LTE-Advanced Technology Introduction
White Paper

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

LTE-Advanced

Meik Kottkamp
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ROHDE&SCHWARZ

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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 have been deployed as a natural evolution of GSM (Global system for mobile communications) and UMTS (Universal Mobile Telecommunications System).
The ITU (International Telecommunication Union) has coined the term IMT-Advanced to identify mobile systems whose capabilities go beyond those of IMT 2000 (International Mobile Telecommunications). Specifically data rate requirements have been increased. In order to support advanced services and applications 100Mbps for high and 1Gbps for low mobility scenarios must be realized. Throughout 2009 3GPP has 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. 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 as described in [1].

Section 2 outlines the IMT-Advanced requirements.

Section 3 summarizes the main technology components including

- section 3.1 on band aggregation,
- section 3.2 on enhanced multiple input / output (MIMO) antenna technologies,
- section 3.3 introducing enhancements of the uplink transmission scheme,
- section 3.4 describing coordinated multiple point transmission and reception schemes (CoMP) and,
- section 3.5 on the application of intelligent relay nodes.

Section 4 concludes this white paper and the Appendix in section 5 provides additional information including 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 [4].

2 LTE-Advanced requirements

Based on the ITU requirements for IMT-Advanced systems 3GPP created a technical report summarizing LTE-Advanced requirements in [2]. 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 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 [2] 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) substate 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

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 Band aggregation

One straight forward possibility to reach high data rates requirements is to aggregate multiple LTE carrier (see Figure 1). Two or more component carrier are aggregated in order to support wider transmission bandwidths up to 100MHz. However initial LTE-Advanced (3GPP Release 10) deployments will likely be limited to the use of maximum two component carrier, i.e. the maximum DL/UL bandwidth will be 40MHz for FDD. This will not preclude higher number of aggregated carriers been specified in 3GPP Release 11 and/or higher.

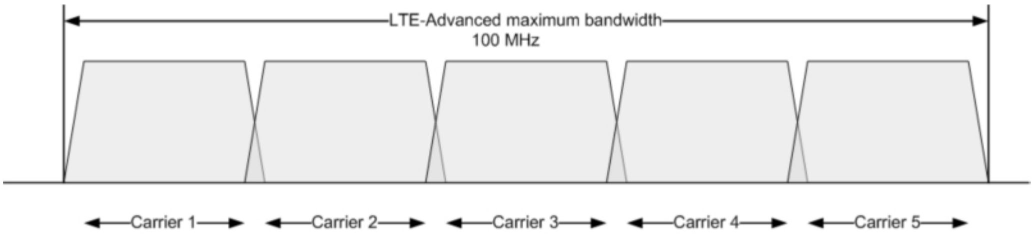

Figure 1:LTE-Advanced maximum bandwidth in contiguous deployment

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 is supported (see Figure 2) which ensures the highest flexibility in spectrum usage according to individual network operator needs.

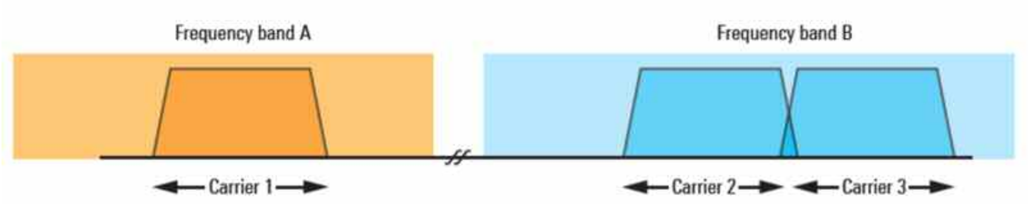

Figure 2: LTE-Advanced non-contiguous spectrum deployment

LTE Release 8 allows a 100 kHz frequency raster placing the LTE channel within the operator owned bandwidth. The 15kHz subcarrier spacing in combination with contiguously aggregated component carriers requires a 300kHz carrier spacing in order to preserve the orthogonality in the downlink transmission scheme. Each component carrier is limited to a maximum of 110 resource blocks in the frequency domain using the LTE Release 8 numerology. Certainly component carriers transmitted by the same eNodeB need to provide the same cell coverage. It is envisaged that different terminal categories will be defined supporting simultaneous transmission and reception of one or more component carriers.

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. Naturally band aggregation in LTE-Advanced will start with a limited number of carrier frequencies. Taking into account global requirements 3GPP standardization bodies have identified focus scenarios as illustrated in Table 3.

