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An Introduction to Carrier Aggregation Testing

Meeting the challenge of high quality mobile services

Content

1.0 Carrier Aggregation as part of LTE-A

Meeting the challenge of high quality mobile services

Today's mobile data services explosion imposes challenges on operators to provide high quality services for mobile applications in a cost effective manner. To support operators, the ITU initiated a global standard initiative for IMT Advanced systems which are required to meet enhanced user and service demands with peak data rate targets of 100 Mb/sec for high mobility and 1 Gb/sec for low mobility. In addition, IMT-A systems have to have key features such as functional commonality, intersystem operability, global roaming and user friendly applications.

In November 2010, LTE-A was ratified as the technology to meet all IMT-A requirements. Therefore, LTE-A, which is first released with Release 10, builds on 3GPP specifications for LTE Releases 8 and 9. To satisfy the peak data rates, LTE-A needs to minimally support bandwidths of up to 100 MHz. The ability to achieve higher data rates is constrained by spectrum fragmentation and, as large portions of contiguous spectrum are rare, the bandwidth increase can be ensured only by the aggregation of multiple component carriers of smaller bandwidths of different frequencies, and this technique is called carrier aggregation (hereinafter referred to as simply CA). CA can be used for both Time-division duplexing (TDD) and Frequency-division duplexing (FDD).

CA provides advantages in addition to faster data rates, such as spectrum efficiency, deployment flexibility, and backward compatibility. The spectrum can be more efficiently utilized by aggregating non-continuous carriers. Proper utilization of different carriers can support various deployment scenarios for both homogenous and heterogeneous networks. Each component carrier is LTE compatible, thereby allowing operators to migrate from LTE to LTE-A while maintaining service to legacy LTE users. In addition, re-utilization of the LTE design on each of the component carriers minimizes the implementation and specification efforts. CA provides support for several uses cases, starting with Release 10, which was frozen by the 3GPP in April of 2011:

1. CA allows operators with higher licensed frequency spectrum like 3.5 GHz to provide higher peak rates and capacity without being restricted by the Release 8 and 9 20 MHz limit. In the lower frequency bandwidths like 700 MHz, where spectrum is licensed in much narrower blocks like 6 MHz in the U.S., CA enables operators to pool their spectrum resources together (up to 100 MHz total) within the same band or across different bands to achieve higher peak rates and capacity.
2. CA allows operators to provide multiple services simultaneously over multiple carriers.
3. CA can improve network efficiency and user performance by dynamically allocating traffic across the entire available spectrum. This can be implemented using CA capable devices that report channel quality for carriers across a wide spectrum. This improves resource allocation and handover in heterogeneous networks where both the number of carriers and the carrier transmit powers can vary significantly across sites. Both the macro and the small cells (pico/femto) can transmit aggregated multiple carriers and dynamically allocate resources across carriers.
4. CA already supports cross carrier scheduling that can mitigate the control channel intercell interference resulting from spectrum sharing between macrocells and pico/femto cells.

CA provides advantages in addition to faster data rates, such as spectrum efficiency, deployment flexibility, and backward compatibility. The spectrum can be more efficiently utilized by aggregating non-continuous carriers. Proper utilization of different carriers can support various deployment scenarios for both homogenous and heterogeneous networks.

2.0 Basics on 3GPP Specifications Related to Carrier Aggregation

2.1 Component Carrier Combination and Bands

CA is realized by using up to five component carriers with a total maximum bandwidth of 100MHz, but initially only two carriers are deployed. Each component carrier can have bandwidths of 1.4, 3, 5, 10, 15 or 20 MHz. In FDD the number of aggregated carriers can be different in DL and UL. However, the number of UL component carriers is always equal to or lower than the number of DL component carriers. The individual component carriers can also be of different bandwidths. For TDD the number of component carriers as well as the bandwidths of each component carrier will normally be the same for DL and UL. The downlink and uplink linkage is configurable via radio resource control (RRC) signaling.

Depending on the available spectrum, operators can choose from three types of CA: intra-band contiguous, inter-band and intra-band non-contiguous spectrum aggregation. The first two types are covered by Release 10, while the latter by Release 11 (**Figure 1**). For the non-contiguous scenario, frequency gaps of N x 30 KHz (N=integer) need to be ensured.

1. Aggregated Transmission Bandwidth Configuration (ATBC), which represents the total number of aggregated physical resource blocks (PRB).

2. CA bandwidth class, which indicates a combination of maximum ATBC and maximum number of component carriers. In Release 10 and Release 11 three classes are defined:
   A (ATBC ≤ 100, maximum number of component carriers = 1), B (ATBC ≤ 100, maximum number of component carriers = 2), and C (100 < ATBC ≤ 200, maximum numberof component carriers = 2).

3. CA configuration, which indicates a combination of E-UTRA operating band(s) and CA bandwidth classes. Release 10 defines three CA combinations ([1], [2]), while Release 11 defines additional CA configurations ([1], [2]). The maximum aggregated bandwidth is still 40 MHz and maximum number of carrier components is 2. In addition, for both Release 10 and Release 11, any UL component carrier will have the same bandwidth as the corresponding DL component carrier. Also for inter-band CA there will only be one UL component carrier, i.e., no UL CA.

Figure 1. Three types of Carrier Aggregation

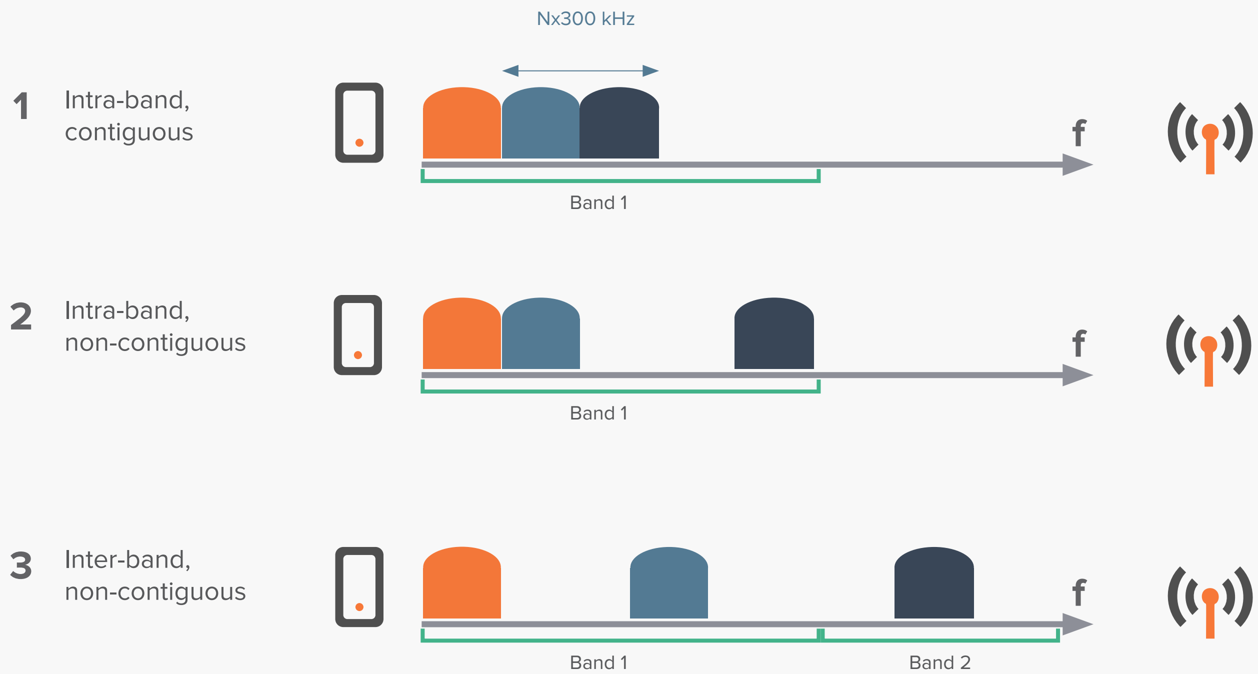
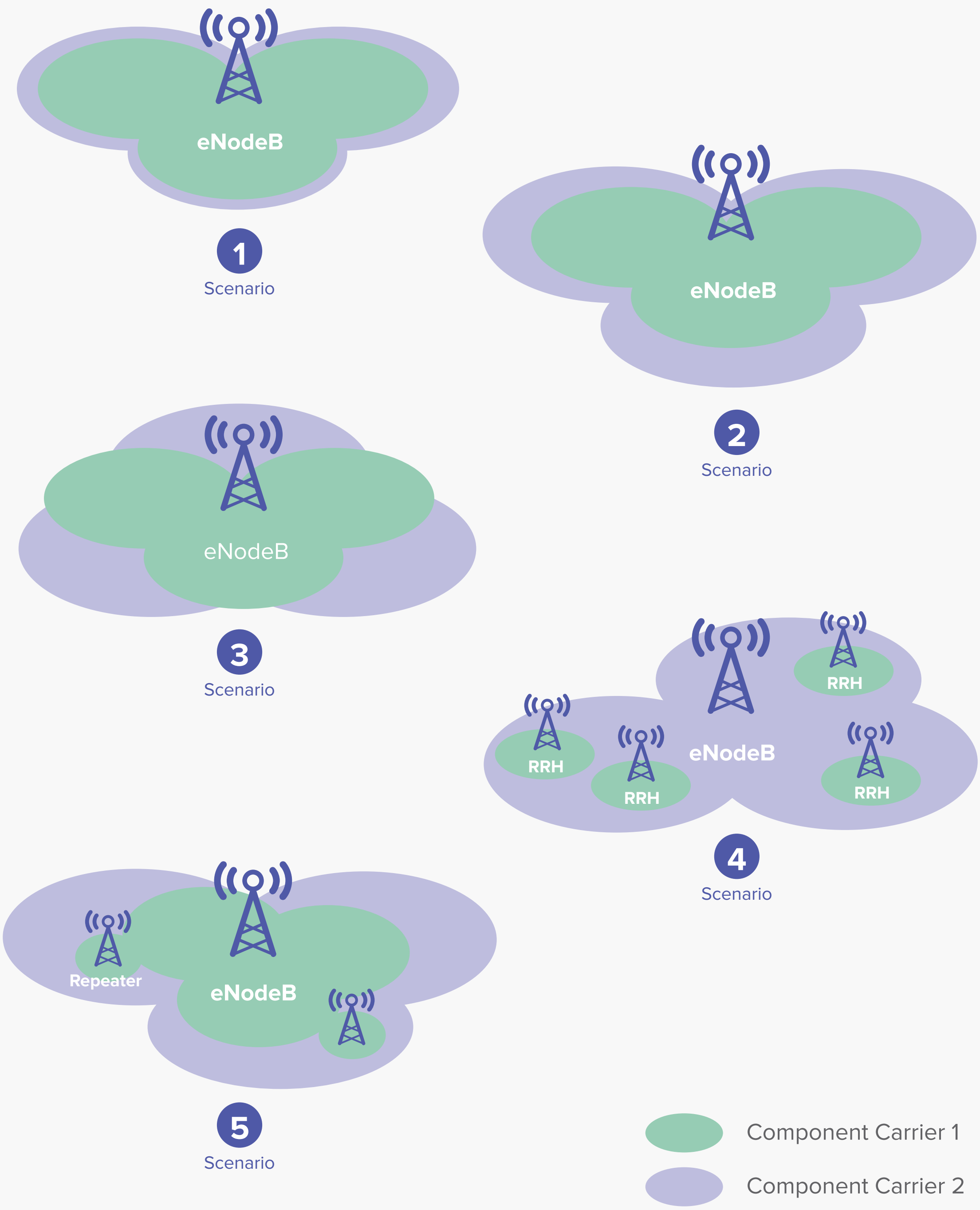


