LTE-Advanced Technology Introduction

White Paper

Although the commercialization of LTE technology began in end 2009, the technology is being enhanced in order to meet ITU-Advanced requirements. This white paper summarizes these necessary improvements specified in 3GPP Release 10, which are also known as LTE-Advanced.

ROHDE&SCHWARZ

LTE-Advanced

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Table of Contents

1 Introduction

LTE (Long Term Evolution) standardization within the 3GPP (3rd Generation Partnership Project) has reached a mature state. Changes in the specification are limited to corrections and bug fixes. Since end 2009, LTE mobile communication systems are deployed as a natural evolution of GSM (Global system for mobile communications) and UMTS (Universal Mobile Telecommunications System).
The ITU (International Telecommunication Union) coined the term IMT-Advanced to identify mobile systems whose capabilities go beyond those of IMT 2000 (International Mobile Telecommunications). Specifically data rate requirements are increased. In order to support advanced services and applications 100Mbps for high and 1Gbps for low mobility scenarios must be realized. Throughout 2009 3GPP worked on a study with the purpose of identifying the LTE improvements required to meet IMT-Advanced requirements. In September 2009 the 3GPP Partners made a formal submission to the ITU proposing that LTE Release 10 & beyond (LTE-Advanced) should be evaluated as a candidate for IMT-Advanced. In October 2010 LTE-Advanced successfully completed the evaluation process in ITU-R complying with or exceeding the IMT-Advanced requirements and thus became an acknowledged 4G technology. Beyond achieving technical requirements, a major reason for aligning LTE with the call for IMT-Advanced is that IMT conformant systems will be candidates for future new spectrum bands that are still to be identified. This ensures that today's deployed LTE mobile networks provide an evolutionary path towards many years of commercial operation. This white paper summarizes LTE-Advanced features based on [3] and finally specified in 3GPP RAN specification.

Section 2 outlines the IMT-Advanced requirements and section 3 summarizes the main technology components (see Figure 1). Section 3.1 introduces new UE categories common to all LTE-Advanced technology components, followed by

- section 3.2 on band aggregation,
- section 3.3 on enhanced multiple input / output (MIMO) antenna technologies in both downlink and uplink direction,
- section 3.4 introducing enhancements of the uplink transmission scheme,
- section 3.5 describing enhanced inter-cell interference coordination techniques,
- section 3.6 on the application of intelligent relay nodes.

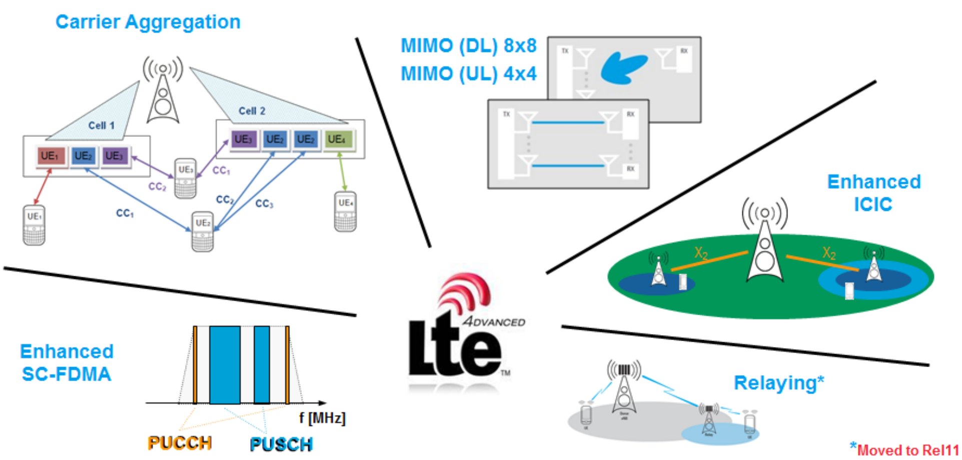

Figure 1: Main LTE-Advanced technology components (overview)

Section 4 concludes this white paper. The appendix in section 5 and section 6 provide additional information including a summary of LTE frequency bands and literature references.

Note that this white paper assumes basic knowledge of the LTE technology as specified in 3GPP Release 8. An easy-to-read LTE technology introduction can be found in [1].

2 LTE-Advanced requirements

Based on the ITU requirements for IMT-Advanced systems, 3GPP created a technical report summarizing LTE-Advanced requirements in [4]. The IMT-Advanced key features delineated in the circular letter inviting candidate radio interface technologies are given below:

- a high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner;
- compatibility of services within IMT and with fixed networks;
- capability of interworking with other radio access systems;
- high quality mobile services;
- user equipment suitable for worldwide use;
- user-friendly applications, services and equipment;
- worldwide roaming capability; and
- enhanced instantaneous peak data rates to support advanced services and applications (100 Mbps for high and 1 Gbps for low mobility were established as targets for research).

In [4] the LTE-Advanced requirements are detailed as follows. In general the above IMT-Advanced requirements shall be met or even exceeded. Additionally all existing LTE requirements are equally applicable to LTE-Advanced. For several categories concrete requirements have been set.

Peak data rate

The system should target a downlink peak data rate of 1 Gbps and an uplink peak data rate of 500 Mbps.

Latency

C-Plane: The target for transition time from idle mode (with internet protocol (IP) address allocated) to connected mode should be less than 50 ms including the establishment of the user plane (excluding the S1 interface transfer delay). The target for the transition from a "dormant state" to connected mode (i.e. discontinuous reception (DRX) sub-state in connected mode) should be less than 10 ms (excluding the DRX delay).
U-Plane: LTE-Advanced should allow for reduced U-plane latency compared to LTE Release 8.

Spectrum efficiency

LTE-Advanced aims to support downlink (8x8 antenna configuration) peak spectrum efficiency of 30 bps/Hz and uplink (4x4 antenna configuration) peak spectrum efficiency of 15 bps/Hz. Additionally average spectrum efficiency targets have been set according to Table 1. Average spectrum efficiency is defined as the aggregate throughput of all users (the number of correctly received bits over a certain period of time) normalized by the overall cell bandwidth divided by the number of cells.

	Antenna configuration	Target [bps/Hz/cell]
Uplink	1x2 / 2x4	1.2 / 2.0
Downlink	2x2 / 4x2 / 4x4	2.4 / 2.6 / 3.7

Table 1: Targets for average spectrum efficiency

Cell edge user throughput

LTE-Advanced should allow cell edge user throughput to be as high as possible. The cell edge user throughput is defined as the 5% point of the cumulative density function (CDF) of the user throughput normalized with the overall cell bandwidth. Requirements for cell edge performance are given in Table 2 below.

	Antenna configuration	Target [bps/Hz/cell/user]
Uplink	1x2 / 2x4	0.04 / 0.07
Downlink	2x2 / 4x2 / 4x4	0.07 / 0.09 / 0.12

Table 2: Targets for cell edge user throughput

VoIP capacity

VoIP capacity should been improved for all antenna configurations in comparison to LTE Release 8.

Mobility

Mobility requirements have been formulated in comparison to LTE Release 8. The system shall support mobility across the cellular network for various mobile speeds up to 350km/h (or even up to 500km/h depending on the frequency band). In comparison to LTE Release 8, the system performance shall be enhanced for 0 up to 10 km/h.

Spectrum flexibility

The initial identified frequency bands in addition to the already allocated bands in LTE Release 8 (see section 5.1) are as follows:

- 450−470 MHz band,
- 698−862 MHz band,
- 790−862 MHz band,
- 2.3−2.4 GHz band,
- 3.4−4.2 GHz band, and
- 4.4-4.99 GHz band.

LTE-Advanced shall operate in spectrum allocations of different sizes including wider spectrum allocations than those of LTE Release 8. The main focus for bandwidth solutions wider than 20MHz should be on consecutive spectrum. However aggregation of the spectrum for LTE-Advanced should take into account reasonable user equipment (UE) complexity. Frequency division duplex (FDD) and time division duplex (TDD) should be supported for existing paired and unpaired frequency bands, respectively.

3 Technology Components of LTE-Advanced

3.1 UE categories for LTE-Advanced

Independent from the LTE-Advanced technology components, new UE categories 6, 7 and 8 are added into LTE Release 10 according to Table 3 and Table 4.

UE Category	Maximum number of DL-SCH transport block bits received within a TTI	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL
…	…	…	…	…
6	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
7	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
8	2998560	299856	35982720	8

Table 3: New downlink UE categories [11]

UE Category	Maximum number of DL-SCH transport block bits received within a TTI	Maximum number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM in UL	Total layer 2 buffer size [bytes]
…	…	…	…	…
6	51024	51024	No	3 300 000
7	102048	51024	No	3 800 000
8	1497760	149776	Yes	42 200 000

Table 4: New uplink UE categories [11]

These categories describe to a certain extend the devices capabilities. For instance categories 6 and 7 support MIMO 2x2 and/or 4x4 and go up to data rates of 300 Mbps. Whereas category 8 is the highest category, supporting 8x8 MIMO leading to a peak data rate of 3 Gbps, if the maximum of five component carriers are aggregated. Uplink category 8 leads to 1.5 Gbps data rate using 4x4 MIMO and 64QAM modulation. Note that this UE category significantly exceeds the IMT-Advanced requirements. The UE category is only an indication of the user devices capabilities. It is used as kind of an upper bound for achievable data rates. Much more detailed information on the UE capabilities is signaled to the network on RRC layer. The initial attach procedure is unchanged compared with LTE Release 8 (see Figure 2). After EPS bearer setup and during the UE capability transfer, the device identifies itself as LTE Release10 capable by providing additional information on top of the “standard” LTE Release 8 capabilities. These more detailed capabilities refer to the LTE-Advanced features described in the following sections of this white paper as well as regarding support for more general capabilities, i.e. support of specific frequency bands (see Figure 3).

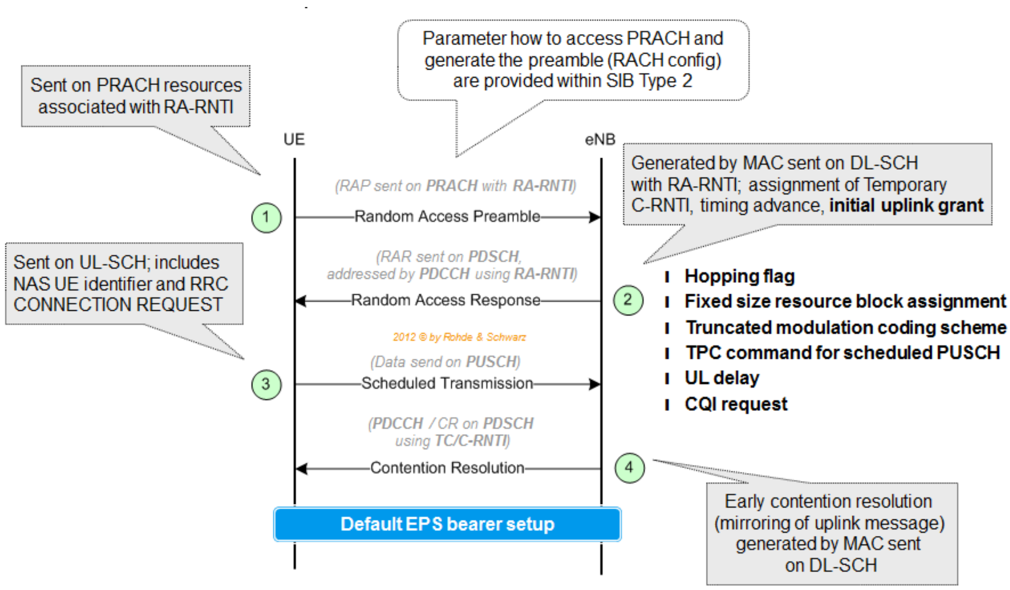

Figure 2: LTE attach procedure

```
-- ASN1START
...
UE-EUTRA-Capability-v1020-IEs ::=   SEQUENCE {
    ue-Category-v1020                    INTEGER (6..8)                           OPTIONAL,
    phyLayerParameters-v1020             PhyLayerParameters-v1020                 OPTIONAL,
    rf-Parameters-v1020                  RF-Parameters-v1020                      OPTIONAL,
    measParameters-v1020                 MeasParameters-v1020                     OPTIONAL,
    featureGroupIndicators-v1020         BIT STRING (SIZE (32))                   OPTIONAL,
    interRAT-ParametersCDMA2000-v1020    IRAT-ParametersCDMA2000-1XRTT-v1020      OPTIONAL,
    ue-BasedNetwPerfMeasParameters-r10   UE-BasedNetwPerfMeasParameters-r10       OPTIONAL,
    interRAT-ParametersUTRA-TDD-v1020    IRAT-ParametersUTRA-TDD-v1020            OPTIONAL,
    nonCriticalExtension                 SEQUENCE {}                              OPTIONAL
}
                                        2012 © by Rohde&Schwarz
...
PhyLayerParameters-v1020 ::=             SEQUENCE {
    twoAntennaPortsForPUCCH-r10              ENUMERATED {supported}                   OPTIONAL,
    tm9-With-8Tx-FDD-r10                     ENUMERATED {supported}                   OPTIONAL,
    pmi-Disabling-r10                        ENUMERATED {supported}                   OPTIONAL,
    crossCarrierScheduling-r10               ENUMERATED {supported}                   OPTIONAL,
    simultaneousPUCCH-PUSCH-r10              ENUMERATED {supported}                   OPTIONAL,
    multiClusterPUSCH-WithinCC-r10           ENUMERATED {supported}                   OPTIONAL,
    nonContiguousUL-RA-WithinCC-List-r10     NonContiguousUL-RA-WithinCC-List-r10     OPTIONAL
}
...
```