Intra-band contiguous carrier aggregation	
FDD	UL/DL: 40 MHz in Band 3
TDD	UL/DL: 50 MHz in Band 40
Inter-band non-contiguous carrier aggregation	
Region 1 (Europe)	UL/DL: 40 MHz; 20 MHz CC (Band 7) and 20 MHz CC (Band 20)
	UL/DL: 40 MHz; 20 MHz CC (Band 3) and 20 MHz CC (Band 20)
	UL/DL: 40 MHz; 20 MHz CC (Band 7) and 20 MHz CC (Band 3)
Region 2 (US)	UL/DL: 20 MHz; 10 MHz CC (Band 5) and 10 MHz CC (Band 12)
	UL/DL: 10 MHz; 5 MHz CC (Band 17) and 5 MHz CC (Band 4)
Region 3 (Asia)	UL/DL: 20 MHz; 10 MHz CC (Band 1) and 10 MHz CC (Band 18/19)
	UL/DL: 40 MHz; 20 MHz CC (Band 38) and 20 MHz CC (Band 40)
Intra-band non-contiguous carrier aggregation	
FDD/TDD	None

Table 3: Carrier aggregation focus scenarios according to 3GPP

3.1.1 User plane

Figure 3 and Figure 4 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.

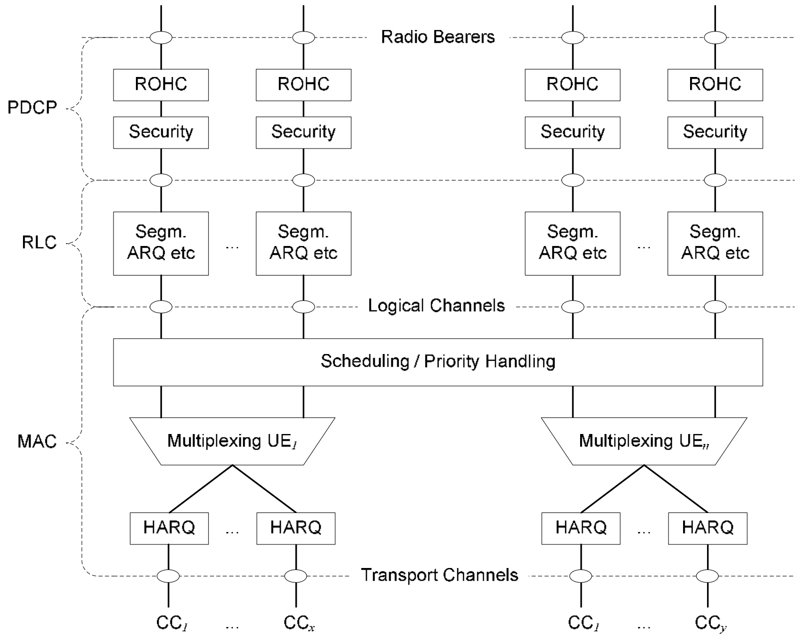

Figure 3: Downlink layer 2 structure [1]

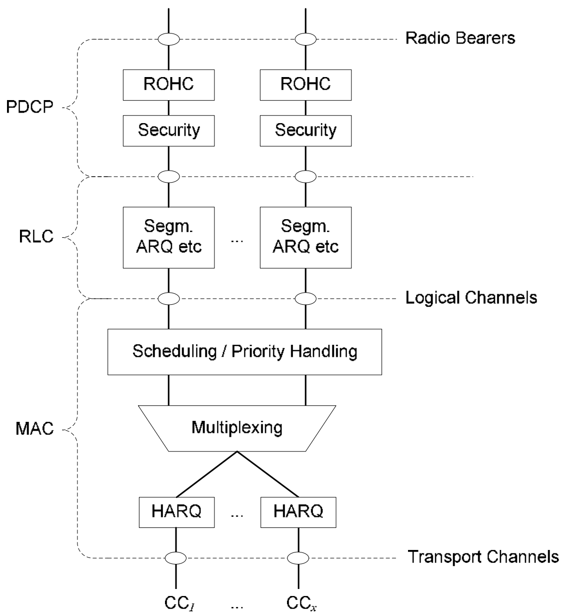

Figure 4: Uplink layer 2 structure [1]

3.1.2 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 will be possible for a network to configure only a subset of component carriers for idle mode camping.

3.2 Enhanced multiple antenna technologies

LTE Release 8 supports multiple input / output antenna schemes in both downlink and uplink direction. In downlink direction up to four transmit antennas may be used whereas the maximum number of codewords is two irrespective of the number of antennas. 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 one can expect two antenna operation in downlink and one antenna operation in uplink to be the standard case for initial LTE deployment.

