LTE-Advanced Pro Introduction eMBB Technology Components in 3GPP Release 13/14

White paper

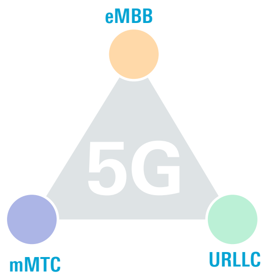
White paper | Version 01.00

ROHDE&SCHWARZ

Table of contents

When LTE was first specified as a fourth generation cellular communication technology, the main target use case was to provide high data rate services to mobile end users, e.g. smartphones. With the recent enhancements provided by 3GPP Release 10 through 3GPP Release 12, also known as LTE-Advanced, the mobile data use case remained dominant although additional improvements such as NB-IoT and device-to-device communications indicated optimization towards new and diverse use cases. From 3GPP Release 13 onwards, further improvements clearly lead towards the support of a triangle of use cases similar to those addressed by 5G. In addition to efficient support of enhanced mobile broadband services, the aim is to cost-efficiently support massive machine type connectivity as well as low latency and reliable communications motivated by vertical industries such as automotive, eHealth and robots. This white paper summarizes the LTE-Advanced Pro enhancements in 3GPP Releases 13 and 14 that address the mobile broadband use case. More detailed descriptions of the enhancements in 3GPP Releases 10, 11 and 12 are available in [1], [2] and [3].

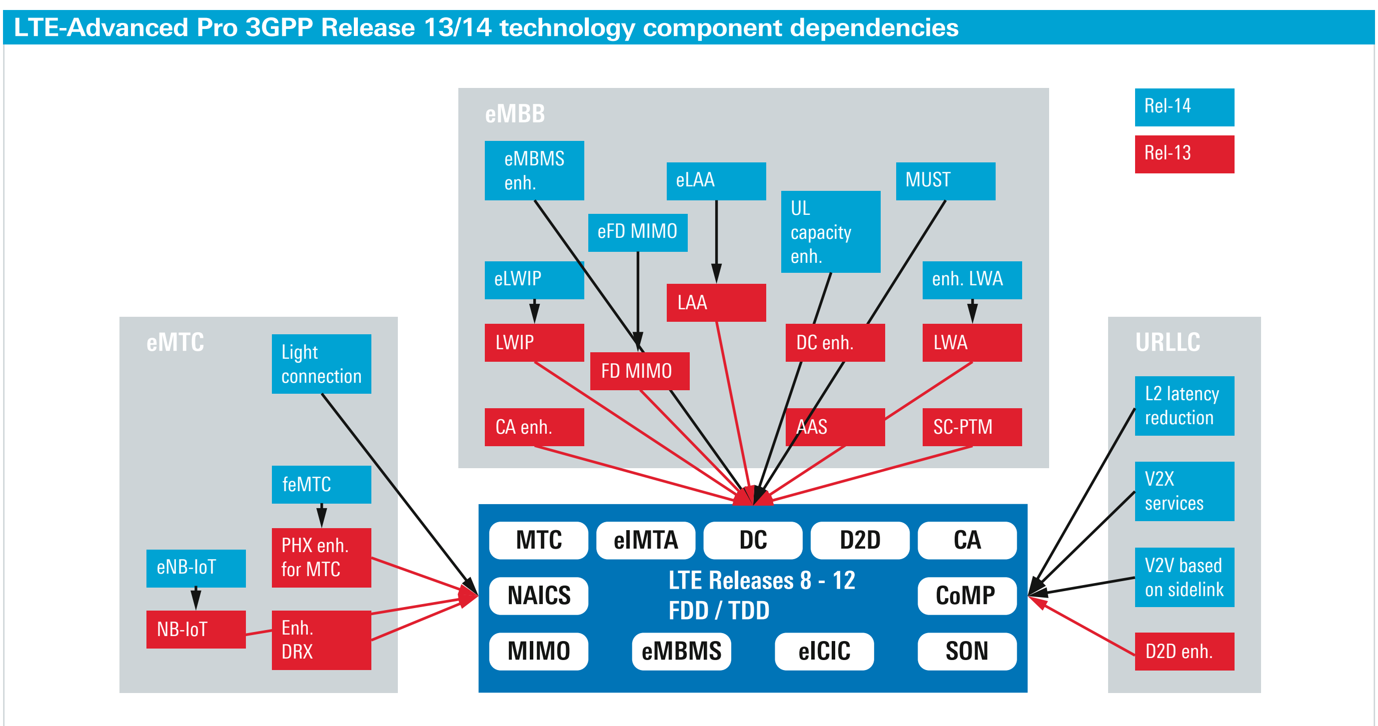
Introduction



Concrete and confined use cases such as mobile voice in 2G and mobile data in 4G dominated the definition of past cellular technologies. In contrast, 5G introduces a paradigm change towards a user/application centric technology framework that aims to support the following triangle of important use case families. The enhanced mobile broadband (eMBB) use case represents the well-known continuation of the ever-increasing requirement to support both higher peak data rates per user and more system capacity. Massive machine type communications (mMTC) describes a use case family that allows billions of devices to be connected in a cost-efficient way while not overloading the cellular network. In 5G, this is sometimes also referred to as massive Internet of Things (mIoT).

Ultra-reliable low-latency communications (URLLC) opens up an entirely new use case family whose aim is to support new requirements from vertical industries, e.g. autonomous driving from automotive, remote surgery from eHealth and robotics from Industry 4.0. The LTE-Advanced Pro technology components provided by 3GPP Releases 13 and 14 indicate a transition phase towards the coverage of this 5G use case triangle. Fig. 1.1 illustrates the technology component dependency on top of LTE-Advanced as specified up to and including 3GPP Release 12. Section 2 of this white paper provides a detailed description of the eMBB technology components.

Fig. 1.1: LTE-Advanced Pro 3GPP Release 13/14 technology component dependencies.



Section 3 concludes this white paper. Sections 4, 5 and 6 provide additional information, including a summary of LTE frequency bands and literature references.

2 LTE-Advanced Pro technology components relevant to eMBB

Since it was first introduced in 2010, LTE/LTE-Advanced technology has been continually improved by adding new technology components and enhancing existing ones. 3GPP has used the UE category concept since the initial specification of the LTE technology. For LTE specified in Release 8 to Release 11, a single UE category describes an overall capability. The UE also indicates support for individual capabilities via dedicated signaling as listed in [11]. This includes physical layer and RF parameters (e.g. supported frequency bands), inter-RAT parameters (e.g. FDD or TDD) and many more. Table 2.1 summarizes the UE capabilities in the DL and UL described by the UE category.

Table 2.1: UE capabilities based on UE category up to 3GPP Release 11.

UE category	Max. data rate in Mbps		CC		MIMO		Modulation		Comment
	DL	UL	DL	UL	DL	UL	DL	UL	
1	~ 10	~ 5	1	1	1	1	64QAM	16QAM	Initial specification as of 3GPP Release 8
2	~ 50	~ 25			2				
3	~ 100	~ 50							
4	~ 150								
5	~ 300	~ 75			4			64QAM	
6	~ 300	~ 50	1	1	4	1	64QAM	16QAM	Including enhanced MIMO schemes (DL/UL) and DL carrier aggregation as of 3GPP Release 11
			2		2/2				
7	~ 300	~ 100	1	1	4	2			
			2		2/2				
8	~ 3000	~ 1500	5	5	8	4		64QAM	
9	~ 450	~ 50	2	1	2/4	1	64QAM	16QAM	
			3		2/2/2				
10	~ 450	~ 100	2	1	2/4	2			
			3		2/2/2				
11	~ 600	~ 50	2	1	4/4	1			
			3		2/2/4				
			4		2/2/2/2				
12	~ 600	~ 100	2	1	4/4	2			
			3		2/2/4				
			4		2/2/2/2				

The base station needs to respect the signaled UE radio access capability parameters when configuring and scheduling the UE.

3GPP Release 12 introduced new separate categories in the downlink and uplink direction, i.e. instead of a single UE category, UE DL category and UE UL category fields are defined. This separation is maintained in subsequent 3GPP Releases. Table 2.2 provides an overview of DL capabilities related to the DL category field. Note that the number of component carriers (CC), the number of spatial layers (MIMO) and the modulations in Table 2.2 and Table 2.3 are examples, i.e. additional combinations are possible.

Table 2.2: UE DL capabilities based on UE DL category field up to 3GPP Release 14.

UE DL category	Max. data rate in Mbps	CC	MIMO	Modulation	Comment
11/12	~ 600	2	4/4	64QAM	256QAM added in 3GPP Release 12
			2/4	256QAM	
		3	2/2/4	64QAM	
			2/2/2	256QAM	
		4	2/2/2/2	64QAM	
13	~ 400	1	4	256QAM	
		2	2		
14	~ 4000	5	8	256QAM	
15	~ 750 - 800	2	4/4	256QAM	
		3	4/4/2	2*64QAM/256QAM	
		4	2/2/2/2	256QAM	
16	~ 1000	3	2/4/4	256QAM	
		3	4/4/4	2*64QAM/256QAM	
		4	2/2/2/4	256QAM	
		5	2/2/2/2/2	256QAM	
17	~ 25000	32	8	256QAM	Carrier aggregation beyond 5CC added in 3GPP Release 13
18	~ 1200	6	2/2/2/2/2/2	256QAM	
		4	4/4/4/4	64QAM	
		3	4/4/4	256QAM	
		2	4/8	256QAM	
19	~ 1600	8	2/2/2/2/2/2/2/2	256QAM	
		6	2/2/2/2/4/4	256QAM	
		4	4/4/4/4	256QAM	
		2	8/8	256QAM	
20	~ 2000	8	2/2/2/2/2/2/4/4	256QAM	
		5	4/4/44/4	256QAM	
		4	4/4/4/8	256QAM	
		3	4/8/8	256QAM	

Table 2.3 provides an overview of UL capabilities related to the UL category field.

Table 2.3: UE UL capabilities based on the UE UL category field up to 3GPP Release 14.

UE UL category	Max. data rate in Mbps	CC	MIMO	Modulation	Comment
13	~ 150	2	1	64QAM	256QAM added in 3GPP Release 14
14	~ 9600	32	2	64QAM	
15	~ 225	3	1	64QAM	
16	~ 105	1	1	256QAM	
17	~ 2100	5	4	256QAM	
18	~ 210	2	1	256QAM	
19	~ 13500	16	4	256QAM	
20	~ 315	3	1	256QAM	
21	~ 300	4	1	64QAM	

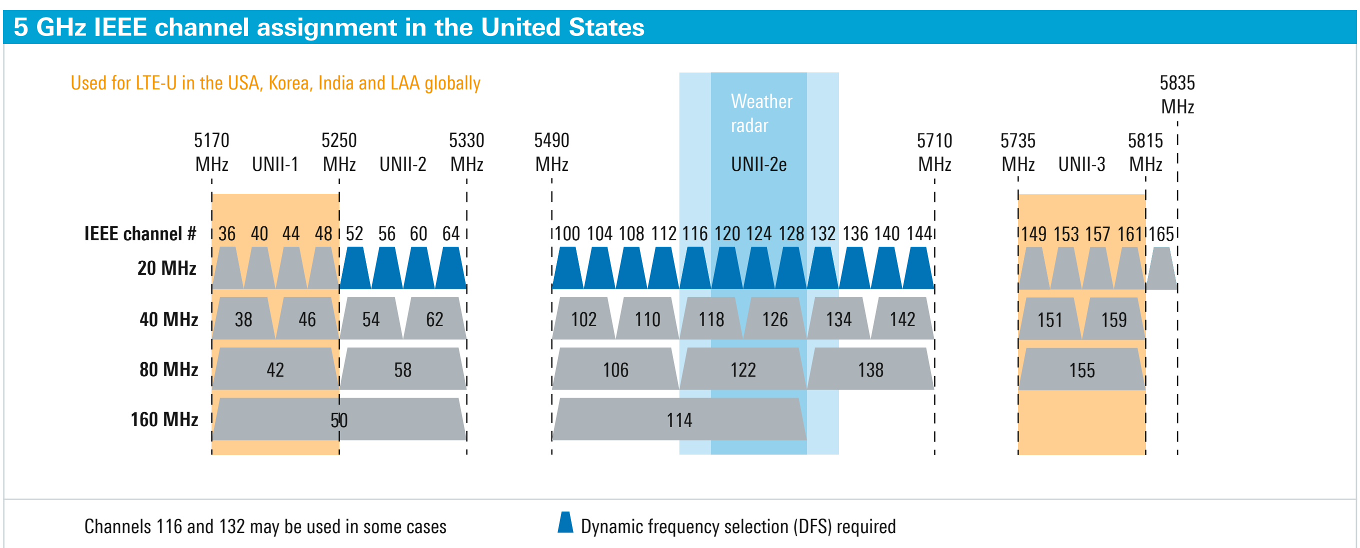
2.1 Efficient use of unlicensed frequency spectrum

2.1.1 Introduction

Spectrum is not an infinite resource, and spectrum assets used by already deployed wireless systems – both commercial and non-commercial – cannot easily be revoked. Regulators worldwide have therefore started looking into alternatives to use the available spectrum more efficiently while exploring the concept of shared spectrum. In the meantime, the cellular industry, led by several network operators, infrastructure vendors and chipset manufacturers, has eyed unlicensed spectrum, particularly the 5 GHz industrial, scientific and medical (ISM) band, to serve the immediate need for additional spectrum for mobile broadband applications due to the ever increasing mobile data traffic.

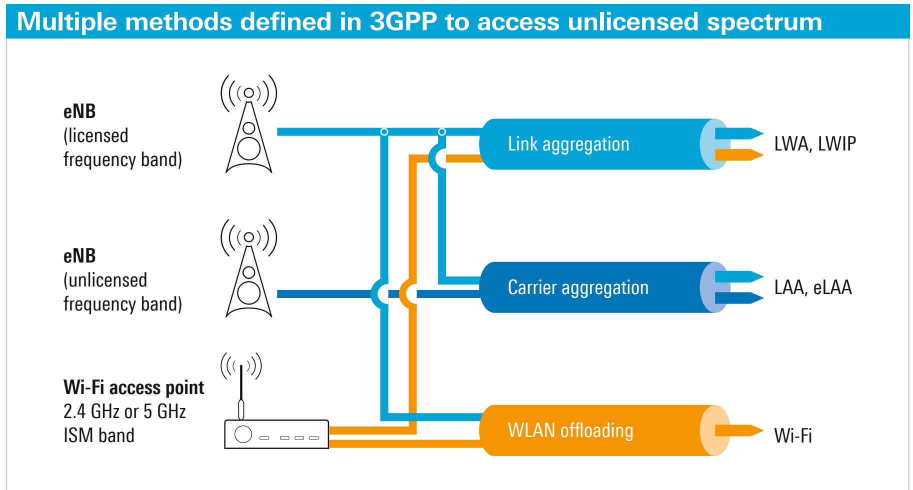
The ISM bands are generally defined by the ITU Radio Regulations (Article 5) [21], but are regulated differently by each region (e.g. ETSI in Europe or FCC in USA). The exact frequency allocation and detailed regulation depends on the country (e.g. South Korea vs. Japan). Fig. 2.1 shows as an example of the IEEE channel assignments for the 5 GHz ISM band in the United States.

Fig. 2.1: 5 GHz IEEE channel assignment in the United States.



3GPP has defined multiple ways to access the 5 GHz band. Which of these methods is used depends on the network operators' overall strategy and their existing network deployments. Fig. 2.2 shows these different methods from a high-level perspective.

Fig. 2.2: Multiple methods defined in 3GPP to access unlicensed spectrum.



In the following two sections, we discuss licensed assisted access (LAA, Release 13, section 2.1.2) and enhanced licensed assisted access (eLAA, Release 14, section 2.1.3). LAA/eLAA is the dominant method for accessing the unlicensed 5 GHz ISM band. It is favored by the majority of network operators worldwide and is therefore the focus of this section. For operators with existing WLAN deployments, two additional methods exist to combine both access technologies. These two methods are LTE-WLAN aggregation (LWA) and LTE-WLAN radio level integration with IPsec tunnel (LWIP). A high-level description is provided in section 2.1.4. For an introduction to WLAN offloading, please see the Rohde & Schwarz white paper [4].

To provide a complete picture, there are other non-standard-based industry alternatives, such as LTE in unlicensed spectrum (LTE-U) [1] and MuLTEFire [2], used to gain access to unlicensed spectrum. These two additional methods are not discussed in this white paper.

[1] See http://www.lteuforum.org/ for more details.

[2] MuLTEFire is a trademark of Qualcomm Incorporated; see https://www.multefire.org/ for further details.

2.1.2 Licensed-assisted access (LAA, Release 13)

2.1.2.1 Overview

Licensed-assisted access (LAA) is a 3GPP Release 13 feature that takes advantage of carrier aggregation. In LAA, the primary cell (PCell) is deployed in any licensed 3GPP band acting as an anchor carrier. Secondary cells (SCell) are used in Release 13 for downlink-only operation and are deployed in the 5 GHz ISM band (3GPP frequency band 46) to boost data rates. The regulatory requirements to access this frequency band have been captured in section 4 of [18]. Release 13 foresees deploying up to four LAA SCells in this frequency band. To enable this new functionality, additional features were introduced in Release 13 that can be summarized as follows:

- Frame structure type 3 and discontinuous transmission (partial subframe)
- Listen before talk
- Additional UE signal quality measurements for carrier selection

These features are analyzed in more detail in the following sections. The requirements for this feature set are based on the deployment scenarios and design targets listed in [18].

2.1.2.2 Frame structure type 3

The need to ensure fair sharing and coexistence with other technologies made it necessary to introduce frame structure type 3, which is defined in [7]. It is applicable to LAA secondary cell operation with normal cyclic prefix only. The radio frame duration for frame structure type 3 is still 10 ms. All 10 subframes [1 ms each] are available for downlink transmission, where a transmission can occupy one or more consecutive subframes, starting within a subframe at the first or second slot boundaries.

Limiting the flexibility to start a transmission only to slot boundaries simplifies implementation at the eNB end. The transmission also does not need to end with the subframe. Instead, the downlink pilot time slot (DwPTS) architecture from frame structure type 2 (TDD) is reused. That means the last subframe of the "LAA radio frame" can either be fully occupied or follow one of the DwPTS durations listed in Table 2.4.