Figure 3: UE-EUTRA capability information element [12]

3.2 Band aggregation

One straight forward possibility to reach high data rates requirements is to aggregate multiple LTE carrier (see Figure 4). Two or more component carriers (CC) are aggregated in order to support wider transmission bandwidths up to 100MHz. Each component carrier has a maximum of 110 resource blocks (RB). However initial LTE-Advanced (3GPP Release 10) deployments will be limited to the use of maximum two component carrier, i.e. the initial maximum DL/UL bandwidth will be 40MHz. In fact even less bandwidth will initially be used, because the band aggregation feature will allow a more flexible use of diverse spectrum allocations available in an operator network. Existing band allocations to an individual operator often consists of spectrum fractions in various frequency bands. Therefore offering the possibility to aggregate e.g. 5MHz in one frequency band with 10 MHz in a different frequency band is equally important than achieving highest data rates.

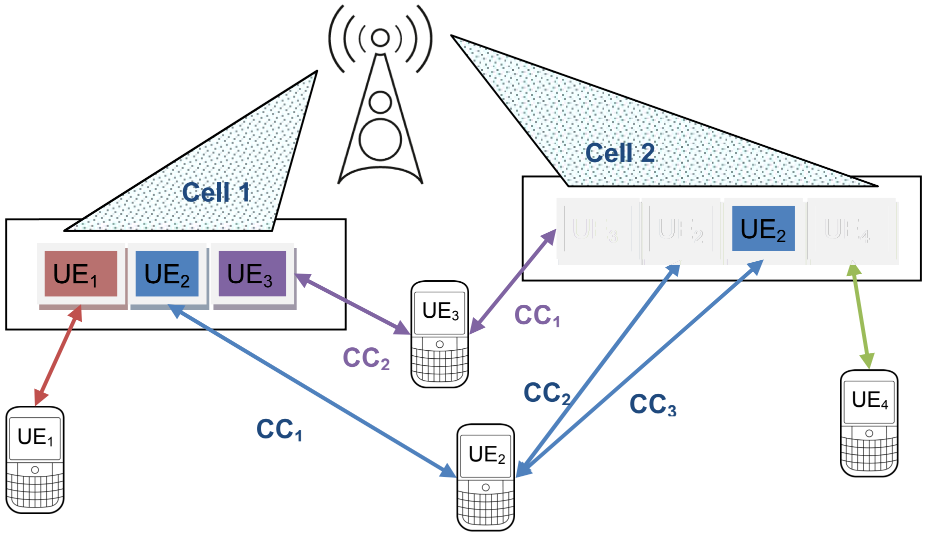

Figure 4: LTE-Advanced maximum bandwidth in contiguous deployment

The component carrier set is UE specific, whereas registration with the network is always taking place on the primary component carrier (PCC). Additional bandwidth is provided by secondary component carriers (SCC) with a maximum of four SCCs. In downlink direction PDCCH allocation on SCC is optional whereas in uplink direction only the PCC carries PUCCH (see Figure 5).

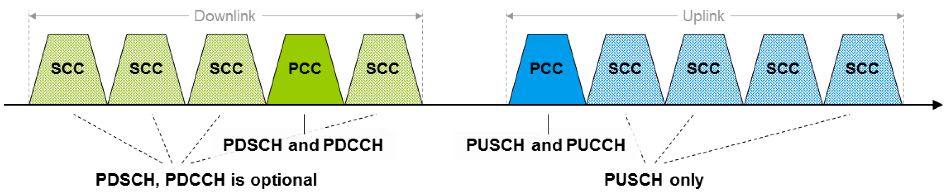

Figure 5: Channel allocation on PCC and SCC

On the radio link control (RLC) layer there is only one connection per UE independent of the number of component carriers assigned. Multiple CCs are handled on the Medium Access Control (MAC) layer, i.e. in the scheduler of the eNodeB. There are separate HARQ transmissions and acknowledgements for each CC. Common timing control for all UL component carriers (one timing advance (TA) command) is applied, but individual power control for each carrier (TPC commands) is realized. Handover is only applicable for the PCC as well as RACH procedures are naturally only executed on the PCC. The UE provides individual channel state information (CSI) reporting for each individual CC. In LTE FDD more downlink CCs may be allocated than in uplink in order to address asymmetric traffic requirements. Note that for TD-LTE all component carriers have the same DL/UL time slot configuration, since asymmetric traffic may be addressed by the appropriate number of time slots in DL and UL, respectively.

Independent of the initial asymmetric aggregation of carriers, there is a need for enhanced uplink feedback mechanisms to feed back all the information related to the transmission and channel quality parameters. For acknowledgement/non-acknowledgements PUCCH format 1b has been enhanced, now with channel selection.

Additionally a new PUCCH format 3 is introduced. In contrast to the existing LTE Release 8 PUCCH formats, it is not a Zadoff-Chu sequence anymore. The new PUCCH format is more a type of PUSCH transmission, using QPSK modulation. Orthogonal Cover Codes are applied to transmit a large number of ACK/NACK bits, i.e. 20 bits in case of LTE TDD and 10 bits for LTE FDD (see details in [7], [8] and [9]). This allows the transmission of ACK/NACK for up to 5 carriers assuming 2x2 MIMO is applied to each carrier, resulting in 10 ACK/NACK bits for the two code words eventually transmitted per component carrier. The resources to be used for PUCCH format 3 are explicitly signaled to the user device.
In order to support legacy LTE Release 8 terminals it is required that each of the component carriers can be configured to be a LTE Release 8 carrier. However not all component carriers are necessarily LTE Release 8 compatible. Contiguous and non-contiguous component carrier aggregation as well as intra-band and inter-band carrier aggregation is supported (see Figure 6). The high degree in flexible allocations allows addressing individual operator needs including the support of heterogeneous network deployments (see section 3.5).

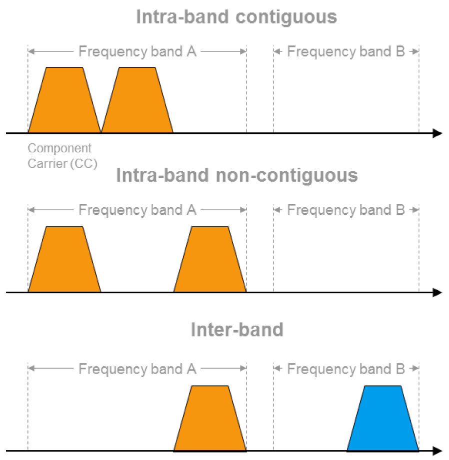

Figure 6: LTE-Advanced spectrum deployment

3.2.1 Frequency deployment scenarios

The different regions in the world have different frequency deployments of existing technologies. Band aggregation is also used in WCDMA/HSPA networks. Consequently a high variety of evolution scenarios exist to migrate from existing technologies to LTE / LTE-Advanced. The interest in a high number of different band combinations resulted into a limited number of carrier frequency scenarios specified in RAN4 within the 3GPP Release 10 timeframe. It was agreed to work out requirements for these limited scenarios first before adding scenarios with more practical relevance in a release independent manner later. Note that support for frequency bands is generally release independent. Frequency bands are added to 3GPP specifications whenever identified. Still a UE may support a certain frequency band added in a later 3GPP Release (e.g. Release 9) even if it generally supports an earlier 3GPP Release feature set (e.g. Release 8) only. The initial work in 3GPP RAN4 concentrated on the following intra- and inter-band scenarios (see Table 5).

E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band	Downlink (DL) operating band	Duplex Mode
Intra band CA operating bands				
CA_1	1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
CA_40	40	2300 – 2400 MHz	2300 – 2400 MHz	TDD
Inter band CA operating bands				
E-UTRA CA Band	**E-UTRA Band**	**Uplink (UL) operating band**	**Downlink (DL) operating band**	**Duplex Mode**
CA_1-5	1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
	5	824 – 849 MHz	869 – 894 MHz	

Table 5: Intra- and inter-band carrier aggregation focus scenarios according to 3GPP RAN4 [5]

Subsequently a fairly high number of different work items were started to work on individual operator relevant frequency band combinations as shown in Table 6. The rapporteur name indicates which region in the world is interested in the specific band combination. The different frequency ranges are marked in order to provide an illustration on the important frequency bands. Obviously for LTE using FDD mode there is a high interest in aggregating lower frequency bands around 800 MHz with frequency bands around 2 GHz as well as some interest in aggregating frequency bands around 2 GHz with frequency bands around 2.6 GHz. There are two carrier aggregation work items on LTE in TDD Mode, which are relevant for intra-band carrier aggregation only. One single work item addresses the case of two uplink carrier frequencies, i.e. all other do not apply carrier aggregation in uplink.

Title	700 - 900 MHz	1.5 – 1.6 GHz	1.8 – 2.1 GHz	2.6 GHz	Rapporteur
Intra band carrier aggregation (2DL, 1UL)					
LTE-A CA in B7				✓	China Unicom
LTE-A CA of B38 (TD-LTE)				✓	Huawei
LTE-A CA of Band 41 (TD-LTE)				✓	Clearwire
LTE-A CA in B3			✓		SK Telecom
LTE-A CA in B25			✓		Sprint
Inter band carrier aggregation (2DL, 1UL)					
LTE-A CA of B1_B 7			✓	✓	China Telecom
LTE-A CA of B1_B18	✓		✓		KDDI
LTE-A CA of B1_B19	✓		✓		NTT DoCoMo
LTE-A CA of B1_B 21		✓	✓		NTT DoCoMo
LTE-A CA of B2_B17	✓		✓		AT&T
LTE-A CA of B3_B5	✓		✓		SK Telecom
LTE-A CA of B3_B7			✓	✓	TeliaSonera

Title	700 - 900 MHz	1.5 – 1.6 GHz	1.8 – 2.1 GHz	2.6 GHz	Rapporteur
Inter band carrier aggregation (2DL, 1UL)					
LTE-A CA of B3_B8	✓		✓		SK Telecom
LTE-A CA of B3_B20	✓		✓		Vodafone
LTE-A CA of B4_B5	✓		✓		AT&T
LTE-A CA of B4_B7			✓	✓	Rogers Wireless
LTE-A CA of B4_B12	✓		✓		Cox Communications
LTE-A CA of B4_B13	✓		✓		Ericsson
LTE-A CA of B4_B17	✓		✓		AT&T
LTE-A CA of B5_B12	✓				US Cellular
LTE-A CA of B5_B17	✓				AT&T
LTE-A CA of B7_B20	✓			✓	Huawei
LTE-A CA of B8_B20	✓				Vodafone
LTE-A CA of B11_B18	✓	✓			KDDI
Inter band carrier aggregation (2DL, 2UL)					
LTE-A CA of B3_B5	✓		✓		SK Telecom

Table 6: Intra- and inter-band carrier aggregation scenarios with work item started in 3GPP RAN4

LTE Release 8 allows a 100 kHz frequency raster placing the LTE channel within the operator owned bandwidth. The 15 kHz subcarrier spacing in combination with contiguously aggregated component carriers requires a 300 kHz carrier spacing in order to preserve the orthogonality in the downlink transmission scheme.

