LTE Transmission Modes and Beamforming
White Paper

Multiple input multiple output (MIMO) technology is an integral part of 3GPP E-UTRA long term evolution (LTE). As part of MIMO, beamforming is also used in LTE.
This white paper discusses the basics of beamforming and explains the ten downlink and two uplink MIMO transmission modes in LTE Release 12.

White Paper

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1 Introduction

Modern communications networks use MIMO technology to achieve high data rates. As a special MIMO technique, beamforming also permits targeted illumination of specific areas, making it possible to improve transmission to users at the far reaches of cell coverage. Like other communications standards such as WLAN and WiMAX™, LTE also defines beamforming. Beamforming is particularly important for the time division duplex (TDD) mode in LTE. This white paper describes the available ten downlink and two uplink transmission modes (TM) in LTE as specified in 3GPP Release 12, as well as how beamforming is used in LTE.

2 MIMO and Beamforming Technologies

2.1 MIMO

This paper discusses the MIMO concepts only to the extent that they apply to LTE transmission modes (see 3.2). Refer to [3] for a more detailed description of the MIMO concept as well as for a look at how MIMO is used in various communications systems.

MIMO systems are used to improve the robustness of data transmission or to increase data rates. Typically, a MIMO system consists of m transmit antennas and n receive antennas (Figure 1).

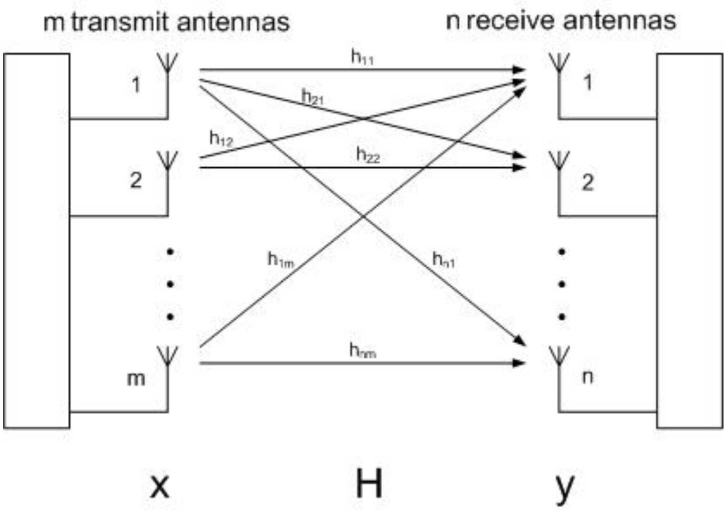


Figure 1: MIMO system with m TX and n RX antennas

Simply stated, the receiver receives the signal **y** that results when the input signal vector **x** is multiplied by the transmission matrix **H**.

y = **H** * **x**

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{..} & h_{1m} \\ h_{21} & h_{22} & h_{..} & h_{2m} \\ h_{..} & h_{..} & h_{..} & h_{.m} \\ h_{n1} & h_{n2} & h_{n.} & h_{nm} \end{bmatrix}$$

Transmission matrix **H** contains the channel impulse responses h_{nm}, which reference the channel between the transmit antenna m and the receive antenna n.
Many MIMO algorithms are based on the analysis of transmission matrix **H** characteristics. The rank (of the channel matrix) defines the number of linearly independent rows or columns in H. It indicates how many independent data streams (layers) can be transmitted simultaneously.

- Increasing the robustness of data transmission – transmit diversity

When the same data is transmitted redundantly over more than one transmit antenna, this is called TX diversity. This increases the signal-to-noise ratio. Space-time codes are used to generate a redundant signal. Alamouti developed the first codes for two antennas. Today, different codes are available for more than two antennas.

- Increasing the data rate – spatial multiplexing

Spatial multiplexing increases the data rate. Data is divided into separate streams, which are then transmitted simultaneously over the same air interface resources. The transmission includes special sections (also called pilots or reference signals) that are also known to the receiver. The receiver can perform a channel estimation for each transmit antenna's signal. In the closed-loop method, the receiver reports the channel status to the transmitter via a special feedback channel. This enables fast reactions to changing channel circumstances, e.g. adaptation of the number of multiplexed streams.

When the data rate is to be increased for a single user equipment (UE), this is called Single User MIMO (SU-MIMO). When the individual streams are assigned to various users, this is called Multi User MIMO (MU-MIMO)

2.2 Beamforming basics

Beamforming uses multiple antennas to control the direction of a wavefront by appropriately weighting the magnitude and phase of individual antenna signals (transmit beamforming). For example this makes it possible to provide better coverage to specific areas along the edges of cells. Because every single antenna in the array makes a contribution to the steered signal, an array gain (also called beamforming gain) is achieved.