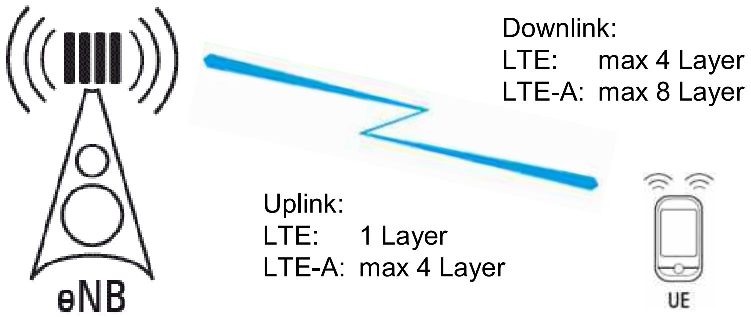

Figure 5: Supported transmit layers in LTE Release 8 and LTE-Advanced

LTE-Advanced extends the MIMO capabilities of LTE Release 8 to now supporting eight downlink antennas and four uplink antennas (see Figure 5). 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 simply extended as described in the following sections.
As well as MIMO transmission schemes, transmit diversity is possible in both downlink and uplink direction as described in the subsequent sections.

3.2.1 Downlink

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 4 describes the differences, marked in shaded orange, of the code word to layer mapping between LTE Release 8 and LTE-Advanced. The expressions $d^{(0)}$, $d^{(1)}$ denote the code word symbols of maximum two code words and $x^{(0)}$ - $x^{(7)}$ denote the symbols on maximum eight antenna 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 4, 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).

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 transmit antennas are applied, the Release 8 transmit diversity scheme is reused, though details of the solution are not yet specified.

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/etc 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.
Reference signals targeting CSI estimation are cell specific, sparse in the frequency and time domain and punctured into the data region of normal subframes.

Codeword to layer mapping for spatial multiplexing

Number of layers	Number of code words	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	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$ $x^{(2)}(i) = d^{(1)}(2i)$ $x^{(3)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2 = M_{\text{symb}}^{(1)}/2$
3	1	$x^{(0)}(i) = d^{(0)}(3i)$ $x^{(1)}(i) = d^{(0)}(3i+1)$ $x^{(2)}(i) = d^{(0)}(3i+2)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/3$

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

Table 4: Codeword to layer mapping for spatial multiplexing (LTE Release 8 and LTE-Advanced) [1]

3.2.2 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 or two 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 of layers that are used. Further more different precoding is used depending on whether two or four transmit antennas are available. Also the number of bits used for the codebook index is different depending on the 2 and 4 transmit antenna case, respectively.
For uplink spatial multiplexing with two transmit antennas a 3-bit precoding is defined according to Table 5. 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.

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 5: 3-bit precoding codebook for uplink spatial multiplexing with two transmit antennas [1]

For uplink spatial multiplexing with four transmit antennas a 6-bit precoding is defined according to Table 6 if one layer applies and according to Table 7 if two layers apply.

Precoding codebook for uplink spatial multiplexing (4 Tx antennas)								
One layer trasmission								
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 6: 6-bit precoding codebook for uplink spatial multiplexing with four transmit antennas: precoding matrices for 1-layer transmission [1]

Precoding codebook for uplink spatial multiplexing (4 Tx antennas)								
Two layer trasmission								
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 7: 6-bit precoding codebook for uplink spatial multiplexing with four transmit antennas: precoding matrices for 2-layer transmission [1]

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. Details of the scheme remain to be specified in 3GPP.

3.3 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 (see Figure 6).

- Control-data decoupling
- Non-contiguous data transmission with single DFT per component carrier