3.2.2 UE bandwidth classes

New UE bandwidth classes applicable to carrier aggregation are specified in [5]. Note that 3GPP RAN4 defines the number of resource blocks in a transmission bandwidth based on the channel bandwidth according to Table 7. I.e. in 20 MHz channel the maximum number of resource blocks including guard band considerations is equal to 100 in contrast to a maximum of 110 resource blocks per carrier specified in 3GPP RAN1.

Channel bandwidth $BW_{Channel}$ [MHz]	1.4	3	5	10	15	20
Transmission bandwidth configuration N_{RB}	6	15	25	50	75	100

Table 7: Transmission bandwidth configuration N_{RB} in E-UTRA channel bandwidths [5]

For intra-band carrier aggregation parameters are specified according to Figure 7. Six UE bandwidth classes are foreseen, whereas only three are fully specified up to now. Bandwidth classes are defined in terms of number of resource blocks with the aggregated transmission bandwidth and the maximum number of component carriers supported (see Table 8).

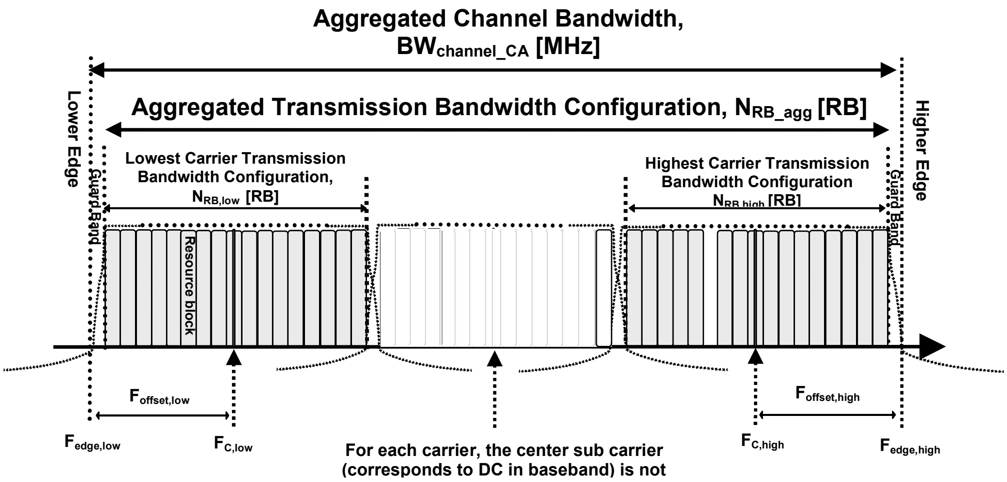

Figure 7: Definition of Aggregated channel bandwidth and aggregated channel bandwidth edges [5]

CA Bandwidth Class	Aggregated Transmission Bandwidth Configuration	Maximum number of CC	Nominal Guard Band BW_{GB}
A	$N_{RB,agg} \leq 100$	1	$0.05BW_{Channel(1)}$
B	$N_{RB,agg} \leq 100$	2	FFS
C	$100 < N_{RB,agg} \leq 200$	2	$0.05\ max(BW_{Channel(1)},BW_{Channel(2)})$
D	$200 < N_{RB,agg} \leq [300]$	FFS	FFS
E	$[300] < N_{RB,agg} \leq [400]$	FFS	FFS
F	$[400] < N_{RB,agg} \leq [500]$	FFS	FFS
$BW_{Channel(1)}$ and $BW_{Channel(2)}$ are channel bandwidths of two E-UTRA component carriers according to Table 7			

Table 8: CA bandwidth classes and corresponding nominal guard bands

Supported bandwidth classes are indicated to the network on a per band basis individually for each up- and downlink direction, including the support of either intra-band (contiguous or non-contiguous) or inter-band carrier aggregation (see section 3.2). Figure 8 provides an example which terminology is used by the device to indicate its support of carrier aggregation for a particular frequency band or band combination. Take the intra-band non-contiguous case with CA_25A_25A as an example. It tells the network, that this device is able to receive (or transmit) two separate carriers in frequency band 25; each one with a maximum bandwidth of 100 RB (20 MHz). If this device would be able to aggregate two carriers in that frequency band, but continuously, the acronym would change to CA_25C. Bandwidth class C (see Table 8) defines an aggregated transmission bandwidth between 100 and 200 RB, allocated to two component carriers.

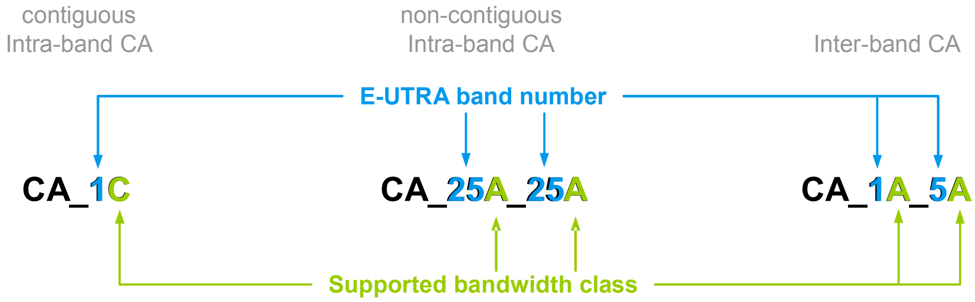

Figure 8: **Notation of carrier aggregation support (type, frequency band, and bandwidth)**

The carrier aggregation feature allows a high degree of flexibility to adapt to individual spectrum deployments. However not all combinations are of practical relevance. For the initial LTE Release10 carrier aggregation scenarios as shown in Table 5, the following carrier aggregation configurations are considered:

CA Configuration / N_{RB_agg}				
CA Configuration	**E-UTRA Band**	**50RB+100RB (10 MHz + 20 MHz)**	**75RB+75RB (15 MHz + 15 MHz)**	**100RB+100RB (20 MHz + 20 MHz)**
CA_1C	1		Yes	Yes
CA_40C	40	Yes	Yes	Yes

Table 9: Supported CC combinations per CA configuration for intra-band contiguous CA [5]

CA operating / Channel bandwidth							
CA Configuration	**E-UTRA Bands**	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**
CA_1A-5A	1				Yes		
	5				Yes		

Table 10: Supported CC combinations per CA configuration for intra-band contiguous CA [5]

3.2.3 Cross carrier scheduling

As of LTE Release 8 each component carrier may use PDCCH to schedule resources for an individual UE that receives multiple carriers in downlink. This scheduling method is backward compatible to LTE Release 8. Additionally and optionally cross carrier scheduling was introduced. This method uses the PDCCH on the PCC in order to schedule resources on the SCCs by using the new carrier indicator field (CFI), see Figure 9.

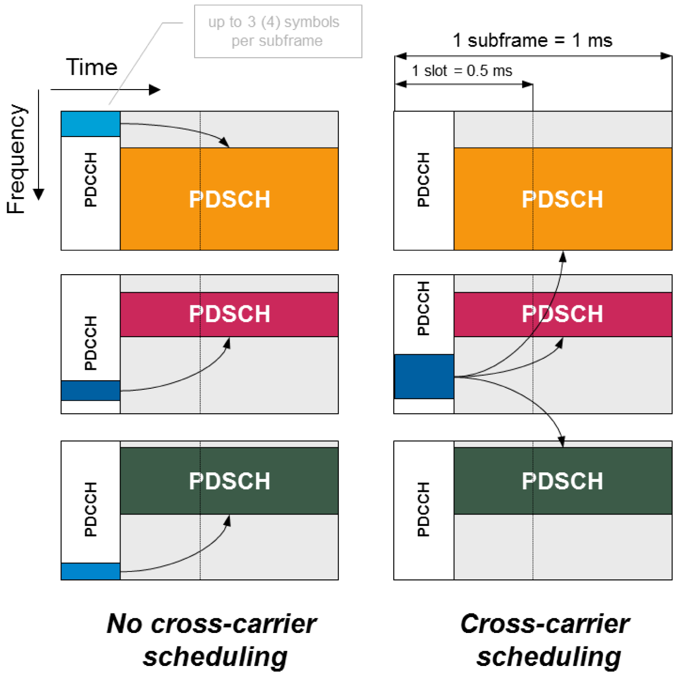

Figure 9: Cross carrier scheduling in comparison to LTE Release 8

The motivation behind the definition of cross-carrier scheduling is to spare signaling capacity and to enable heterogonous networks with support of load balancing for different cell layers (see section 3.5). The PDCCH start can be configured in the time domain by dedicated RRC signaling, i.e. an overlap of PDCCH in different cell layers can be avoided. Note that if a component carrier is already scheduled via ONE component carrier, it cannot be scheduled by another component carrier. In the example in Figure 10 we have 5 component carriers and cross carrier scheduling is activated. CC#1 schedules resources on CC#1 and #2. For that specific user device CC#5 is not allowed to schedule any resources on CC#2.

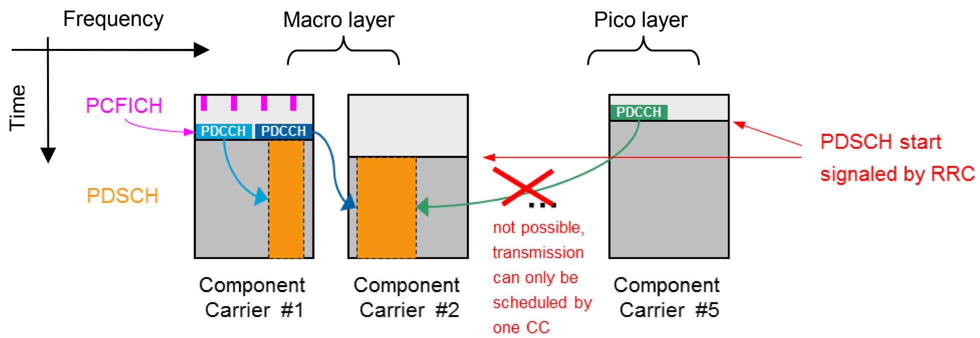

Figure 10: Cross carrier scheduling for support in heterogeneous networks

In order to allow cross carrier scheduling the existing LTE Release 8 DCI format scheme is extended. From 3GPP Release 10 onwards the downlink control information includes a 3 bit carrier indicator field (CFI), which provides index information of that carrier, which carries PDCCH for resource allocation.

3.2.4 HARQ ACK/NACK procedure for multiple cells, PUCCH format 3

In LTE Release 8 PUCCH format 1a/1b/2/2a/2b are used to acknowledge (ACK) / not acknowledge (NACK) the correct reception of transport blocks in downlink direction. This ACK/NACK feedback can be combined with uplink scheduling requests (SR) and/or channel state information (CSI). The scheme was enhanced to allow ACK/NACK reporting for carrier aggregation scenarios resulting into multiple cells received by a single UE. Table 11 summarizes all PUCCH formats specified in 3GPP Release 10 ([7], [9]) while modifications compared to 3GPP Release 8 are highlighted in orange.

PUCCH format	Content	Modulation scheme	Number of bits per subframe
1	Scheduling Request (SR)	N/A	N/A (information is indicated by the presence or absence of transmission)
1a	ACK / NACK, ACK / NACK + SR	BPSK	1
1b	ACK / NACK, ACK / NACK + SR	QPSK	2 4 (more than 1 serving cell FDD/TDD or single cell TDD)
2	CSI (any cyclic prefix), CSI + ACK / NACK (extended cyclic prefix only)	QPSK	20
2a	CSI + ACK / NACK (normal cyclic prefix only)	QPSK + BPSK	21 (20 CSI + 1 ACK/NACK)
2b	CSI + ACK / NACK (normal cyclic prefix only)	QPSK + QPSK	22 (20 CSI + 2 ACK/NACK)
3	ACK / NACK, ACK / NACK + SR	QPSK	48 (10 ACK/NACK for FDD and 20 ACK/NACK for TDD) (10 ACK/NACK + 1 SR for FDD and 20 ACK/NACK + 1 SR for TDD)

Table 11: PUCCH formats and content [7], [9]

There are two principle solutions to enhance the scheme. Either the ACK/NACK feedback is provided in the same way as of LTE Release 8 with the enhancement to select the channel (i.e. carrier) of the transport block that is (not- /) acknowledged. Or a new feedback scheme is introduced, which allows to ACK/NACK multiple transport blocks on multiple carriers in a single extended message. Both solutions are introduced into 3GPP Release 10 specifications. PUCCH format 1b is enhanced to allow individual ACK/NACK with channel selection and a new PUCCH format 3 was added.