Receive beamforming makes it possible to determine the direction that the wavefront will arrive (direction of arrival, or DoA). It is also possible to suppress selected interfering signals by applying a beam pattern null in the direction of the interfering signal.

Adaptive beamforming refers to the technique of continually applying beamforming to a moving receiver. This requires rapid signal processing and powerful algorithms.

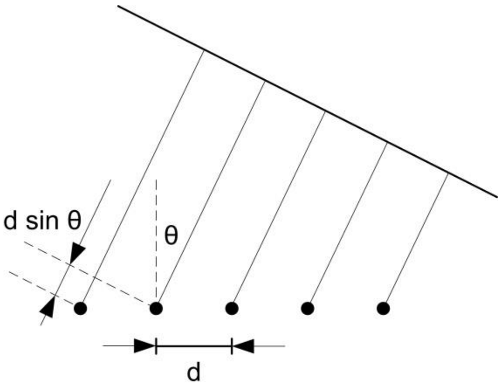


Figure 2: Antenna array with a distance d between the individual antennas. The additional path that a wavefront must traverse between two antennas is d * sin θ.

As seen in Figure 2, the wavefront of a signal must traverse the additional distance **d * sin θ** to the next antenna. Using the speed of light c, it is possible to calculate the delay between the antennas.

$$\tau_i = \frac{(i-1)d\sin\theta}{c} = (i-1)\tau$$

$$\tau = \frac{d\sin\theta}{c}$$

The signal s_i at each antenna is:

$$s_0(t) = s(t)$$

$$s_1(t) = s(t-\tau) \approx s(t)e^{-j\theta}$$

$$s_{M-1}(t) = s(t-(M-1)\tau) \approx s(t)e^{-j(M-1)\theta}$$

This approximation is valid only for narrowband signals.

Written as a vector:

$$\mathbf{s}(t) = \begin{bmatrix} 1 \\ e^{-j\theta} \\ e^{-j2\theta} \\ e^{-j3\theta} \\ \vdots \\ e^{-j(M-1)\theta} \end{bmatrix} \cdot s(t) = \mathbf{a}(\theta) \cdot s(t),$$

where **a** is the array steering vector.

Figure 3 shows an example of the amplitude response of an antenna array with eight elements (uniform linear array, ULA) versus the angle θ. In this example, the maximum is obtained when a signal coming from the boresight direction (θ = 0) impinges on the array.

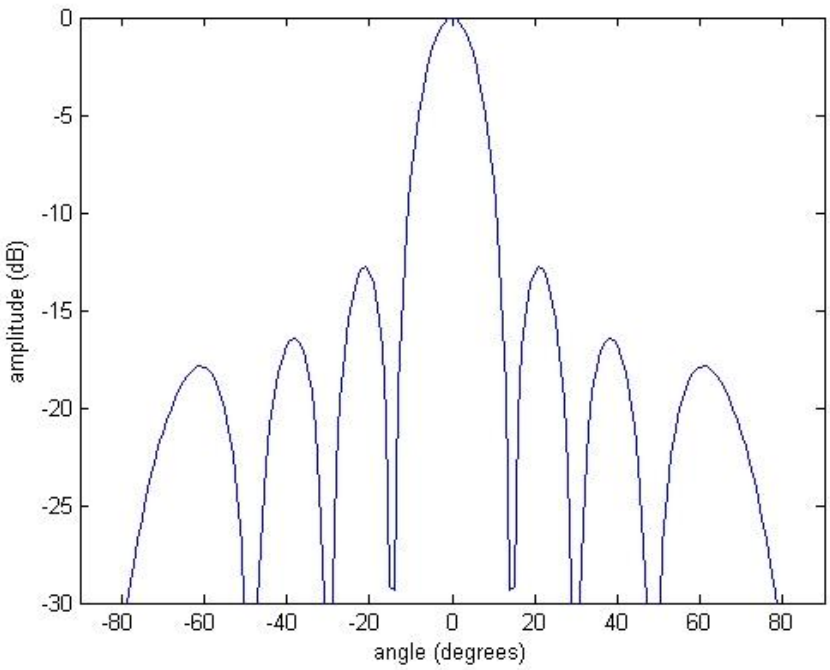


Figure 3: Beampattern example of an 8-element ULA

Beamforming is made possible by weighting the magnitude and/or phase of the signal at the individual antennas:

$y(t) = \mathbf{w}^H \cdot \mathbf{a}(\theta) \cdot s(t)$,

where **w** is the weight vector. The signals are weighted so that they can be added constructively in the direction of an intended transmitter/receiver, and destructively in the direction of interferers.

Because beamforming is intended to provide the best signal possible to a UE at a specific location, finding the weight vector **w** is an essential step. Two basic methods for finding the weight vector can be used which also affects the arrangement of the antenna array. The distance **d** between the antennas is a critical factor as well.