Table 2.4: Configuration of special subframe[3].

Configuration of special subframe (lengths of DwPTS, GP, UpPTS)	
Special subframe configuration	Normal cyclic prefix in downlink DwPTS
0	$6952 \times T_s$
1	$19760 \times T_s$
2	$21952 \times T_s$
3	$24144 \times T_s$
4	$26336 \times T_s$
5	$6952 \times T_s$
6	$19760 \times T_s$
7	$21952 \times T_s$
8	$24144 \times T_s$
9	$13168 \times T_s$
10	$13168 \times T_s$

[3] Subset of Table 4.2-1 in [7].

To simplify implementation on the user equipment (UE) end, the start position and the number of OFDM symbols of the current and next downlink subframe in that LAA SCell is signaled to the device [see Fig. 2.3].

Fig. 2.3: Subframe transmitting start position via RRC signaling [14].

```
LAA-SCellConfiguration-r13 ::=          SEQUENCE {
    subframeStartPosition-r13               ENUMERATED {s0, s07},
    laa-SCellSubframeConfig-r13             BIT STRING (SIZE(8))
```

The number of occupied OFDM symbols in the last subframe of the transmission is signaled via downlink control information (DCI) format 1C scrambled with the cell controlling radio network temporary identifier (CC-RNTI).

Table 2.5: Subframe configuration for LAA in current and next subframe.

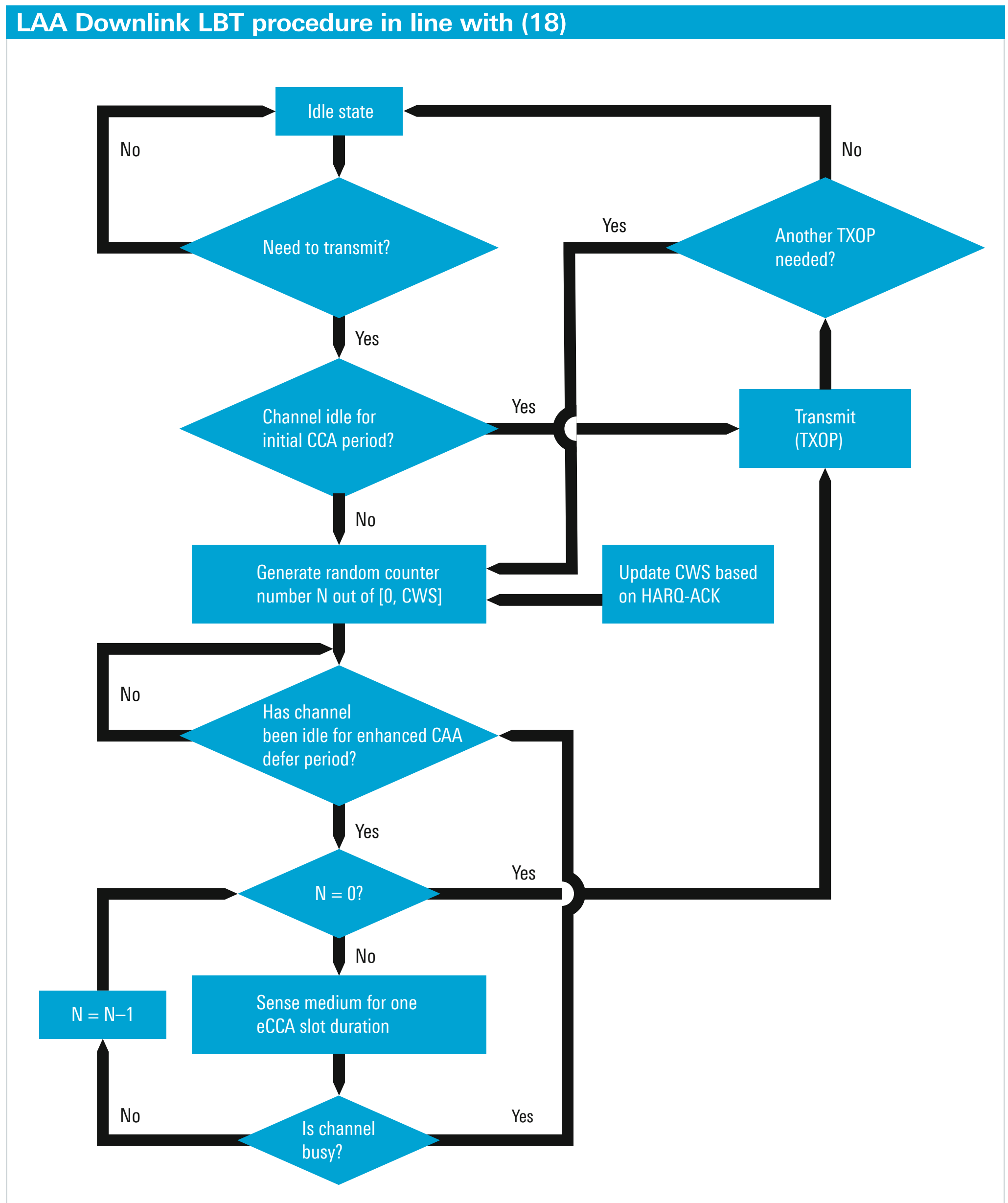
Value of 'Subframe configuration for LAA' field in current subframe	Configuration of occupied OFDM symbols (current subframe, next subframe)
0000	(–, 14)
0001	(–, 12)
0010	(–, 11)
0011	(–, 10)
0100	(–, 9)
0101	(–, 6)
0110	(–, 3)
0111	(14, *)
1000	(12, –)
1001	(11, –)
1010	(10, –)
1011	(9, –)
1100	(6, –)
1101	(3, –)
1110	reserved
1111	reserved
Note: (–, Y) means the UE may assume the first Y symbols in the next subframe are occupied and other symbols in the next subframe are not occupied. (X, –) means the UE may assume the first X symbols in the current subframe are occupied and other symbols in the current subframe are not occupied. (X, *) means the UE may assume the first X symbols in the current subframe are occupied and at least the first OFDM symbol of the next subframe is not occupied.	

No PBCH is transmitted within frame structure type 3.

2.1.2.3 Listen before talk

LAA ensures fair sharing and coexistence with other technologies using the 5 GHz ISM band by applying the listen before talk (LBT) principle to ensure minimum channel occupancy time. A category 4 LBT mechanism based on clear channel assessment (CCA) was adopted in LAA. Category 4 describes LBT mechanisms that use random backoff with a variable-sized contention window. The following flow chart describes the LBT procedure for LAA in the downlink direction.

Fig. 2.4: LAA Downlink LBT procedure in line with [18].



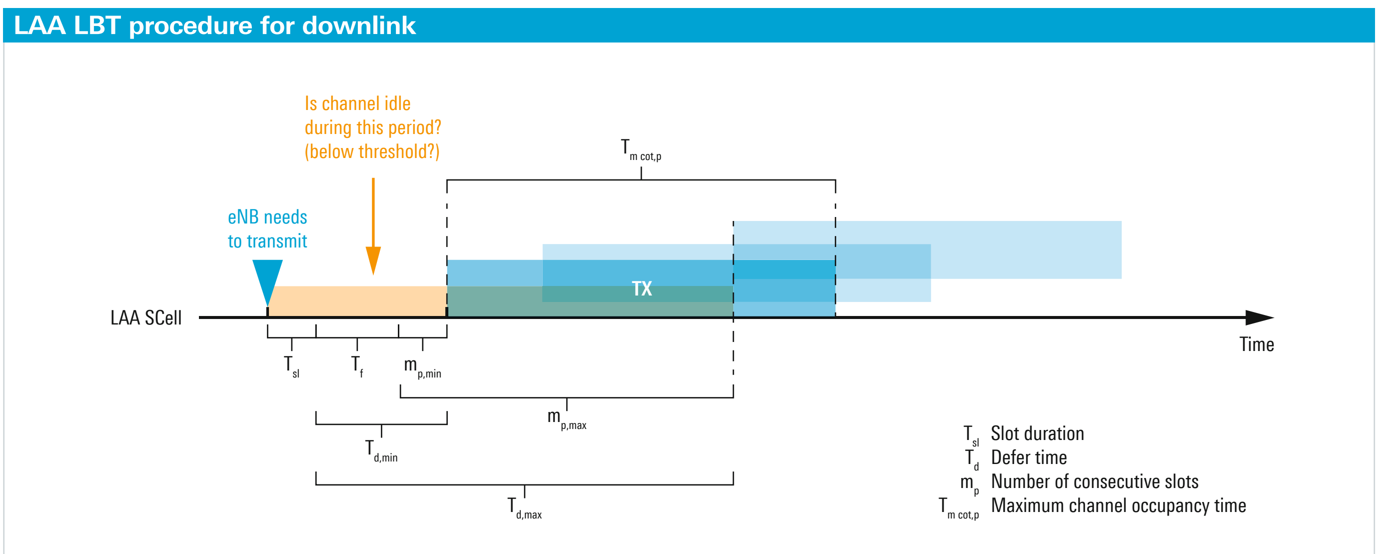
LAA applies CCA in two steps: an initial CCA and an enhanced CCA. In LAA, CCA is based on energy detection (ED) over a defined time duration that does not exceed a certain threshold value (ED threshold). In the presence of other technologies, such as Wi-Fi, the ED threshold is defined as shown in Equation 2 1. In general, the threshold is scenario and deployment dependent since T_{max}(dBm)= –75 dBm/MHz + 10 $\log_{10}$ BW, P_H is defined with +23 dBm and T_A is an adjustable parameter that depends on the type of transmission. For data transmission T_A=10 dB; for transmission of the discovery signal (see section 2.1.2.5), T_A=5 dB.

Equation 2.1: Definition of energy detection (ED) threshold in LAA [9].

$$X_{Thres\_max} = \max \left\{ \begin{array}{l} -72 + 10 \cdot \log 10(BWMHz/20MHz)\ dBm, \\ \min \left\{ \begin{array}{l} T_{max}, \\ T_{max} - T_A + \left(P_H + 10 \cdot \log 10(BWMHz/20MHz) - P_{TX}\right) \end{array} \right\} \end{array} \right\}$$

With a channel bandwidth (BW) of 20 MHz for LAA SCells and a maximum base station output power of +24 dBm that corresponds to a typical small cell (= local area base station, see [6]), the detection threshold ED can vary between –72 dBm/20 MHz (for data) and –68 dBm/20 MHz (for the discovery signal). The detected energy level needs to be below this threshold for a certain amount of time with a slot duration T_{sl} and defer time T_d. T_{sl} is 9 µs, where $T_d = T_f + m_p$ with $T_f = 16\ \mu s$. m_p is based on the channel access priority class and is therefore traffic type dependent and has a duration of at least one slot. The defer time is required to specifically protect Wi-Fi ACK/NACK transmission between access points and clients. As a result, the channel needs to be idle for an initial CCA period of 34 µs and a maximum wait time of 88 µs before an LAA-capable eNB can start its transmission.

Fig. 2.5: LAA LBT procedure for downlink.



If the channel is sensed to be clear, the transmitter can only transmit for a limited amount of time defined as the maximum channel occupancy time ($T_{m\,cot,p}$). If the channel is sensed to be occupied during that time or after a successful transmission, the "enhanced CCA" period is started by generating a random number that is within the contention window (CW). Since there are different traffic types (VoIP, video, background traffic, etc.), different channel priority access classes have been defined with different CW sizes and $T_{m\,cot,p}$ [Table 2.6].

Table 2.6: Channel access priority class for LAA downlink.[4)]

Channel access priority class (p)	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{mcot,p}$	allowed CW_p sizes
1	1	3	7	2 ms	{3,7}
2	1	7	15	3 ms	{7,15}
3	3	15	63	8 or 10 ms	{15,31,63}
4	7	15	1023	8 or 10 ms	{15,31,63,127,255,511,1023}

4) For access classes 3 and 4, $T_{(m\,cot,p)}$ is 8 ms in the presence of other technologies such as Wi-Fi, otherwise it is 10 ms.

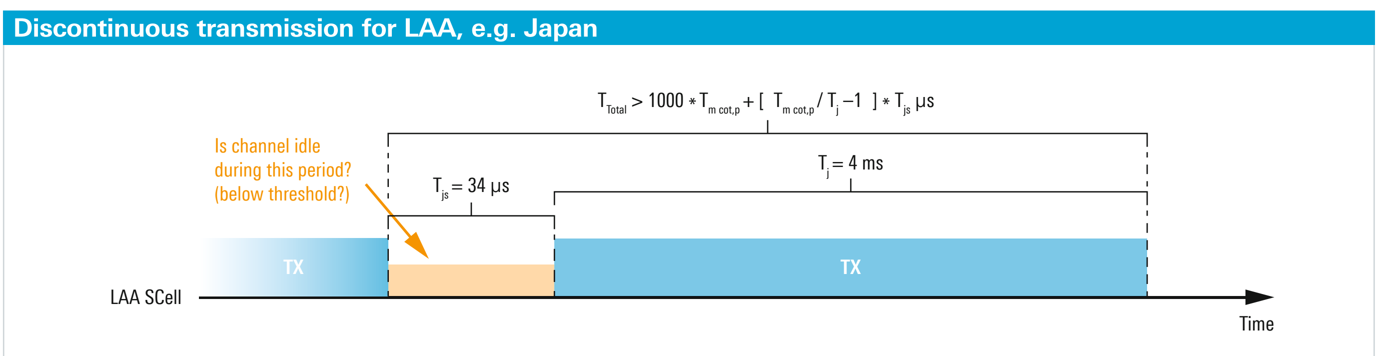
CW_p (= CW size) is selected before every transmission and set to be $CW_{min,p}$ based on the channel access priority class. The random backoff counter N is now chosen from that range, e.g. channel priority class 3 (best effort traffic) takes a value between 0 and 15. The eNB now senses the channel for one slot duration [9 µs] and if the channel is idle, it decrements the counter by 1. Assuming the channel stays idle, the base station continues with this procedure until N = 0. If the channel is not idle after one slot duration, the eNB has to sense the channel for an additional period – the defer time T_d. If the channel is detected to be idle during T_d, the eNB decrements the counter N by 1 and continues with the procedure until N = 0.

The counter N is impacted by the HARQ process. If more than 80% of all transmissions in reference subframe k are NACK/DTX, CW_p is incremented to the next possible value. For priority class 3, that would be 31.

2.1.2.4 Discontinuous transmission

For LAA operation in some geographical regions (e.g. Japan), discontinuous transmission is part of the specification. An eNB can transmit again on the LAA SCell for a maximum duration of 4 ms (T_j) immediately after sensing the channel to be idle for a sensing interval of 34 µs (T_{js}).

Fig. 2.6: Discontinuous transmission for LAA, e.g. Japan.



The total transmission time needs to be less than the equation shown in Fig. 2.6. The transmission time T_j can therefore only become maximum if the maximum channel occupancy time ($T_{(m\,cot,p)}$) is 2 or 3 ms, i.e. if the channel access priority class is either 1 or 2.

2.1.2.5 Discovery reference signal in LAA

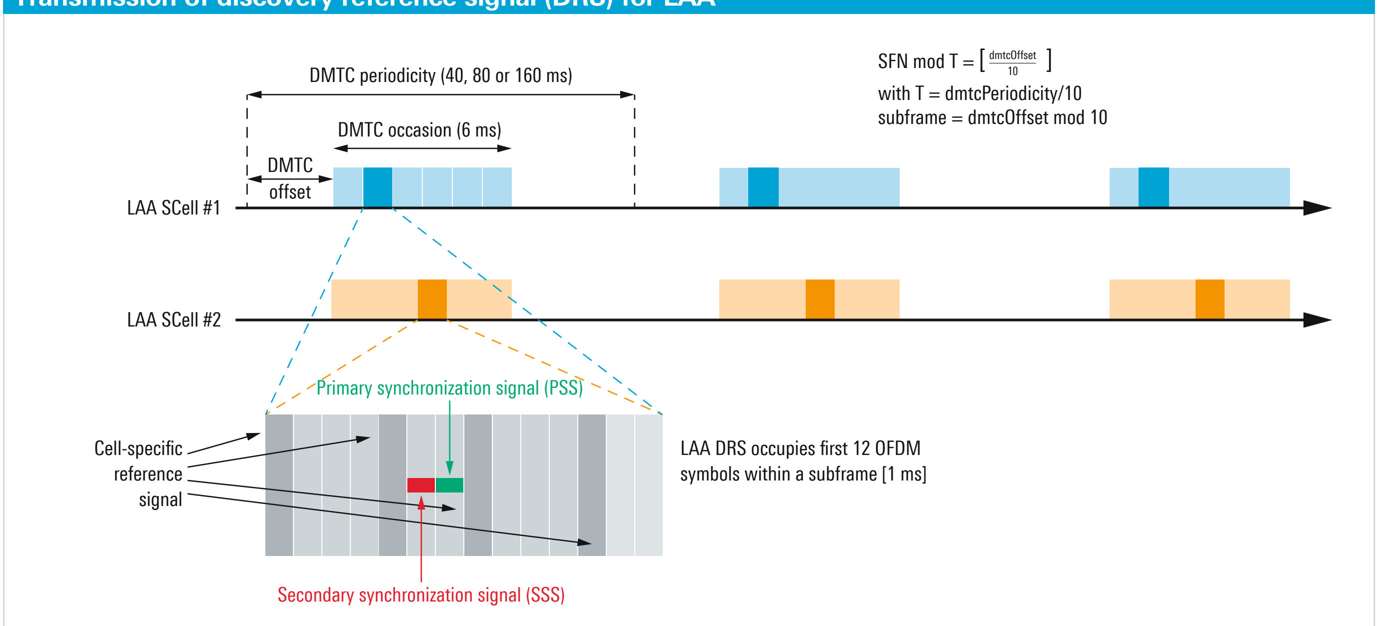
The discovery reference signal (DRS) was introduced in 3GPP Release 12 as part of a feature set for enhancement towards small cell operation. A small cell (typically deployed as a secondary cell (SCell)) does not need to be 'on' all the time. However in this case, a UE cannot make quality measurements on that SCell and thus the network cannot efficiently decide when to turn the cell back on. DRS was therefore introduced to allow a small cell to quickly transition from the off state to the on state and transmit a low duty cycle signal for radio resource management (RRM) purposes. In Release 12, DRS consists of the first 5 subframes of a radio frame to include PSS/SSS, PBCH and reference signals[5] that are transmitted with a periodicity of 40, 80 or 160 ms.