PUCCH format 1b has to be used for FDD UEs that support aggregating at most two serving cells. For UEs (FDD and TDD) able to aggregate more than two carriers, higher layer allow to configure either PUCCH format 1b or PUCCH format 3 to be used.

3.2.5 User plane

Figure 11 and Figure 12 illustrate the downlink and uplink layer 2 structure in case of carrier aggregation. It becomes obvious that the packet data control protocol (PDCP) and radio link control (RLC) layer are reused from LTE Release 8 operation. In contrast to LTE Release 8 one UE may be multiplexed to several component carriers, whereas there is one transport block and one independent hybrid acknowledge request (HARQ) entity per scheduled component carrier.

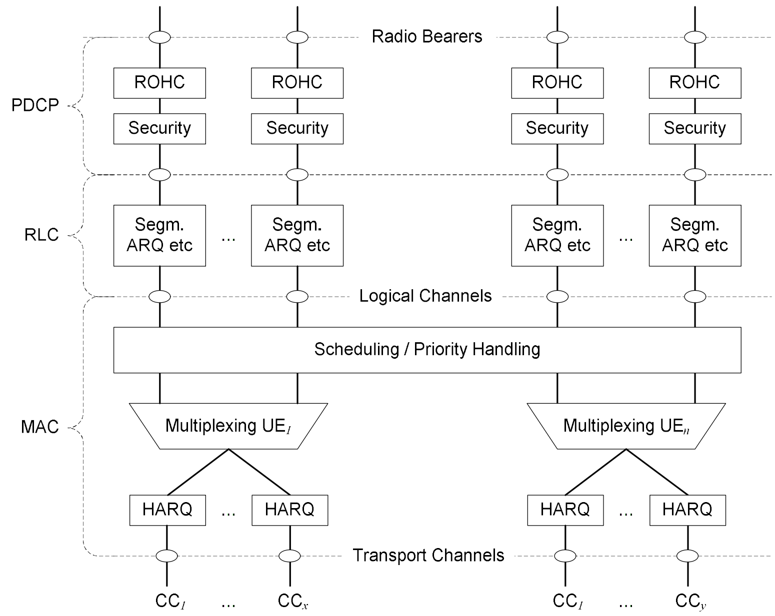

Figure 11: Downlink layer 2 structure [3]

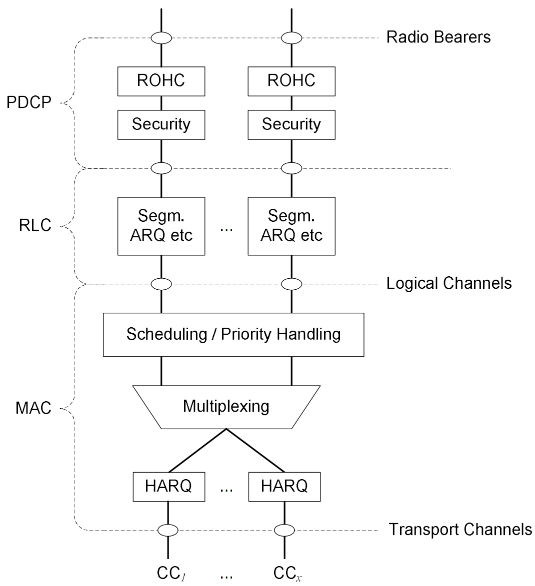

Figure 12: Uplink layer 2 structure [3]

3.2.6 Control plane

There is no difference in the control plane structure compared with LTE Release 8. After radio resource control (RRC) connection establishment, the configuration and/or activation of additional component carriers is performed by dedicated signaling. At intra-LTE handover, multiple component carriers can be included in the handover command for usage in the target cell.
Idle mode mobility procedures as of LTE Release 8 equally apply in a network deploying carrier aggregation. It is possible for a network to configure only a subset of component carriers for idle mode camping.

3.3 Enhanced multiple antenna technologies

LTE Release 8 supports multiple input / output (MIMO) antenna schemes. In downlink direction up to four transmit antennas may be used whereas the maximum number of codewords is two irrespective of the number of antenna ports. Spatial division multiplexing (SDM) of multiple modulation symbol streams to both a single UE using the same time-frequency resource - also referred to as Single-User MIMO (SU-MIMO) - and to different UEs using the same time-frequency resource - also referred to as MU-MIMO - are supported. In uplink direction only MU-MIMO is used, i.e. there is only one modulated symbol stream per UE to be received by the eNodeB, whereas multiple UEs may transmit on the same time-frequency resource. Considering the defined UE capability classes two antenna operation in downlink and one antenna operation in uplink is the standard case for initial commercial LTE deployment.

Before illustrating the details of the enhancements specified in LTE-Advanced, it is worthwhile recalling some basic definitions. The LTE standard specifies so-called antenna ports, see [7].
According to 3GPP an "*antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed*".
In other words, LTE symbols that are transmitted over identical antenna port are subject to the same propagation conditions. The mapping of these antenna ports to physical antennas in real life operation is not specified in 3GPP. As LTE Release 8 support 2x2 and 4x4 MIMO schemes, it is assumed that a 1:1 mapping for antenna ports 0 to 3 is applied (see Figure 13). Note that cell specific reference symbols are defined for up to four antenna ports. For cell specific reference symbols the scheme is such that when one antenna port transmits a reference symbol the other antenna port(s) do not transmit any symbol (see [1], [7]). MBSFN reference symbols, which are needed to support Multimedia Broadcast Multicast Services (MBMS), are transmitted on antenna port 4. Antenna port 5 is used for transmitting user specific reference symbols. LTE Release 8 specifies up to 4 layer transmission.

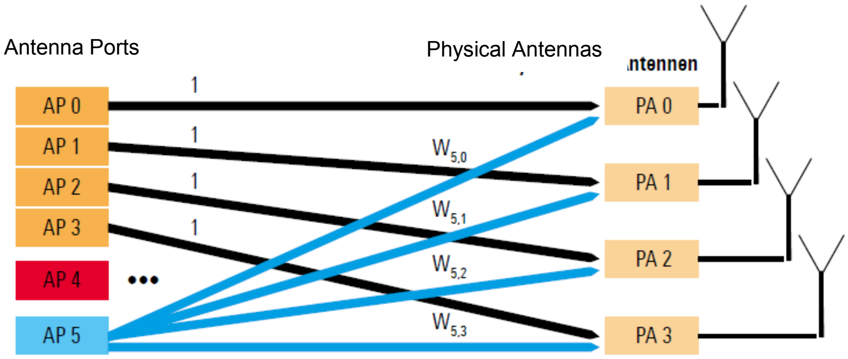

Figure 13: Mapping of logical antenna ports to physical transmit antennas (3GPP Release 8)

LTE-Advanced extends the MIMO capabilities of LTE Release 8 to now supporting eight downlink and four uplink layers (see Figure 14). In LTE-Advanced uplink direction the same principles as defined in LTE Release 8 downlink apply whereas in LTE-Advanced downlink direction the existing LTE Release 8 scheme is extended as described in the following sections. In addition to spatial multiplexing schemes, transmit diversity is possible in both downlink and uplink direction.

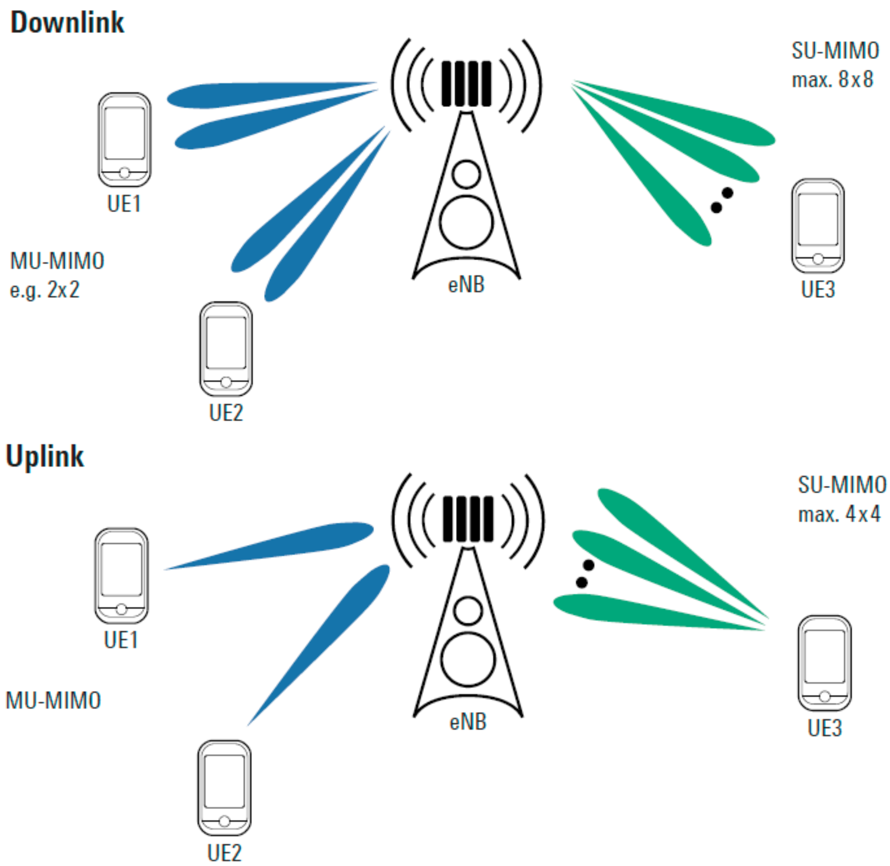

Figure 14: Supported transmit layers in LTE-Advanced

3.3.1 Downlink

3.3.1.1 Layer mapping for downlink spatial multiplexing

In the downlink 8-by-x single user spatial multiplexing scenario of LTE-Advanced, up to two transport blocks can be transmitted to a scheduled UE in one subframe per downlink component carrier. Each transport block is assigned its own modulation and coding scheme. For HARQ ACK/NACK feedback on uplink, one bit is used for each transport block.

Table 12 describes the differences, marked in shaded orange, of the codeword to layer mapping between LTE Release 8 and LTE-Advanced. The expressions $d^{(0)}$, $d^{(1)}$ denote the codeword symbols of maximum two codewords and $x^{(0)}$ - $x^{(7)}$ denote the symbols on maximum eight layers after the mapping procedure. For up to four layers, the codeword-to-layer mapping is the same as for LTE Release 8. As illustrated in Table 12, the symbol rate M_{Symb}^{layer} per code word is up to fourth times increased compared to the symbol rate $M_{Symb}^{(x)}$ on one layer (x=0,1).

Note that codebook based precoding with and without UE feedback – the same way as in LTE Release 8 – is used when cell specific reference signals are applied (up to four layers, two and four antenna ports). However if UE specific reference signals are applied, usually needed for beamforming, there is no codebook based precoding anymore. UE-specific reference signals are always transmitted only on the resource blocks upon which the corresponding PDSCH is mapped. In consequence if more than four layers are used, beamforming and MIMO is becoming a kind of merged feature. For the up to 8 layer PDSCH transmission antenna ports 7 – 14 are used (AP 7 – AP 14, see also Figure 13 in section 3.3.1.3).

In the same way as LTE Release 8 does, LTE-Advanced also allows for downlink transmit diversity schemes to be applied as the use of space-frequency block codes (SFBC) and frequency switched transmit diversity (FSTD). In the case of LTE-Advanced and if more than four antenna ports are applied, the Release 8 transmit diversity scheme is reused.