Determining the weighting using DoA

If the position of the UE is known, the beamforming weightings can be adapted accordingly to optimize transmission for this UE. Therefore, specialized algorithms, such as MUSIC [4] or ESPRIT [5]), could be used in the base station to determine the DoA for the UE signal, and thus to determine its location. A uniform linear array (ULA) antenna array is typically used, where the distance **d** between the individual antennas is the same and **d ≤ λ/2**. This type of array can be seen as a spatial filtering and sampling in the signal space. Just as the Nyquist criterion applies to sampling a signal over time, the distance here must be d ≤ λ/2 in order to determine the DoA.

Determining the weighting using channel estimation

Other algorithms determine the optimum beamforming weighting from a channel estimation; for example, by using existing training sequences. In a TDD system, uplink and downlink are on the same frequency and thus the channel characteristics are the same. That is why a feedback is not needed from the UE when a suitable uplink signal is present that the base station can use to estimate the channel. In the case of TD-LTE, the uplink sounding reference signal can be used.

Figure 4 shows how the distance between the antenna elements affects the antenna characteristics, based on a simple example of a two-element array. With increasing distance between the antenna elements, the side lobes are increasing.

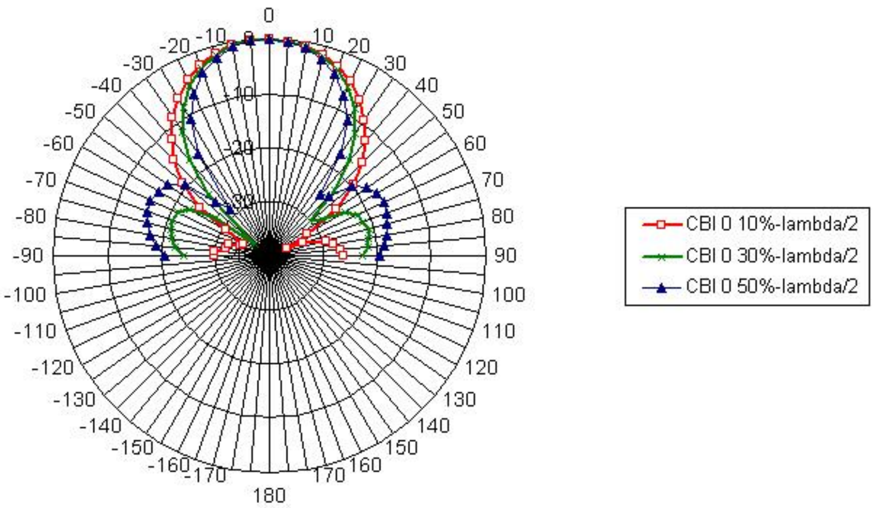


Figure 4: The antenna diagram is affected by the distance d between the antennas. In this example, d is 10 %, 30 %, and 50 % greater than λ/2. (CBI 0 refers to code book index 0, see chapter 3.2.4)

2.3 Base Station Antennas

As described in the above section, the geometric characteristics of the antenna array significantly affect the radiation characteristics. This is discussed here using the example of conventional base station antennas.

At present, conventional passive base station antennas are typically made up of multiple cross-polarized elements. In the y-axis, multiple elements are combined in order to set the illumination (cell radius). All elements that have the same polarity radiate the same signal (shown in color at the left antenna of Figure 5). Especially relevant for MIMO and beamforming is the arrangement of the cross-polarized elements and the columns in the x-axis.

The antenna at the left consists of two elements arranged at 90° to each other (cross-polarized). Each "polarization column" (blue or red) represents an antenna element that can transmit a different signal. This makes it possible to transmit two signals with a compact antenna arrangement, such as for 2x2 MIMO or TX diversity. Analogously, the antenna at the middle can radiate four independent signals (4xN MIMO), while the antenna at the right can radiate eight independent signals (8xN MIMO).

The antennas shown in Figure 5 could also be used for beamforming. However, beamforming requires correlated channels; that is, elements with the same polarization (+45° or –45°) must be used. Also the distance between the columns should not be too large. Beamforming could be carried out with two antenna elements (columns with the same polarization) in the antenna layout in the middle, or with four antenna elements in the layout on the right.

Base station antenna architectures are currently evolving. Active antennas are an important trend that allow seamless integration of beamforming concepts, e.g. by implementing dedicated transceivers for the required number of antenna elements.