This concept has been adopted for LAA. DRS can be transmitted in any subframe within the discovery measurement timing configuration (DMTC) occasion that is 6 ms long. Only one subframe and only the first 12 OFDM symbols of this subframe are used for transmission. No PBCH is transmitted. PDSCH is only transmitted if it is scheduled in that particular subframe, in which case DRS is embedded with the data. Generally speaking, DRS transmission can be seen as a transmission on an unloaded carrier.

The radio frame and subframe in which DRS can be transmitted depends on the RRC parameters (dmtcOffset, dmtcPeriodicity) that are signaled to the device.

Fig. 2.7: Transmission of discovery reference signal (DRS) for LAA.

Transmission of discovery reference signal (DRS) for LAA



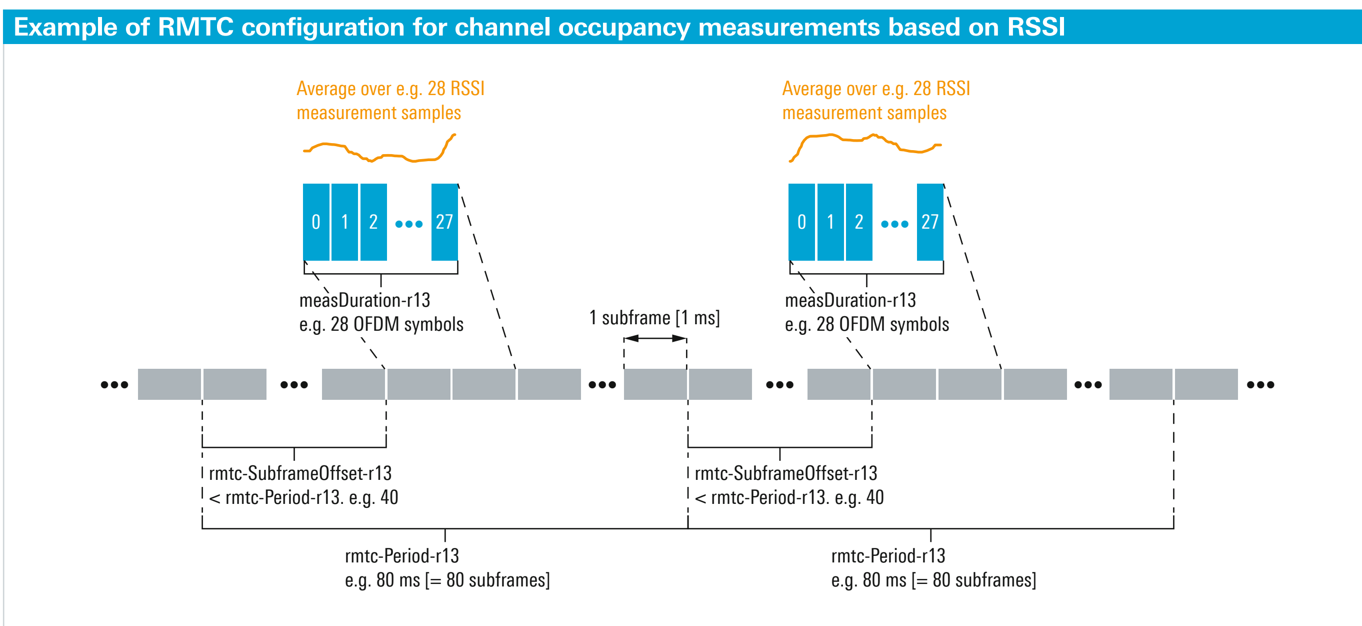
DRS is subject to the LBT principle and is therefore not necessarily transmitted as periodically as indicated in Fig. 2.7.

5) Cell-specific reference signals and channel state information reference signals (CSI-RS; if configured).

2.1.2.6 Radio resource management in LAA

Coexistence with other technologies is very important for LAA and therefore accessing and using already congested frequencies/channels that are used by Wi-Fi access points and clients should be avoided. Since radio resource management (RRM) is critical for this task, LTE defines signal quality measurements such as reference signal received power (RSRP [dBm]) and reference signal received quality (RSRQ [dB]). RSRQ is derived from RSRP over RSSI [10], where RSSI can serve as the key performance indicator for interference on a given carrier. To measure RSSI, DRS needs to be present. But since DRS is subject to LBT, any RSSI measurement report of an LAA-capable UE needs to include time information on when the measurements were taken. Therefore higher layers configure an RSSI measurement time configuration (RMTC) with a measurement period [40, 80, 160, 320 or 640 ms], a subframe offset [0…639] and a measurement duration [1, 14, 28, 42 or 70 OFDM symbols]. The device averages the RSSIs over the measurement duration and takes measurements according to the signaled periodicity [see Fig. 2.8].

Fig. 2.8: Example of RMTC configuration for channel occupancy measurements based on RSSI.



The device reports the average RSSI as well as the channel occupancy (CO), which is defined as the percentage of measured RSSI samples above a predefined (RSSI) threshold that is also signaled by higher layers. Both measures provide an indication of the load and interference situation on the given LAA SCell.

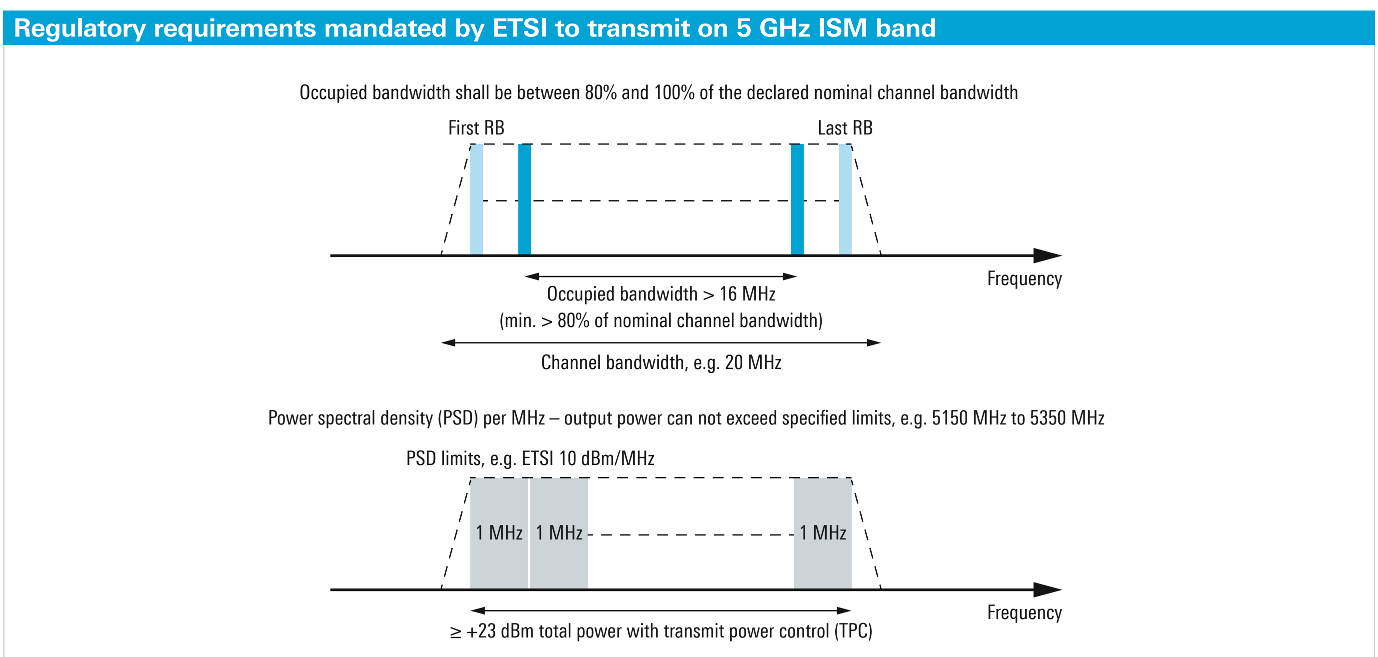
2.1.3 Enhanced LAA (eLAA, Release 14)

2.1.3.1 Introduction

Enhanced licensed assisted access (eLAA) is part of 3GPP Release 14. It defines how user equipment can access the 5 GHz ISM band to transmit data in the uplink direction. The first major difference to LAA is that generally all uplink transmissions in LTE are scheduled and therefore under the control of the serving LTE base station (eNB). Since this affects the channel contention between devices, the required LBT scheme that was defined in LAA for downlink operation needs to be adapted to work in the uplink direction.

The second major difference is the regulatory requirements that have to be fulfilled while using the 5 GHz ISM band in certain regions. For example, the European Telecommunication Standardization Institute (ETSI) mandates that the occupied channel bandwidth, defined by 3GPP to be the bandwidth containing 99% of the power of the signal, shall be between 80% and 100% of the declared nominal channel bandwidth. As an initial approach, multi-cluster PUSCH operation, standardized in 3GPP Release 10, was considered to fulfill this ETSI requirement. Multi-cluster PUSCH allows two clusters of resource blocks to be scheduled far enough from each other to fulfill e.g. the 80% bandwidth requirement. The upper portion of Fig. 2.9 illustrates this requirement.

Fig. 2.9: Regulatory requirements mandated by ETSI to transmit on 5 GHz ISM band.



Further investigation by 3GPP's contributing members have shown that multi-cluster PUSCH is not the most efficient way to address this requirement and therefore another solution was required.

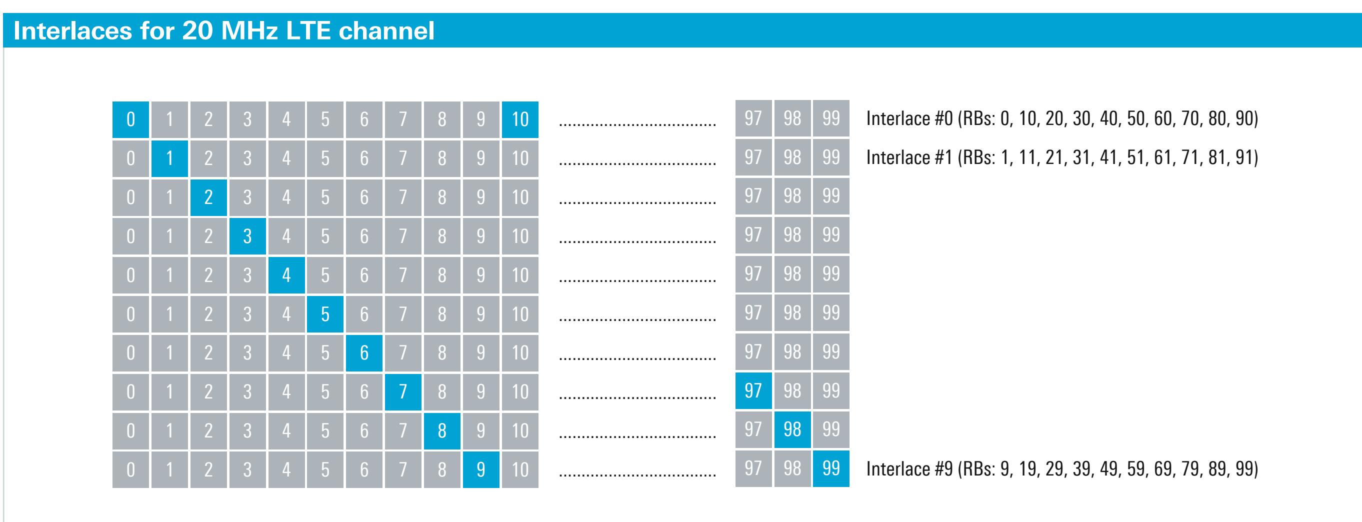
2.1.3.2 New uplink waveform for eLAA

A second requirement that made an approach other than multi-cluster PUSCH necessary was the power spectral density (PSD) limits defined for the 5G GHz ISM band. As an example, the 10 dBm/MHz defined by the ETSI for the 5150 MHz to 5350 MHz frequency range is shown in Fig. 2.9. For 5470 MHz to 5725 MHz, the ETSI allows a PSD of 17 dBm/MHz if transmit power control can be applied [9]. The U.S. regulator, the Federal Communication Commission (FCC), defines a PSD of 11 dBm/MHz for the 5150 MHz to 5350 MHz frequency range.

In conclusion, 3GPP adapted the principle of block interleaved frequency division multiplex (B-IFDMA) for eLAA. The available number of resource blocks are organized in interlaces that are equally spaced in the frequency domain. A UE can now transmit on one or multiple interlaces. Like in generic LTE uplink transmissions, the total number of allocated resource blocks still needs to be a multiple of 2, 3 or 5 to minimize the complexity of the discrete Fourier transformation (DFT). To embed this specific access mode into the standard, 3GPP Release 14 standardized a new uplink resource allocation type 3 that is only applicable for LAA [9]. As a result, two new scheduling grants (DCI format 0A/0B, 4A/4B) have been introduced. Formats 0A and 4A schedule single subframes for single antenna (0A) and multi-antenna (4A) transmission. Formats 0B and 4B allow scheduling of up to four consecutive subframes for SISO and MIMO, respectively.

Like all existing DCI formats, these new uplink grants provide the UE with a resource indication value (RIV) that is either 5-bit or 6-bit (5-bit for 10 MHz channel and 6-bit for 20 MHz channel). The RIV represents a start value (RBStart) and the actual number of allocated resource blocks L. For a 20 MHz wide LTE channel, corresponding to 100 RB, there are ten interlaces with 10 RB/interlace. Interlace #0 contains resource blocks {0, 10, 20, 30, 40, 50, 60, 70, 80, 90} (see Fig. 2.10).

Fig. 2.10: Interlaces for 20 MHz LTE channel.



Let's assume the device transmits on 4 out of the 10 available RBs per interlace (L=4). In that case, the RIV is calculated according to [9] as RIV = N(L-1)+RBStart. With N = 10 due to 20 MHz LTE channel bandwidth (L=4), RBStart can have a value between 0 and 6 and thus RIV can be between 30 and 36. The RIV is signaled with the DCI format to the device. In addition to this and other information, the DCI format also includes the method on how to access the channel, i.e. how to perform LBT in the uplink.

2.1.3.3 LBT for eLAA

There are two channel access types defined for eLAA. Which one the UE has to use is signaled with the uplink scheduling grant (DCI format 0A, 0B, 4A, 4B).

The type 1 channel access procedure is identical to the procedure for LAA, which is described in this document in section 2.1.2.3. The difference is that there are separate channel access priority classes defined for the uplink. These are listed in Table 2.7.

Table 2.7: Channel access priority class for eLAA uplink.

Channel access priority class (p)	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{mcot,p}$	allowed CW_p sizes
1	2	3	7	2 ms	{3,7}
2	2	7	15	4 ms	{7,15}
3	3	15	1023	6 ms or 10 ms	{15,31,63,127,255,511,1023}
4	7	15	1023	6 ms or 10 ms	{15,31,63,127,255,511,1023}

Type 2 is a procedure similar to transmitting DRS in the downlink (see section 2.1.2.5). After sensing that the channel is idle for 25 µs, the device can start its PUSCH transmission.

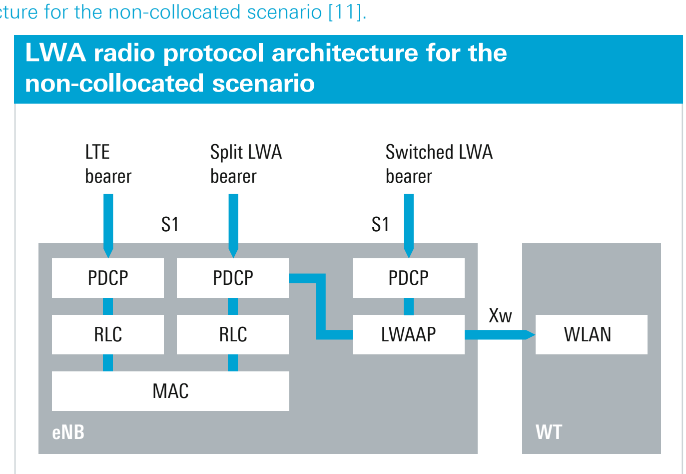
2.1.4 LTE-WLAN radio level integration and interworking enhancement (LWA and enhanced LWA)

One main aspect of DC in 3GPP Release 13 is dual connectivity for LTE and WLAN (known as LWA), which was further extended in 3GPP Release 14 to eLWA.

LWA is actually quite similar to LTE-LTE DC, but it uses WLAN as a secondary cell. LTE always serves as the MeNB, and for 3GPP Release 13, only LTE carries the UL. WLAN is used as an additional downlink resource in an SeNB, which in LWA is called the WLAN termination node (WT).

Since the WLAN access point is not necessarily collocated with the LTE eNodeB (eNB), a new interface between these two entities is required in order to exchange control and data traffic. This is called the Xw interface, which is considered a non-ideal connection between the eNB and the WT (see Fig. 2.11).

Fig. 2.11: LWA radio protocol architecture for the non-collocated scenario [11].



The WT does not require a core network connection, which is a major benefit of LWA. It can however be connected to the core network using ePDG as in 3GPP Release 12 WLAN offloading to provide both LWA and offloading functionality using the same WLAN network. However both features, LWA and WLAN offloading, cannot be operated at the same time or with the same UE.

Since the WLAN system does not support RLC and does not know radio bearers, a new protocol, the LTE-WLAN aggregation adaptation protocol (LWAAP) specified in 3GPP TS36.360, is implemented to generate LWA PDUs. LWAAP adds data radio bearer (DRB) IDs to each PDCP PDU to identify the PDCP/RLC instances and forwards these LWA PDUs to the WT by encapsulating them in a Wi-Fi MAC packet.