Table 1. CA deployment scenarios

Scenario	High level description
1	Antennas of the cells are co-located and the cells are overlaid with small frequency separation; component carriers in the same band. Almost same coverage is provided due to similar path loss. Mobility is supported on either carrier. Higher data rates are achievable throughout the cell by CA.
2	Antennas of the cells are collocated and the cells are overlaid with large frequency separation; component carriers in different bands. Different coverage is provided on different carriers; and the higher frequency carriers do show smaller coverage due to larger path loss. Mobility is supported on the carrier in the lower frequency band providing sufficient coverage. Higher data rates and throughput are ensured by the carrier in the higher frequency band
3	Antennas of the cells are collocated; but the antenna directions are different in order to fill the coverage hole at the cell boundary; component carriers are in different bands. Coverage holes exist for cells in the higher frequency band due to the larger path loss. CA is supported in areas with overlapping coverage. Mobility management is typically not performed on the cells in the higher frequency band. Antennas oriented to the cell edge to achieve improved cell edge data rates and throughput.
4	Antennas of the cells are not collocated, because remote radio heads (RRHs) are used in addition to normal eNB cells; component carriers are usually of different bands, eNB cells providing macro coverage, and RRHs placed in hot spots. CA is applicable to users within the coverage of RRHs and the underlying macro cells by performing eNB scheduling in one place; both eNB cells and RRH cells are under the control of the eNB. However, due to different positioning, the propagation delays of eNB cells and RRH cells are also different, and the UE is required to maintain respective uplink timing for eNB and RRH cells. Mobility is performed based on the cell coverage of macro cells. Throughput is improved at hot spots by RRHs.
5	Although similar to scenario 2, in scenario 5, frequency selective repeaters are additionally deployed to extend the coverage for one of the carrier frequencies, generally in various environments where penetration loss is large like urban indoor and underground. Repeaters are not necessarily deployed for all the bands, but rather depending on an operator's deployment policy considering link budgets and costs. Similar to scenario 4, different cells experience different propagation delays due to the presence of repeaters. Therefore, this scenario also requires the maintenance of multiple uplink timing.

Figure 2. CA deployment scenarios



Based on real world spectrum allocation and operators' need, 3GPP RAN 4 has been working on 14 different band combinations, most of which aggregate two carriers to achieve up to 40MHz total bandwidth in both downlink and uplink. Some of the operators' combinations of interest are presented in [2].

Based on the demand to support the asymmetric downlink heavy user traffic pattern, the Release 10 and 11 RF specification work has been prioritized to focus on downlink CA, while the work on uplink CA is expected to follow in Release 12.

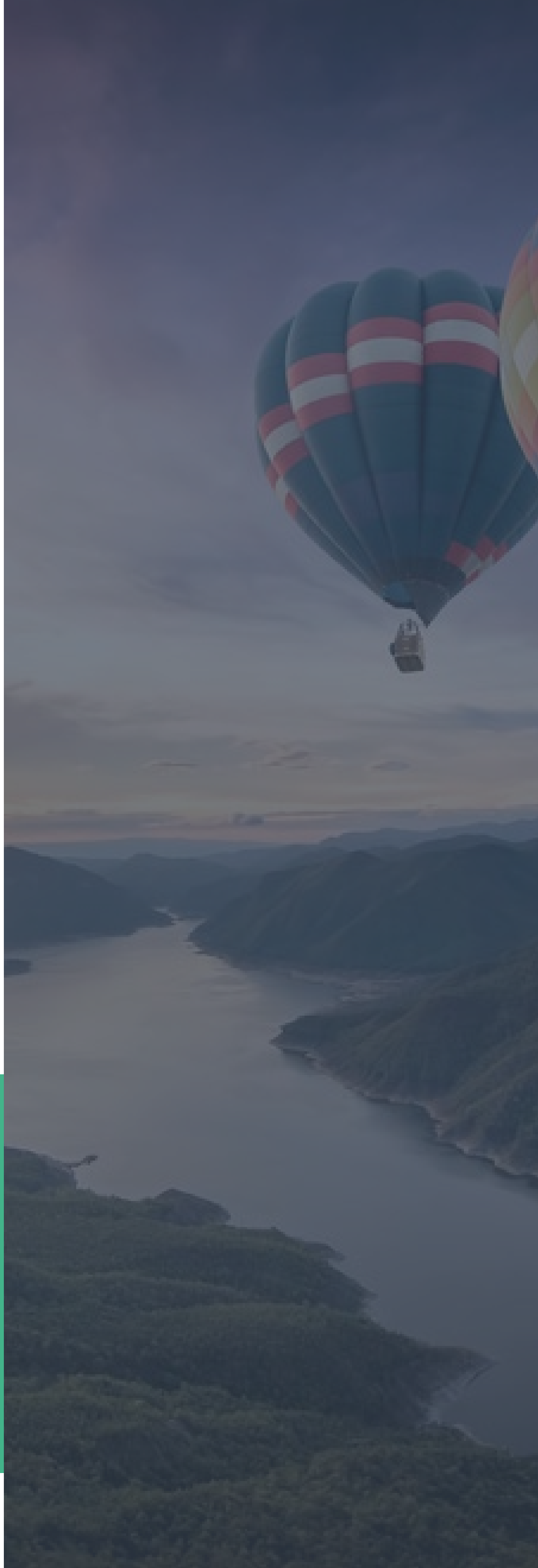
2.2 Deployment Scenarios

CA deployment scenarios aim to improve data rates for users within overlapped areas of cells and depend largely on the operator's needs. For efficient deployment, operators take into consideration various factors, such as spectrum allocation, urban/suburban/rural areas antenna direction and location, hot spots, and the presence of frequency-selective repeaters.

Table 1 and **Figure 2** describe the possible deployment scenarios [3], [4].

The downlink CA operation does not affect uplink timing in any of the scenarios described in Table 1. Therefore, downlink CA is already covered starting with Release 10, while the uplink case has been deferred to Release 11.

Backward compatibility is required for smooth migration and maximal reuse of the LTE Releases 8 and 9 design. Each component carrier in 3GPP LTE-A should be accessible by LTE Releases 8 and 9 user equipment (UE). Therefore, the complete set of Releases 8 and 9 downlink physical channels and signals are transmitted on each component's carrier based on the LTE Releases 8 and 9 procedures, including system information, synchronization and reference signals, and control channels.



3.0 Carrier Aggregation Design Principles

3.1 General Rules

The design of LTE-A CA considers three main principles: backward compatibility, minimal protocol impact, and limited control procedure change.

Backward compatibility is required for smooth migration and maximal reuse of the LTE Releases 8 and 9 design. Each component carrier in 3GPP LTE-A should be accessible by LTE Releases 8 and 9 user equipment (UE). Therefore, the complete set of Releases 8 and 9 downlink physical channels and signals are transmitted on each component's carrier based on the LTE Releases 8 and 9 procedures, including system information, synchronization and reference signals, and control channels.

Minimal impact from user plane protocol perspective is ensured by the fact that the component carriers are invisible to the Packet Data Convergence Protocol (PDCP) and the radio link control (RLC) layers. The multiple component carriers are just data transmission pipes managed by a single medium access control (MAC) layer. Each component has its own hybrid automatic repeat request (HARQ) entity controlling a number of LTE Release 8 and 9 compatible HARQ processes for the physical (PHY) layer. Figure 3 shows layer 2 structures with CA, both downlink and uplink. As it can be seen, the PHY and MAC design for LTE-A is agnostic to the CA type (intra-/ inter-band, contiguous or non-contiguous). Limited control procedure change is ensured by the fact that there is no notion of CA in either the RRC_IDLE state or the RRC_CONNECTED state of the UE. In the latter case, the UE follows the LTE Release 8 and 9 connection procedure before being able to operate on multiple CA.

3.2 Higher Layer Aspects

The services provided by higher layers are fulfilled by user and control plane functions. For efficient utilization of multiple carriers for data transmission, additional procedures such as cell management and cell activation/ deactivation can be employed.