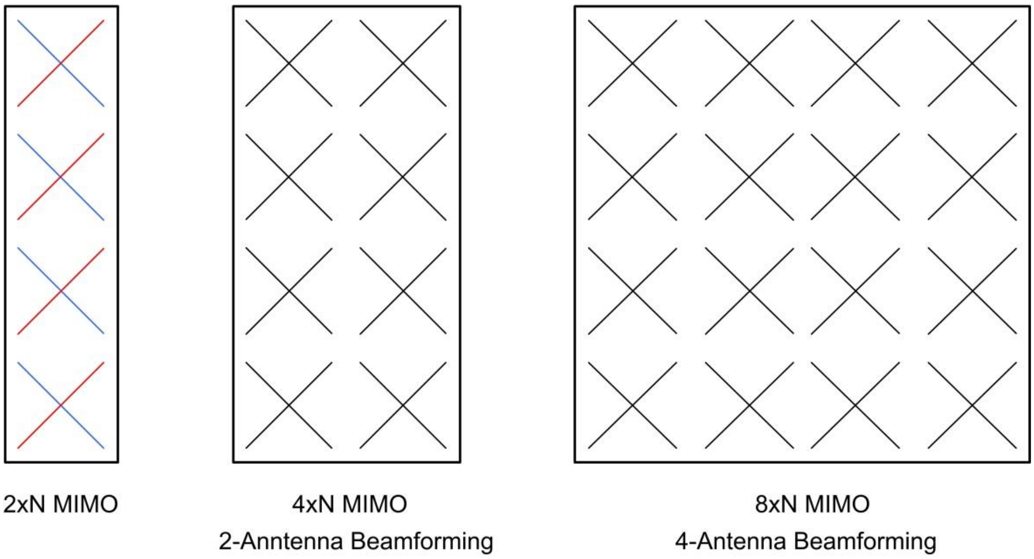


Figure 5: Various cross-polarized base station antenna arrays for MIMO and beamforming.

3 Transmission modes and Beamforming in LTE

3.1 Brief overview of LTE

A complete description of LTE is found in [2] for LTE-A in [9] and [10]. This white paper provides just a brief overview.

3.1.1 Physical Channels and Signals

LTE defines a number of channels in the downlink as well as the uplink. Table 1 and Table 2 provide an overview.

Downlink		
LTE downlink physical channels		
Name	**Purpose**	**Comment**
PDSCH	Physical downlink shared channel	user data
PDCCH	Physical downlink control channel	control information
PCFICH	Physical control format indicator channel	indicates format of PDCCH
PHICH	Physical hybrid ARQ indicator channel	ACK/NACK for uplink data
PBCH	Physical broadcast channel	information during cell search
LTE downlink physical signals		
	Primary and secondary synchronization signal	information during cell search
RS	Reference signals	enables channel estimation

Table 1: Overview of LTE downlink physical channels and signals

Uplink		
LTE uplink physical channels		
Name	**Purpose**	**Comment**
PUSCH	Physical uplink shared channel	user data
PUCCH	Physical uplink control channel	control information
PRACH	Physical random access channel	preamble transmission
LTE uplink physical signals		
DRS	Demodulation reference signal	channel estimation and demodulation
SRS	Sounding reference signal	uplink channel quality evaluation

Table 2: Overview of LTE uplink physical channels and signals

3.1.2 Downlink reference signal structure

The downlink reference signal structure is important for channel estimation. It defines the principle signal structure for 1-antenna, 2-antenna, and 4-antenna transmission. Specific pre-defined resource elements (indicated by R_{0-3}) in the time-frequency domain carry the cell-specific reference signal sequence. One resource element represents the combination of one OFDM symbol in the time domain and one subcarrier in the frequency domain. Figure 6 shows the principle of the downlink cell specific reference signal structure for 1 antenna and 2 antenna transmission. These reference signals are used for modes like spatial multiplexing or transmit diversity with up to four antennas.