Codeword to layer mapping for downlink spatial multiplexing			
Number of layers	**Number of codewords**	**Codeword-to-layer mapping** $i = 0,1,\ldots M_{symb}^{layer} - 1$	
1	1	$x^{(0)}(i) = d^{(0)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}$
2	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)}$
2	1	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2$
3	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(2i)$ $x^{(2)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)}/2$
4	2	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$ $x^{(2)}(i) = d^{(1)}(2i)$ $x^{(3)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2 = M_{\text{symb}}^{(1)}/2$
…	…	…	…

Codeword to layer mapping for downlink spatial multiplexing			
Number of layers	**Number of codewords**	**Codeword-to-layer mapping** $i = 0,1,\ldots M_{symb}^{layer} - 1$	
3	1	$x^{(0)}(i) = d^{(0)}(3i)$ $x^{(1)}(i) = d^{(0)}(3i+1)$ $x^{(2)}(i) = d^{(0)}(3i+2)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/3$
4	1	$x^{(0)}(i) = d^{(0)}(4i)$ $x^{(1)}(i) = d^{(0)}(4i+1)$ $x^{(2)}(i) = d^{(0)}(4i+2)$ $x^{(3)}(i) = d^{(0)}(4i+3)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/4$
5	2	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/2 = M_{\mathrm{symb}}^{(1)}/3$
		$x^{(2)}(i) = d^{(1)}(3i)$ $x^{(3)}(i) = d^{(1)}(3i+1)$ $x^{(4)}(i) = d^{(1)}(3i+2)$	
6	2	$x^{(0)}(i) = d^{(0)}(3i)$ $x^{(1)}(i) = d^{(0)}(3i+1)$ $x^{(2)}(i) = d^{(0)}(3i+2)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/3 = M_{\mathrm{symb}}^{(1)}/3$
		$x^{(3)}(i) = d^{(1)}(3i)$ $x^{(4)}(i) = d^{(1)}(3i+1)$ $x^{(5)}(i) = d^{(1)}(3i+2)$	
7	2	$x^{(0)}(i) = d^{(0)}(3i)$ $x^{(1)}(i) = d^{(0)}(3i+1)$ $x^{(2)}(i) = d^{(0)}(3i+2)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/3 = M_{\mathrm{symb}}^{(1)}/4$
		$x^{(3)}(i) = d^{(1)}(4i)$ $x^{(4)}(i) = d^{(1)}(4i+1)$ $x^{(5)}(i) = d^{(1)}(4i+2)$ $x^{(6)}(i) = d^{(1)}(4i+3)$	
8	2	$x^{(0)}(i) = d^{(0)}(4i)$ $x^{(1)}(i) = d^{(0)}(4i+1)$ $x^{(2)}(i) = d^{(0)}(4i+2)$ $x^{(3)}(i) = d^{(0)}(4i+3)$	$M_{\mathrm{symb}}^{\mathrm{layer}} = M_{\mathrm{symb}}^{(0)}/4 = M_{\mathrm{symb}}^{(1)}/4$
		$x^{(4)}(i) = d^{(1)}(4i)$ $x^{(5)}(i) = d^{(1)}(4i+1)$ $x^{(6)}(i) = d^{(1)}(4i+2)$ $x^{(7)}(i) = d^{(1)}(4i+3)$	

Table 12: Codeword to layer mapping for downlink spatial multiplexing (LTE Release 8 and LTE-Advanced) [7]

3.3.1.2 Scheduling of downlink resources, Transmission Mode 9 (TM9)

In order to allow scheduling resources to an end user device that supports special layer multiplexing of up to 8 layers, a new DCI format 2C was introduced into the specifications. DCI format 2C consists of the following information (see Table 13):

- Carrier indicator [3 bit]
- Resource allocation header [1 bit], resource allocation Type 0 and 1
- TPC command for PUCCH [2 bit]
- Downlink Assignment Index [2 bit], TDD only
- HARQ process number [3 bit (FDD), 4 bit (TDD)]
- Antenna ports, scrambling identify and # of layers; see Table 12 [3 bit]
- SRS request [0-1 bit], TDD only
- MCS, new data indicator, RV for two transport blocks [each 5 bit]

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	0	2 layers, ports 7-8, n_{SCID}=0
1	1 layer, port 7, n_{SCID}=1	1	2 layers, ports 7-8, n_{SCID}=1
2	1 layer, port 8, n_{SCID}=0	2	3 layers, ports 7-9
3	1 layer, port 8, n_{SCID}=1	3	4 layers, ports 7-10
4	2 layers, ports 7-8	4	5 layers, ports 7-11
5	3 layers, ports 7-9	5	6 layers, ports 7-12
6	4 layers, ports 7-10	6	7 layers, ports 7-13
7	Reserved	7	8 layers, ports 7-14

Table 13: Antenna port(s), scrambling identity and number of layers indication [8]

3.3.1.3 Downlink reference signal structure

In addition to the spatial multiplexing scheme the LTE-Advanced downlink reference signal structure has been enhanced compared with LTE Release 8 by

- reference signals targeting PDSCH demodulation and
- reference signals targeting channel state information (CSI) estimation (for CQI/PMI/RI reporting when needed)

The reference signals for PDSCH demodulation are UE-specific, i.e. the PDSCH and the demodulation reference signals intended for a specific UE are subject to the same precoding operation. Therefore these reference signals are mutually orthogonal between the layers at the eNodeB. The design principle for the reference signals targeting PDSCH modulation is an extension to multiple layers of the concept of Release 8 UE-specific reference signals used for beamforming. Complementary the use of Release 8 cell-specific reference signals by the UE is not precluded.
In contrast reference signals targeting CSI estimation are cell specific, sparse in the frequency and time domain and punctured into the data region of normal subframes. CSI reference signals are transmitted on one, two, four or eight antenna ports (see Figure 13, AP 15 – AP 22). Note that the UE shall assume that CSI reference signals are not transmitted

- in the special subframe(s) in case of frame structure type 2 (LTE-TDD),
- in subframes where transmission of a CSI-RS would collide with transmission of synchronization signals, PBCH, or *SystemInformationBlockType1* messages,
- in subframes configured for transmission of paging messages for any UE with the cell-specific paging configuration.

Figure 15 illustrates the new defined antenna ports for LTE-Advanced and the mapping to physical antennas (compare Figure 13 for LTE Release 8 only). Note that antenna port 6 is used for positioning reference signals. Support for positioning is part of the LTE Release 9 feature set.

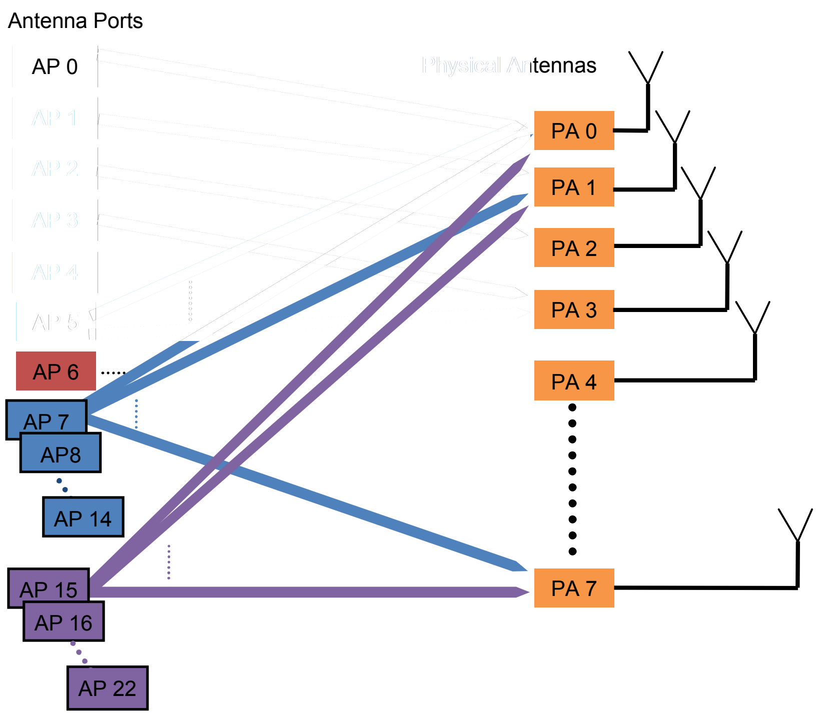

Figure 15: Mapping of logical antenna ports to physical transmit antennas (3GPP Release 10)

3.3.2 Uplink

With LTE-Advanced a scheduled UE may transmit up to two transport blocks. Each transport block has its own modulation and coding scheme (MCS level). Depending on the number of transmission layers, the modulation symbols associated with each of the transport blocks are mapped onto one up to four layers according to the same principle as for LTE Release 8 downlink spatial multiplexing. The transmission rank can be adapted dynamically. Different codebooks are defined depending on the number antenna ports and layers that are used. Furthermore different precoding is used depending on whether two or four antenna ports are available.

3.3.2.1 Layer mapping for uplink spatial multiplexing

Table 14 describes the codeword to layer mapping in uplink direction. The expressions $d^{(0)}$, $d^{(1)}$ denote the codeword symbols of maximum two codewords and $x^{(0)}$ - $x^{(3)}$ denote the symbols on maximum four layers after the mapping procedure. As illustrated in Table 12, the symbol rate M_{Symb}^{layer} per code word is up to two times increased compared to the symbol rate $M_{Symb}^{(x)}$ on one layer (x=0,1).

Codeword to layer mapping for uplink spatial multiplexing			
Number of layers	**Number of codewords**	**Codeword-to-layer mapping** $i = 0,1,\ldots M_{symb}^{layer} - 1$	
1	1	$x^{(0)}(i) = d^{(0)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}$
2	1	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} / 2$
2	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)}$
3	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(2i)$ $x^{(2)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)} / 2$
4	2	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$ $x^{(2)}(i) = d^{(1)}(2i)$ $x^{(3)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} / 2 = M_{\text{symb}}^{(1)} / 2$

Table 14: Codeword-to-layer mapping for uplink spatial multiplexing [7]

For uplink spatial multiplexing with two transmit antennas precoding is defined according to Table 15. In contrast to the LTE Release 8 downlink scheme, whereas several matrices for full-rank transmission are available, only the identity precoding matrix is supported in LTE-Advanced uplink direction. I.e. the two codewords are not mapped to two layers, but codeword one is mapped to layer 1 and codeword two is mapped to layer 2.

Precoding for uplink spatial multiplexing (2 Tx antennas)		
Codebook index	**Number of layers**	
	1	**2**
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	
4	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix}$	
5	$\frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$	

Table 15: Codebook for uplink spatial multiplexing on two transmission antenna ports [7]

For uplink spatial multiplexing with four transmit antennas precoding is defined according to Table 16, if one layer applies, according to Table 17, if two layers apply, according to Table 18, if three layers apply, and according to Table 19, if four layers apply.