A component carrier is referred to as a serving cell and it is treated as such by the higher layers. In FDD, a serving cell comprises a pair of different downlink and uplink carrier frequencies, while in TDD a single carrier frequency is used, with downlink and uplink transmissions in different time intervals. Each UE has a single serving cell and it is referred to as the primary cell (PCell); other serving cells are called secondary (SCell) and the key differences between these in LTE-A CA are presented in **Table 2**.

3.2.1 Cell Management

Depending on the carrier where the initial access is performed, different UEs in a CA 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 CA capability to meet traffic demands.The network uses dedicated RRC signaling to convey necessary information (e.g. system information) of an SCell to the UE, to add/ remove/reconfigure SCells, or to change the PCell of a UE to improve the link quality. The PCell change in LTE-A CA can only be performed via handover procedure, but it does not require the UE to switch to single carrier operation. In addition, intra-LTE handover in LTE-A allows the target PCell to configure one or more SCells for the UE to use immediately after handover.

3.2.2 Mobility Management

Mobility management as well as cell management in conjunction with CA requires the UE to perform various types of measurements as instructed by the network, such as intra- and inter-frequency measurements for LTE carriers and IRAT measurements for carriers with non-LTE RAT. A special measurement event dedicated to compare the channel quality of neighboring cell relative to a reference SCell is introduced for LTE-A CA. This event ensures fast reconfiguration in a CA scenario.

3.2.3 Cell Activation/ Deactivation

To reduce the UE power consumption, the UE determines, through network configuration and ongoing HARQ process, the discontinuous reception (DRX) ON/OFF duration common to all serving cells. To further reduce UE battery consumption, an SCell can be activated or deactivated in LTE-A CA the functions provided by the PCell require that the PCell remains activated during the RRC connection.

The SCell activation or deactivation is enabled by a combination of 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. The process is performed independently for each SCell, allowing the UE to be activated only on a necessary set of SCells.

To understand the impact of the CA benefits as well as its operability, it is important to monitor intra-handover information (before and after), UE measurement events related to CQI of neighboring cells in relationship to a reference SCell, as well as cell activation/deactivation events and processes.

3.3 Main Physical Layer Aspects

LTE-A CA largely inherits the LTE Release 8 and 9 data transmission procedure per component carrier [6], [7], [8], including the multiple access scheme, modulation and channel coding. In addition to those, starting with Release 10 additional UEfunctionalities aimed at CA support are introduced.

These new capabilities refer to: data transmission over two clusters of contiguous bandwidth in the same carrier, simultaneous transmission of a control channel and a data channel in the PCell, data transmission from multiple antennas with spatial multiplexing, and improved design of downlink and uplink control to efficiently support data transmission. The latter represents the core of the physical layer design for CA. Some of the downlink and uplink improved designs are discussed in this section. Some testing requirements are also pointed out.

3.3.1 Downlink Control Design

Physical Downlink Control Channel (PDCCH)

PDCCH provides information on resource allocation, modulation and coding scheme (MSC), and other related parameters for downlink (Physical Downlink Shared Channel, PDSCH) and uplink (Physical Uplink Shared Channel, PUSCH) data transmission. In LTE-A, CA allows the configuration of each component carrier to transmit PDCCH scheduling of a PDSCH on the same carrier frequency and PDCCH scheduling of a PUSCH on a linked UL carrier frequency where the linkage of the DL and UL carriers is conveyed as system information. A new field, Carrier Indicator Field (CIF), which is delivered through the PDCCH, indicates the target component carrier where the allocated radio resources exist. In addition, PDCCH on a component carrier can be configured to schedule PDSCH and PUSCH transmissions on other component carrier by means of cross carrier scheduling. There are three benefits of this CA feature:

- It is effective in a HetNet environment, where neighboring cell interference alters the PDCCH signals and radio resource allocation for the interfered cell may not be possible. Cross carrier scheduling solves the problem because the eNB can configure cells other than the interfered cell for PDCCH transmission.
- It improves the scheduling flexibility of the eNB, in the sense that the eNB has multiple DL component carriers' options for the transmission of the resource allocation information.
- It reduces the processing burden of the UE's PDCCH blind decoding because using cross carrier scheduling allows the UE to monitor a smaller number of DL component carriers rather than all of the configured DL component carriers.

PDCCH Search Space

A PDCCH search space is monitored by all UEs only in their respective PCell for receiving system, paging, power control and random access related information. In addition, each UE has its own specific PDCCH search space which is a function of the UE's radio network temporary identifier (RNTI). Since the same set of resources for PDCCH transmission is shared, a PDCCH to a UE may not be transmitted due to at least partial overlapping with PDCCH to another UE, creating PDCCH blocking. To maintain the same level of blocking probability as in Release 8 and 9, LTE-A UE monitors one UE-specific PDCCH search space for each activated component carrier. If cross carrier scheduling is used, then the UE-specific PDCCH search space is defined by a combination of the UE's RNTI and the serving cell index [8].

Physical Control Format Indicator Channel (PCFICH)

PCFICH transmitted in each sub frame conveys the control format indicator (CFI) field which indicates the number of OFDM symbols carrying control information in the sub frame and which is decoded by the UE to determine the starting OFDM symbol used for PDSCH transmission. The UE is required to decode the CFI for PDSCH scheduled by PDCCH on the same component carrier, however, in cross carrier allocation scenarios, the UE is not required to decode the CFI for the PDSCH on the aggregated CC as the starting OFDM is communicated by higher layers.

Physical HARQ Indicator Channel (PHICH)

PHICH carrying the HARQ feedback information associated with the PUSCH transmission is sent in LTE-A CA similar to LTE Release 8 and 9, on the component carrier where the PDCCH schedules the PUSCH transmission. The PHICH

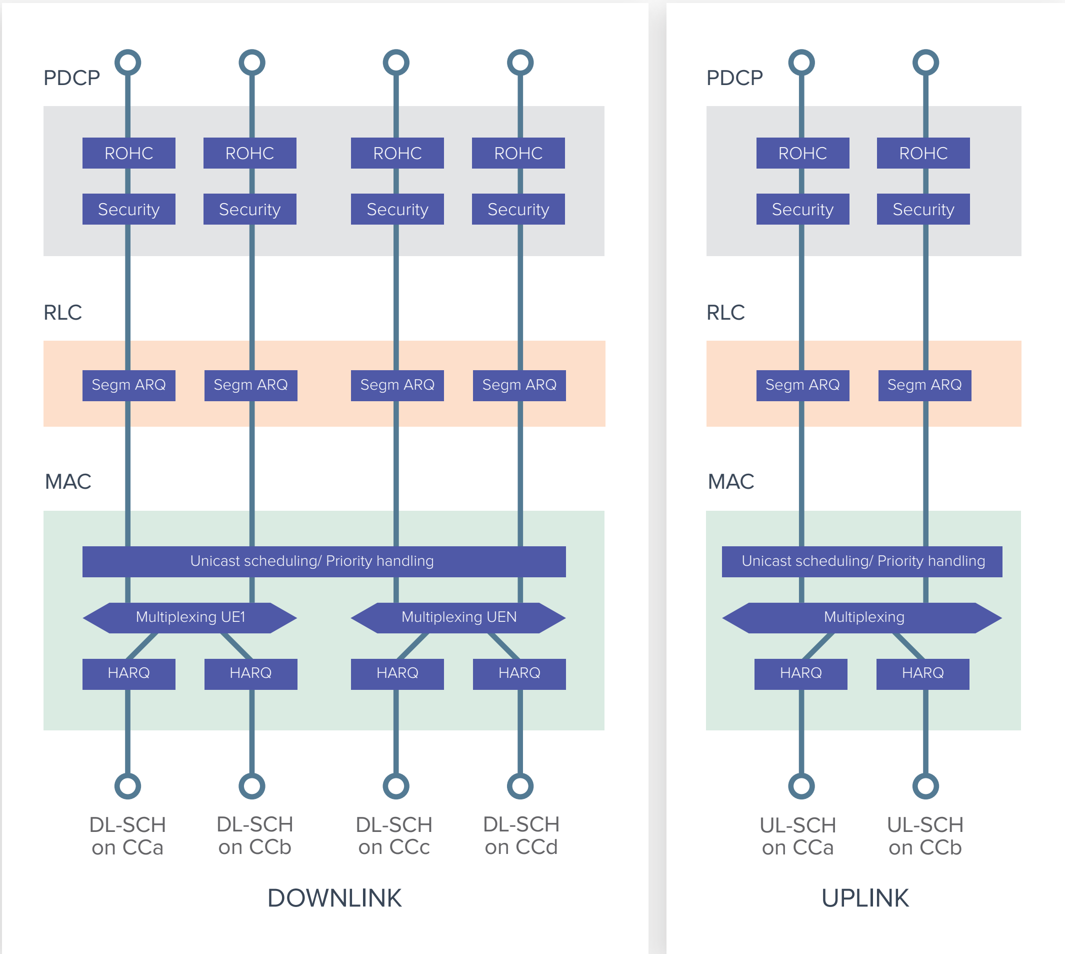


Figure 3: 3GPP DL and UL Layer 2 Structure for Carrier Aggregation

for a corresponding PUSCH is always transmitted on the component carrier where the PDCCH schedules the PUSCH transmission.

Monitoring and testing of all these downlink CA specific features, configurations and transmission characteristics is important, and requires detailed information from the UE reporting on its capabilities as well as on the configuration setup of the PCell and SCells involved in the transmission at a certain moment in time. Information on either, if the UE uses cross scheduling or not, and/or what band combination types it supports, can explain UE behavior as well as the performance of the provided service to the UE.

3.3.2 Uplink Control Design

Uplink Control Information (UCI)

Similar to LTE Release 8 and 9, UCI including the HARQ feedback on potentially multiple PDSCH, on channel state information (CSI), and on scheduling request (SR), can be transmitted in a sub frame on PUSCH or Physical Uplink Control Channel (PUCCH). LTE-A further supports simultaneous PUCCH and PUSCH transmissions in one sub frame, allowing the network to flexibly control the performance of PUCCH and PUSCH independently.