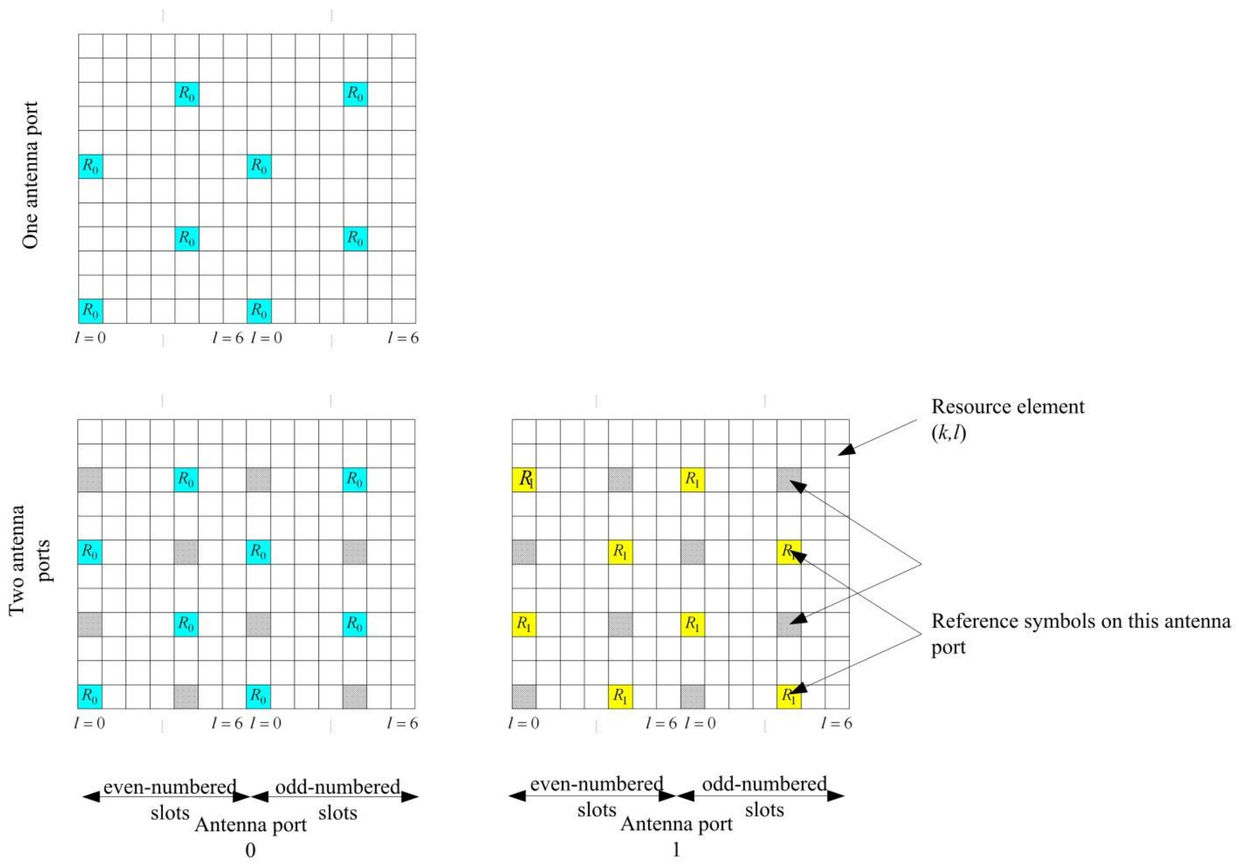


Figure 6: Distribution of the downlink cell specific reference signals in LTE; see top for one antenna and bottom for two antennas. [1]

A different pattern is used for beamforming (see section 3.2.7). UE-specific reference signals are used here. These are needed because whenever beamforming is used, the physical downlink shared channel for each UE is sent with a different beamforming weighting. The UE-specific reference signals and the data on the PDSCH for a UE are transmitted with the same beamforming weighting.

LTE TDD UEs must (mandatory) support UE-specific reference signals, while it is optional for LTE FDD UEs. Beamforming is of particular interest for LTE TDD because the same frequency is used in the downlink and uplink.

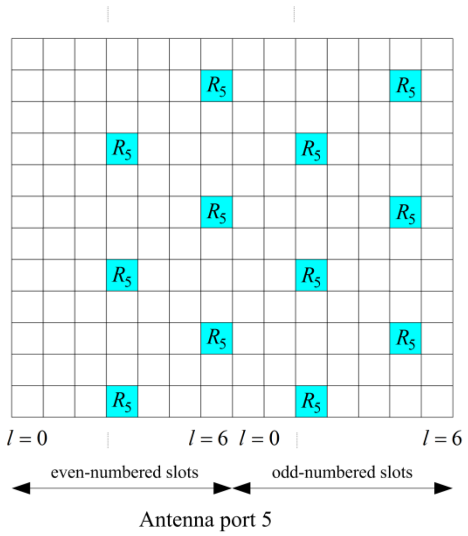


Figure 7: Distribution of reference signals for transmission mode 7 [1]

In TM 8 also UE-specific reference signals (RS) are used. Since the same elements are used for both streams, the reference signals must be coded differently so that the UE can distinguish among them. Figure 15 in section 3.2.8 shows the position of the RS in TM8.

TM 9 and TM10 also use UE-specific reference signals (RS). Here again the same elements are used for different streams, the reference signals must be coded differently so that the UE can distinguish among them (see 3.2.9).

3.2 Transmission modes (TM) in LTE downlink

In the downlink, LTE uses technologies such as MIMO to achieve high data rates; however, it also offers fallback technologies such as transmit diversity or SISO. In the Release 9 specification [1], up to four antennas are defined in the base station and up to four antennas in the UE.

Since Release 10 up to eight antennas are possible in the downlink.

Beamforming is also supported. However, in this case the number of base station antennas is not specified; it depends on the implementation.