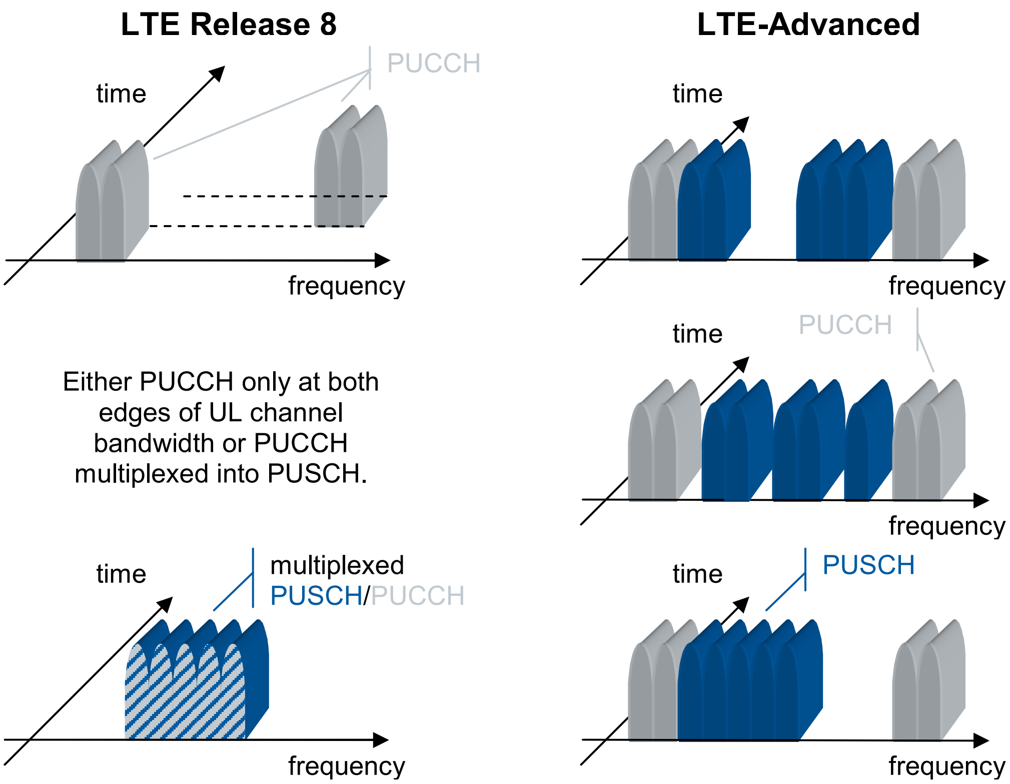

Figure 6: LTE Release 8 and LTE-Advanced uplink transmission schemes

Control-data decoupling:

In LTE Release 8 a UE only uses physical uplink control channel (PUCCH) when it does not have any data to transmit on PUSCH. I.e. if a UE has data to transmit on PUSCH, it would multiplex the control information with data on PUSCH. This is not longer valid in LTE-Advanced, which means that simultaneous PUCCH and PUSCH transmission is possible in uplink direction.

Non-contiguous data transmission with single DFT

The LTE Release 8 uplink scheme SC-FDMA differs from the LTE Release 8 downlink schemes, as an additional DFT is used in the transmission chain that transforms the modulation symbols into the frequency domain. In Release 8 localized SC-FDMA is allowed only, i.e. in uplink direction only consecutive subcarriers are transmitted. This is the essential advantage of the scheme, since it reduces the peak to average ratio of the transmitted signal and consequently allows more efficient power amplifier implementation. LTE-Advanced extends the uplink transmission scheme by allowing 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 (see Figure 6). 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 7 provides the uplink block diagram of the transmission chain.

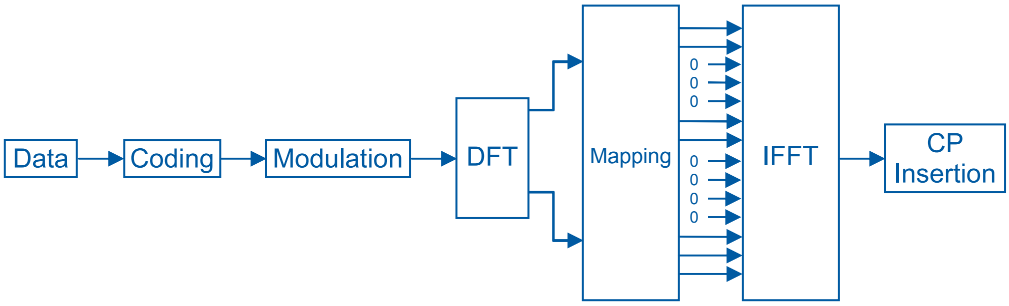

Figure 7: Block diagram for clustered SC-FDMA in uplink LTE-Advanced

3.4 Coordinated multiple point transmission and reception (CoMP)

Coordinated multi-point (CoMP) transmission/reception is considered for LTE-Advanced as a tool to improve the coverage of high data rates, the cell-edge throughput and to increase system throughput.
In a cellular deployment and specifically if frequencies are reused in each cell, other-cell interference traditionally degrades the system capacity. The target in CoMP is to turn the other cell interference into a useful signal specifically at the cell border. This requires dynamic coordination in the scheduling / transmission, including joint transmission, from multiple geographically separate points and also support for joint processing of received signals at multiple geographically separated points as illustrated in Figure 8.