Channel State Information (CSI) Feedback

CSI, used to perform PDSCH scheduling (e.g., resource and MCS selection, transmission rank adaptation and pre-coding matrix determination), is fed back for each component carrier in LTE-A CA, either periodically or aperiodically. Periodic CSI feedback is independently configured for each component carrier and transmitted on PUCCH in a sub frame. 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 from one carrier collides with feedback from other carriers in a sub frame. Aperiodic CSI feedback is

Cell	PUCCH Config	RL Mon	System info acquisition	NAS mobility Info	Security input	RA procedure	Semi-persistent scheduling	Deactivated state	Data transmit	Sounding reference signal
PCell	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES
SCell	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES

Table 2: Key Differences between PCell and SCell

transmitted on PUSCH and LTE-A CA can support single or multiple component carriers in a sub frame in order for the network to balance feedback overhead.

Uplink Power Control

The uplink power control mechanism is used by the UE to determine a PUSCH or PUCCH transmission power [8], which ensures that the respective reception reliability targets are achieved. The mechanism is based on an open loop adjusting for the path loss between the UE and its serving node and a closed loop transmitting power control (TPC) commands in PDCCH to the UE.

The process is independent among the activated cells, and it is the same as in LTE Release 8 and 9. The key difference of a CA scenario (Release 10 and upwards) comes when the sum of nominal transmission powers for either PUSCH or PUCCH from the UE exceeds the total maximum output power for which the UE has been configured in a sub frame. As mentioned above, depending on the UCI, the UE may transmit in a sub frame one PUCCH, one PUSCH or more, or some other combination. If the total maximum power is exceeded, then the UE transmission power is distributed by descending priority to PUCCH, PUSCH with UCI, and then PUSCH without UCI, where the nominal transmission power for a channel with higher priority is first guaranteed until the UE reaches the maximum output power. For one or more PUSCH without UCI, the UE scales each PUSCH power by the same factor, considering that the same QoS for data transmission is required on all component carriers.

Monitoring the uplink designed improvements characteristic to CA helps complete the view on the CA operational performance. For example, monitoring the periodic CSI feedback on each component can help detect performance degradation in a CA scenario caused by excessive drops of CSI feedback due to collisions within the same transmission sub frame on PUCCH. Similarly, monitoring the uplink power control mechanism of CA capable devices can help correlate the QoS behavior to the UE scaling down of the PUSCH power on each component carrier when the total maximum power is exceeded.

3.4 Some Further Enhancements

To simplify design, one of the principles of CA (section 3.1) is backward compatibility. However, this comes at the price of irreducible overhead on each component carrier for transmission of broadcast information, such as common reference signals, synchronization signals and downlink control signals. Therefore, usage of non-backward compatible component carriers not requiring the large overhead for signaling can further improve the spectrum efficiency, especially for scenarios aggregating fragmented and small pieces of transmission bandwidths and for energy-efficient network implementations. The non-backward compatible carriers shall 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-A CA, such as 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. Other enhancements include joint CSI and HARQ feedback for UE configured with downlink CA and extension of downlink control channels in the PDSCH region to increase capacity and allow for interference coordination in the frequency domain.

In addition, to support CA deployment scenarios 4 and 5 (see **Table 2**, section 2.2), different UE uplink transmission timings matching different propagation delays of the component carriers need to be supported.

Along with the development and deployment of these enhancements, testing and monitoring of CA functionality needs to evolve, especially in the area of uplink timing and support of non-backward compatible component carriers.

4.0 Carrier Aggregation Testing With TEMS Tools

TEMS™ Investigation is our leading product in CA performance monitoring in live networks as well as testing in the lab. The developed features are perfectly suited for detailed studies of secondary carrier assignments including performance measurements, site verification, coverage measurements, neighbor optimization, UE and network capabilities and settings, and troubleshooting. Therefore, the TEMS solution for CA covers from the deployment to the optimization and troubleshooting phase.

This section covers some examples of what can be done today with TEMS Investigation.

4.1 Carrier Aggregation Deployment Monitoring

As it has been discussed in section 3.2 above, the CA feature's performance depends to a large extent on the SCell deployment.

When deploying a secondary carrier, the performance in terms of end-user throughput varies with many parameters including cell configuration, UE capabilities, radio environment, etc. Therefore, monitoring all these information elements is critical for successful CA deployments.

4.1.1 Cell Configuration

TEMS Investigation includes detailed information about serving cell configuration, both primary and secondary cell. The information is presented in text format (**Figure 4**) and it refers to the band (band number and frequency band), as well as the frequency of the deployed cells (both EARFCN and the MHz value). Also, bandwidth of the cells can easily be found (see **Figure 5**). There are a series of parameters related to the secondary carrier assignment and its configuration.

4.1.2 UE Capabilities

As discussed in section 3.2, the UE needs to be able to support the CA feature. Therefore, capturing the UE capabilities' information plays a significant role in CA deployment monitoring. However, as it can be seen in the screenshot presented in **Figure 6** below, the UE Capability Information message can consist of a large number of information lines (almost 1,900 for the presented case).

Therefore, it is crucial to discuss the most meaningful information that can be used for understanding the UE's capabilities for CA support.

UE Category

The field ue-Category in the UE Capability Information indicates performance figures related to maximum throughput and number of MIMO layers supported as described in [9]. It should be noted that a UE category 4 can perfectly support CA. The only limitation is that the maximum throughput is only 150MB/sec.

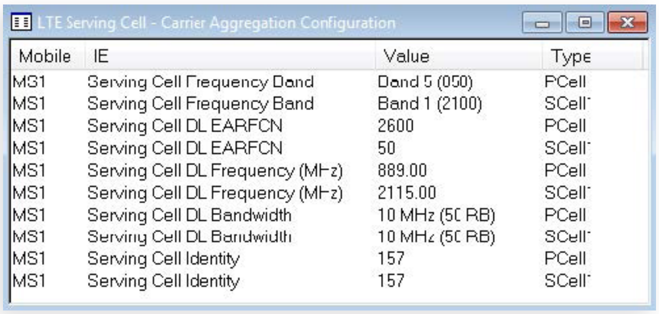
Figure 7 is an extract from 3GPP TS 36.306 [9] defining the meaning of different UE categories.

PARAMETERS' CATEGORY	PARAMETERS
CrossCarrierSchedulingConfig	cif-Presence - pdsch-Start - schedulingCellId
UplinkPowerControlDedicatedSCell	-p0-UE-PUSCH -deltaMCS-Enabled-r10
CQI-ReportConfigSCell-r10	- cqi-ReportPeriodicSCell-r10 - pmi-RI-Report-r10
UplinkPowerControlCommonSCell-r10	- p0-NominalPUSCH-r10 - alpha-r10
PUSCH-ConfigDedicatedSCell-r10	-groupHoppingDisabled-r10 -dmrs-WithOCC-Activated-r10

Table 3: SCell Configuration Parameters

Band Support

Layer 3 message UE Capability Information includes CA support. If supported, it consists of the information element supportedBandCombination-r10 as described in [10]. That, inturn, holds a list of band combinations. It is worth mentioning that as of today (February 2014) only downlink CA UEs exist.



LTE Serving Cell - Carrier Aggregation Configuration

Mobile	IE	Value	Type
MS1	Serving Cell Frequency Band	Band 5 (850)	PCell
MS1	Serving Cell Frequency Band	Band 1 (2100)	SCell
MS1	Serving Cell DL EARFCN	2600	PCell
MS1	Serving Cell DL EARFCN	50	SCell
MS1	Serving Cell DL Frequency (MHz)	889.00	PCell
MS1	Serving Cell DL Frequency (MHz)	2115.00	SCell
MS1	Serving Cell DL Bandwidth	10 MHz (50 RB)	PCell
MS1	Serving Cell DL Bandwidth	10 MHz (50 RB)	SCell
MS1	Serving Cell Identity	157	PCell
MS1	Serving Cell Identity	157	SCell

Figure 4: PCELL and SCELL configuration

Below is an example of band 3 and 8 for downlink. The ca-BandwidthClassDL-r10 is used as an indexing letter according to [1] (**Figure 9**) to state the bandwidth supported, in this case (letter a) 20MHz.

The screenshot in **Figure 8** should be read as follows: Band 3 and 8 supported for CA in downlink (only the downlink is presented for the secondary cell). In 3GPP, specs is written as CA_3A_8A. **Figure 9** is an extract from 3GPP TS 36.306 [9] defining the meaning of different UE categories.

In addition, the UE Capability Information message shows the supported band combination described by information element supportedBandCombinationExt-r10 (**Figure 10**).

As shown in **Figure 10**, the supported Bandwidth Combination Set consists of 32 bits, pointing out which of the bandwidth combination sets are supported (if none are specified, all sets are supported). So, in this case, for band combination set (4), the bandwidth combination set (1) is supported, while for the other band combination sets, all sets are supported. As can be seen in **Figure 11** (excerpt from [1]), the CA_3A-8A has two sets where (1) is 20MHz max bandwidth and band 3 is 10MHz and band 8 is either 5 or 10MHz. While current UEs support at the maximum 20MHz in total, later UEs will support wider bandwidths such as bandwidth combination 0 (30MHz) in this case, ensuring therefore a significant increase of the available spectrum.

It is important to note that the table in **Figure 11** shows a variety of spectrum combinations that are already and/or soon to be available and used. Significant bandwidth increase and therefore capacity ensured by the CA feature come, however, at the price of challenges stemming from the need for complex hardware architectures and signal processing implemented in the devices, as well as from network. Continuous monitoring and performance evaluations of the CA feature with tools like TEMS Investigation become crucial for operators that need to make sure that they are efficiently using the spectrum.