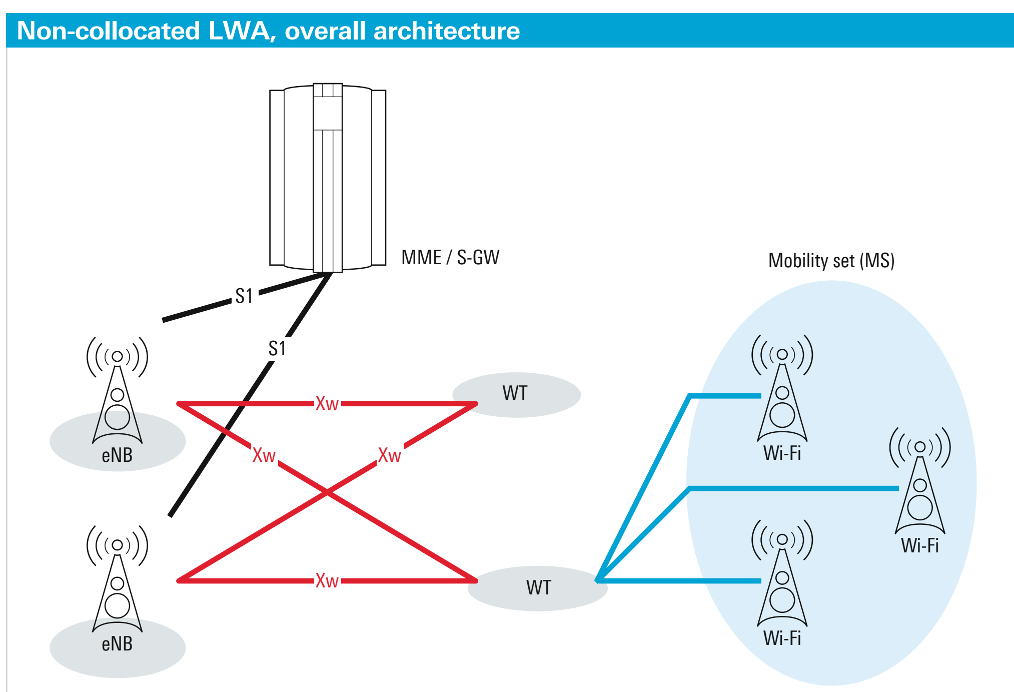
The WT forwards the LWA PDUs to the UE using an IEEE 802.3 specified LWA EtherType where two octets are used to indicate which protocol is encapsulated in the payload and to identify that the packet is for an LWA bearer.

The scheduling decision to send a PDU via LTE or via WLAN is done at the eNB. Since both ways are possible but might cause different delays to the PDCP PDUs, a reordering mechanism is required at the receiver. This is the same mechanism used for LTE DC in 3GPP Release12.

2.1.4.1 LWA mobility

Within LWA, UE mobility transparent to the eNB is supported in a WLAN mobility set, i.e. a group of WLAN access points that are controlled by one WT logical entity. As long as the UE moves between APs of the same mobility set, it does not need to inform the LTE eNodeB about this movement.

Fig. 2.12: Non-collocated LWA, overall architecture [11].



Only when the UE leaves the mobility set (inter WLAN mobility set mobility) does the eNB decide to change the access point based on WLAN measurements and signal the UE accordingly.

In addition to LWA, 3GPP Release 13 specifies other ways of LTE/WLAN interworking that are not directly related to dual connectivity and therefore not discussed in detail in this section.

One way is LWIP, which uses an IPsec tunnel to connect LTE and WLAN above the PDCP layer and bypasses the LTE U-plane protocol stack. In contrast to LWA, the LWIP does not require any changes on the WLAN network.

Another way is RAN controlled LTE WLAN interworking (RCLWI) specified in 3GPP Release 13, which is an extension to the 3GPP Release 12 WLAN offloading functionality and is intended to provide better performance by moving the decision to offload data traffic from the core network to the eNB.

With the 3GPP Release 14 enhancements of LWA (eLWA), features similar to the ones for LTE DC in 3GPP Release 13 have been introduced, for example:

- Uplink data transmission on WLAN including UL bearer switch and bearer split.
  This extension basically makes it possible to configure a UL bearer split and run an additional UL on the WT WLAN connection.
- Avoidance of bearer switching during eNB handover.
  Similar to the LTE DC extension in Rel.13, this feature makes it possible to keep the WT connection unchanged during an LTE MeNB handover procedure.
- Interworking with WLAN in line with IEEE 802.11ax, IEEE 802.11ad, IEEE 802.11ay.
  Here the main improvements focus on the higher frequency ranges up to 60 GHz for WLAN IEEE 802.11ad and IEEE 802.11ay as well as on the higher data rate handling for those WLAN standards that require PDCP optimizations.
- Improved performance through better estimation and reporting of available WLAN capacity.
  This extension is intended to improve the overall performance of LWA by increasing the probability of finding and utilizing available WLAN resources.
- Improved discovery of WLAN via automatic neighbor relation. Similar to the above extension, this feature is also intended to help in discovering and utilizing more WLAN resources.

2.2 Carrier aggregation beyond 5CC

Technology component carrier aggregation was first introduced in 3GPP Release 10. The maximum number of aggregated 20 MHz LTE carriers was limited to five, i.e. the maximum aggregated bandwidth supported by a single UE was 100 MHz. A number of arguments provided the motivation to extend the available carrier aggregation framework until 3GPP Release 12, i.e. the ability to aggregate FDD and TDD carriers and the increasing number of LTE frequency bands, including availability of unlicensed spectrum. 3GPP Release 13 enables the support of up to 32 component carriers. The principle of carrier aggregation was kept, but a number of modifications were required as described in the following subsections. From a principle perspective, two PUCCH cell groups are defined, which requires configuring at least two uplink carriers for the UE. PUCCH transmission is therefore possible on two serving cells, i.e. on PCell for SCells in PUCCH cell group 1 or on SCell configured by higher layers to carry PUCCH for SCells in cell group 2. The UE informs the base station about its extended capabilities to support more than 5 carriers as part of its Layer 1 capability signaling (e.g. including the newly defined fields `aperiodicCSI-reporting or crossCarrierScheduling-B5C)` [12].

2.2.1 Physical layer impact of CA beyond 5CC

The same scheme is used in the downlink direction, i.e. resources are scheduled on each single carrier or cross-carrier scheduling is applied. In the case of cross-carrier scheduling, the known 3-bit carrier indication field (CIF) is used. CIF provides index information about the carrier that carries PDCCH for resource allocation.

In the uplink direction, more comprehensive modifications were required to cover the increased amount of feedback control data such as ACK/NACK information and CSI reporting. Two additional PUCCH formats 4 and 5 are defined in TS 36.211 as shown in Table 2.8. In both cases, one demodulation reference symbol per slot is included. PUCCH format 4 is similar to PUSCH, i.e. a certain number of physical resource blocks (3 bits) are used and an index number provides the starting PRB. PUCCH format 5 comprises one physical resource block and applies an additional orthogonal sequence, i.e. multiplexing of multiple users is possible.

Table 2.8: Supported PUCCH formats [9].

PUCCH format	Modulation scheme	Number of bits per subframe, M_{bit}
1	N/A	N/A
1a	BPSK	1
1b	QPSK	2
2	QPSK	20
2a	QPSK+BPSK	21
2b	QPSK+QPSK	22
3	QPSK	48
4	QPSK	$M_{\mathrm{RB}}^{\mathrm{PUCCH4}} \cdot N_{\mathrm{sc}}^{\mathrm{RB}} \cdot \left(N_0^{\mathrm{PUCCH}} + N_1^{\mathrm{PUCCH}}\right) \cdot 2$
5	QPSK	$N_{\mathrm{sc}}^{\mathrm{RB}} \cdot \left(N_0^{\mathrm{PUCCH}} + N_1^{\mathrm{PUCCH}}\right)$

$M_{\mathrm{RB}}^{\mathrm{PUCCH4}}$ represents the bandwidth of PUCCH format 4 in terms of resource blocks and corresponds to the higher layer parameter `numberOfPRB-format-r13` (see Table 2.10).

N_0^{PUCCH} and N_1^{PUCCH} are given in Table 2.9.

Table 2.9: The quantities N_0^{PUCCH} and N_1^{PUCCH}

Subframe type	Normal cyclic prefix		Extended cyclic prefix	
	N_0^{PUCCH}	N_1^{PUCCH}	N_0^{PUCCH}	N_1^{PUCCH}
Normal subframe	6	6	5	5
Shortened subframe	6	5	5	4

Table 2.10: Number of PRBs for PUCCH format 4 $M_{\mathrm{RB}}^{\mathrm{PUCCH4}}$ corresponding to higher layer parameter `numberOfPRB-format4-r13`.

Value of `numberOfPRB-format4-r13`	$M_{\mathrm{RB}}^{\mathrm{PUCCH4}}$
0	1
1	2
2	3
3	4
4	5
5	6
6	8
7	Reserved

Note that one DMRS symbol is defined for both PUCCH formats 4 and 5 (see Table 2.11)

Table 2.11: Demodulation reference signal location for different PUCCH formats.

PUCCH format	Set of values for l	
	Normal cyclic prefix	Extended cyclic prefix
1, 1a, 1b	2, 3, 4	2, 3
2, 3	1, 5	3
2a, 2b	1, 5	N/A
4, 5	3	2

Like for up to 5CC carrier aggregation, the UE can be configured to provide aperiodic CSI reports using the CSI request field in the DCI format. The CSI request bits in DCI format 0 and DCI format 4 are enhanced to a 3-bit field (in contrast to a 2-bit field) for more than 5CC (see [11]).

The downlink assignment index (DAI) is the value transmitted to the UE. The DAI indicates the number of downlink subframes with PDCCH that are to be acknowledged. and thus the number of DL HARQ-ACK reports that are to be transmitted on either the uplink or on the PUSCH/PUCCH channel. In order to allow the increased amount of feedback with the higher number of aggregated carriers, the number of bits of the DAI field is increased to 4 (formerly 2 bits). The 4-bit field consists of a 2-bit counter DAI $V_{C-DAI,c}^{DL}$ and a 2-bit total DAI V_{T-DAI}^{DL}. The details of the HARQ reporting procedure are described in TS 36.213, section 7.3. See Table 2.12 for the details on DAI values.

Table 2.12: Value of counter DAI and total DAI.

DAI MSB, LSB	$V_{C-DAI,c}^{DL}$ or V_{T-DAI}^{DL}	Number of serving cells with PDSCH transmission associated with PDCCH/EPDCCH and serving cell with PDCCH/EPDCCH indicating DL SPS release
0,0	1	1 or 5 or 9 or 13 or 17 or 21 or 25 or 29
0,1	2	2 or 6 or 10 or 14 or 18 or 22 or 26 or 30
1,0	3	3 or 7 or 11 or 15 or 19 or 23 or 27 or 31
1,1	4	0 or 4 or 8 or 12 or 16 or 20 or 24 or 28 or 32

The uplink power control procedure is modified to reflect PUCCH formats 4 and 5, in particular the bandwidth and amount of feedback (see TS 36.213). The UE transmit power PPUCCH for the physical uplink control channel (PUCCH) transmission in subframe i for serving cell c is defined by:

$$P_{\mathrm{PUCCH}}(i)=\min\left\{\begin{array}{l}P_{\mathrm{CMAX,c}}(i)\\ P_{0\_\mathrm{PUCCH}}+PL_c+10\log_{10}\left(M_{\mathrm{PUCCH,c}}(i)\right)+\Delta_{\mathrm{TF,c}}(i)+\Delta_{\mathrm{F\_PUCCH}}(F)+g(i)\end{array}\right\}$$

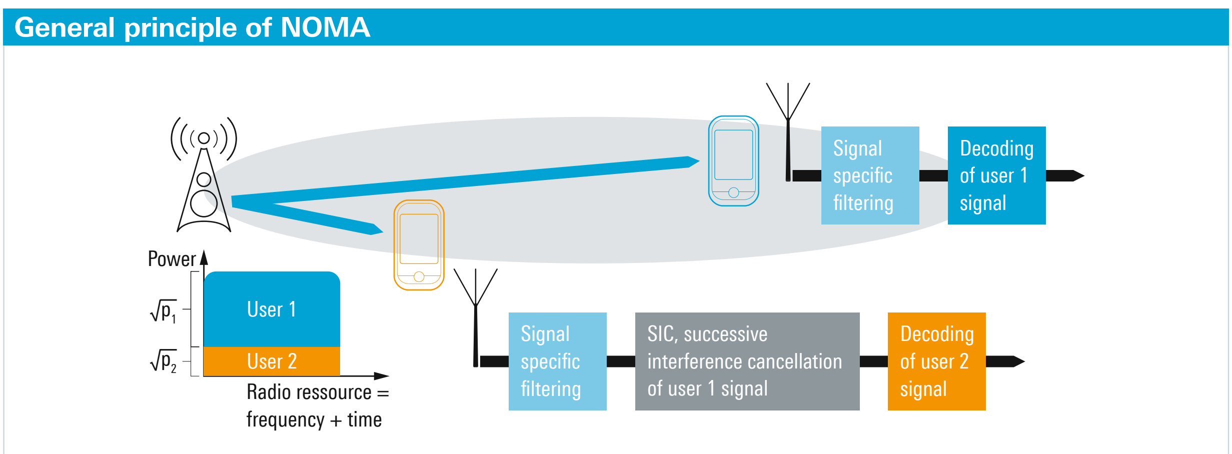
The terms $P_{CMAX,c}(i)$, PL_c, $\Delta_{FPUCCH}(F)$ and g(i) are the same as in the existing procedure. The following changes are introduced with $M_{PUCCH,c}(i)$ and $\Delta_{TF,c}(i)$:

- For PUCCH format 4, $M_{PUCCH,c}(i)$ is the bandwidth of PUCCH format 4 expressed in number of resource blocks valid for subframe i and serving cell c. For PUCCH format 5, $M_{PUCCH,c}(i) = 1$.
- $\Delta_{TF,c}(i) = 10 \log_{10}(2^{1.25 \times BPRE(i)} - 1)$ where $BPRE(i) = O_{UCI}(i)/N_{RE}(i)$,
  - $O_{UCI}(i)$ is the number of HARQ-ACK/SR/RI/CQI/PMI bits including CRC bits transmitted on PUCCH format 4/5 in subframe i;
  - $N_{\mathrm{RE}}(i)=M_{\mathrm{PUCCH,c}}(i)\cdot N_{sc}^{RB}\cdot N_{\mathrm{symb}}^{\mathrm{PUCCH}}$ for PUCCH format 4 and $N_{\mathrm{RE}}(i)=N_{sc}^{RB}\cdot N_{\mathrm{symb}}^{\mathrm{PUCCH}}/2$ for PUCCH format 5;
  - $N_{\mathrm{symb}}^{\mathrm{PUCCH}}=2\cdot\left(N_{\mathrm{symb}}^{\mathrm{UL}}-1\right)-1$ if shortened PUCCH format 4 or shortened PUCCH format 5 is used in subframe i and $N_{\mathrm{symb}}^{\mathrm{PUCCH}}=2\cdot\left(N_{\mathrm{symb}}^{\mathrm{U}}-1\right)$ otherwise.

2.3 Multiuser superposition transmission (MUST)

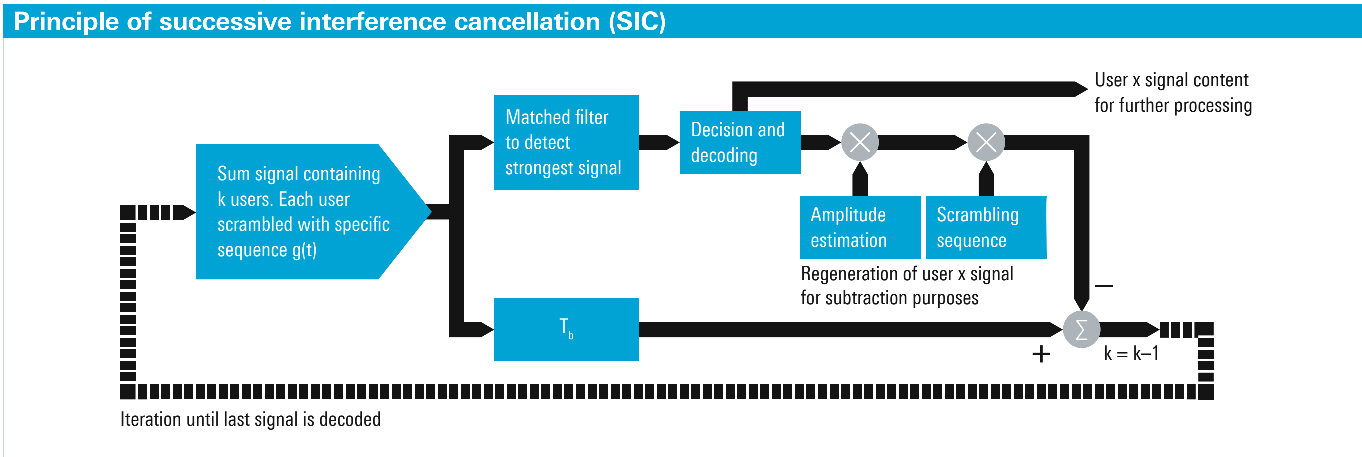
The 3GPP technical report TR 36.859 [16] contains a proposal concept for joint optimization of multiuser (MU) operation from both the transmitter and receiver perspectives. The idea is that, like in 3G WCDMA systems, multiple signals from different users will be jointly transmitted in common time and frequency radio resources. Challenges and discussion topics include what this joint transmission will look like and how the signal detection and separation can be performed. The reason for the proposal is the potential to further improve multiuser system capacity even if the transmission/precoding is non-orthogonal, which could result from, but is not limited to, the simultaneous transmission of a large number of non-orthogonal beams/layers with the possibility of more than one layer of data transmission in a beam. The academic background is non-orthogonal multiple access (NOMA), which allows multiple users to share the same resource elements without spatial separation and allows system capacity for networks to be improved [19]. Fig. 2.13 describes this principle.

Fig. 2.13: General principle of NOMA, e.g. two UEs in near and far situation sharing same radio resource.