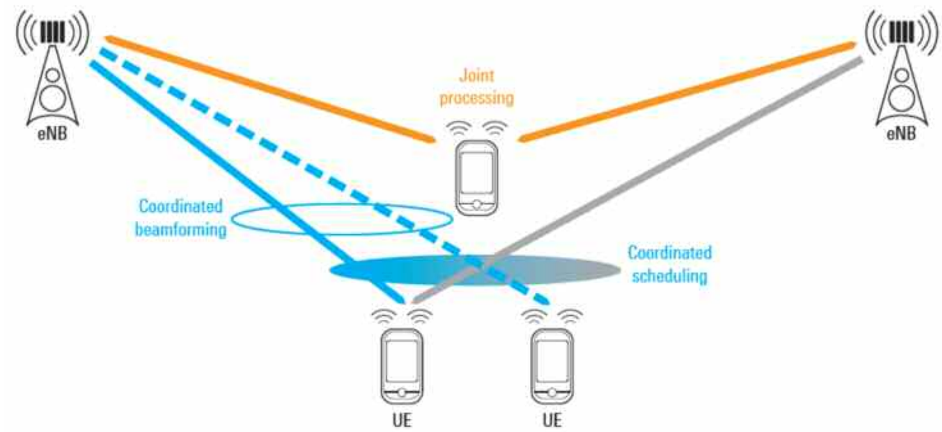

Figure 8: Example of CoMP in a distributed network architecture

Different CoMP categories exist which describe different ways of CoMP operation. In downlink direction one need to distinguish between joint processing (JP) and coordinated scheduling (CS) / coordinated beamforming (CB). In the joint processing case, transmission data to a single UEs is available at each transmission point, i.e. multiple eNodeBs. The availability of the user data allows two variants of operation. Joint transmission is characterized by *simultaneous* transmission of the user data to a single UE from multiple eNodeBs, whereas in the dynamic cell selection case data is transmitted from one eNodeB at a time only.

For coordinated scheduling / beamforming data is always transmitted from one eNodeB only, however user scheduling / beamforming decisions are made with coordination among cells.
The different modes of CoMP operations in downlink (transmission) are summarized in Table 8.

CoMP – tranmission (downlink)		
Joint Processing		**Coordinated Scheduling / Beamforming**
Joint transmission	**Dynamic cell selection**	
Data available at each transmission point	Data available at each transmission point	Data available at serving cell only
Data transmitted simultaneously from multiple transmission points	Data transmitted from one transmission point at a time	Data transmitted from one transmission point but user scheduling / beamforming decisions are made with coordination among cells

Table 8: Modes of operation in CoMP –transmission (downlink)

In order to support CoMP downlink operation feedback from the UE is required. The feedback information will need to include detailed information on channel properties as well as noise and interference measurements. Details of the UE feedback information remain to be specified in 3GPP.

In the CoMP uplink (reception) direction multi point reception implies coordination among multiple, geographically separated points, i.e. eNodeBs. Uplink CoMP reception involves joint reception (JR) of the transmitted signal at multiple reception points and/or coordinated scheduling (CS) decisions among cells to control interference. The impact on the existing LTE Release 8 specifications is judged fairly limited.

Taking a closer look at the network architecture, there are again different approaches possible. In a centralized implementation one unit receives all relevant feedback data, pre-computes all waveforms, which are sent to remote base stations for over the air transmission. As a consequence, high capacity backhaul transmission is required fulfilling demanding latency requirements on the S1 interface, i.e. in the order of the cyclic prefix length (few µs). In a distributed cooperation approach eNodeBs exchange data and UE channel feedback via the X2 interface in small clusters of grouped eNodeBs where each eNodeB computes the waveforms. This approach reduces the overall backhaul efforts and the latency constraints (few ms) on the S1 / X2 interfaces at the expense of redundant precoding computation at each eNodeB within the cluster. In both cases the solution relies on fast channel feedback information either received via a feedback channel from the UE (FDD) or by exploiting channel reciprocity (TDD). Additionally the air interface transmission from involved eNodeBs needs to be tightly synchronized in frequency ($\sim 10^{-9}$) and time (~ 100ns). The principle of the de-centralized approach is shown in Figure 9. In this two eNodeB example the goal is to crosswise eliminate the interference between the two cells.
There are several modifications required on top of LTE Release 8 in order to facilitate the CoMP feature. Among those are:

- Clock synchronization between eNodeBs
- Synchronous data exchange
- Cell specific pilots