Band Support in General

Even though not directly related to CA, the screenshot from one of the latest mobile devices (**Figure 12**) gives an indication of the capabilities of the RF modules in the devices, which in this case is of 19 different LTE bands. This information helps to understand in some scenarios performance limitations caused by the device itself. In addition, operators supporting multiple bands with overlapping coverage in more than one layer need tools like TEMS Investigation to get a single view of all available bands such as the one presented in the **Figure 12** screenshot. This all-in-one glance better prepares operators to cope with the challenges of configuring the network so that the traffic is balanced between the different layers.

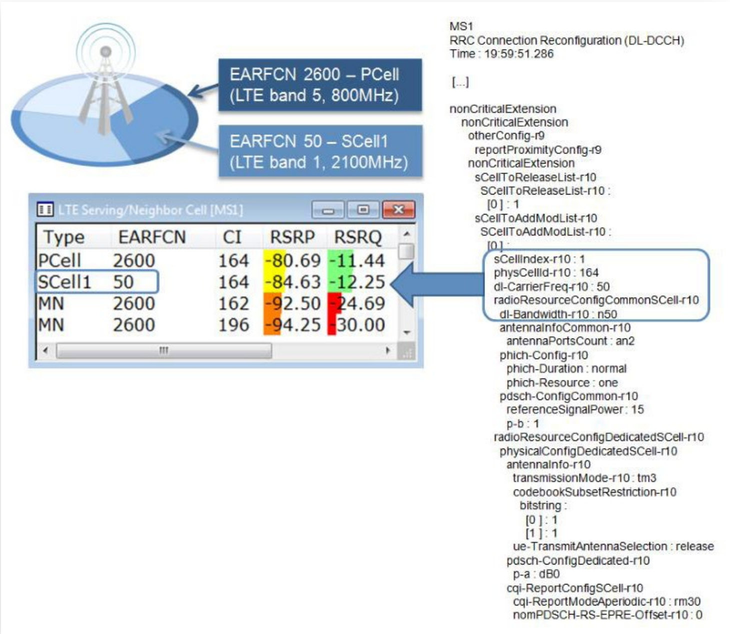


Figure 5: SCELL information

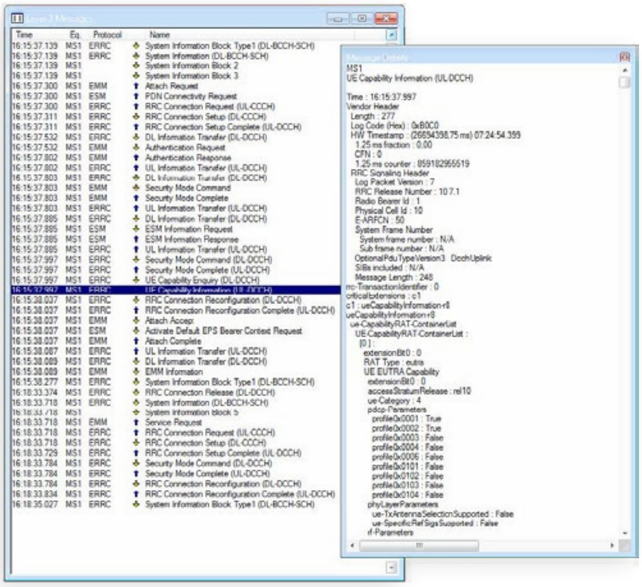


Figure 6: UE Capabilities’ Information Message

4.1 *ue-Category*

The field *ue-Category* defines a combined uplink and downlink capability. The parameters set by the UE Category are defined in subclause 4.2. Tables 4.1-1 and 4.1-2 define the downlink and, respectively, uplink physical layer parameter values for each UE Category. A UE indicating category 6 or 7 shall also indicate category 4. A UE indicating category 8 shall also indicate category 5. Table 4.1-4 defines the minimum capability for the maximum number of bits of a MCH transport block received within a TTI for an MBMS capable UE.

Table 4.1-1: Downlink physical layer parameter values set by the field *ue-Category*

UE Category	Maximum number of DL-SCH transport block bits received within a TTI (Note)	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL
Category 1	10296	10296	250368	1
Category 2	51024	51024	1237248	2
Category 3	102048	75376	1237248	2
Category 4	150752	75376	1827072	2
Category 5	299552	149776	3667200	4
Category 6	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
Category 7	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
Category 8	2998560	299856	35982720	8

NOTE: In carrier aggregation operation, the DL-SCH processing capability can be shared by the UE with that of MCH received from a serving cell. If the total eNB scheduling for DL-SCH and an MCH in one serving cell at a given TTI is larger than the defined processing capability, the prioritization between DL-SCH and MCH is left up to UE implementation.

Figure 7: 3GPP TS 36.306 Excerpt: UE Capability

```
[4] :
 BandCombinationParameters-r10 :
  [0] :
   bandEUTRA-r10 : 3
   bandParametersUL-r10
    BandParametersUL-r10 :
     [0] :
      extensionBit0 : 0
      ca-BandwidthClassUL-r10 : a
   bandParametersDL-r10
    BandParametersDL-r10 :
     [0] :
      extensionBit0 : 0
      ca-BandwidthClassDL-r10 : a
      supportedMIMO-CapabilityDL-r10 : twoLayers
  [1] :
   bandEUTRA-r10 : 8
   bandParametersDL-r10
    BandParametersDL-r10 :
     [0] :
      extensionBit0 : 0
      ca-BandwidthClassDL-r10 : a
      supportedMIMO-CapabilityDL-r10 : twoLayers
```

Figure 8: Screenshot CA with UE Capabilities: Band Support

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Table 5.6A-1: CA bandwidth classes and corresponding nominal guard

CA Bandwidth Class	Aggregated Transmission Bandwidth Configuration	Maximum number of CC	Nominal Guard Ban
A	$N_{RB,agg} \le 100$	1	$a_1 BW_{Channel(1)} - 0.5\Delta f_1$
B	$N_{RB,agg} \le 100$	2	FFS
C	$100 < N_{RB,agg} \le 200$	2	$0.05\ max(BW_{Channel(1)}, BW_{Ch}$
D	$200 < N_{RB,agg} \le [300]$	FFS	FFS
E	$[300] < N_{RB,agg} \le [400]$	FFS	FFS
F	$[400] < N_{RB,agg} \le [500]$	FFS	FFS

NOTE 1: $BW_{Channel(1)}$ and $BW_{Channel(2)}$ are channel bandwidths of two E-UTRA component

Figure 9: 3GPP Excerpt: CA Bandwidth Classes

```
supportedBandCombinationExt-r10
 SupportedBandCombinationExt-r10 :
  [0] :
  [1] :
  [2] :
  [3] :
  [4] :
   supportedBandwidthCombinationSet-r10
    Binary string (Bin) : 01000000000000000000000000000000
     [0] : 0
     [1] : 1
     [2] : 0
     [3] : 0
     [4] : 0
     [5] : 0
     [6] : 0
     [7] : 0
     [8] : 0
     [9] : 0
     [10] : 0
     [11] : 0
     [12] : 0
     [13] : 0
     [14] : 0
     [15] : 0
     [16] : 0
     [17] : 0
     [18] : 0
     [19] : 0
     [20] : 0
     [21] : 0
     [22] : 0
     [23] : 0
     [24] : 0
     [25] : 0
     [26] : 0
     [27] : 0
     [28] : 0
     [29] : 0
     [30] : 0
     [31] : 0
```

Figure 10: Screenshot with UE Capabilities: Supported Band Combinations

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Table 5.6A.1-2: E-UTRA CA configurations and bandwidth combination sets defined for inter-band CA

E-UTRA CA configuration / Bandwidth combination set									
E-UTRA CA Configuration	E-UTRA Bands	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Maximum aggregated bandwidth [MHz]	Bandwidth combination set
CA_1A-5A	1				Yes			20	0
	5				Yes				
CA_1A-18A	1			Yes	Yes	Yes	Yes	35	0
	18			Yes	Yes	Yes			
CA_1A-19A	1			Yes	Yes	Yes	Yes	35	0
	19			Yes	Yes	Yes			
CA_1A-21A	1			Yes	Yes	Yes	Yes	35	0
	21			Yes	Yes	Yes			
CA_2A-17A	2			Yes	Yes			20	0
	17			Yes	Yes				
CA_2A-29A	2			Yes	Yes			20	0
	29		Yes	Yes	Yes				
CA_3A-5A	3				Yes	Yes	Yes	30	0
	5			Yes	Yes				
	3				Yes			20	1
	5			Yes	Yes				
CA_3A-7A	3			Yes	Yes	Yes	Yes	40	0
	7				Yes	Yes	Yes		
CA_3A-8A	3				Yes	Yes	Yes	30	0
	8			Yes	Yes				
	3				Yes			20	1
	8			Yes	Yes				
CA_3A-20A	3			Yes	Yes	Yes	Yes	30	0
	20			Yes	Yes				
CA_4A-5A	4			Yes	Yes			20	0
	5			Yes	Yes				
CA_4A-7A	4			Yes	Yes			30	0
	7			Yes	Yes	Yes	Yes		
CA_4A-12A	4	Yes	Yes	Yes	Yes			20	0
	12			Yes	Yes				
CA_4A-13A	4			Yes	Yes	Yes	Yes	30	0
	13				Yes				
	4			Yes	Yes			20	1
	13				Yes				
CA_4A-17A	4			Yes	Yes			20	0
	17			Yes	Yes				
CA_4A-29A	4			Yes	Yes			20	0
	29		Yes	Yes	Yes				
CA_5A -12A	5			Yes	Yes			20	0
	12			Yes	Yes				
CA_5A-17A	5			Yes	Yes			20	0
	17			Yes	Yes				
CA_7A-20A	7				Yes	Yes	Yes	30	0
	20			Yes	Yes				
CA_8A-20A	8			Yes	Yes			20	0
	20			Yes	Yes				
CA_11A-18A	11			Yes	Yes			25	0
	18			Yes	Yes	Yes			

NOTE 1: The CA Configuration refers to a combination of an operating band and a CA bandwidth class specified in Table 5.6A-1 (the indexing letter). Absence of a CA bandwidth class for an operating band implies support of all classes.
NOTE 2: For each band combination, all combinations of indicated bandwidths belong to the set
NOTE 3: For the supported CC bandwidth combinations, the CC downlink and uplink bandwidths are equal

Figure 11: 3GPP Excerpt with UE Capabilities - CA Configuration and Band Combination Sets

4.1.3 Features Directly Related to Carrier Aggregation

Multiple Timing Advance

It should be noted that the origin of the radio signals of the two cells, primary and secondary, must be from the same transmission point since the UE can only handle one timing advance value. Later UEs will support multiple timing advance values and these will be indicated in the parameter shown in **Figure 13** opposite, according to [10].