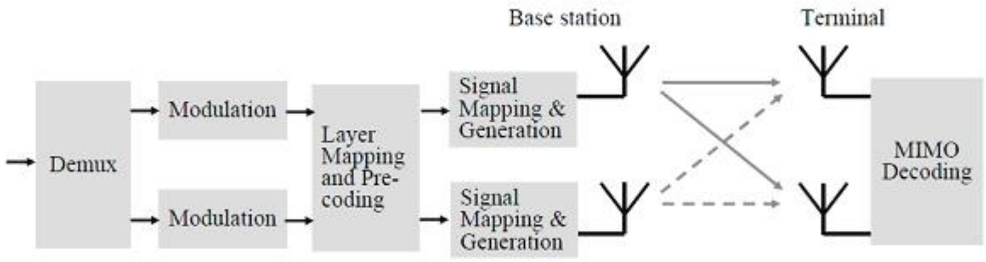


Figure 8: Block diagram of LTE transmission. One or two code words are mapped to one to four layers. The layers are then applied to one to eight antenna ports.

The various scenarios for the downlink are reflected in the different transmission modes (TMs). Release 12 describes ten different TMs, which are explained below. See Table 3 for an overview.

Downlink Transmission modes in LTE Release 12			
Transmission modes	**Description**	**DCI** (Main)	**Comment**
1	Single transmit antenna	1/1A	single antenna port port 0
2	Transmit diversity	1/1A	2 or 4 antennas ports 0,1 (…3)
3	Open loop spatial multiplexing with cyclic delay diversity (CDD)	2A	2 or 4 antennas ports 0,1 (…3)
4	Closed loop spatial multiplexing	2	2 or 4 antennas ports 0,1 (…3)
5	Multi-user MIMO	1D	2 or 4 antennas ports 0,1 (…3)
6	Closed loop spatial multiplexing using a single transmission layer	1B	1 layer (rank 1), 2 or 4 antennas ports 0,1 (…3)
7	Beamforming	1	single antenna port, port 5 (virtual antenna port, actual antenna configuration depends on implementation)
8	Dual-layer beamforming	2B	dual-layer transmission, antenna ports 7 and 8
9	8 layer transmission	2C	Up to 8 layers, antenna ports 7 - 14
10	8 layer transmission	2D	Up to 8 layers, antenna ports 7 - 14

Table 3: Overview of the ten downlink transmission modes in LTE Release 12.

3.2.1 TM 1 – Single transmit antenna

This mode uses only one transmit antenna.

3.2.2 TM 2 – Transmit diversity

Transmit diversity is the default MIMO mode. It sends the same information via various antennas, whereby each antenna stream uses different coding and different frequency resources. This improves the signal-to-noise ratio and makes transmission more robust.

In LTE, transmit diversity is used as a fallback option for some transmission modes, such as when spatial multiplexing (SM) cannot be used. Control channels, such as PBCH and PDCCH, are also transmitted using transmit diversity.

For two antennas, a frequency-based version of the Alamouti codes (space frequency block code, SFBC) is used, while for four antennas, a combination of SFBC and frequency switched transmit diversity (FSTD) is used.

3.2.3 TM 3 – Open loop spatial multiplexing with CDD

This mode supports spatial multiplexing of two to four layers that are multiplexed to two to four antennas, respectively, in order to achieve higher data rates. It requires less UE feedback regarding the channel situation (no precoding matrix indicator is included), and is used when channel information is missing or when the channel rapidly changes, e.g. for UEs moving with high velocity.
In addition to the precoding as defined in Table 4, the signal is supplied to every antenna with a specific delay (cyclic delay diversity, or CDD), thus artificially creating frequency diversity.

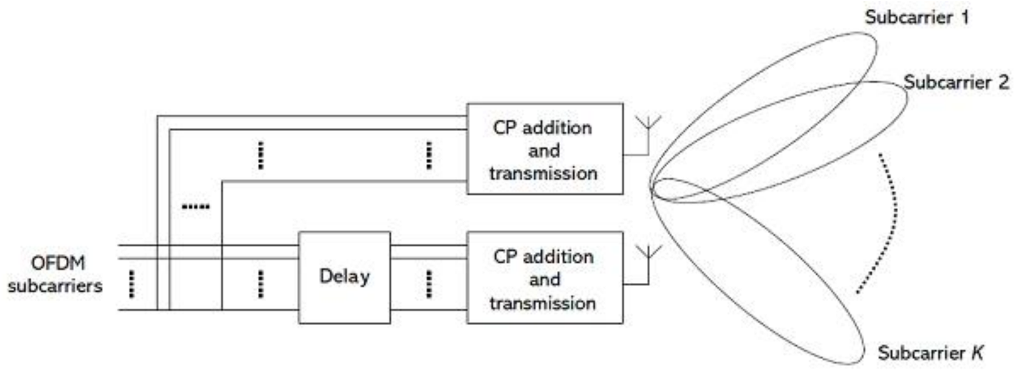


Figure 9: TM 3: Spatial multiplexing with CDD; the individual subcarriers are delayed artificially.