Precoding codebook uplink spatial multiplexing (4 Tx antenna ports)								
One layer transmission								
Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	$\frac{1}{2}\begin{bmatrix}1\\1\\1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\1\\j\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\1\\-1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\1\\-j\\-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\j\\1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\j\\j\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\j\\-1\\-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\j\\-j\\-1\end{bmatrix}$
Index	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	$\frac{1}{2}\begin{bmatrix}1\\-1\\1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-1\\j\\-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-1\\-1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-1\\-j\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-j\\1\\-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-j\\j\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-j\\-1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\-j\\-j\\1\end{bmatrix}$
Index	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	$\frac{1}{2}\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\0\\-1\\0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\0\\j\\0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1\\0\\-j\\0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0\\1\\0\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0\\1\\0\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0\\1\\0\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0\\1\\0\\-j\end{bmatrix}$

Table 16: Precoding codebook for uplink spatial multiplexing with four transmit antenna ports: precoding matrices for 1-layer transmission [7]

Precoding codebook uplink spatial multiplexing (4 Tx antenna ports)								
Two layer transmission								
Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	$\frac{1}{2}\begin{bmatrix}1&0\\1&0\\0&1\\0&-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\1&0\\0&1\\0&j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\-j&0\\0&1\\0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\-j&0\\0&1\\0&-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\-1&0\\0&1\\0&-j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\-1&0\\0&1\\0&j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\j&0\\0&1\\0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\j&0\\0&1\\0&-1\end{bmatrix}$
Index	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\1&0\\0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\1&0\\0&-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\-1&0\\0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\-1&0\\0&-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\0&1\\1&0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\0&-1\\1&0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\0&1\\-1&0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0\\0&1\\0&-1\\-1&0\end{bmatrix}$

Table 17: Precoding codebook for uplink spatial multiplexing with four transmit antenna ports: precoding matrices for 2-layer transmission [7]

Precoding codebook uplink spatial multiplexing (4 Tx antenna ports)				
Three layer transmission				
Index	**0**	**1**	**2**	**3**
	$\frac{1}{2}\begin{bmatrix}1&0&0\\1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0&0\\-1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0&0\\0&1&0\\1&0&0\\0&0&1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0&0\\0&1&0\\-1&0&0\\0&0&1\end{bmatrix}$

Precoding codebook uplink spatial multiplexing (4 Tx antenna ports)				
Three layer transmission				
Index	**4**	**5**	**6**	**7**
	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\\1 & 0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\\-1 & 0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\1 & 0 & 0\\1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\1 & 0 & 0\\-1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$
Index	**8**	**9**	**10**	**11**
	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\1 & 0 & 0\\0 & 0 & 1\\1 & 0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\1 & 0 & 0\\0 & 0 & 1\\-1 & 0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\1 & 0 & 0\\1 & 0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\1 & 0 & 0\\-1 & 0 & 0\end{bmatrix}$

Table 18: Precoding codebook for uplink spatial multiplexing with four transmit antenna ports: precoding matrices for 3-layer transmission [7]

Precoding codebook uplink spatial multiplexing (4 Tx antenna ports)	
Four layer transmission	
Index	**0**
	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix}$

Table 19: Precoding codebook for uplink spatial multiplexing with four transmit antenna ports: precoding matrices for 4-layer transmission [7]

LTE-Advanced supports uplink transmit diversity. However for those UEs with multiple transmit antennas, a so-called uplink Single Antenna Port Mode is defined. In this mode the LTE-Advanced UE behavior is the same as the one with a single antenna from eNodeB's perspective and it is always used before the eNodeB is aware of the UE transmit antenna configuration. In the transmit diversity scheme, the same modulation symbol from the uplink channel is transmitted from two antenna ports, on two separate orthogonal resources.

3.3.2.2 Scheduling of uplink resources, Transmission Mode 2 (TM2)

Transmission mode as of LTE Release 8 allows only the use of DCI format 0 to schedule resources on a single antenna port. To enable scheduling of resources for spatial multiplexing in uplink a new DCI format 4 was introduced. DCI format 4 consists of the following information:

- Carrier indicator [0-3 bit]
- Resource Block Assignment [number of bits depends on system bandwidth and corresponding RBG size (P), see Table 19 in section 3.4.2.1], resource allocation Type 0 and Type 1
- TPC command for PUSCH [2 bit]
- Cyclic shift for DM RS and OCC index [2 bit]
- UL index [2 bit], TDD only for UL-DL configuration 0
- Downlink Assignment Index [2 bit], TDD only, for UL-DL configuration 1 to 6
- CSI request [1 or 2 bit], 2 bit for cells with more than two cells in the DL (carrier aggregation)
- SRS request [2 bit]

- Resource Allocation Type [1 bit].
- For each of the two transport blocks: MCS, RV [5 bit], new data indicator [1 bit]
- Precoding information
  - [3 bits for 2 antenna ports], see Table 20 - Transmitted Precoding Matrix Index (TMPI) according to Table 14
  - [6 bits for 4 antenna ports], see Table 21 - Transmitted Precoding Matrix Index (TMPI) according to Table 15 - 18

One codeword: Codeword 0 enabled Codeword 1 disabled		Two codewords: Codeword 0 enabled Codeword 1 enabled	
Bit field mapped to index	**Message**	**Bit field mapped to index**	**Message**
0	1 layer: TPMI=0	0	2 layers: TPMI=0
1	1 layer: TPMI=1	1-7	reserved
2	1 layer: TPMI=2		
…	…		
5	1 layer: TPMI=5		
6-7	reserved		

Table 20: Content of precoding information field for 2 uplink antenna ports [8]

One codeword: Codeword 0 enabled Codeword 1 disabled		Two codewords: Codeword 0 enabled Codeword 1 enabled	
Bit field mapped to index	**Message**	**Bit field mapped to index**	**Message**
0	1 layer: TPMI=0	0	2 layers: TPMI=0
1	1 layer: TPMI=1	1	2 layers: TPMI=1
…	…	…	…
23	1 layer: TPMI=23	15	2 layers: TPMI=15
24	2 layers: TPMI=0	16	3 layers: TPMI=0
25	2 layers: TPMI=1	17	3 layers: TPMI=1
…	…	…	…
39	2 layers: TPMI=15	27	3 layers: TPMI=11
40-63	reserved	28	4 layers: TPMI=0
		29 - 63	Reserved

Table 21: Content of precoding information field for 4 uplink antenna ports [8]

3.4 Enhanced uplink transmission scheme

The uplink transmission scheme of LTE-Advanced has been maintained to a large extent, i.e. single carrier – frequency division multiple access (SC-FDMA) is used, which is a discrete fourier transformed (DFT) precoded orthogonal frequency division multiple access (OFDMA) scheme. The transmission of the physical uplink shared channel (PUSCH) uses DFT precoding in both MIMO and non-MIMO modes. However the following enhancements have been incorporated into the system:

- Decoupling of control information and data transmission
- Non-contiguous data transmission with single DFT per component carrier

These two features are optional to support by a Release 10 capable device. They are indicated to the network during the UE capability information transfer as parts of the initial attach procedure. This will lead to the in Figure 16 shown combinations of PUCCH and PUSCH for 3GPP Release 10, on top of the principles defined with 3GPP Release 8. Both enhancements will be discussed in the following sections in greater detail.

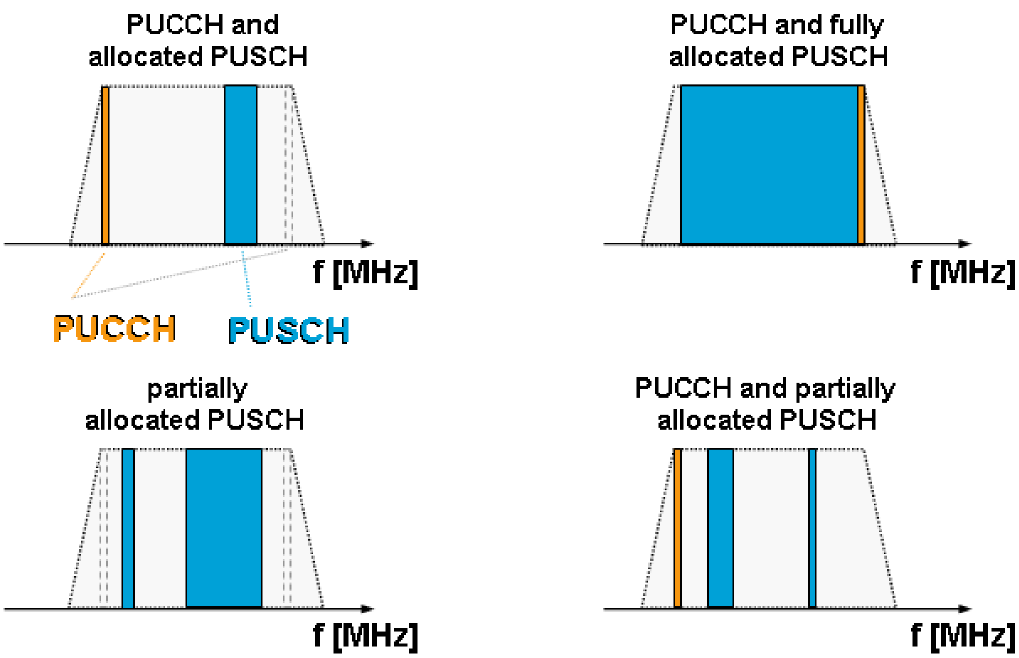

Figure 16: PUSCH and PUCCH combinations in 3GPP Release 10

3.4.1 Simultaneous PUCCH and PUSCH transmission

In LTE Release 8 a terminal utilizes the Physical Uplink Control Channel (PUCCH) to providing uplink control information, such as (non-)acknowledgments (ACK/NACK), CQI, PMI and RI to the network, when there is no user data to be transmitted. In case there is data to be transmitted, the terminal multiplexes this control information with its user data, following well-defined principles, onto the Physical Uplink Shared Channel (PUSCH). Due to the introduction of carrier aggregation as well as enhanced MIMO transmission of up to 8 spatial layers there will be a high amount of control information to be fed back to the network. To avoid the definition of new and additional mechanism to multiplex control information and user data, the decoupling of control information and data transmission has been enabled with LTE-Advanced as of 3GPP Release 10. Simulations have shown that this leads to an improved uplink spectral efficiency as well as a better utilization of uplink resources (PUSCH) for its desired purpose (user data transmission).

3.4.2 Multi-cluster transmission

Two different access schemes have been defined for downlink and uplink with LTE as of 3GPP Release 8. Both are OFDM-based, however the uplink access scheme SC-FDMA differs from the downlink schemes, as an additional DFT is used in the transmission chain that transforms the modulation symbols into the frequency domain, before the actual subcarrier mapping and transformation from the frequency domain into the time domain takes place. The reason is to overcome one of the drawbacks of OFDM signal generation, resulting in a high peak-to-average-power ratio (PAPR), putting some challenges on power amplifier design being used in a handset. With SC-FDMA the PAPR is significantly lower than OFDMA, but it is now modulation scheme dependent, that means it matters if the device is using QPSK or 16QAM modulation, eventually 64QAM.
With Release 8 only localized SC-FDMA is supported. That means the transmission in the uplink is always contiguous, the terminal transmits only on consecutive subcarriers. This decision has been made, as it supports the initial goal to reduce the PAPR of the transmitted signal and consequently allows a more efficient power amplifier implementation. The drawback was that there is now possibility to overcome any frequency-selective fading that might affect the uplink radio channel. With LTE-Advanced the uplink transmission scheme is extend by allowing so called clustered SC-FDMA, i.e. the uplink transmission is not anymore restricted to the use of consecutive subcarriers, but clusters of subcarriers may be allocated. This allows uplink frequency selective scheduling and consequently will increase the link performance. However the peak to average ratio of the transmission signal will be increased compared with the localized scheme of LTE Release 8. Figure 17 provides the uplink block diagram of the transmission chain.

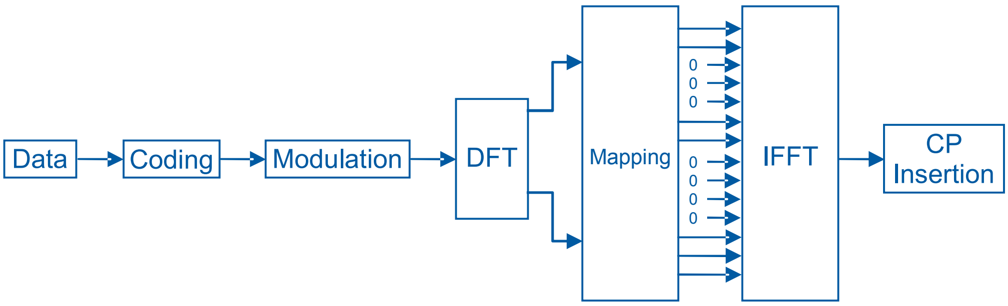

Figure 17: Block diagram for clustered SC-FDMA

3.4.2.1 Scheduling of multi-clustered transmission

In order to support multi-cluster transmission there are now two resource allocation types available in the uplink. Uplink resource allocation type 0 corresponds to the contiguous allocation as defined in 3GPP Release 8. Depended on desired RB allocation, RB offset and available bandwidth a Resource Indication Value (RIV) is calculated, which is signaled with DCI format 0 to the device.

With 3GPP Release 10 uplink resource allocation type 1 will be introduced. Here the available bandwidth is divided into two sets of RB, where each set contains a number of Resource Block Groups (RBG). The size of a RBG depends on the available bandwidth and is given in Table 22.