Other important UE capabilities affecting the performance include the following [10], [12]:

- SimultaneousPUCCH-PUSCH-r10
- CrossCarrierScheduling-r10
- MultiClusterPUSCH-WithinCC-r10
- NonContiguousUL-RA-WithinCC-List-r10
- RsrqMeasWideband

Once available, all these metrics are used to support CA functionalities at the PHY/MAC layer as described in section 3.3. Therefore, these metrics need to be monitored to troubleshoot a CA feature's operability as well as to evaluate possible performance limitations. Even though CA is fully operational today, many of the features like the ones above are introduced to utilize the spectrum in a much more efficient way, especially the interaction between the control channels and the user channel where there is room for improvements in current implementations. Scheduling of resources and utilizing the control channels between two carriers is a challenging task, especially in coming deployments where the control channel and data channels can be separated geographically.

The Feature Group Indicators (R10)

Residing in the UE Capability Information message, the Feature Group Indicators (R10) (featureGroupIndRel10 in [10]) includes meaningful functions for CA, namely the ones numbered 111, 112, and 113. As shown in the screenshot in **Figure 14**, current CA UEs support the event A6 reporting, which is used to indicate to the radio access network that the UE has found a neighboring cell that is better than the current secondary cell (with a configurable offset). Details on event A6 are presented in [10].

4.1.4 Performance Measurement

When deploying the secondary carrier, a two-fold end user throughput increase is expected. Therefore, it is important to check the throughput on different protocol layers. **Figure 15** presents a scenario in which the maximum throughput for a given specific configuration is tested in good RF conditions. It is very clear how the two physical layers (one per carrier) can be checked individually in the information element PDSCH Phy Throughput Per Carrier (kbit/s). TEMS Investigation also shows how the two layers are aggregated at higher layers (above PHY/MAC) where component carriers are no longer visible, as discussed in section 3.1-3.3.

Figure 15 also shows that a convenient way to check when two (or more) serving cells are activated is to check the information element called Serving Cell Count, indicating when you are in a CA enabled mode (value is higher than one (1)) or when in non-CA mode (value is equal to one (1)).

The performance of the two carrier components can be identified also by variations between the two physical carriers. The TEMS Investigation screenshot in **Figure 16** shows such a scenario, where due to the mismatch between the sampling of the PDCP and RLC throughput, unexpected higher throughput on PDCH than on RLC can be detected.

This kind of behavior can indicate a device malfunctioning, rather than a network problem, and therefore in these scenarios more detailed information on device operability needs to be collected and analyzed.

4.2 Network Optimization

4.2.1 Coverage

Coverage can easily be studied per carrier using serving cell measurements and by just simply selecting the carrier as the information element argument. These measurements can be then plotted on a map or as in the line chart in **Figure 17**. Important measures that describe the coverage per carrier include: signal strength on reference symbols (RSRP), Total received power (RSSI), Signal to interference on reference symbols (CINR/SINR), and the RSRP/RSSI relationship (RSRQ).

4.2.2 Neighbour Call Measurements

A well designed LTE network keeps the number of intra-frequency neighbors low in order to mitigate the interference. However, at the cell border, a number of neighbors can be found, and in a CA deployment, the number of detected neighbors can reach high numbers. Therefore, monitoring all these neighbors as well as their strength (as shown in **Figure 18**) is crucial in identifying and troubleshooting interference and handover issues, as well as in explaining performance degradations within the CA context.

4.2.3 Handover

Handover procedures play a significant role both in the optimization process and in performance evaluation. Monitoring the handover signaling procedures is crucial in understanding the performance improvement brought by the CA feature. **Figure 19** shows such a HO signaling procedure: eventA3 (defined by: “neighbor becomes better than PCell with an offset”) is reported and then followed by a handover to another cell where CA is also deployed (the lower chart shows the number of carriers in red). In addition, as shown in the screenshot in **Figure 20**, along with the normal measurements reported on the PCell, the SCell is included in the Measurement Report.

```
rf-Parameters
 supportedBandListEUTRA
  SupportedBandListEUTRA :
   [0] :
    bandEUTRA : 1
    halfDuplex : False
   [1] :
    bandEUTRA : 2
    halfDuplex : False
   [2] :
    bandEUTRA : 3
    halfDuplex : False
   [3] :
    bandEUTRA : 5
    halfDuplex : False
   [4] :
    bandEUTRA : 6
    halfDuplex : False
   [5] :
    bandEUTRA : 7
    halfDuplex : False
   [6] :
    bandEUTRA : 8
    halfDuplex : False
   [7] :
    bandEUTRA : 9
    halfDuplex : False
   [8] :
    bandEUTRA : 11
    halfDuplex : False
   [9] :
    bandEUTRA : 18
    halfDuplex : False
   [10] :
    bandEUTRA : 19
    halfDuplex : False
   [11] :
    bandEUTRA : 25
    halfDuplex : False
   [12] :
    bandEUTRA : 26
    halfDuplex : False
   [13] :
    bandEUTRA : 28
    halfDuplex : False
   [14] :
    bandEUTRA : 34
    halfDuplex : False
   [15] :
    bandEUTRA : 38
    halfDuplex : False
   [16] :
    bandEUTRA : 39
    halfDuplex : False
   [17] :
    bandEUTRA : 40
    halfDuplex : False
   [18] :
    bandEUTRA : 41
    halfDuplex : False
```

Figure 12: Screenshot of Supported LTE Bands in a February 2014 Device

```
BandCombinationParameters-v1130 ::= SEQUENCE {
    multipleTimingAdvance-r11       ENUMERATED {supported}                  OPTIONAL,
    simultaneousRx-Tx-r11           ENUMERATED {supported}                  OPTIONAL,
    bandParameterList-r11           SEQUENCE (SIZE (1..maxSimultaneousBands-r10)) OF BandParameters-
v1130   OPTIONAL,
```

Figure 13: Multiple Timing Advance Feature

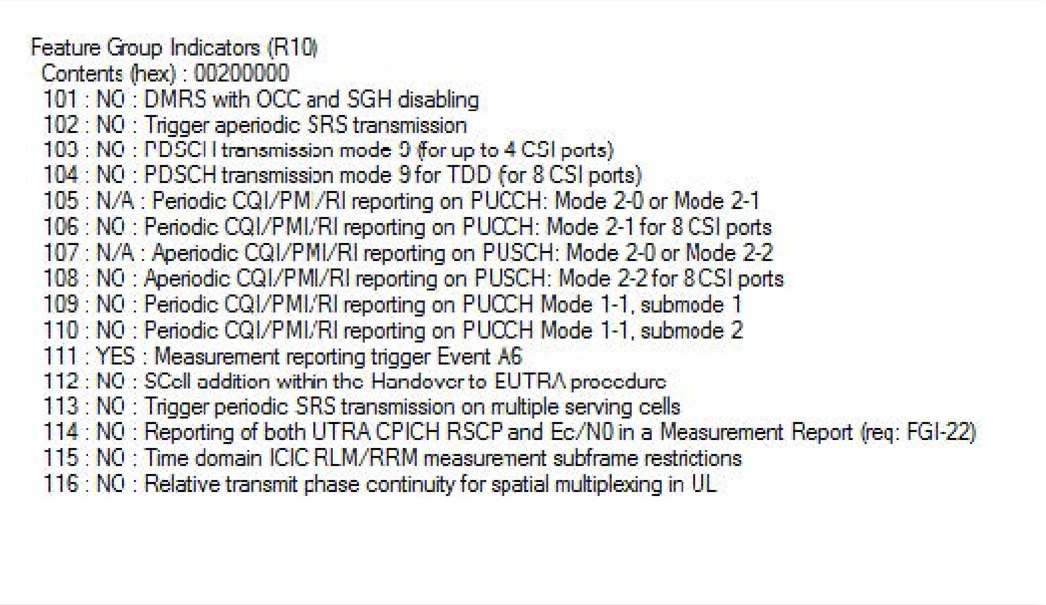

Feature Group Indicators (R10)
Contents (hex) : 00200000
101 : NO : DMRS with OCC and SGH disabling
102 : NO : Trigger aperiodic SRS transmission
103 : NO : PDSCH transmission mode 9 (for up to 4 CSI ports)
104 : NO : PDSCH transmission mode 9 for TDD (for 8 CSI ports)
105 : N/A : Periodic CQI/PMI/RI reporting on PUCCH: Mode 2-0 or Mode 2-1
106 : NO : Periodic CQI/PMI/RI reporting on PUCCH: Mode 2-1 for 8 CSI ports
107 : N/A : Aperiodic CQI/PMI/RI reporting on PUSCH: Mode 2-0 or Mode 2-2
108 : NO : Aperiodic CQI/PMI/RI reporting on PUSCH: Mode 2-2 for 8 CSI ports
109 : NO : Periodic CQI/PMI/RI reporting on PUCCH Mode 1-1, submode 1
110 : NO : Periodic CQI/PMI/RI reporting on PUCCH Mode 1-1, submode 2
111 : YES : Measurement reporting trigger Event A6
112 : NO : SCell addition within the Handover to EUTRA procedure
113 : NO : Trigger periodic SRS transmission on multiple serving cells
114 : NO : Reporting of both UTRA CPICH RSCP and Ec/N0 in a Measurement Report (req: FGI-22)
115 : NO : Time domain ICIC RLM/RRM measurement subframe restrictions
116 : NO : Relative transmit phase continuity for spatial multiplexing in UL