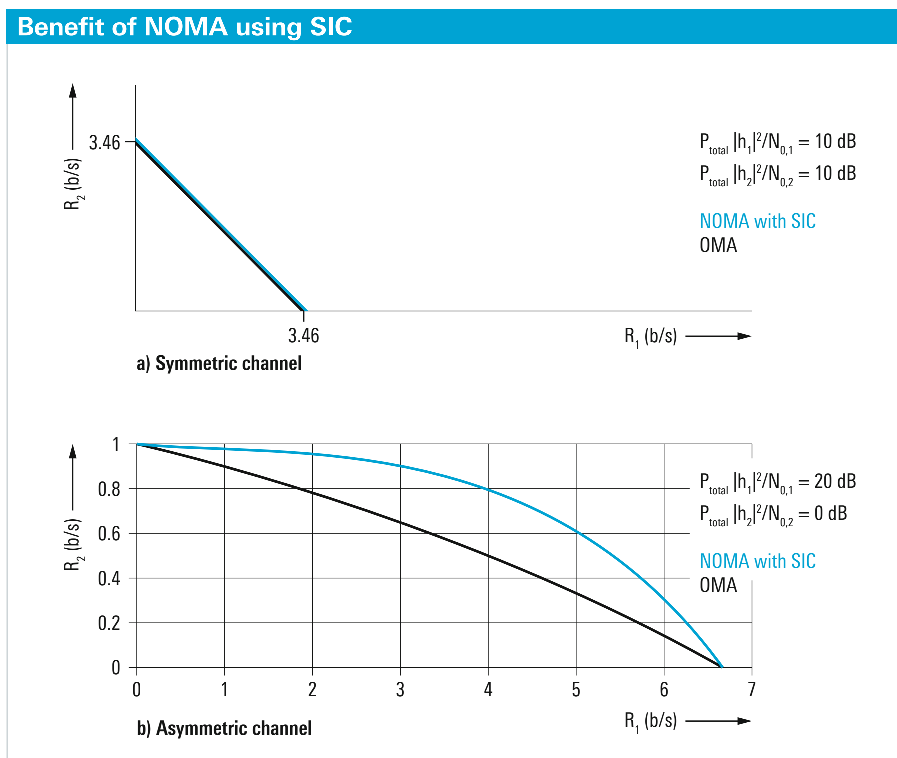
In our example, two UEs are sharing the same radio resource (frequency and time) in a non-orthogonal way by superimposing the power levels. At the receiver end, various concepts exist to cancel out the “interference” caused by the other user. A well-known approach is successive interference cancellation (SIC), which will be concisely presented as one possibility. The background idea is to superimpose two UEs at various distances, like the near and far situation here, resulting in high and low power superimposing. The difference in power levels can now be used to separate the various UE signals from each other. A sum signal is fed into the receiver chain of each UE, and a matched filter tries to detect the strongest signal component. This is followed by a decision process as to whether this signal corresponds to the respective user and then a subsequent signal processing chain that can include decoding, CRC check, deciphering, etc. If the signal does not belong to the respective UE, a process of strongest signal component “regeneration” starts. The idea is to combine the inverse of the strongest signal component with the sum signal. This results in a subtraction [19] just like the common equalizing method known as zero-forcing where the received signal is combined with the inverse of the channel response. Such a principle can be seen in Fig. 2.14 where the upper part shows the signal detection and regeneration. The lower part shows the feedthrough of the sum signal with a time alignment step. On the right is the combining of the inverse with the sum signal. The remaining signal is then fed back into the receiver and represents the new “sum” signal. The SIC receiver can be understood as daisy-chained cascading of receivers plus interference cancellation steps.

Fig. 2.14: Principle of successive interference cancellation (SIC).



The benefit of MUST is shown as an example in Fig. 2.15. See also [16], a study containing some evaluation results.

Fig. 2.15: Benefit of NOMA using SIC.



In a), you see the scenario of a symmetric channel. Two users are sharing the resources in an orthogonal multiple access (OMA) scenario. R1 and R2 are the achievable rates for each user. The straight line shows the sharing concept as a fair sharing transition. First user 1 gets the full resource and then user 2 gets the full resource. In b), both user signals are superimposed by jointly transmitting. The resulting bold blue line shows the advantage of NOMA over OMA. An example of the benefit of the system capacity increase: If user 2 wants to achieve a rate R2 of 0.8 bps, user 1 could get a rate R1 of 2 bps in OMA but a rate of 4 bps in NOMA.

2.3.1 Multiuser superposition transmission schemes

Table 2.13 identifies the key characteristics of three major MUST schemes presented in [16] and [20] resulting in three different MUST UE categories.

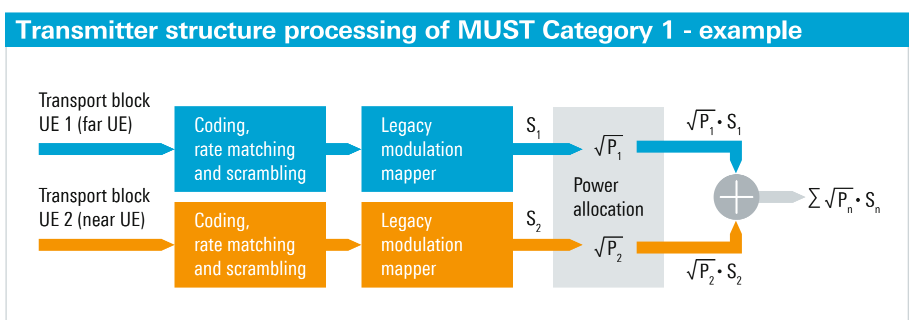
Table 2.13: Classification of MUST schemes and their key characteristics [16].

Categories	Power ratio	Gray mapping	Label-bit assignment
MUST category 1	adaptive, on component constellations	N	on component constellations
MUST category 2	adaptive, on component constellations	Y	on the composite constellation
MUST category 3	N/A	Y	on the composite constellation

MUST category 1: superposition transmission with adaptive power ratio on component constellations and non-Gray-mapped composite constellation

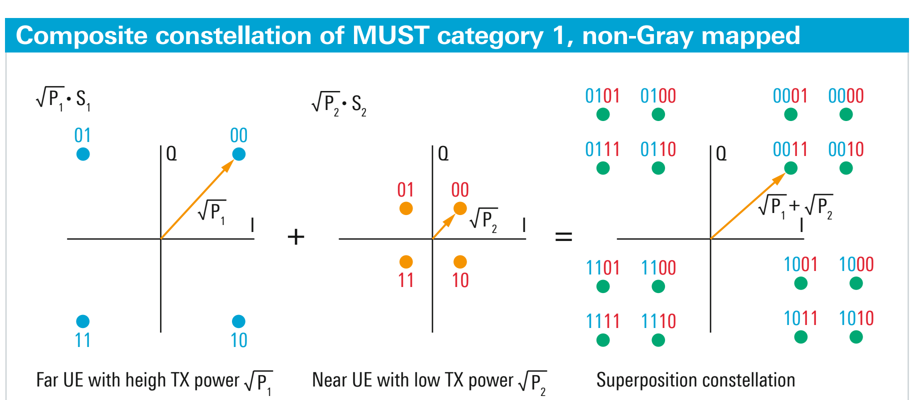
This category, which represents the basic NOMA concept, includes MUST schemes with independent mapping of coded bits of two or more co-scheduled UEs to component constellation symbols, which are superimposed with an adaptive power ratio. The assignment of label bits to UEs is done on component constellations. An example of processing for this category on the transmitter end is shown in Fig. 2.16. After independent channel coding, rate matching (RM), scrambling, and mapping to modulation symbols, the signals of MUST-near UEs and MUST-far UEs are combined with amplitude weighting.

Fig. 2.16: Transmitter structure processing of MUST Category 1 - example.



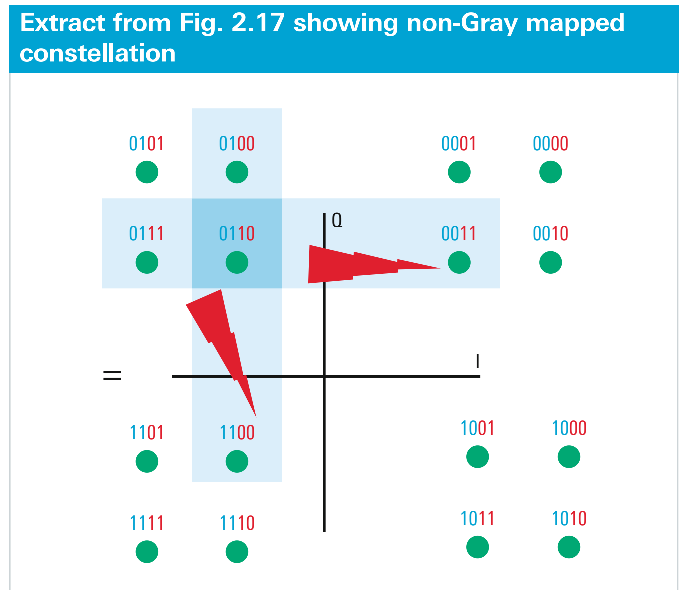
Each signal input can be understood as a complex modulation symbol of a legacy QAM modulator. The resulting composite constellation will be a higher order QAM. As an example, Fig. 2.17 shows two input signals representing two UEs (near and far) with each of them using QPSK, but with varying power levels. The resulting composite constellation is a kind of 16QAM constellation scheme.

Fig. 2.17: Composite constellation of MUST category 1, non-Gray mapped.



Note that the composite constellation of MUST category 1 will be a non-Gray mapped constellation scheme. Gray mapping is a method of mapping the bit labels in the constellation diagram so that the bit difference between two adjacent symbols (Hamming distance) is not more than 1 bit to minimize the error probability at the detector. Fig. 2.18 contains an extract to highlight that this principle is the major difference to MUST category 2 described later:

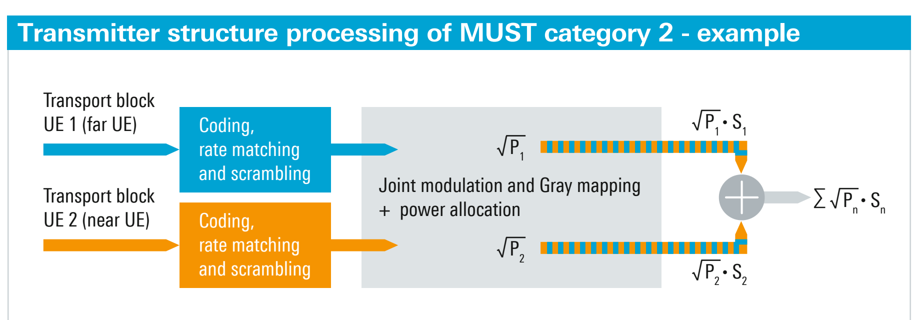
Fig. 2.18: Extract from Fig. 2.17 showing non-Gray mapped constellation.



MUST category 2: superposition transmission with adaptive power ratio on component constellations and Gray-mapped composite constellation

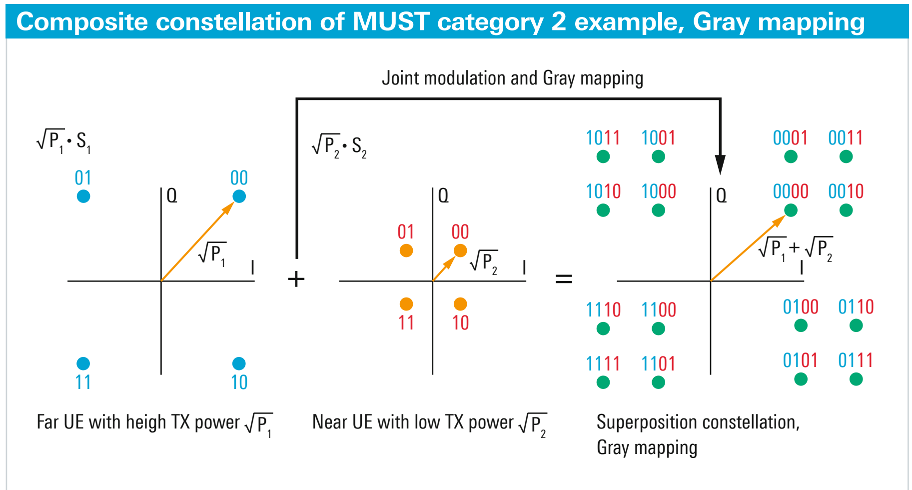
Similar to MUST category 1, the input signals are superimposed with adaptive power ratios. The difference is that MUST category 2 is a joint modulation and mapping procedure that results in a Gray mapping scheme of the constellation diagram. It is also called semi-orthogonal multiple access (SOMA) in the academic literature and does not necessarily require a SIC receiver. A possible transmitter structure is shown in Fig. 2.19.

Fig. 2.19: Transmitter structure processing of MUST category 2 – example.



The resulting constellation, now showing Gray mapping functionality, is presented in Fig. 2.20.

Fig. 2.20: Composite constellation of MUST category 2, Gray mapping.

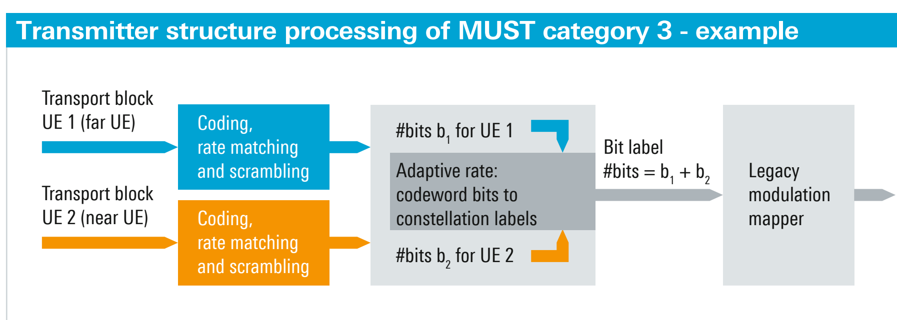


MUST category 3: superposition transmission with label-bit assignment on Gray-mapped composite constellation

This category includes MUST schemes where the coded bits in the codewords of two or more UEs are directly superimposed onto the symbols of a composite constellation. The assignment of label bits to UEs is done on the composite constellation. By changing the bit mapping of multiple non-orthogonal multiplexed users based on channel condition, a certain rate adaptation is achieved. This concept is also described as rate-adaptive constellation expansion multiple access (RA-CEMA).

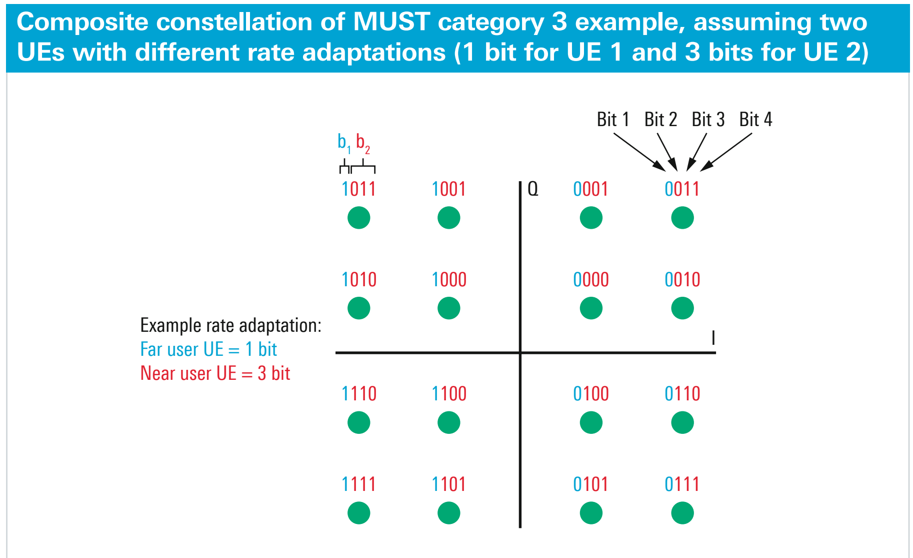
An example of transmitter processing for this category is shown in Fig. 2.21. In this category, all operations are performed on the composite constellation instead of the component constellations.

Fig. 2.21: Transmitter structure processing of MUST Category 3 - example.



The composite constellation is uniform quadrature amplitude modulation (QAM) with Gray mapping. A legacy constellation can be reused. Fig. 2.22 shows an example composite constellation of MUST category 3. Here we assume two UEs with near and far condition. The rate adaptation mechanism allocates 1 bit to UE 1 and 3 bits to UE 2 by using a legacy 16QAM modulation scheme.

Fig. 2.22: Composite constellation of MUST category 3 example, assuming two UEs with different rate adaptations (1 bit for UE 1 and 3 bits for UE 2).



Common for all three MUST mechanisms is that the receiver has to cancel out the interference. Fig. 2.14 shows the general principle of successive interference cancellation (SIC). The 3GPP technical report TR 36.866 [17] contains a description of various receiver types in a study of network assisted interference cancellation. To keep this white paper from becoming too complex, please see this literature for further information.

2.3.2 MUST signaling aspects for network and UE

A UE supporting MUST will send a frequency band specific `must-CapabilityPerBand-r14` information element in its capability report. This element contains transmission mode specific parameters: `must-TM234-UpTo2Tx-r14, must-TM89-UpToOneInterferingLayer-r14, must-TM10-UpToOneInterferingLayer-r14, must-TM89-UpToThreeInterferingLayers-r14, must-TM10-UpToThreeInterferingLayers-r14` indicating MUST support in combination with transmission modes supporting MIMO (TM 2, 3 and 4), beamforming (TM 8 and 9) and also higher order MIMO (TM10). More details on those transmission modes can be found in [27]. The signaling parameter "UE MUST support" also indicates the maximum number of multi-users, which can be either two or four. This represents the number of interfering layers that a UE supports.

Like in LTE, a UE receiving downlink signals has to estimate downlink power levels for RSRP and RSRQ evaluation. In MUST, the ratio of PDSCH EPRE to cell-specific RS EPRE has to be determined. Optionally, the network can adjust the power levels via the layer 3 parameter `p-a-must` to reduced or increase PDSCH downlink power levels.

If a UE supports MUST, the network can select a multi-user superimposed transmission. Therefore, several downlink control information (DCI) formats are extended by a value indicating MUST interference presence, power ratio, antenna ports and modulation. Depending on the DCI format, these MUST-indicating parameters are defined in [8]:

Table 2.14: DCI content of MUST interference presence and modulation for an antenna port.

Bit field	Message
00	No interference presence
01	Interference is present with QPSK
10	Interference is present with 16QAM
11	Interference is present with 64QAM or 256QAM

Table 2.15: DCI content of MUST interference presence and antenna port.

Bit field	Message
00	No interference presence
01	First antenna port
10	Second antenna port
11	Third antenna port

Table 2.16: DCI content of MUST interference modulation.

Bit field	Message
00	QPSK
01	16QAM
10	64QAM
11	256QAM

The layer mapping procedure for the various modulation schemes and the resulting power ratios are based on a signaled parameter `MUSTIdx` and defined in [7].