- Channel feedback / Channel state information
- Precoded Pilots

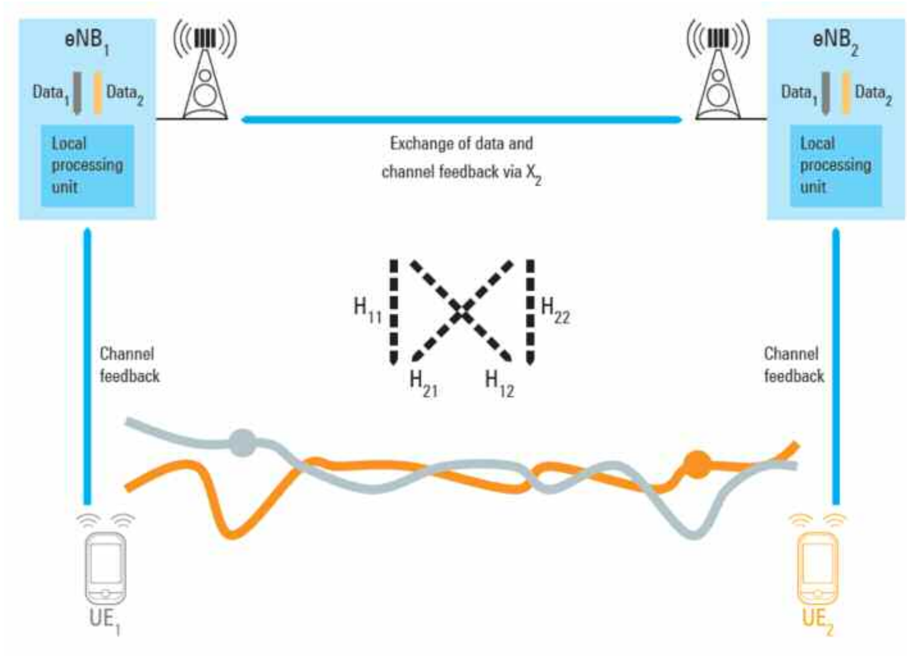

Figure 9: Principle of CoMP processing in a distributed approach between two eNodeBs

3.5 Relaying

LTE-Advanced extends LTE Release 8 with support for relaying in order to enhance coverage and capacity. In the case of relaying, the UEs communicate with the relay node which in turn communicates with a *donor* eNodeB also called *anchor* eNodeB. The relay node is wirelessly connected to the *donor* cell of a *donor* eNodeB via the U_n interface, and UEs connect to the relay station via the U_u interface as shown in Figure 10. The (anchor) eNodeB may, in addition to serving one or several relays, also communicate with non-relayed UEs directly according to the Release 8 specifications.

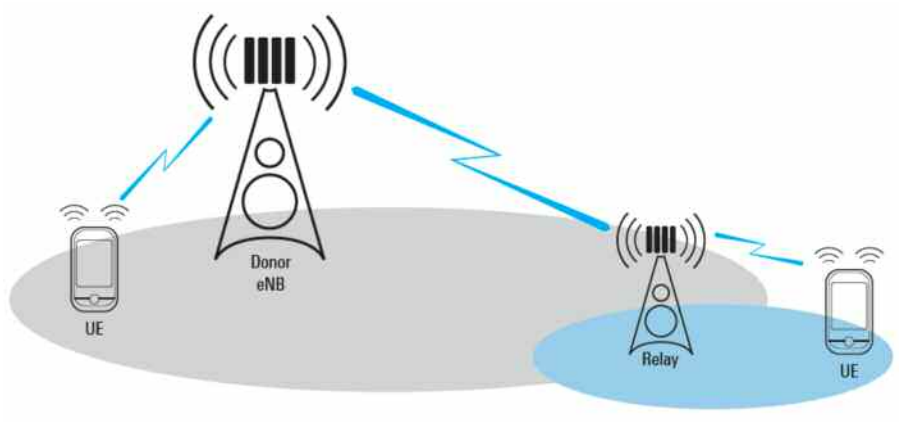

Figure 10: Relaying

3.5.1 Classification of relay stations

When discussing relay stations a number of different classifications exist. One important classification is the amount of protocol knowledge a relay station has implemented. In consequence of this, relay stations may be distinguished based on protocol layers. The simplest implementation would be a Layer 1 relay station (repeater), which simply receives the donor eNodeB signal and amplifies it into its own coverage area. A Layer 2 relay station will have medium access control (MAC) layer functionality, i.e. decoding of received signals and re-coding of transmit signals is possible in order to achieve higher link quality in the relay cell area. The performance gain comes at the expense of higher complexity (cost) of the relay and will also add delay to the communication link. A layer 3 relay station would include functionality like mobility management, session set-up and handover and as such acts as a full service (sub-) eNodeB. This adds more complexity to the implementation of such a relay node and the delay budget is further increased.