Figure 14: Screenshot UE Capabilities: Feature Group Indicator

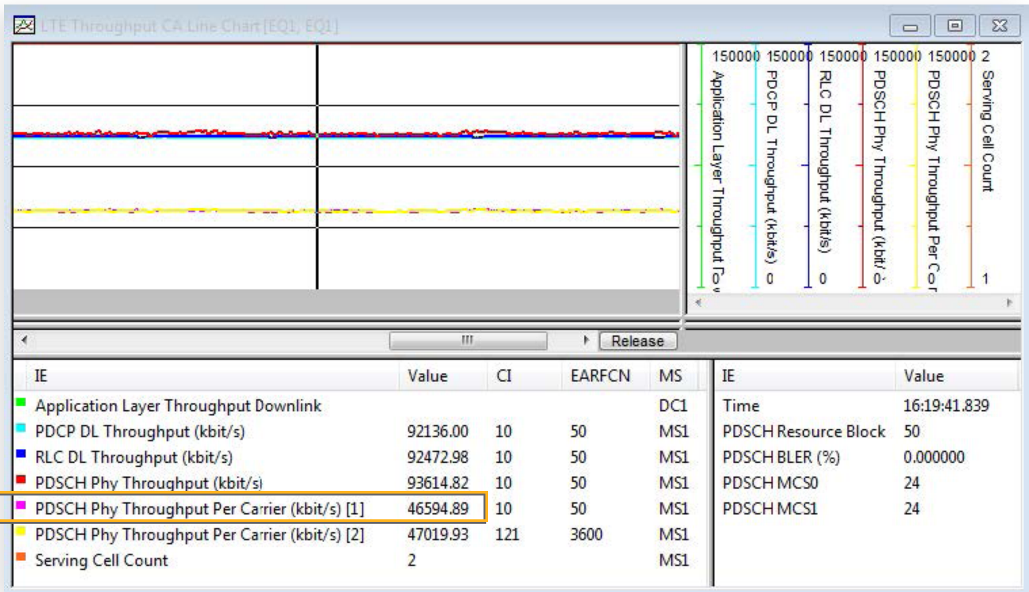


Figure 15: Screenshot Throughput at Various Layers

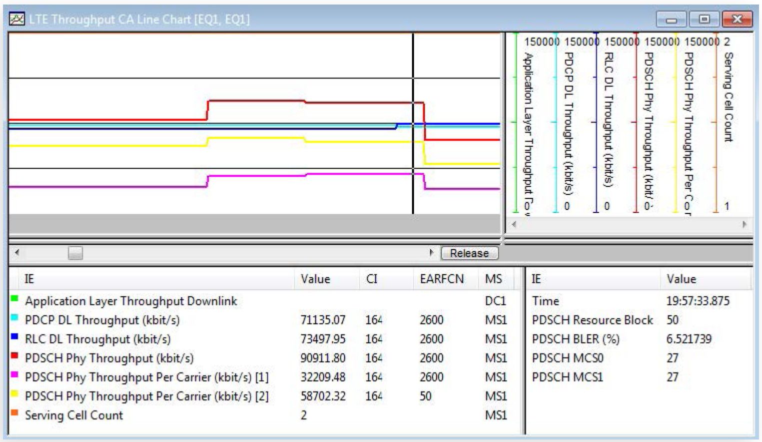


Figure 16: Carrier Component Throughput Variations

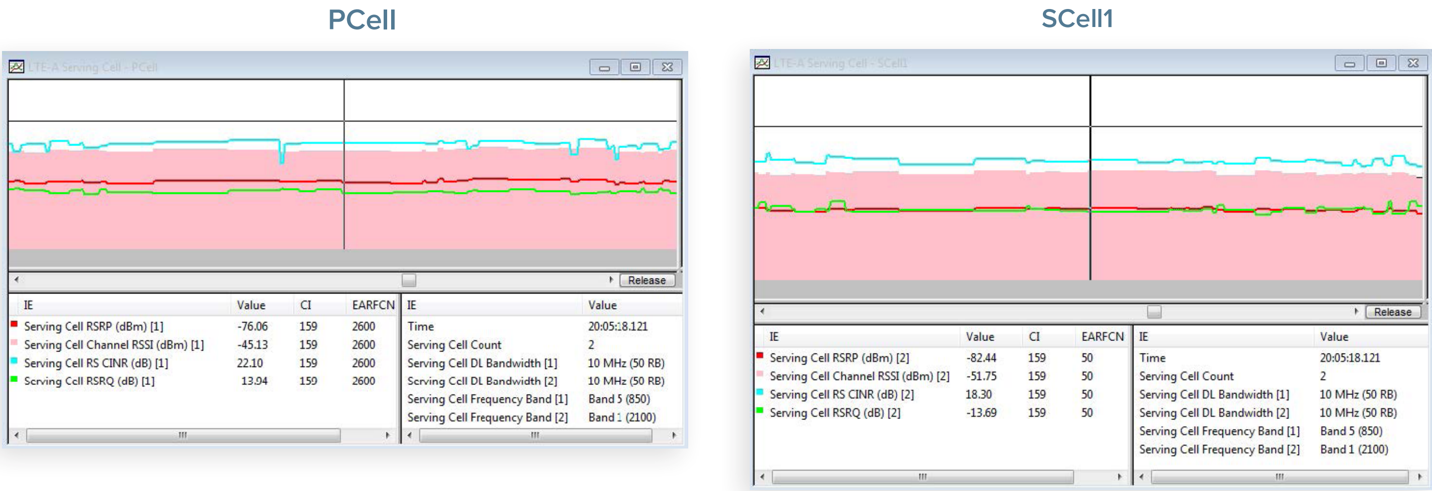
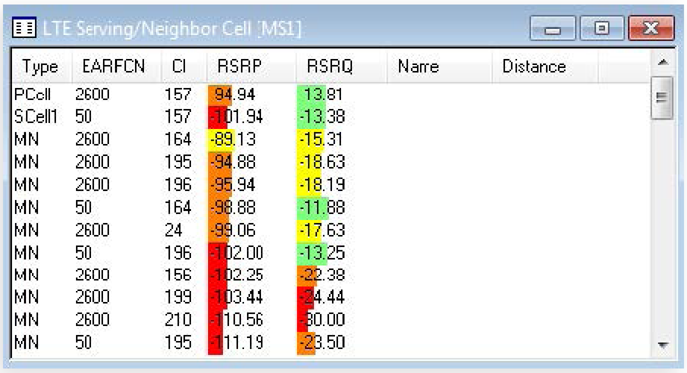


Figure 17: Screenshot: Coverage Performance per Carrier Component


LTE Serving/Neighbor Cell [MS1]

Type	EARFCN	CI	RSRP	RSRQ	Name	Distance
PCell	2600	157	94.94	13.81		
SCell1	50	157	-101.94	-13.38		
MN	2600	164	-89.13	-15.31		
MN	2600	195	-94.88	-18.63		
MN	2600	196	-95.94	-18.19		
MN	50	164	-98.88	-11.88		
MN	2600	24	-99.06	-17.63		
MN	50	196	-102.00	-13.25		
MN	2600	156	-102.25	-22.38		
MN	2600	199	-103.44	-24.44		
MN	2600	210	-110.56	-30.00		
MN	50	195	-111.19	-23.50		

Figure 18: Screenshot: Neighbour Call Measurements

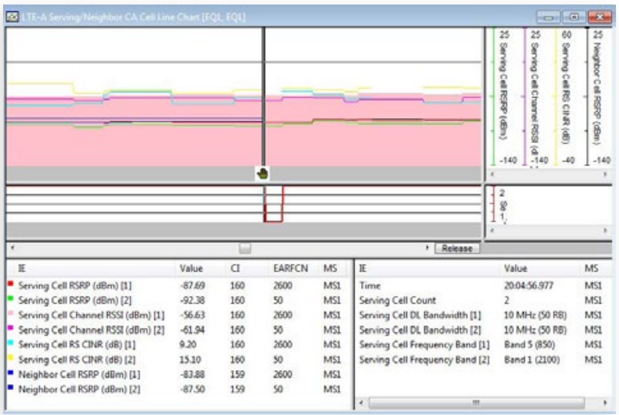


Figure 19: Screenshot: HO Signallling Procedures within CA Context

4.2.4 Pathloss

Using just downlink signal strength measurements on reference symbols (RSRP) misses one important aspect when optimizing the radio network: pathloss.

In a typical two-band deployment, the frequency of the two carriers can differ a lot. Due to the nature of the radio waves, attenuation is frequency dependent where higher frequencies attenuate more than lower ones. This means that traditional signal strength measurements based on RSRP do not map according to the expected coverage plans if the eNB output power is the same on both carriers. A better approach is to use the pathloss, defined as:

- Pathloss = eNB output power - received signal strength (RSRP)

Using this, a better understanding of the actual cell configuration and actual coverage of the two carriers can be achieved. In addition, tuning can be performed to get a good balance between the two carriers. In the future, UEs will support CA in the uplink too, and with that, an uplink/downlink balance per carrier can also be tuned.

The eNB output power is given by layer 3 signaling in RRC Connection Reconfiguration
(DL-DCCH), individually for the carriers as the:

- pdsch-ConfigCommon / referenceSignalPower: 15

Using pathloss, as shown in the screenshot in **Figure 21**, a benefit of a carrier difference of 8 to 10dB can be the result, using the same output power on both carriers, where one is on the 850 MHz band and the other on the 2100 MHz band.