To verify the performance of a UE supporting MUST, 3GPP has defined a minimum performance requirement (see [5]). More specifically, a 70% throughput performance limit is required under a defined fixed reference channel (FRC) and activated transmission modes for transmit diversity, open loop or closed loop transmission modes.

Table 2.17: Test parameters for minimum requirement 2 TX antenna port - superposed transmission (FRC).

Parameter		Unit	Test 1
Downlink power allocation	ρ_A	dB	-3
	ρ_B	dB	-3
	σ	dB	0
Noc at antenna port		dBm/15 kHz	–98
PDSCH transmission mode			2
MUSTIdx			11
p-a-must-r14			N/A

2.4 Dual connectivity enhancements

The general concept of dual connectivity (DC) as specified in 3GPP Release12 was introduced in [3]. The main focus of 3GPP Release 12 DC was on mobility robustness in small cell deployments as well as on downlink throughput enhancements. With 3GPP Release 13, the following main extensions to DC were added:

- Uplink split bearer data transmission and uplink transmission time difference
- System frame number (SFN) and subframe offsets between master eNodeB (MeNB) and secondary eNodeB (SeNB)
- Bearer switching during MeNB handover

The new uplink split bearer data transmission makes it possible to configure UL bearer split for each PDCP instance via an RRC message. The procedure is threshold based. If the available PDCP data to be sent in the uplink is below a configurable per bearer threshold, the UE will send UL data to only one eNB. This is either the MeNB or the SeNB depending on the configuration provided by the `RRCConnectionReconfiguration` message. As soon as the available UL PDCP data is above the threshold, this is indicated to both MAC entities on MeNB and on SeNB via the buffer status report (BSR). The UE can now be scheduled to send data to both MeNB and SeNB. The path to send the package via master cell group (MCG) or secondary cell group (SCG) is autonomously selected for each PDCP package. Possible PDCP reordering delays due to discarded PDCP SDUs shall be minimized by the UE design implementation.

Since the MeNB and SeNB are physically different eNBs and are probably not collocated, a new requirement resulting from the UL split bearer is the maximum uplink transmission time difference between the primary cell (PCell) and primary SCell (PSCell). In 3GPP Release 13, this was defined by RAN4 to be 35.21 µs for synchronous DC. For asynchronous DC, the 3GPP Release 12 specified uplink transmission time difference of 500 µs remained unchanged in 3GPP Release 13, as can be seen in [22] 7.17.2.

In 3GPP Release 12 dual connectivity, the solution to determine the SFN and sub-frame timing difference between MeNB and SeNB used operation administration and management (OAM) functionality. This was found to no longer be sufficient, especially for asynchronous dual connectivity deployments and in e.g. DRX cases. Therefore, 3GPP Release 13 introduced a new, non-network-based method to determine the timing difference between MeNB and SeNB.

This new method is based on the UE using the SFN and subframe number of both the PCell and PSCell and calculating the timing offset between MeNB and SeNB. This difference is reported back from the UE to the network. The reporting is configured by the network as a one-shot reporting and contains `SFN-Offset`, `FrameBoundaryOffset` and `SubFrameBoundaryOffset`.

If an MeNB handover occurs during a dual carrier connection, the bearers connected to the SCG are temporarily switched back to the MCG in line with Release12. This causes unwanted network signaling and can have a negative effect on the user experience and especially on the data throughput, even though the SCG signal strength would not require a release of the SeNB bearer. To overcome these potential data gaps and signaling overhead, Release 13 defined the possibility to keep the SeNB bearer unchanged during an MeNB handover procedure.

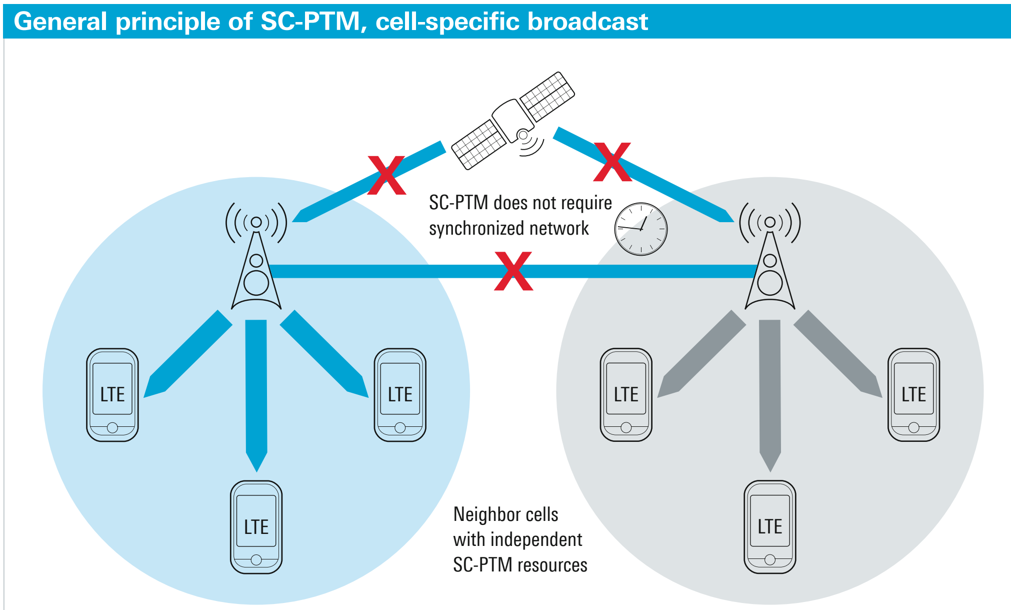
2.5 Single-cell point-to-multipoint (SC-PTM)

Single-cell point-to-multipoint (SC-PTM) was introduced in 3GPP Release 13 to enhance the multimedia broadcast and multicast functionality of the LTE network. By reusing the eMBMS system architecture, SC-PTM improves the radio efficiency. The main concept of SC-PTM is to support broadcast/multicast services over a single cell by using cell-specific radio resources via a PDSCH.

3GPP Release 9 introduced multimedia broadcast multicast services (MBMS) to allow operators to broadcast data over their LTE network. Critical communications such as public safety, group communication system enablers for LTE (GCSE_LTE) were introduced in 3GPP Release 12 and use several features provided by eMBMS. Broadcasting based on eMBMS requires the definition of a broadcast area (MBSFN area) that is rather static and cannot be dynamically adjusted according to user distribution. In addition, the eMBMS is based on a more static frame configuration for the entire MBSFN area in the time domain, and it occupies the entire system bandwidth in the frequency domain. The motivation for SC-PTM is to provide a more flexible radio interface architecture and a dynamic multicast area based on cell level to improve efficiency in data broadcast scenarios. It does away with the synchronized transmission scheme over several eNBs belonging to the same MBSFN. Unlike MBSFN, SC-PTM uses the physical downlink shared channel (PDSCH). It improves efficiency by activating the HARQ retransmissions request from the UEs and channel status feedback for better link adaptation. To improve coverage, the LTE feature TTI bundling can also be applied.

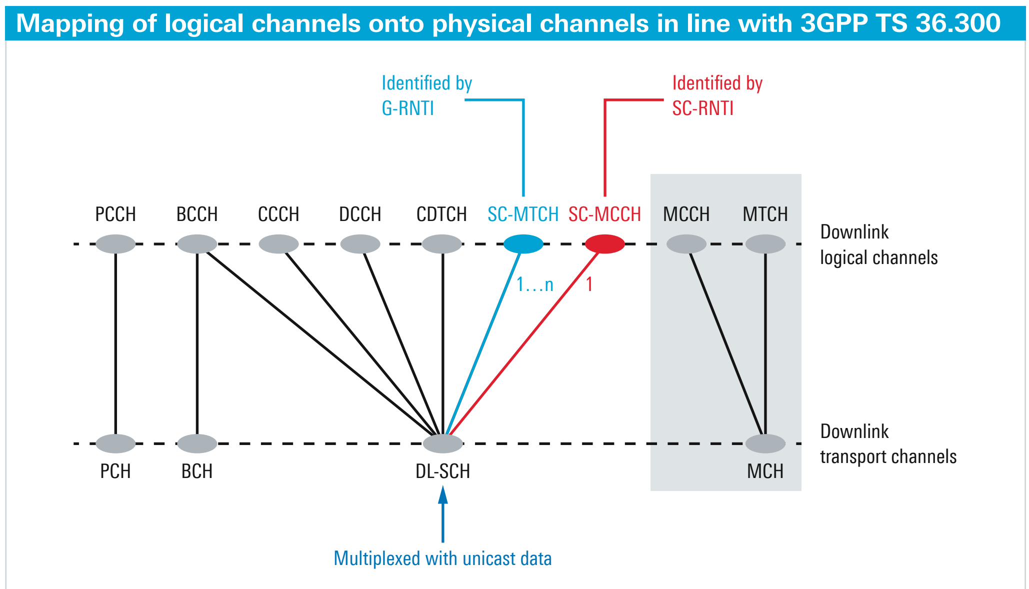
Fig 2-12 General principle of SC-PTM, cell-specific broadcast.

General principle of SC-PTM, cell-specific broadcast



SC-PTM introduces two new logical channels for broadcasting data and control information, the single cell multicast control channel (SC-MCCH) and the single cell multicast transport channel (SC-MTCH). The SC-MCCH carries information about the broadcast configuration, such as the `SCPTMConfiguration` message which indicates the active MBMS sessions and the scheduling information for each session (scheduling period, scheduling window and start offset). The `SCPTMConfiguration` message also provides information about the neighbor cells transmitting the active MBMS sessions on the current cell. The SC-MCCH information is transmitted periodically using a configurable repetition period. Transmissions are indicated on PDCCH using a DCI message scrambled with the identifier SC-RNTI. A UE interested in receiving MBMS services obtains information about SC-PTM via `SystemInformationBlockType20`.

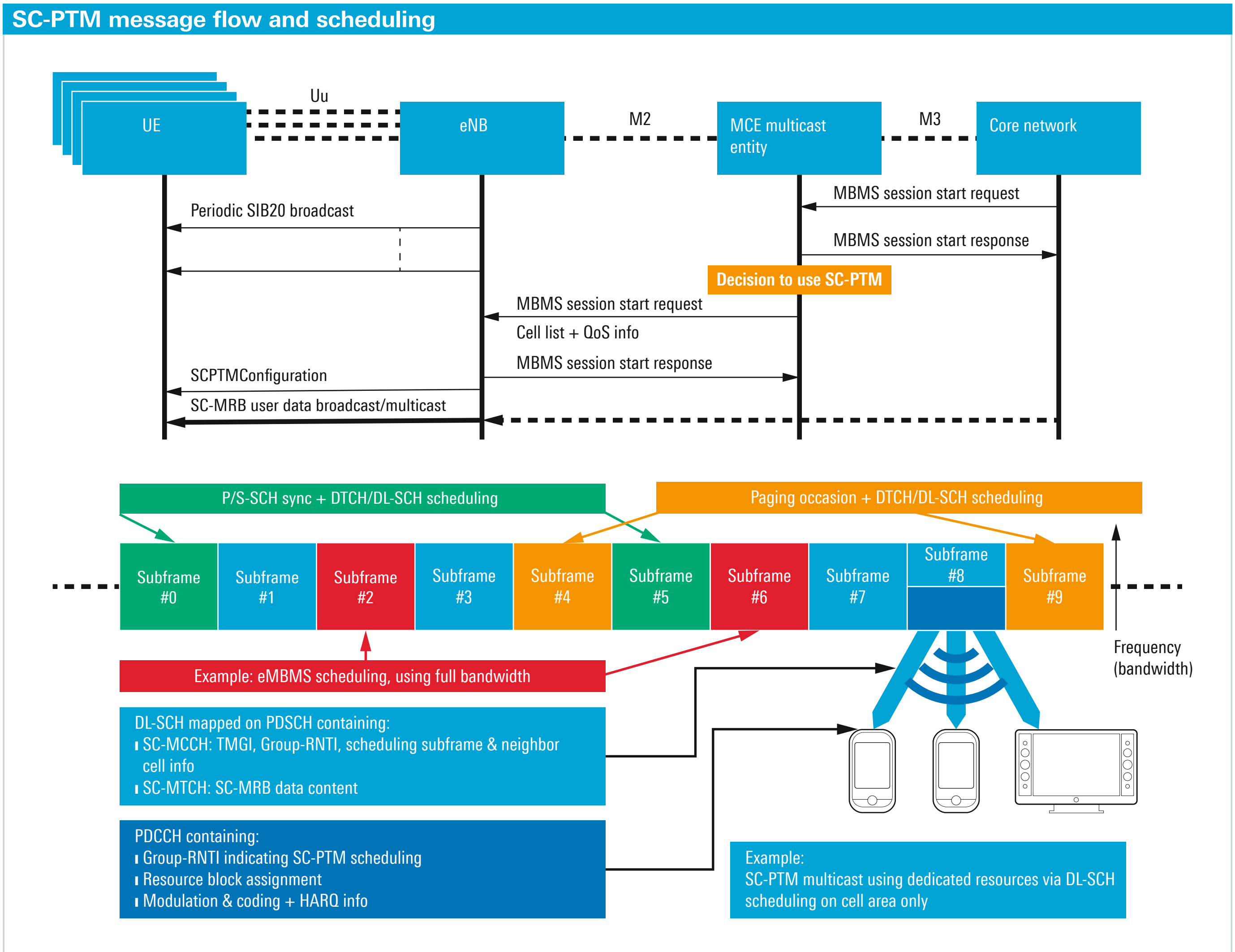
Fig. 2.23: Mapping of logical channels onto physical channels in line with 3GPP TS 36.300.



Three identities are used for scheduling SC-PTM transmission: SC-RNTI for identifying the SC-MCCH transmission for configuration information, SC-N-RNTI for SC-MCCH change notifications and G-RNTI for SC-MTCH transmissions.

The general message flow for an SC-PTM call setup in line with [14] is as follows.

Fig. 2.24: SC-PTM message flow and scheduling.



The core network initiates the broadcast of data by sending a session start request to the multicell/multicast entity (MCE), which decides whether to use a wide area broadcast using eMBMS or using SC-MRB, an SC-PTM based data broadcast. Such an SC-MRB instance of the MBMS bearer service is identified by an IP multicast address and an access point network (APN) identifier. In addition, a temporary mobile group identifier (TMGI) together with an MBMS session ID are used to identify one MBMS bearer service inside one PLMN. The MCE informs the relevant eNBs about the session start. An eNB supporting SC-PTM indicates this by broadcasting the system information SIB20 to provide information about the SC-MCCH scheduling. To enable the UEs for SC-PTM reception, the eNB broadcasts the `SCPTMConfiguration` via the SC-MCCH. Now the UE is able to receive the SC-MTCH logical channel sent via the PDSCH using DCI scheduling with the G-RNTI identifier.

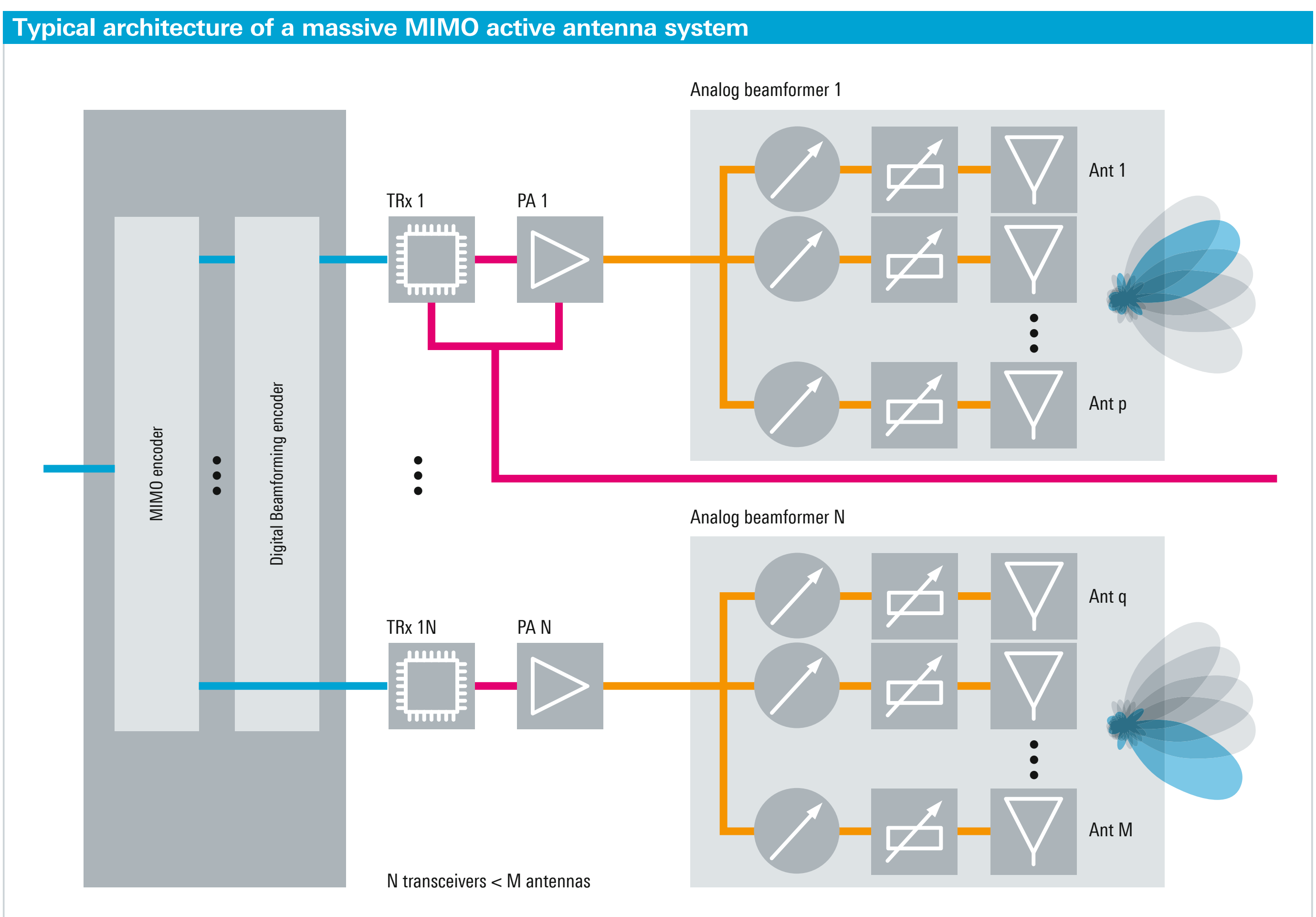
A UE supporting SC-PTM indicates this in its capability report. Details are specified in [12]: SC-PTM support, SC-PTM simultaneous reception of dedicated and broadcast DL-SCH transport blocks, SC-PTM support of secondary cell in carrier aggregation scenarios and also SC-PTM reception capability in RRC idle mode, a feature that is restricted to LTE Cat-M devices only for machine type communication enhancements. There are no specific UE performance requirements for SC-PTM.