Figure 9 shows the CDD principle. For two transmit antennas, a fixed precoding (codebook index 0 is used as defined in Table 4), while for four antennas, the precoders are cyclically switched.

3.2.4 TM 4 – Closed loop spatial multiplexing

This mode supports spatial multiplexing with up to four layers that are multiplexed to up to four antennas, respectively, in order to achieve higher data rates. To permit channel estimation at the receiver, the base station transmits cell-specific reference signals (RS), distributed over various resource elements (RE) and over various timeslots. The UE sends a response regarding the channel situation, which includes information about which precoding is preferred from the defined codebook. This is accomplished using an index (precoding matrix indicators, or PMI) defined in the codebook, a table with possible precoding matrices that is known to both sides.

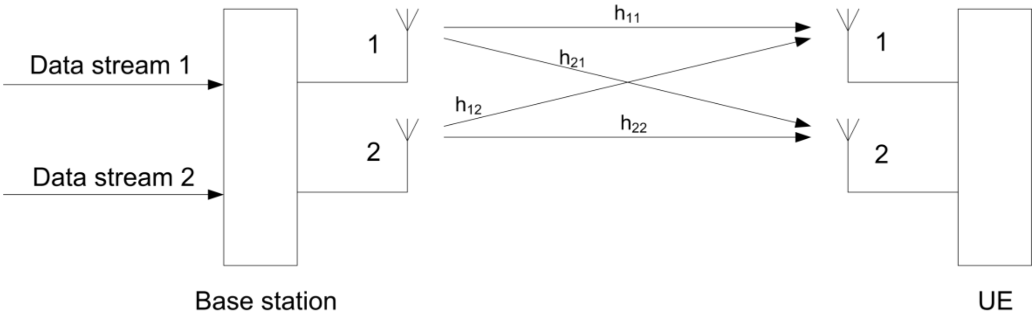


Figure 10: TM 4: single-user MIMO; the two data streams are for one UE only.

Spatial multiplexing LTE		
Codebook index	**Number of layers υ**	
	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	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

Table 4: Codebook indices for spatial multiplexing with two antennas, green background for two layers; yellow background for one layer or TM 6 [1]

A corresponding table for four antennas (and correspondingly with up to four layers) is also defined and is available in [1].

3.2.5 TM 5 – Multi-user MIMO

Mode 5 is similar to mode 4. It uses codebook-based closed loop spatial multiplexing, however one layer is dedicated for one UE.

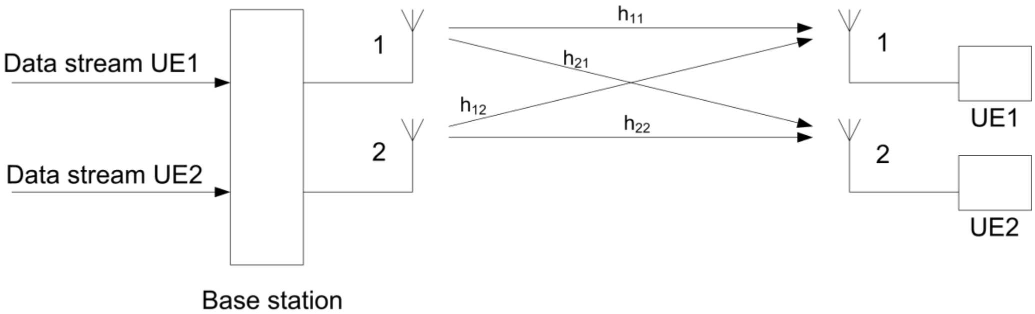


Figure 11: TM 5: Multi-user MIMO; the two data streams are split to two UEs.

3.2.6 TM 6 – Closed loop spatial multiplexing using a single transmission layer

This mode is a special type of closed loop spatial multiplexing (TM 4). In contrast to TM 4, only one layer is used (corresponding to a rank of 1). The UE estimates the channel and sends the index of the most suitable precoding matrix back to the base station. The base station sends the precoded signal via all antenna ports. The codebooks from Table 4 are used, but only the 1-layer variants (yellow background).

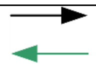
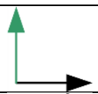
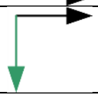
Weights for 1 Layer			
Codebook index	**Matrix**	**Weights**	**Phase**
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$		0°
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$		180°
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$		90°
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$		270°

Table 5: Precoding/weighting for a 1-layer scenario using the codebook index (the phase column indicates the phase difference between the two antenna signals)

The precoding in the baseband of the signals to the different antennas results in a beamforming effect (see Figure 12 for two antennas). With four transmit antennas there are 16 different beamforming diagrams. This “implicit” beamforming effect is to be distinguished from classical beamforming used in transmission modes 7 and 8, that are aiming at achieving a direct impact on the antenna diagram, e.g. for illuminating particular areas of a cell.