A different classification is used in 3GPP standardization and distinguishes between Type 1 and Type 2 relay stations. A Type 1 relay effectively creates its own cell, i.e. transmits its own identity number (Cell_ID) and own synchronization and reference signals. The UE receives scheduling information and HARQ feedback directly from and sends its own control channels to the relay station. From an UE perspective this Type1 relay station looks like a eNodeB. It is also required that LTE Release 8 terminals are supported by this Type 1 relay station. It has already been agreed to include Type 1 relay stations into LTE-Advanced specifications.
In contrast, a Type 2 relay station will not have its own Cell_ID and thus would not create any new cell(s) as illustrated in Figure 11. Consequently the UE will not be able to distinguish between transmitted signals form the eNodeB and the relay station. In such a scenario it would be possible to transmit control information from the eNodeB and data via the relay station. The performance of such Type 2 relay stations needs to be evaluated, i.e. discussion in the standardization bodies is ongoing and the inclusion into LTE-Advanced specifications has not been agreed (as of yet).

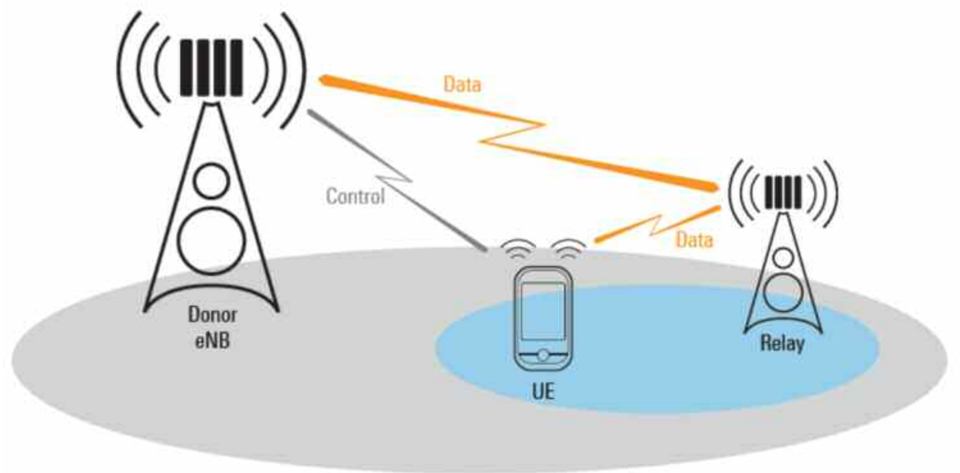

Figure 11: Type 2 relay station

3.5.2 Backhauling link to relay station

As mentioned above the relay node is wirelessly connected to the *donor* cell of a *donor* eNodeB via the U_n interface. This allows inband (same frequency band) and outband operation (different frequency band) of the link between the two nodes.
For inband relaying, the eNodeB-to-relay link (Un) operates in the same frequency spectrum as the relay-to-UE link (Uu). Due to the relay transmitter causing interference to its own receiver, simultaneous eNodeB-to-relay and relay-to-UE transmissions on the same frequency resource may not be feasible unless sufficient isolation of the outgoing and incoming signals is provided. Similarly, at the relay it may not be possible to receive UE transmissions simultaneously with the relay transmitting to the eNodeB. One solution to this interference scenario is to operate the Un interface in a time division manner, i.e. allocate specific time periods for either transmission of data to the UEs or for reception from data received from the eNodeB. These "gaps", when terminals (including Release 8 terminals) are not supposed to expect any relay transmission, can be created by configuring mobile broadcast multicast service (MBMS) single frequency network (MBSFN) subframes as illustrated in Figure 12.