System Bandwidth	RBG Size (*P*)
≤10	1
11 – 26	2
27 – 63	3
64 – 110	4

Table 22: Resource Block Group (RBG) size

Further a combinatorial index r is provided, that defines the starting and ending RBG for both RB sets (RB set #1: s_0, s_1-1 | RB set #2: s_2, s_3-1). Thus only two-cluster transmission is supported within 3GPP Release 10. It is further required, that these parameters are selected in the way, that $s_0 < s_1 < s_2 < s_3$. This ensures, that the minimum gap between both clusters is at least one RBG and therefore depend on the bandwidth either 1, 2, 3 or 4 RB. Figure 18 shows an example allocation for a 10 MHz (50 RB) signal, where RBG=3 leads to a total of 17 RBGs that results in the shown allocation assuming s_0=2, s_1=9, s_2 =10, s_3=11.

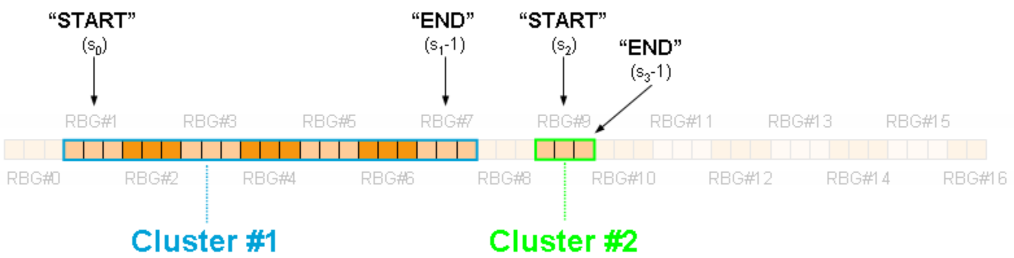

Figure 18: Example for a two-cluster allocation for a 10 MHz (50 RB) signal

3.5 Enhanced Inter-cell Interference Coordination (eICIC)

With LTE being a single frequency network, the pertinent handling of interferences on cell borders was an important topic from Release 8 onwards.
In a pure macro cell network, a UE connected with its respective serving cell (green line on the left in Figure 19) suffers at the cell edge interferences from a neighboring cell (red line on the right). Additional UEs create interferences on the UL (red lines on the left) which cannot be removed by suitably selecting the transmission power.

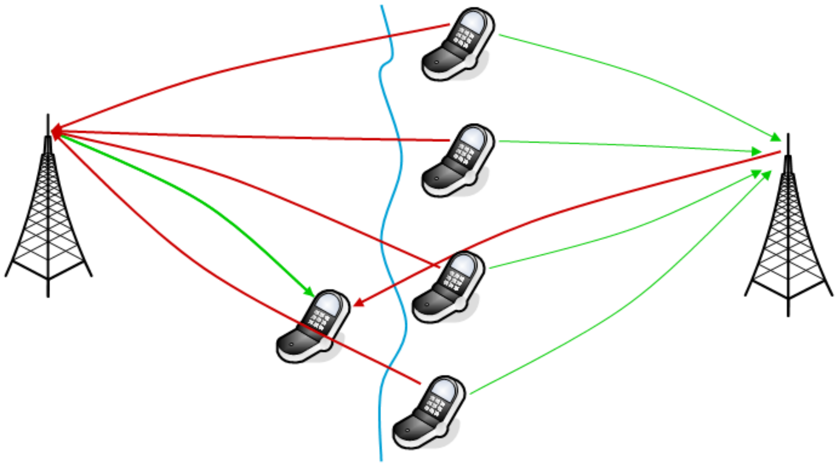

Figure 19: Interference scenario in a macro cell network

To handle these interferences in a proper way, the following methods are used:

- Randomization in the physical layer bit stream
- Interference cancellation on the receiver
- Interference coordination, where eNBs exchange over the X2 interface information about possible or existing interferences. This way it is possible to partition interfered resource blocks among the UEs.

However, for Release 10 networks, these methods are not sufficient anymore. New interference coordination methods are needed when the so called *Heterogeneous Networks* (HetNets) are rolled out:

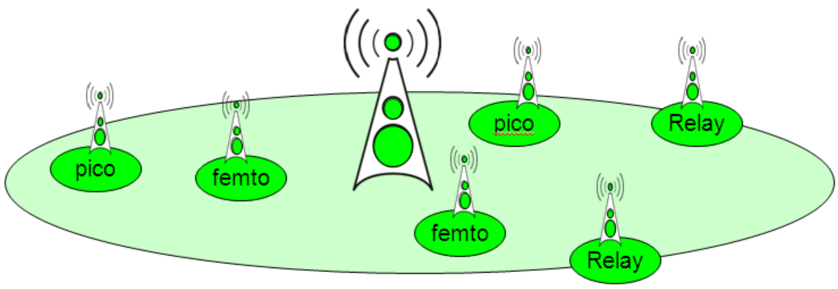

Figure 20: Example cell layout of a heterogeneous network

These are networks which are built up by a macro cell (MC) to ensure coverage, and by pico cells (PC), femto cells (FC) and relay stations to illuminate shaded regions or to enhance the data rate in hot spots. All cells are using the same frequency and more severe interference scenarios do exit compared to single layer deployments (see Figure 20). In Release 10, mainly the interferences involving PCs and in addition FCs have been tackled.

For the PC, the situation can best be described by the following picture:

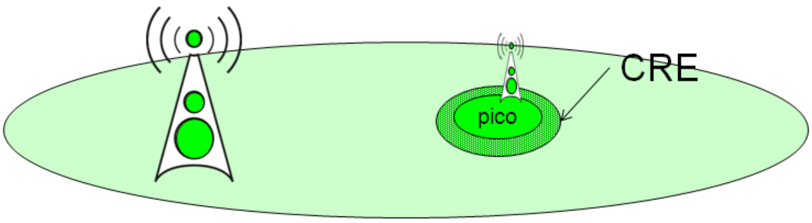

Figure 21: Example cell layout of a heterogeneous network using a pico cell within a marco cell

There are two borders to the PC, the conventional cell edge where the DL signal from the PC is the strongest one, and a so called *Cell Range Extension* (CRE). In this range, the path loss on the UL to the PC is still smaller than the path loss to the MC, whereas the DL signal from the MC is the stronger one. This is different to a MC – MC deployment, where one can assume that if a neighbor cell DL signal becomes stronger than the serving cell DL signal, also the uplink of that neighbor cell will be the better choice. In contrast in the MC to PC/FC case, within the CRE it may actually be better to stay connected to the FC/PC. The reason behind this asymmetry is the difference between the transmission powers, which is usually much higher for the MC. Therefore CRE is optional and is used to avoid interferences in the UL and for a pertinent load balancing. It causes problems for the UE to get the DL signals decoded, because these are correspondingly interfered by the MC.

In the case of FCs there is the problem of the so called closed subscriber groups (CSG). This means that only selected UEs are permitted to connect with the FC, whereas other UEs are not allowed, irrespective of the signal quality.

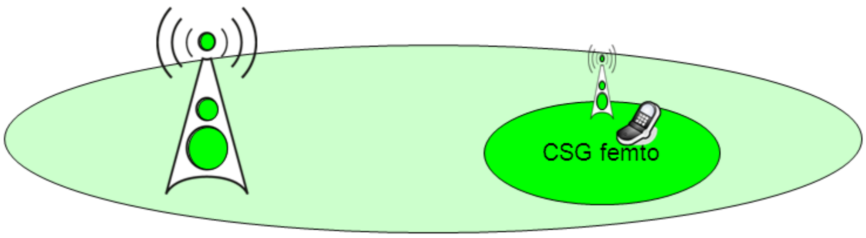

Figure 22: Interference scenario for Femto cells

The UE shown in Figure 21 is not part of the CSG and therefore has to connect with the MC. It is easy to imagine that this UE is heavily interfered by the FC in the DL and vice versa interferes the FC's UL.

Consequently, there are two qualitative new issues to solve in HetNets:

- The control channel is difficult to decode.
- The UE measurements on the reference signals are falsified.

The ICIC methods in Release 8 and 9 are restricted to the data channels and therefore do not contribute to a relief of these problems.

In order to cope with these new challenges, the concept of *almost blank subframes* (ABS) was introduced. These are subframes without any data transmission and thus without the corresponding control information (Figure 23).

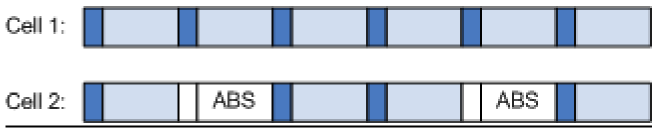

Figure 23: Visualization of Almost Blank Subframes

Due to the backward capability requirement, also Release 8 and 9 UEs must be able to connect with these HetNets. So, all signals relevant for Release 8 UEs have to be transmitted even when applying ABS. These are the cell reference signals (CRS), synchronization signals, broadcast messages and paging messages. Beside CRS all of these signals are transmitted in subframes #0, 4, 5 and 9, i.e. using other subframes than these for ABS will not disturb LTE Release 8 UEs. In order to also get rid of at least part of the CRS, the ABSs can be declared as MBSFN subframes.

For PCs used with cell range extension, the ABSs are created by the MCs. In these subframes the PC schedules the relevant information for the interfered UE which can in addition take the DL signal measurements therein. The opposite situation applies on FCs with CSGs. Here it is the task of the FC to blank out certain subframes in which the UE exchanges data with the MC and takes RRC measurements.

In the PC ↔ MC situation the MC sends its ABS information via the X2 interface. So, according to the properties of this interface the ABS assignment is of semi-statical duration and is signaled via the *LoadInformation* message, either requested by the PC or in an unsolicited way.
Two bitmaps are contained therein, one to indicate the set of all ABS used by the MC, and the other one as a subset of the first to indicate the recommended subframes to take measurements. Both patterns have a periodicity of 40 subframes for FDD, and a configuration dependent periodicity for TDD.

Upon reception of this message, the PC derives from these bitmaps pertinent subframe patterns for measurement restrictions. These are sent to the UE via dedicated RRC signaling, so that it is possible to address only those UEs which are located in the interfered region.

There are 3 kinds of measurement restriction patterns for a UE:

- Pattern 1 describes an RRM/RLM restriction on the PCell.
- Pattern 2 describes an RRM restriction for neighbor cells which are operating on the same frequency as the PCell.
- Pattern 3 describes two subsets for CSI measurements on the PCell. The CSI reporting is done for each of the configured subsets. There are no restrictions about its selection, but it is recommended that one subset selects the subframes from the ABSs and the other one from the non-ABSs.

The measurements themselves are the same as for the non-ABS case, with the exception of RSRQ measurements for RRM. Here, the underlying RSSI values are taken from all OFDM symbols of the subframe in order to reduce the impact of the interfering CRS.
For FCs there is no X2 interface. The only way to set up the ABS and the corresponding measurement patterns is via the O&M center.

3.6 Relaying

LTE-Advanced extends LTE Release 8 with support for relaying in order to enhance coverage and capacity. UEs communicate with a relay node (RN), which in turn communicates with a donor eNodeB (DeNB) as shown in Figure 24. The DeNB may, in addition to serving one or several RNs, also communicate with non-relayed UEs directly according to the Release 8 specifications.

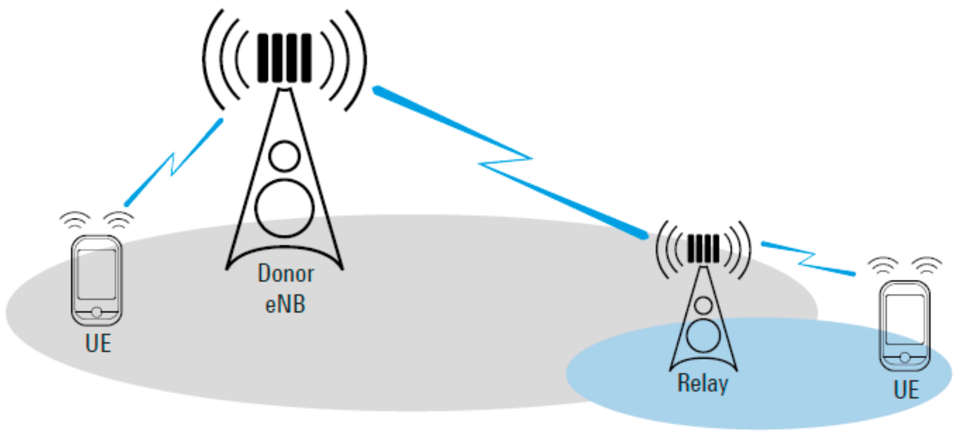

Figure 24: Relaying

The RN of Figure 24 is the so called *Type 1* relay. This means that it creates its own cell, i.e. transmits its own Cell_ID and own synchronization and reference signals. The UE communicates only with the RN and is oblivious of the DeNB. So, from an UE perspective this Type1 RN looks like a conventional eNodeB and cannot be distinguished from it. For Release 10, only this type is defined. Other types are left to later releases.