Service continuity is discussed in [23] on the basis of two scenarios. If the neighbor cell also supports SC-PTM, the current serving cell will provide such information via the SC-MCCH channel. The neighbor cell will continue broadcasting the same MBMS session. The second scenario covers the situation where the neighbor cell does not support SC-PTM. In such a case, the UE will switch from multicast to a unicast session and data provisioning using LTE dedicated bearers. Both scenarios will inherit a certain session interruption time of roughly hundreds of milliseconds.

2.6 Base station antenna evolution

For previous cellular technologies such as GSM and UMTS, and even during the first years of LTE deployments, base station antennas were primarily designed with a fixed (desired) antenna pattern, e.g. 60° beamwidth in a three-sector cell layout. These implementations generally used a passive antenna. Improvements, mainly in system capacity and energy consumption, can be realized with active antenna systems. This advanced antenna technology makes it possible to adapt the beam pattern to specific environments (e.g. for optimal coverage of a street canyon) or to varying user distributions (e.g. changing the antenna tilt due to a traffic jam). More recently, the concept of massive MIMO has been adopted in real networks. The use of a high number of TX and RX antenna elements with amplitude and phase control allows multiple precoded data streams. This makes it possible to leverage multiple paths in the propagation channel (multi-user MIMO), realize high beamforming gains or a combination of both. Both multi-user MIMO (MU-MIMO) and beamforming increase cell capacity. Beamforming also significantly reduces energy consumption by targeting signals assigned to the individual UEs. Fig. 2.25 illustrates the architecture of a typical massive MIMO active antenna system.

Fig. 2.25: Typical architecture of a massive MIMO active antenna system.



3GPP published a dedicated technical report on the RF requirement background for active antenna systems (AAS) (see [24]). The study and work item phase contains a list of radiated requirements as well as a list of conducted requirements based on the identified representative deployment scenarios. In conclusion, requirements for transmit and receive measurements applicable to AAS were approved. An AAS is defined as a base station system which combines an antenna array with a transceiver unit array and a radio distribution network.

Fig. 2.26: General AAS radio architecture.

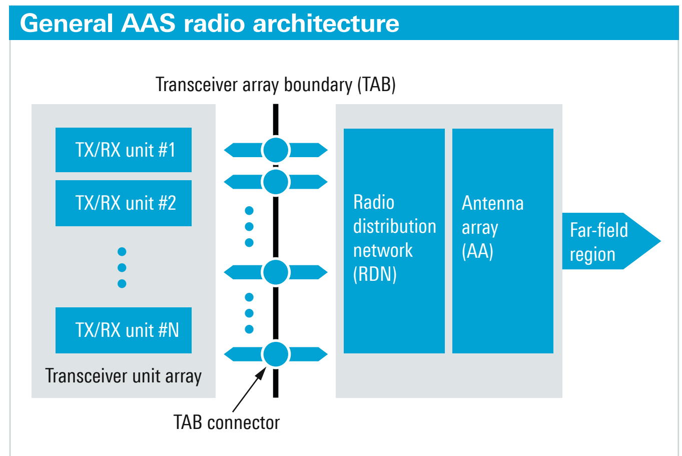
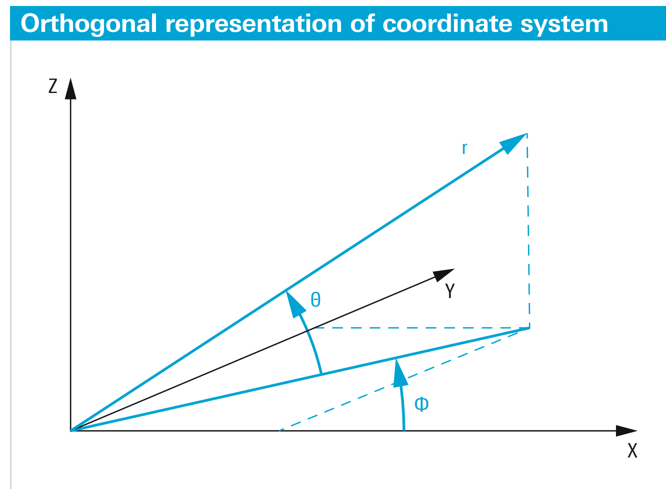


Fig. 2.26 defines the general AAS BS RF architecture. The point where a transmitter unit or a receiver unit connects to the radio distribution network (RDN) is equivalent to an "antenna connector" of a non-AAS BS and is known as a transceiver array boundary connector (TAB connector). The TAB connector is defined as the conducted reference point. The work on AAS in 3GPP Release 13 resulted in the definition of two radiated requirements, namely radiated transmit power and OTA sensitivity. Radiated characteristics are defined over the air (OTA) with a point of reference in the far field (Fraunhofer) region. Radiated requirements are also referred to as OTA requirements.

2.6.1 Radiated requirements for active antenna systems (AAS)

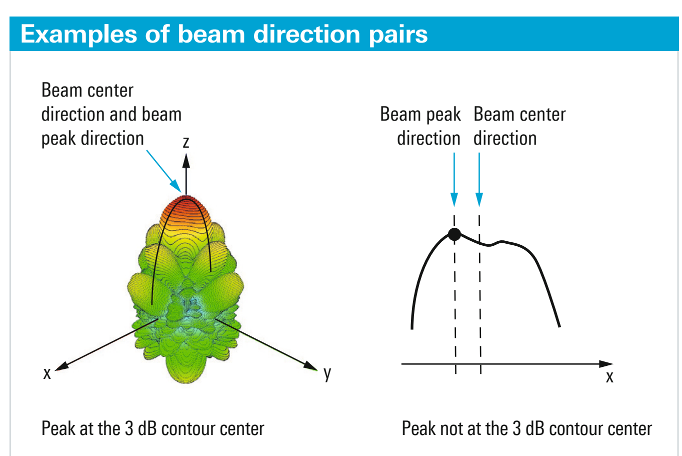
3GPP defines the OTA requirements in terms of electromagnetic and spatial parameters. The electromagnetic parameters are specified either in terms of power (dBm) or field strength (dBμV/m). The spatial parameters are specified in a Cartesian coordinate system (x, y, z) using spherical coordinates (r, Θ, Φ) (see Fig. 2.27).

Fig. 2.27: Orthogonal representation of coordinate system.



The chosen method requires the manufacturer to declare the number of beams intended for cell-wide coverage. Requirements are then to be verified per declared beam. The vendor declares the location of the coordinate system origin in reference to an identifiable physical feature of the AAS BS enclosure. A few basic definitions apply. The declared beam direction pair is associated with the beam center direction and a beam peak direction. A beam center direction and a beam peak direction characterize the capability of the AAS to create a beam. The center direction equals the geometric center of the –3 dB EIRP contour of the beam. The beam peak direction is the direction where the maximum EIRP is to be found (Fig. 2.28).

Fig. 2.28: Examples of beam direction pairs (left: peak at the 3 dB contour center, right: peak not at the 3 dB contour center).

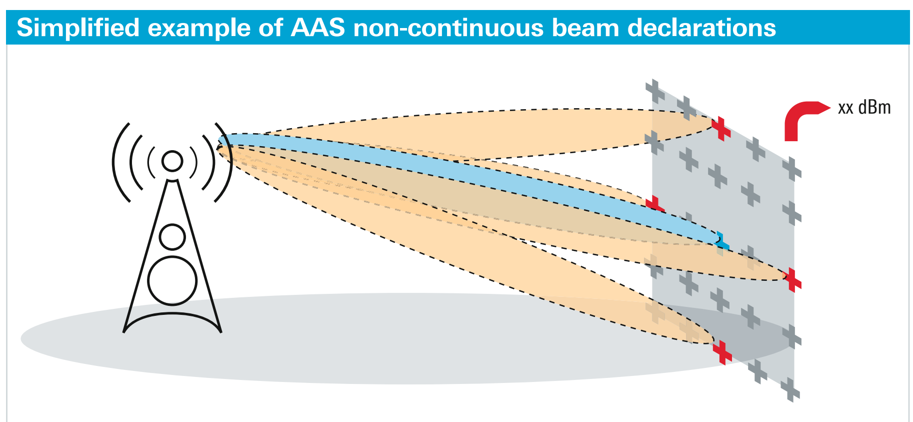


The reference beam direction is the declared beam direction pair achieving the intended maximum EIRP. The beamwidth of a beam is defined as the angles describing the major and minor axes of an ellipsoid with the closest fit to an essentially elliptic half-power contour of the beam. Each beam supported is defined by a unique beam identifier. With respect to characterizing each supported single beam, the manufacturer declares the highest intended EIRP, including the narrowest and widest intended beamwidth, in both azimuth and elevation (Θ, Φ).

2.6.1.1 Radiated transmitter characteristics

The number of beams supported by the AAS is left to the manufacturer to declare. Both continuous and non-continuous beam declarations are possible. Radiated transmit power is defined as the EIRP level for a declared beam at a specific beam peak direction. The claimed EIRP levels (blue and red crosses in Fig. 2.29) are to be achieved for all claimed beam peak directions. For compliance, however, only the declaration of the extreme directions are sufficient to be measured (marked with red crosses in Fig. 2.29). The potential beam directions are not confined to a square and can be specified by the manufacturer according to any arbitrary surface. Those beam directions that are compliant are included in the EIRP accuracy compliance specifications.

Fig. 2.29: Simplified example of AAS non-continuous beam declarations.



The requirement defined in [25] reads:
"For each beam, the requirement is based on declarations (see table 4.10-1) of a beam identifier (D9.3), reference beam direction pair (D9.7), rated beam EIRP at the beam's reference direction pair (D9.8), EIRP accuracy directions set (D9.10), the beam direction pairs at the maximum steering directions (D9.11) and their associated rated beam EIRP (D9.12) and beamwidth(s) for reference beam direction pair and maximum steering directions (D9.13)."

And references the requirement defined in [6], including a specific accuracy, as follows:
"For each declared beam, in normal conditions, for any specific beam peak direction associated with a beam direction pair within the EIRP accuracy directions set, a manufacturer claimed EIRP level in the corresponding beam peak direction shall be achievable to within +2.2 dB and -2.2 dB of the claimed value."

[25] also defines acceptable uncertainties of the test system (see Table 2.18). Consequently, the requirement tested during the test procedure comprises the minimum requirement and the test tolerance.

Table 2.18: Maximum test system uncertainty for transmitter tests.

Subclause	Maximum test system uncertainty	Derivation of test system uncertainty
6.2 Radiated transmit power	±1.0 dB, f ≤ 3.0 GHz	See 3GPP TR 37.842 [1], subclause 10.3.2.2.
	±1.2 dB, 3.0 GHz < f ≤ 4.2 GHz	

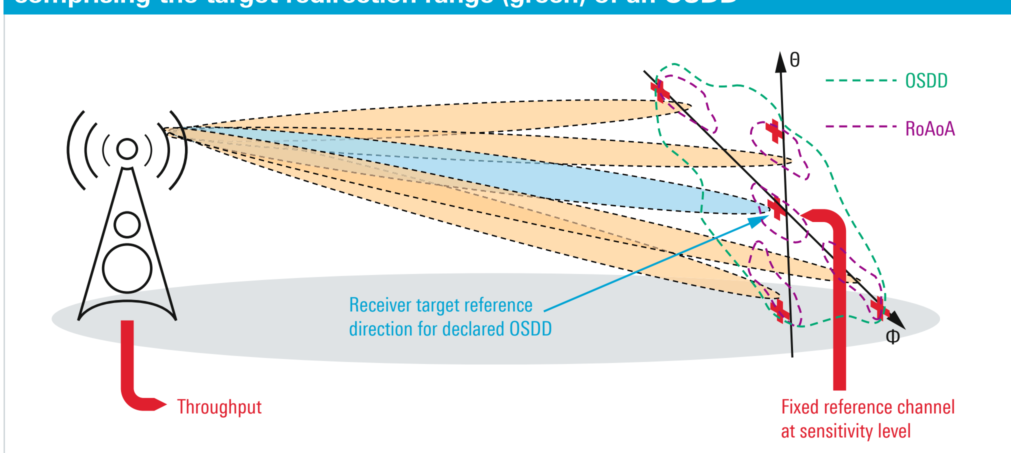
2.6.1.2 Radiated receiver characteristics

Similar to the power measurement in the downlink direction, in the uplink a sensitivity requirement is defined based on the declaration of one or more OTA sensitivity directions declarations (OSDD). The receiver is required to achieve a certain data throughput at a particular OTA sensitivity power level.

The effective isotropic sensitivity (EIS) is defined as the power level relative to an isotropic antenna that is incident on the AAS array from a specified azimuth/elevation direction (angle of arrival) in order to meet the specified receiver sensitivity requirement where the angle of arrival can be described as a combination of Φ and Θ (see Fig. 2.30). The AAS may support multiple ranges of angles of arrival (RoAoA), which describe the overall redirection range capabilities of the antenna. For sensitivity testing, the stimulus signal is the same as the fixed reference measurement channel (FRC) for target throughputs in non-AAS requirements (see [26]). The OTA sensitivity requirement applies per polarization and assumes polarization matching. It is up to the manufacturer to declare whether or not dual polarization is supported by the AAS. As in the downlink case, conformance is to be demonstrated at the extreme directions marked with red crosses in Fig. 2.30.

Fig. 2.30: Five different directions of a sensitivity range of angles of arrival (RoAoA, purple) comprising the target redirection range (green) of an OSDD.

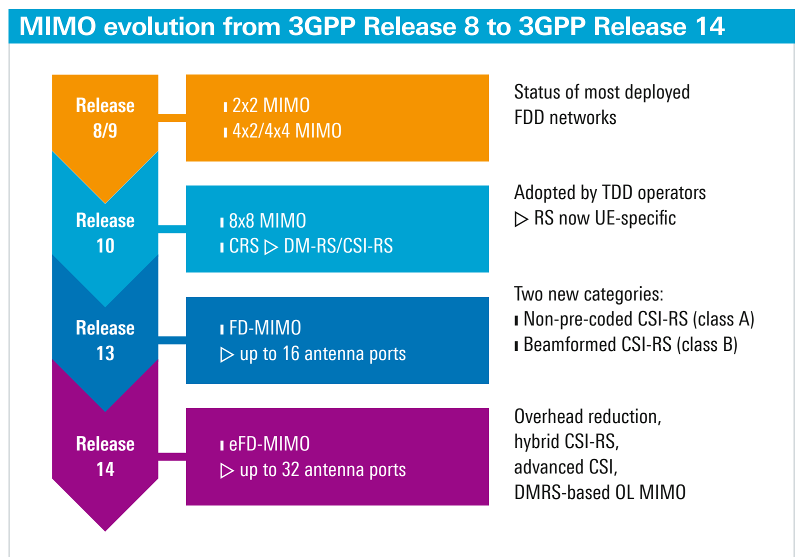
Five different directions of a sensitivity range of angles of arrival (RoAoA, purple) comprising the target redirection range (green) of an OSDD



2.6.2 Full dimension MIMO (FD-MIMO)

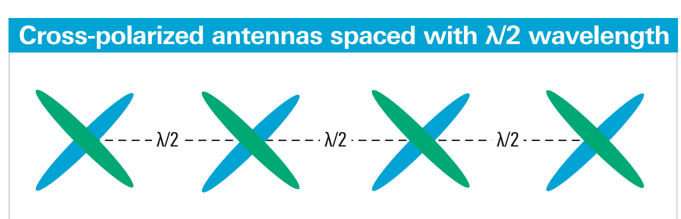
The evolution of the LTE MIMO schemes, from the first specifications made available with 3GPP Release 8 to the latest evolution in 3GPP Release 14, is illustrated in Fig. 2.31. MIMO is a key capability deployed within LTE networks because it was mandatory to be supported by end-user devices from the first release. The majority of deployed commercial networks operate 2x2 MIMO or 4x4 MIMO. The deployed technology component relies on the availability of cell-specific reference symbols (CRS), which are defined at dedicated frequency and time instances per antenna port. This enables appropriate user device feedback so that the best precoding can be applied at the base station. The enhancements added in LTE-Advanced (3GPP Release 10) were in particular adopted in TDD networks. [1] describes the details of these enhancements. The main change was to provide additional resources for reference symbols in the data allocation of a user device, which are known as demodulation reference symbols (DM-RS), as well as cell state information reference symbols (CSI-RS) per cell. Both can be configured and allow more efficient operation depending on the actual use case scenario.

Fig. 2.31: MIMO evolution from 3GPP Release 8 to 3GPP Release 14.



Before illustrating the enhancements added from 3GPP Release 13 onwards, note that transmission mode (TM) 9 of LTE enables spatial multiplexing of up to 8 layers. A dual codebook structure has been adopted for this TM in order to reduce the potential feedback overhead for larger antenna arrays such as 8 TX and to capture the characteristic of cross-polarized antennas (see Fig. 2.32).

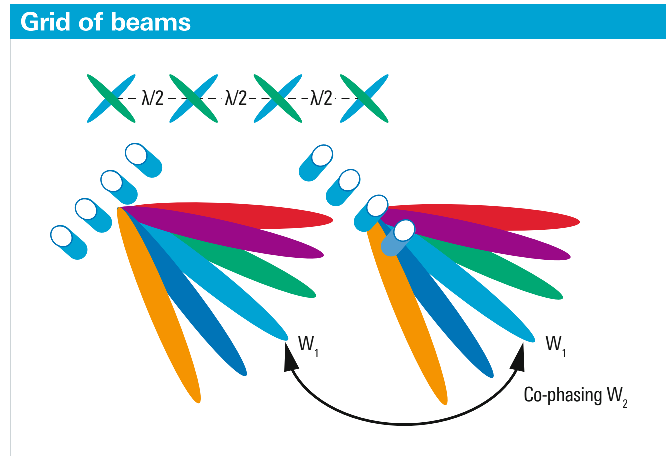
Fig. 2.32: Cross-polarized antennas spaced with λ/2 wavelength.



