strength by an offset. In the case of intra-band SCell’s, this event is less useful, as the strength of the PCell and the SCells usually is very similar. However, with inter-band serving cells, the strength of a neighboring PCell could be significantly different from a serving SCell. Depending on network conditions – such as traffic load distribution – it could be advantageous to execute a handover to the cell identified by Event A6.
UE Implementation and Verification Challenges

RF Conformance Testing

Base stations, historically, have been designed to support multiple cells and multiple carriers and are thus well-positioned to support CA. But CA represents a paradigm shift for UEs. With the possible exception of the simplest CA scenario – contiguous CCs – there are substantial increases in transceiver complexity required to support CA. Non-contiguous downlink CCs necessitate multiple, independent receive chains at the UE. Non-contiguous uplink CCs can be generated through multiple digital chains and a shared transmit front end (with various upconversion options) as long as the CCs are intra-band. But in order to support inter-band uplink CCs, multiple, independent transmit chains are required.

In North America, the E-UTRA Operating Bands of particular interest are bands 2 (PCS), 4 (AWS), 5 (Cellular), and 12, 13, 14, & 17 (Digital Dividend). 3GPP has not, at the time of this writing, prioritized CA band combinations for North America. However, using the European and Asia/Pacific CA band combinations as a guide, it is conceivable that some priority will be placed on a band configuration such as CA_2A-12A (2x10 MHz or 2x20 MHz aggregated) or CA_2B (20 MHz aggregated).

Due to the increase in transceiver complexity resulting from CA – and to the availability of newer North American operating bands – there exist additional challenges in meeting the UE transceiver performance standards established in Release 8 and 9. On the transmit side, conformance to peak and dynamic output power, output signal quality, adjacent channel leakage, spurious emissions, and intermodulation standards must be verified in the context of CA and North American operating bands. On the receive side, sensitivity, selectivity, blocking, spurious response, intermodulation, and spurious emissions must be verified.

Protocol Conformance Testing

Since CA was designed specifically to be backward-compatible with Release 8 and 9 carriers, most of the procedures employed in Release 10 function in a manner similar to the previous releases. Some of the basic protocol extensions to support CA include:

- Radio Resource Control (RRC) supporting the addition and removal of SCells through RRC reconfiguration
- PDCCH control signaling on multiple CCs simultaneously
- PUCCH control signaling on a single CC with information pertaining to each CC
- PDSCH allocations on multiple CCs simultaneously
- PUSCH grants on multiple CCs simultaneously

These “table stakes” protocol extensions must be part of any CA verification effort.

In addition to the basic protocol extensions for CA, there are numerous protocol extensions – directly related to CA or with implications in the context of CA – which are optional for the UE. Some of them are:

- RRC support for SCell measurement reporting (Event A6)
- IRAT handover to E-UTRAN with active SCells
- Cross-carrier scheduling (one PDCCH serving multiple PDSCHs)
- Simultaneous PUCCH and PUSCH transmission
- Multi-cluster PUSCH within a CC
- Non-contiguous uplink resource allocation within a CC
- Periodic SRS transmission on all CCs
Clearly, the power and flexibility of the Carrier Aggregation function demands advanced, flexible verification.

**Performance Testing**

Release 10 LTE introduces three new UE categories – 6, 7, and 8. With the exception of Category 8 – which is specifically designed to deliver the most rigorous requirements of IMT-Advanced – the new UE categories do not introduce significantly higher data rates than were already available in Releases 8 and 9. Categories 6 and 7, however, do introduce new ways in which those data rates can be achieved. Prior to Release 10, the two degrees of freedom available to deliver traffic channel data rates were (a) channel bandwidth and (b) MIMO layers. Release 10 adds to this list component carriers as a degree of freedom. The following table summarizes the ways in which a Category 6/7$^2$ UE can support its peak traffic channel capability of approximately 300 Mbps in the downlink:

<table>
<thead>
<tr>
<th>Component Carrier Bandwidth (MHz)</th>
<th>Component Carriers</th>
<th>MIMO Layers per CC</th>
<th>DL Peak Traffic Channel Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1</td>
<td>4</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>15/15/10</td>
<td>3</td>
<td>2</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>300 Mbps</td>
</tr>
</tbody>
</table>

The configurations which can achieve a particular traffic channel data rate multiply at lower data rates. While some of these configurations are hypothetical in nature, what is clear that the flexibility offered by CA demands flexibility in the context of UE performance validation.

1. Other PCS/Digital Dividend band combinations are possible, such as CA_2A-13A, CA_2A-14A, and CA_2A-17A.
2. Category 6 and category 7 UEs have identical downlink capabilities, differing only in their data rates.

**Conclusion**

Achieving the requirements set out in IMT-Advanced is even more challenging given the fragmentation of the available cellular radio spectrum, particularly in North America. Release 10 of the 3GPP LTE specifications – LTE-Advanced – delivers IMT-Advanced within practical spectrum constraints. It does this through the carrier aggregation feature. Carrier aggregation permits an LTE base station to group several distinct channels into one logical channel, thereby enabling very high peak traffic channel data rates.

Carrier aggregation has significant software and, in particular, hardware implications, particularly on the UE. UE hardware complexity rises dramatically according to the particular carrier aggregation configuration: intra-band contiguous, intra-band non-contiguous, and inter-band. Carrier aggregation-capable hardware, in combination with numerous parameters and optional functionality, demands comprehensive and flexible UE test and verification solutions to ensure successful deployment and high performance in the field.