3.6.1 Air Interface

The backhaul link uses the same air interface resources as the direct link between an eNB and a UE. Consequently, both links either use the same frequency causing the relay to face severe isolation problems, because the difference between the transmitted and the received signal strength may be in the order of 100 dB. These stations are called *inband relays*. Or they avoid the isolation problem by using a different LTE frequency if the DeNB supports carrier aggregation. Therefore, the following categories of Type 1 RNs are considered:

- RNs with a special subframe configuration for avoiding the simultaneous transmission and reception on the same frequency (Type 1).
- RNs working on different frequencies in both links (Type 1a), which are called *outband relays*. These RNs are very well suited on networks which have additional spectrum available.
- RNs with a sufficiently strong isolation between receiver and transmitter (Type 1b).

Type 1a and Type 1b RNs have no implications for the air interface but they are either very difficult to realize (Type 1b) or possibly cannot be used in a given network (Type 1a). Therefore, most emphasis is on the plain Type 1 RNs, which do require considerable changes in the air interface.

An important point on plain type 1 RNs is that gaps have to be created in the link to the UE while the RN is exchanging data with the DeNB (Figure 25). However, the UEs attached to the RN expect CRS in all normal subframes. So, in order to create these gaps those subframes are declared as MBSFN subframes, which do not carry the CRS and are consequently not used by the UE for channel estimation or RLM.

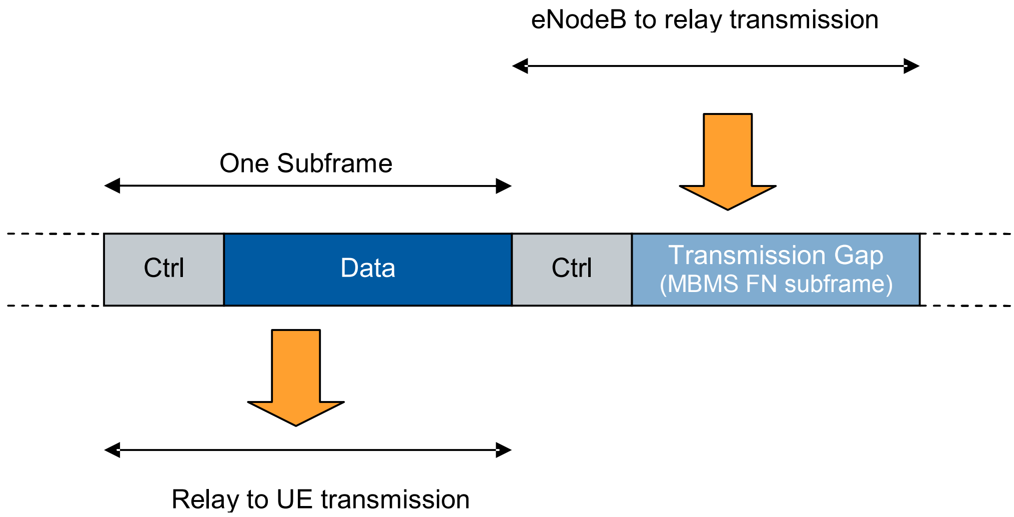

Figure 25: Example of relay-to-UE communication using normal subframes (left) and eNodeB-to-relay communication using MBSFN subframes (right)

3.6.2 Attachment of a Relay Node to the Network

The RN start-up procedure is a two-step process which is based on the normal UE attachment. In the first step, the RN connects as a normal UE in order to get all the information it needs to connect as a relay in the second step.
This may be done to any eNB, regardless of whether it has DeNB capabilities or not. The main purpose is to connect to the O&M centre in order to obtain the list of initial parameters, which comprises most importantly the list of DeNBs. Then the RN detaches and triggers the next step, the attachment for RN operation.

In this second attachment the UE selects one of the DeNBs provided by the O&M. Authentication and security is repeated because now the RN attaches for relay operation. Potential demand and structure for the special subframes are negotiated and finally the O&M can complete the RN configuration. After the setup of S1/X2 connections, the RN can start operating.

4 Conclusion

This white paper summarizes the LTE-Advanced enhancements that have been evaluated and specified throughout the respective study and work item phase within 3GPP. The different features deliver varying performance gains and will have certain impacts on the system complexity and cost. Higher order MIMO schemes up to 8x8 will for example significantly improve peak data rates and spectral efficiency. At the same time this feature will have significant impact on the network side (e.g. antenna installation) and on the UE complexity (additional transmission/reception chains). In comparison, band aggregation will not have any impact on spectral efficiency, cell edge performance, coverage or the network cost. However the peak data rate is improved depending on the number of aggregated carriers (potentially five), with a related impact on the UE complexity. Analyzing the anticipated enhancements on the uplink transmission scheme, they will have limited impact on the UE complexity, with moderate improvement on spectral efficiency and cell edge performance. The cost / benefit evaluation of the different features illustrated in Figure 26 is based on the LTE-Advanced self-evaluation data provided in [3] and completed by the author's own assessment. It should be taken as a qualitative indication rather than a quantitative assessment. LTE-Advanced is an evolution of LTE and was finalized about three years after LTE Release 8 in 3GPP standardization. The specification phase added also modified and new test requirements / methods. An initial description to generate and test LTE-Advanced signals can be found in [2].

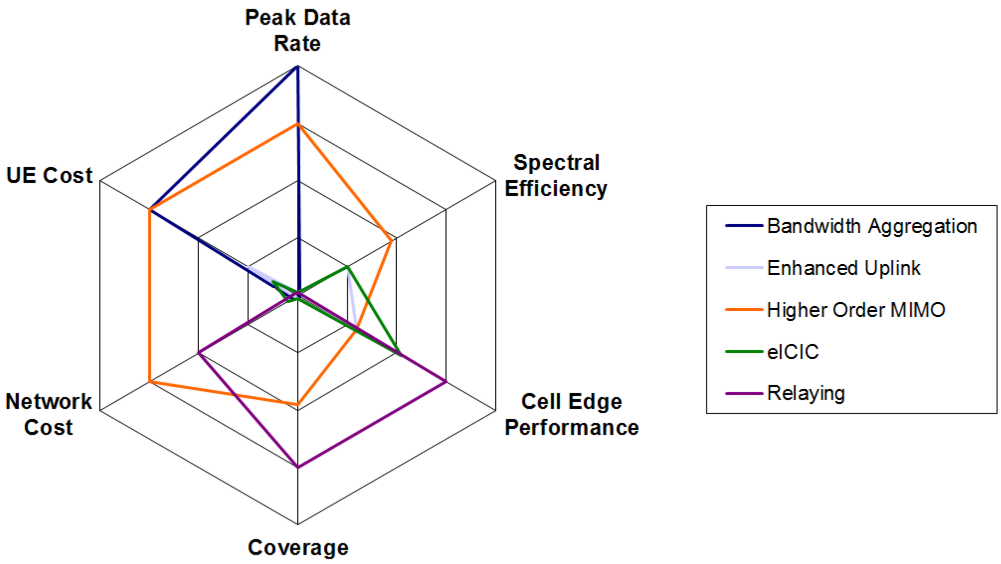

Figure 26: Cost / benefit evaluation of LTE-Advanced Features

Acknowledging that ITU-Advanced 4G requirements including 1Gbps transmission in low mobility scenarios will be achieved, LTE Release 8 / LTE-Advanced will be the innovation platform for the cellular industry for the next decade. In fact the self-evaluation in [3] concludes that most of the requirements are already fulfilled with LTE as of Release 8.

5 Appendix

5.1 LTE-Advanced frequency bands

Operating bands of LTE-Advanced will involve E-UTRA operating bands as well as possible IMT bands identified by ITU-R. E-UTRA (LTE) operating bands are shown in Table 23.

Operating bands for LTE / LTE-Advanced							
Operating Band	Uplink (UL) operating band BS receive/UE transmit			Downlink (DL) operating band BS transmit /UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD
6	830 MHz-	–	840 MHz-	865 MHz	–	875 MHz-	FDD
7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
9	1749.9 MHz	–	1784.9 MHz	1844.9 MHz	–	1879.9 MHz	FDD
10	1710 MHz	–	1770 MHz	2110 MHz	–	2170 MHz	FDD
11	1427.9 MHz	–	1447.9 MHz	1475.9 MHz	–	1495.9 MHz	FDD
12	698 MHz	–	716 MHz	728 MHz	–	746 MHz	FDD
13	777 MHz	–	787 MHz	746 MHz	–	756 MHz	FDD
14	788 MHz	–	798 MHz	758 MHz	–	768 MHz	FDD
15	Reserved			Reserved			-
16	Reserved			Reserved			-
17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	FDD
18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	FDD
19	830 MHz	–	845 MHz	875 MHz	–	890 MHz	FDD
20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	FDD
21	1447.9 MHz	–	1462.9 MHz	1495.9 MHz	–	1510.9 MHz	FDD
22	3410 MHz	–	3500 MHz	3510 MHz	–	3600 MHz	FDD
23	2000 MHz	–	2020 MHz	2180 MHz	–	2200 MHz	FDD
24	1626.5 MHz	–	1660.5 MHz	1525 MHz	–	1559 MHz	FDD
25	1850 MHz	–	1915 MHz	1930 MHz	–	1995 MHz	FDD
...							
33	1900 MHz	–	1920 MHz	1900 MHz	–	1920 MHz	TDD
34	2010 MHz	–	2025 MHz	2010 MHz	–	2025 MHz	TDD
35	1850 MHz	–	1910 MHz	1850 MHz	–	1910 MHz	TDD
36	1930 MHz	–	1990 MHz	1930 MHz	–	1990 MHz	TDD
37	1910 MHz	–	1930 MHz	1910 MHz	–	1930 MHz	TDD
38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
39	1880 MHz	–	1920 MHz	1880 MHz	–	1920 MHz	TDD
40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD
41	3400 MHz	–	3600 MHz	3400 MHz	–	3600 MHz	TDD
42	3400 MHz	–	3600 MHz	3400 MHz	–	3600 MHz	TDD
43	3600 MHz	–	3800 MHz	3600 MHz	–	3800 MHz	TDD

Table 23: Operating bands for LTE / LTE-Advanced [5]

6 Literature

[1] Rohde & Schwarz: Application Note 1MA111 “UMTS Long Term Evolution (LTE) Technology Introduction”

[2] Rohde & Schwarz: Application Note 1MA166 “LTE-Advanced Signals Generation and – Analysis”

[3] 3GPP TR 36.912 V 10.0.0, March 2011; Technical Specification Group Radio Access Network; Feasibility study for further advancements for E-UTRA (LTE-Advanced), Release 10

[4] 3GPP TR 36.913 V 10.0.0, March 2011; Technical Specification Group Radio Access Network; Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) LTE-Advanced, Release 10

[5] 3GPP TS 36.101 V10.6.0, March 2012; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception, Release 10

[6] 3GPP TS 36.104 V10.6.0, March 2012; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception, Release 10

[7] 3GPP TS 36.211 V10.5.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation, Release 10

[8] 3GPP TS 36.212 V10.6.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding, Release 10

[9] 3GPP TS 36.213 V10.6.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, Release 10

[10] 3GPP TS 36.300 V10.8.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Release 10

[11] 3GPP TS 36.306 V10.6.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities, Release 10

[12] 3GPP TS 36.331 V10.6.0, June 2012, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification, Release 10

7 Additional Information

Please send your comments and suggestions regarding this application note to

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