The precoder based on dual-codebook structure can be expressed as $W = W1 \cdot W2$, where W1 is a wideband precoding matrix index (PMI) that represents long-term statistics of the propagation channel such as a cluster of beam directions, and W2 is a subband

PMI that performs beam selection for each polarization group and co-phasing between polarizations. This approach can be visualized as a "grid of beams" (see Fig. 2.33).

Fig. 2.33: Grid of beams.



The enhancements added to 3GP Release 13, also known as full dimension (FD) MIMO, can be summarized as follows:
- Introduction of non-precoded CSI-RS; allows the number of CSI-RS ports to be increased up to 16
- Introduction of beamformed CSI-RS

Non-precoded CSI-RS operation is supported by class A eMIMO-Type with one CSI-RS resource. This operation comprises schemes where different CSI-RS ports have the same wide beamwidth and direction and hence generally wide cell coverage. The UE provides measurement reports and feedback, including PMI, rank indication (RI) and channel quality indication (CQI) as shown in Fig. 2.34. Details on the CSI reporting enhancement are specified in [9], section 7.2. Table 2.19 quantifies the total number of antenna ports when multiple CSI-RS configurations are aggregated.

Fig. 2.34: Illustration of non-precoded CSI-RS operation.

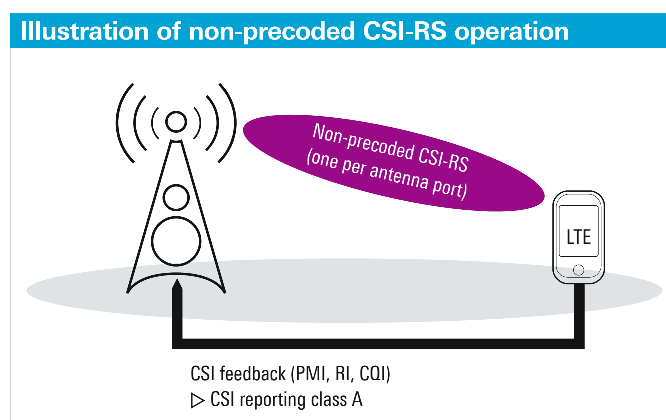


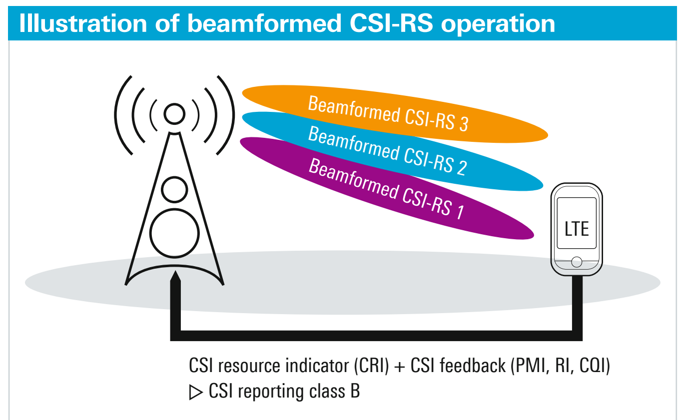
Table 2.19: Aggregation of CSI-RS configurations up to 16 antenna ports [7].

Total number of antenna ports	Number of antenna ports per CSI-RS configuration	Number of CSI-RS configurations
$N_{res}^{CSI} N_{ports}^{CSI}$	N_{ports}^{CSI}	N_{res}^{CSI}
12	4	3
16	8	2

The detailed CSI-RS configuration possibilities are specified in [7], section 6.10.5. A total of 32 different configurations are specified.

Beamformed CSI-RS operation is supported by class B eMIMO-Type with one or more CSI-RS resources. This operation comprises schemes where CSI-RS ports have narrow beamwidths (at least at a given time/frequency) and hence no wide cell coverage, and (at least from the eNB perspective) some CSI-RS port-resource combinations have different beam directions (see Fig. 2.35). The base station can configure multiple beams per UE (maximum number is 8). The UE feeds back a CSI-RS resource indicator (CRI), which provides the known parameters PMI, RI and CQI on the preferred beam.

Fig. 2.35: Illustration of beamformed CSI-RS operation.



With the introduction of FD-MIMO, the downlink DMRS allocation was enhanced. In addition to antenna ports 7 and 8, it is now possible to use antenna ports 11 and 13 for MU-MIMO. At most 8 layers are supported. Note that one bit was added to DCI formats 2C and 2D. If the higher-layer parameter `dmrs-tableAlt-r13` is set to 1, two codewords are enabled, and the field "`Antenna port(s), scrambling identity` and `number of layers`" given by DCI format 2C or 2D is 4 bits instead of 3 bits (see Table 2.20).

Table 2.20: Antenna port(s), scrambling identity and number of layers indication [7].

One codeword: codeword 0 enabled, codeword 1 disabled		**Two codewords: codeword 0 enabled codeword 1 enabled**	
Value	**Message**	**Value**	**Message**
0	1 layer, port 7, n_{SCID}=0 (OCC=2)	0	2 layers, ports 7-8, n_{SCID}=0 (OCC=2)
1	1 layer, port 7, n_{SCID}=1 (OCC=2)	1	2 layers, ports 7-8, n_{SCID}=1 (OCC=2)
2	1 layer, port 8, n_{SCID}=0 (OCC=2)	2	2 layers, ports 7-8, n_{SCID}=0 (OCC=4)
3	1 layer, port 8, n_{SCID}=1 (OCC=2)	3	2 layers, ports 7-8, n_{SCID}=1 (OCC=4)
4	1 layer, port 7, n_{SCID}=0 (OCC=4)	4	2 layers, ports 11,13, n_{SCID}=0 (OCC=4)
5	1 layer, port 7, n_{SCID}=1 (OCC=4)	5	2 layers, ports 11,13, n_{SCID}=1 (OCC=4)
6	1 layer, port 8, n_{SCID}=0 (OCC=4)	6	3 layers, ports 7-9
7	1 layer, port 8, n_{SCID}=1 (OCC=4)	7	4 layers, ports 7-10
8	1 layer, port 11, n_{SCID}=0 (OCC=4)	8	5 layers, ports 7-11
9	1 layer, port 11, n_{SCID}=1 (OCC=4)	9	6 layers, ports 7-12
10	1 layer, port 13, n_{SCID}=0 (OCC=4)	10	7 layers, ports 7-13
11	1 layer, port 13, n_{SCID}=1 (OCC=4)	11	8 layers, ports 7-14
12	2 layers, ports 7-8	12	Reserved
13	3 layers, ports 7-9	13	Reserved
14	4 layers, ports 7-10	14	Reserved
15	Reserved	15	Reserved

Finally, the sounding reference symbol (SRS) capacity in the uplink direction was improved. For instance, the number of UpPTS SC-FDMA symbols was increased (the additional numbers can be {2, 4}), the number of SRS combinations was increased (2 → 4) and the cyclic shift (8 → 12) was increased.

2.6.3 Enhanced full dimension MIMO (eFD-MIMO)

A few shortcomings of the existing FD-MIMO scheme as specified in 3GPP Release 13 led to the specification of additional enhancements in 3GPP Release 14. These are referred to as enhanced FD-MIMO.

The shortcomings identified as of 3GPP Release 13 are:
- "Only" 16 antenna ports
- CSI reporting not optimized for efficient multi-user spatial multiplexing
- Higher robustness against CSI impairments (e.g. high mobility) and requirement for higher CSI accuracy

eFD-MIMO comprises essentially the following enhancements:
Reference signal related enhancements:
- Supports {20,24,28,32} CSI-RS antenna ports
- Reduces CSI-RS overhead
- Improves efficiency for UE-specific beamformed CSI-RS

CSI reporting enhancements:
- Codebook for newly supported CSI-RS ports
- Hybrid CSI-RS and its CSI reporting

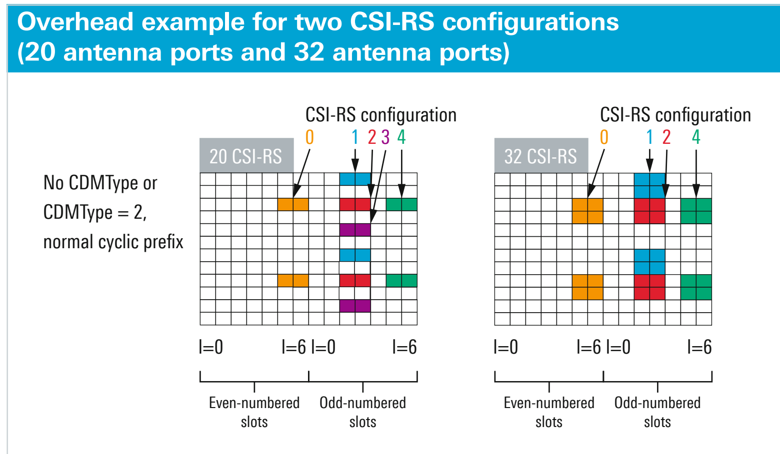
Introduction of DMRS-based open-loop transmission
Table 2.21 reflects the additional aggregation possibilities to reach a maximum of 32 ports.

Table 2.21: Aggregation of CSI-RS configurations up to 32 antenna ports [7].

Total number of antenna ports	Number of antenna ports per CSI-RS configuration	Number of CSI-RS configurations
$N_{res}^{CSI} N_{ports}^{CSI}$	N_{ports}^{CSI}	N_{res}^{CSI}
20	4	5
24	8	3
28	4	7
32	8	4

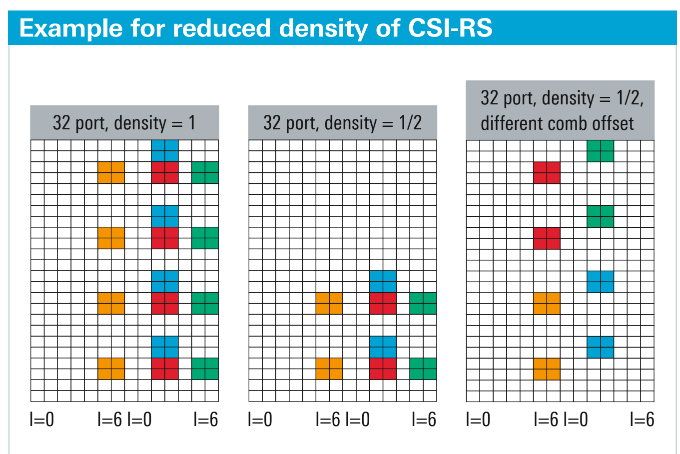
With respect to CSI-RS overhead reduction, Fig. 2.36 illustrates an overhead of 11.9% and 19% for a 20 CSI-RS/antenna port and a 32 CSI-RS/antenna port allocation for the applicable scheme as of 3GPP Release 14.

Fig. 2.36: Overhead example for two CSI-RS configurations (20 antenna ports and 32 antenna ports).



The CSI-RS overhead reduction is supported by comb-like transmission in the frequency domain. For CSI-RS ports larger than 16, a certain density can be applied (1, 1/2 and 1/3) where each CSI-RS configuration can have different comb offsets (see Fig. 2.37).

Fig. 2.37: Example for reduced density of CSI-RS.



In order to improve the efficiency of UE-specific beamformed CSI-RS (especially when the number of UEs is large), two schemes are defined:

- Aperiodic non-zero power (NZP) CSI-RS
- Semi-persistent NZP CSI-RS

3 Conclusion

This white paper describes the eMBB-specific enhancements to LTE-Advanced provided within 3GPP as part of Releases 13 and 14. Obviously the goal is to further increase peak data rate and capacity for mobile broadband services. Features like supporting an even higher number of aggregated carriers and operation of LTE in or in combination with unlicensed spectrum are considered to be the most important in commercial networks. Support for advanced antenna technologies realizing FD-MIMO will further improve spectral efficiency and system capacity. We conclude that LTE-Advanced Pro is well capable of satisfying the need for mobile broadband services in today's cellular networks.

4 LTE/LTE-Advanced frequency bands

Operating bands of LTE/LTE-A up to 3GPP Release 14 are shown in Table 4.1 using paired spectrum and in Table 4.2 using unpaired spectrum.

Table 4.1: LTE/LTE-A/LTE-A Pro frequency bands (FDD).

E-UTRA operating band	Uplink (UL) operating band			Downlink (DL) operating band		
	F_{UL_low} in MHz	–	F_{UL_high} in MHz	F_{DL_low} in MHz	–	F_{DL_high} in MHz
1	1920	–	1980	2110	–	2170
2	1850	–	1910	1930	–	1990
3	1710	–	1785	1805	–	1880
4	1710	–	1755	2110	–	2155
5	824	–	849	869	–	894
6	830	–	840	875	–	885
7	2500	–	2570	2620	–	2690
8	880	–	915	925	–	960
9	1749.9	–	1784.9	1844.9	–	1879.9
10	1710	–	1770	2110	–	2170
11	1427.9	–	1447.9	1475.9	–	1495,9
12	699	–	716	729	–	746
13	777	–	787	746	–	756
14	788	–	798	758	–	768
17	704	–	716	734	–	746
18	815	–	830	860	–	875
19	830	–	845	875	–	890
20	832	–	862	791	–	821
21	1447.9	–	1462.9	1495.9	–	1510.9
22	3410	–	3490	3510	–	3590
23	2000	–	2020	2180	–	2200
24	1626.5	–	1660.5	1525	–	1559
25	1850	–	1915	1930	–	1995
26	814	–	849	859	–	894
27	807	–	824	852	–	869
28	703	–	748	758	–	803
29	N/A			717	–	728
30	2305	–	–	2350	–	2360
31	452.5	–	457.5	462.5	–	467.5
32	N/A			1452	–	1496
65	1920	–	2010	2110	–	2200
66	1710	–	1780	2110	–	2200
67	N/A			738	–	758
68	698	–	728	753	–	783
69	N/A			2570	–	2620
70	1695	–	1710	1995	–	2020

Table 4.2: LTE/LTE-A/LTE-A Pro frequency bands (TDD).

E-UTRA operating band	Downlink/uplink (DL/UL) operating band		
	F_{low} in MHz	–	F_{high} in MHz
33	1900	–	1920
34	2010	–	2025
35	1850	–	1910
36	1930	–	1990
37	1910	–	1930
38	2570	–	2620
39	1880	–	1920
40	2300	–	2400
41	2496	–	2690
42	3400	–	3600
43	3600	–	3800
44	703	–	803
45	1447	–	1467
46	5150	–	5925
47	5855	–	5925
48	3550	–	3700

5 Literature

[1] Rohde & Schwarz 1MA169: LTE-Advanced (3GPP Rel.10) Technology Introduction.
[2] Rohde & Schwarz 1MA232: LTE- Advanced (3GPP Rel.11) Technology Introduction.
[3] Rohde & Schwarz 1MA252: LTE-Advanced (3GPP Rel.12) Technology Introduction.
[4] Rohde & Schwarz 1MA214: WLAN Traffic Offload in LTE
[5] 3GPP TS 36.101 v14.6.0 Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception.
[6] 3GPP TS 36.104 v14.6.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception.
[7] 3GPP TS 36.211 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation.
[8] 3GPP TS 36.212 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding.
[9] 3GPP TS 36.213 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures.
[10] 3GPP TS 36.214 v14.4.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements.
[11] 3GPP TS 36.300 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2.
[12] 3GPP TS 36.306 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities.
[13] 3GPP TS 36.321 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification.
[14] 3GPP TS 36.331 v14.5.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification.
[15] 3GPP TS 36.360 v14.0.0 Evolved Universal Terrestrial Radio Access (E-UTRA); LTE-WLAN Aggregation Adaptation Protocol (LWAAP) specification
[16] 3GPP TR 36.859 v13.0.0 Study on Downlink Multiuser Superposition Transmission (MUST) for LTE
[17] 3GPP TR 36.866 v12.0.1 Study on Network-Assisted Interference Cancellation and Suppression (NAIC) for LTE
[18] 3GPP TR 36.889 v13.0.0 Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum
[19] 3GPP TS 36.141 V14.6.0 Base Station conformance testing
[19] Kenichi HIGUCHI, Anass BENJEBBOUR "Non-orthogonal Multiple Access (NOMA) with Successive Interference Cancellation for Future Radio Access" [IEICE TRANS. COMMUN., VOL.E98–B, NO.3 MARCH 2015]
[20] 3GPP R1-152493 Candidate schemes for superposition transmission
[21] ITU, Radio Regulations, Articles, Edition 2016
[22] 3GPP TS 36.133 v14.6.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management
[23] 3GPP TR 36.890 v13.0.0 Study on Support of single-cell point-to-multipoint transmission in LTE
[24] 3GPP TR 37.842 v13.2.0 Evolved Universal Terrestrial Radio Access (E-UTRA) and Universal Terrestrial Radio Access (UTRA; Radio Frequency (RF) requirement background for Active Antenna System (AAS) Base Station (BS)
[25] 3GPP TS 37.145-2 v 14.3.0 Active Antenna System (AAS) Base Station (BS) conformance testing; Part 2: radiated conformance testing
[26] 3GPP TS 36.141 v14.6.0 Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) conformance testing
[27] Rohde & Schwarz 1MA186: LTE Transmission Modes and Beamforming

6 Additional information

This white paper and the supplied programs may only be used subject to the conditions of use set forth in the download area of the Rohde & Schwarz website.

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

www.rohde-schwarz.com

Regional contact

- Europe, Africa, Middle East | +49 89 4129 12345
  customersupport@rohde-schwarz.com
- North America | 1 888 TEST RSA (1 888 837 87 72)
  customer.support@rsa.rohde-schwarz.com
- Latin America | +1 410 910 79 88
  customersupport.la@rohde-schwarz.com
- Asia Pacific | +65 65 13 04 88
  customersupport.asia@rohde-schwarz.com
- China | +86 800 810 82 28 | +86 400 650 58 96
  customersupport.china@rohde-schwarz.com

PD 5215.8258.52 | Version 01.00 | May 2018 (as)
White paper | LTE-Advanced Pro Introduction
Data without tolerance limits is not binding | Subject to change

5215825852

5215.8258.52 01.00 PDP 1 en