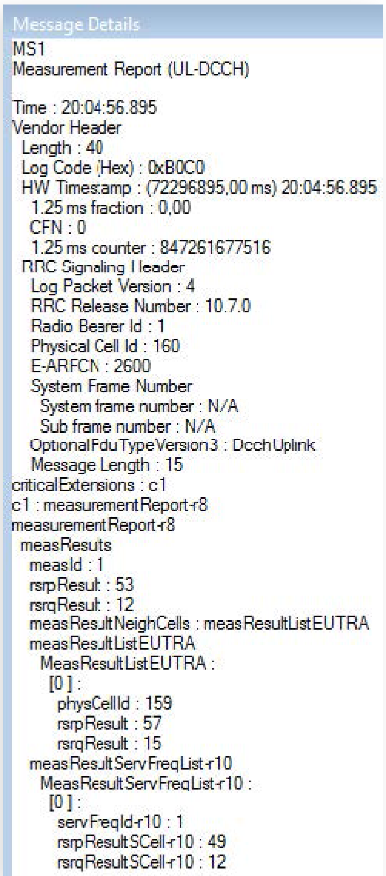


Figure 20: PCell and SCell Measurement Reports

Figure 22: Screenshot: Cells' Timing Verification within a CA Context

4.3 Troubleshooting

4.3.1 Cell Timing Variation

As discussed in section 3, a CA feature's performance is highly dependent on timing verification. Using TEMS Investigation, the timing between the serving cell carriers, as well as the timing to neighboring cells, can be easily checked. Current UEs only support one timing advance value so it is critical to monitor that the timing between the cells is correctly kept to avoid inter-symbol interference. In future CA deployments, with UEs capable of handling different timing advances to different carriers it will be possible to separate the control plane from the user plane. The control signaling can then originate from a macro cell, whereas the user data can originate from a high-speed small cell. Therefore, a smoother CA operation as well as CA support within the HetNet concept will be facilitated.

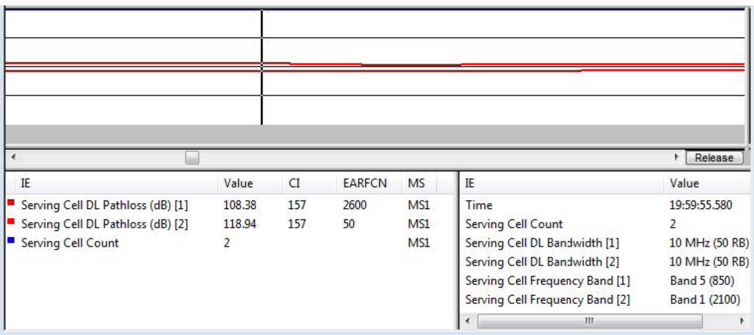


Figure 21: Screenshot: Pathloss on Carrier Component

LTE Serving/Neighbor Cell Frame Timing [MS1]

Type	EARFCN	CI	Timing Rx1	Timing Rx2	Offset Rx1	Offset Rx2
PCell	2600	164	284561	284561		
SCell1	50	164	284551	284551		
MN	2600	196	277583	277583	-6978	-6978
MN	2600	162	284595	284595	34	34
MN	50	162	284585	284585	26	26

Figure 23: Screenshot: SCell Parameter Settings

The **Figure 22** screenshot shows that the timing of the primary cell and the secondary cell is within tolerances. It also shows that the neighbor cells with cell ID 162 is up and running on the same site within tolerances. Cell ID 196 might be a non-CA cell, or at least it can be estimated that it is another site based on the timing.

4.3.2 Secondary Cell Assignment

TEMS Investigation ensures an easy verification of the SCell parameter setttings, if the cell's performance does not meet expectations. Secondary cell assignment is provided in RRC Connection Reconfiguration (**Figure 23**).

Per RX Antenna in the UE

In addition, as can be seen in the **Figure 24** screenshot, TEMS Investigation includes measurements per RX antenna, making it possible to detect if the device is at fault for performance requirements not met on the SCell. This is helpful for quickly ruling out problem causes that are unrelated to the network.

Figure 24: Screenshot: Measurements per Rx Antenna in the UE

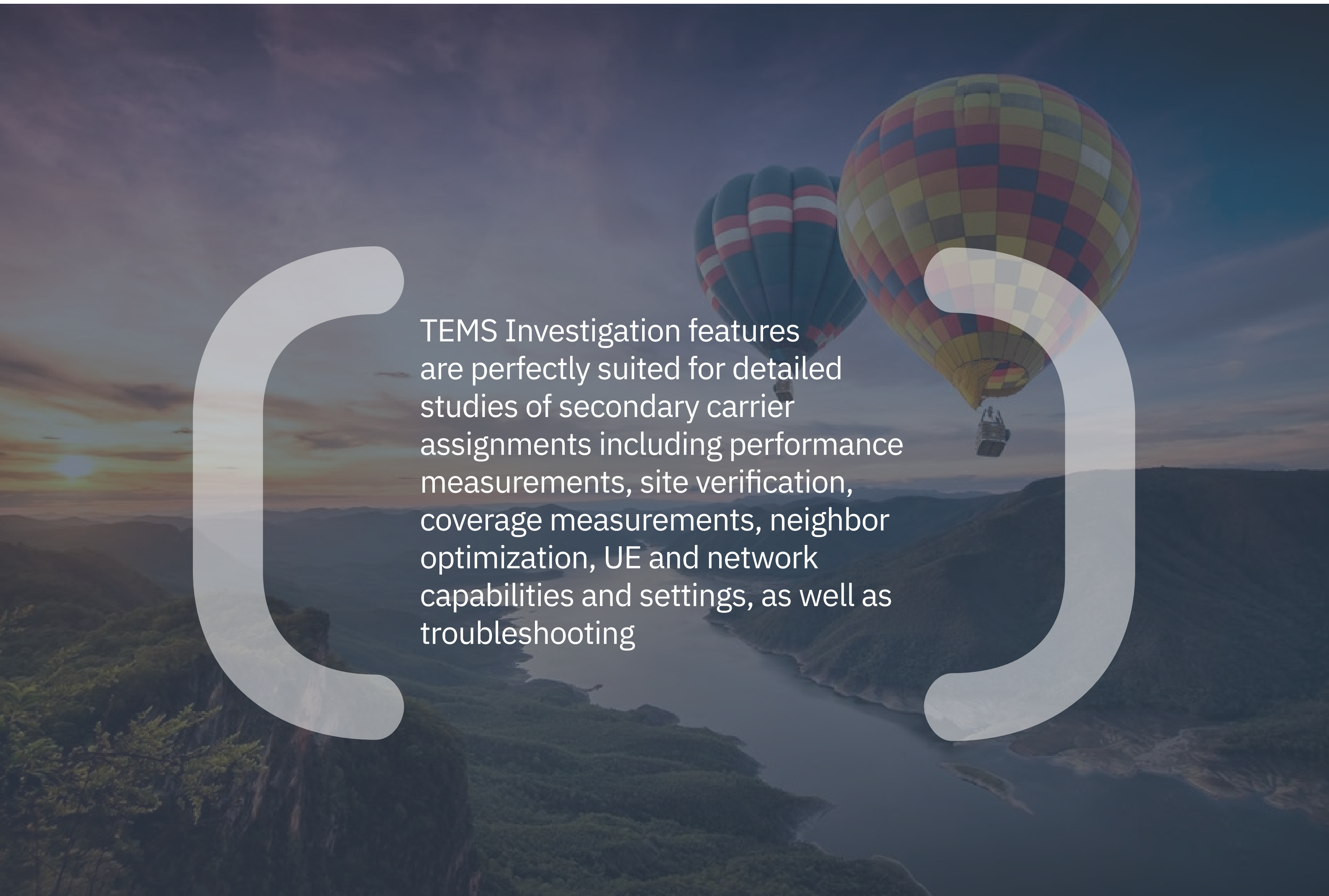
5.0 Conclusions

Carrier aggregation with various 3GPP defined bands and component carrier combinations is the fastest path for operators to increase data rates as well as improve efficient spectrum reutilization in various deployment scenarios. Inheriting the key designs of LTE Release 8 and 9 per component carrier, LTE-A CA (Release 10 and beyond) has the advantages of reducing implementation efforts for faster product availability and system deployment.

However, new capabilities that come from CA operability do require extensive verification, testing and monitoring of performance and events referring to:

- Data transmission over two clusters of contiguous bandwidth in the same carrierSimultaneous transmission of a control channel and a data channel in the PCell
- Data transmission from multiple antennas with spatial multiplexing
- Evaluation of improved CA design of downlink and uplink control to efficiently support improved data transmission speeds.

In addition, monitoring CA's impact on higher layers, such as cell and mobility management, as well as cell activation/deactivation events, is needed in order evaluate CA performance and maximize the benefits of CA functionality. UE-centric testing solutions, such as TEMS Investigation, which unveil UE behavior and correlate this with UE capabilities become key in CA scenario monitoring. In addition, TEMS Investigation features are perfectly suited for detailed studies of secondary carrier assignments including performance measurements, site verification, coverage measurements, neighbor optimization, UE and network capabilities and settings, as well as troubleshooting. The screenshots included in this paper demonstrate how TEMS Investigation can be easily used for CA testing and evaluation from the deployment to the optimization and troubleshooting phase. TEMS solutions for CA monitoring and performance evaluation will grow along with future contemplated CA functionality enhancements, especially in the area of uplink timing and the support of non-backward-compatible component carriers.



6.0 References

[1]. 3GPP TS 36.101,"E-UTRAN: User Equipment (UE) radio transmission and reception"

[2]. G. Yuan, et al, "Carrier Aggregation for LTE-Advanced Mobile Communication Systems," IEEE Communication Magazine, Feb.2011.

[3]. 3GPP TS 36.300, "E-UTRA and E-UTRAN; Overall description; Stage 2"

[4]. S. Yi, et al, "Radio Protocols for LTE and LTE-Advanced," Willey & Sons, 2012

[5]. 3GPP TS 36.321, "E-UTRAN - MAC Protocol specification"

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