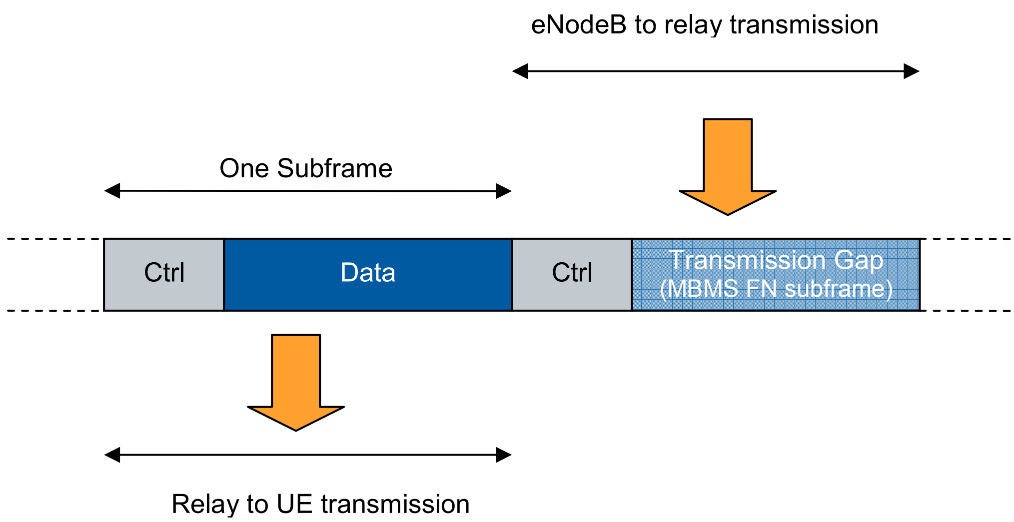

Figure 12: Example of relay-to-UE communication using normal subframes (left) and eNodeB-to-relay communication using MBSFN subframes (right)

4 Conclusion

This white paper summarizes the LTE-Advanced enhancements that have been evaluated throughout the respective study 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. Analysing 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 13 is based on the LTE-Advanced self evaluation data provided in [1] and completed by the author's own assessment. It should be taken as an indication noting that the detailed specification phase of LTE-Advanced features has just started. LTE-Advanced is an evolution of LTE and is about two years behind LTE in 3GPP standardization. The specification phase will also add modified and new test requirements / methods. An initial description to generate and test LTE-Advanced signals can be found in [3].

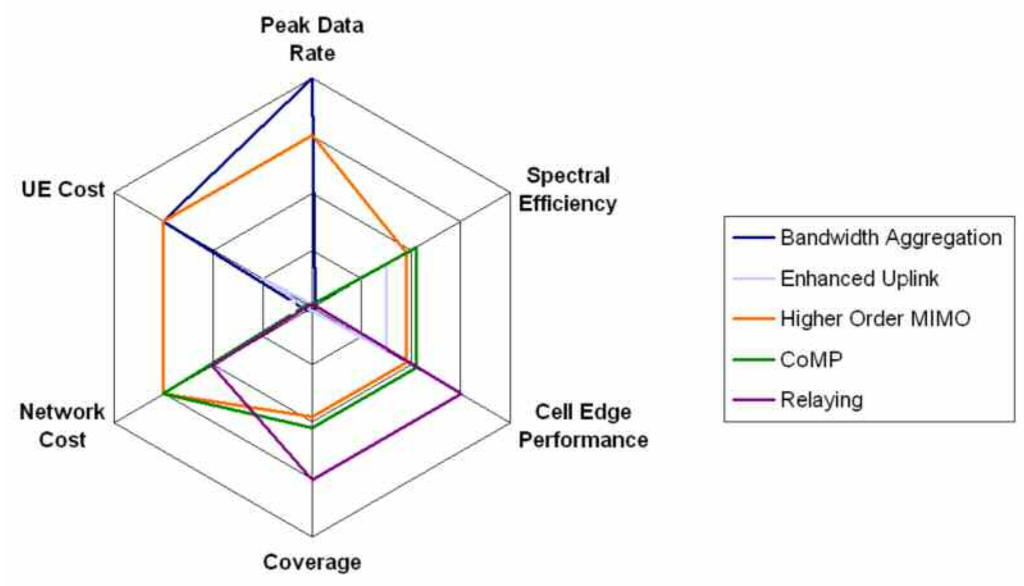

Figure 13: Cost / benefit evaluation of LTE-Advanced Features

Acknowledging that ITU-Advanced 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 sections in [1] conclude that most of the requirements are already fulfilled with LTE 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 9.

Table 9: Operating bands for 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
...							
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

5.2 Literature

[1] Technical Specification Group Radio Access Network; Feasibility study for further advancements for E-UTRA (LTE-Advanced), Release 9; 3GPP TR 36.912 V 9.1.0, December 2009

[2] Technical Specification Group Radio Access Network; Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) LTE-Advanced, Release 8; 3GPP TR 36.913 V 8.0.1, March 2008

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

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

5.3 Additional Information

Please send your comments and suggestions regarding this white paper to

TM-Applications@rohde-schwarz.com

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from outside USA: +1 410 910 7800
CustomerSupport@rohde-schwarz.com

East Asia
+65 65 13 04 88
CustomerSupport@rohde-schwarz.com

Rest of the World
+49 89 4129 137 74
CustomerSupport@rohde-schwarz.com

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com