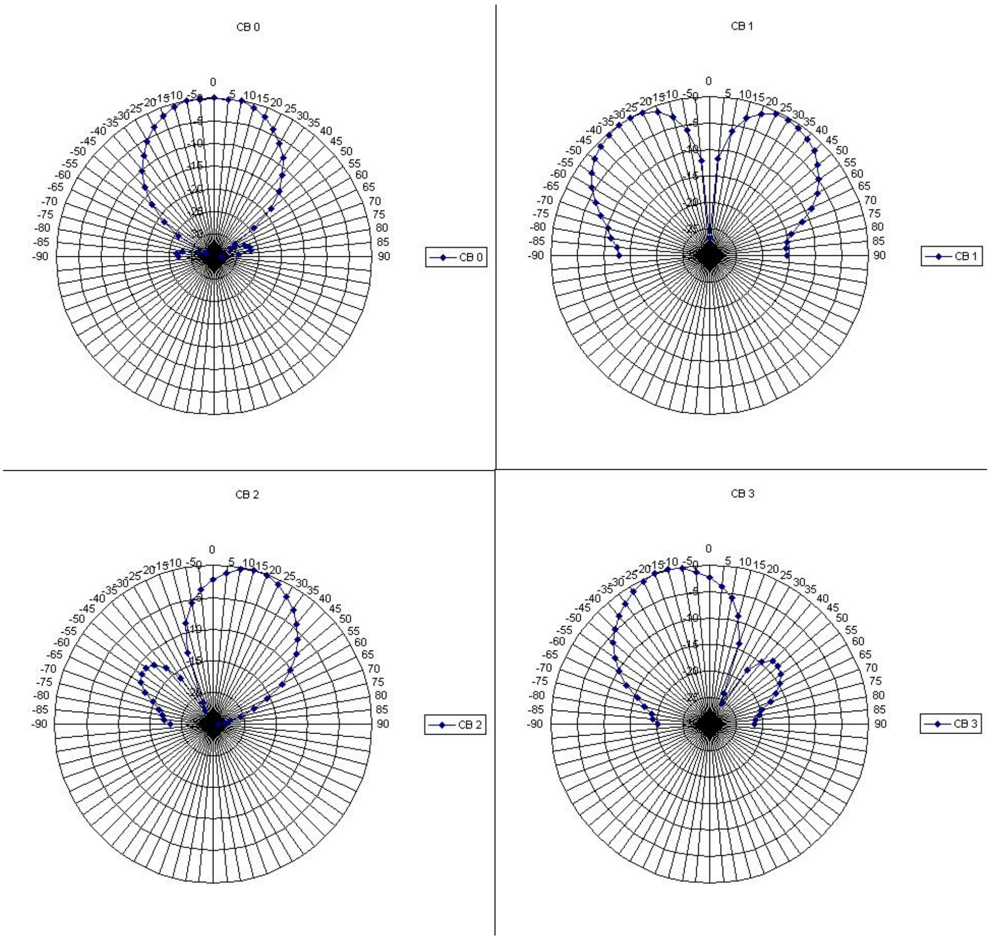


Figure 12: Schematic representation of TM 6 implicit beamforming for two antennas, codebook index 0…3

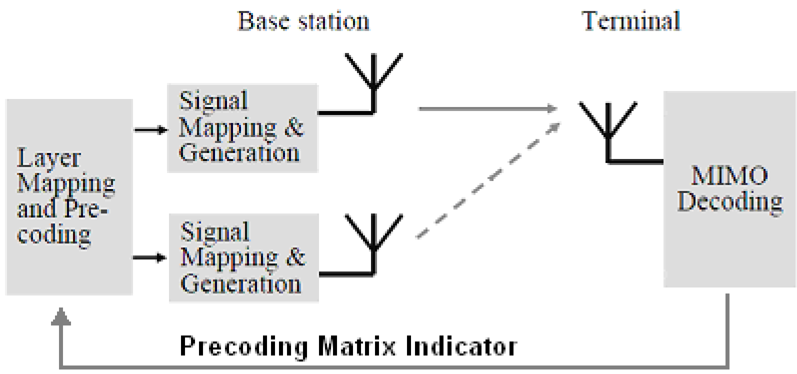


Figure 13: Block diagram for TM 6

Figure 13 shows the fundamental configuration.

3.2.7 TM 7 – Beamforming (antenna port 5)

This mode uses UE-specific reference signals (RS). Both the data and the RS are transmitted using the same antenna weightings. Because the UE requires only the UE-specific RS for demodulation of the PDSCH, the data transmission for the UE appears to have been received from only one transmit antenna, and the UE does not see the actual number of transmit antennas. Therefore, this transmission mode is also called "single antenna port; port 5". The transmission appears to be transmitted from a single "virtual" antenna port 5.

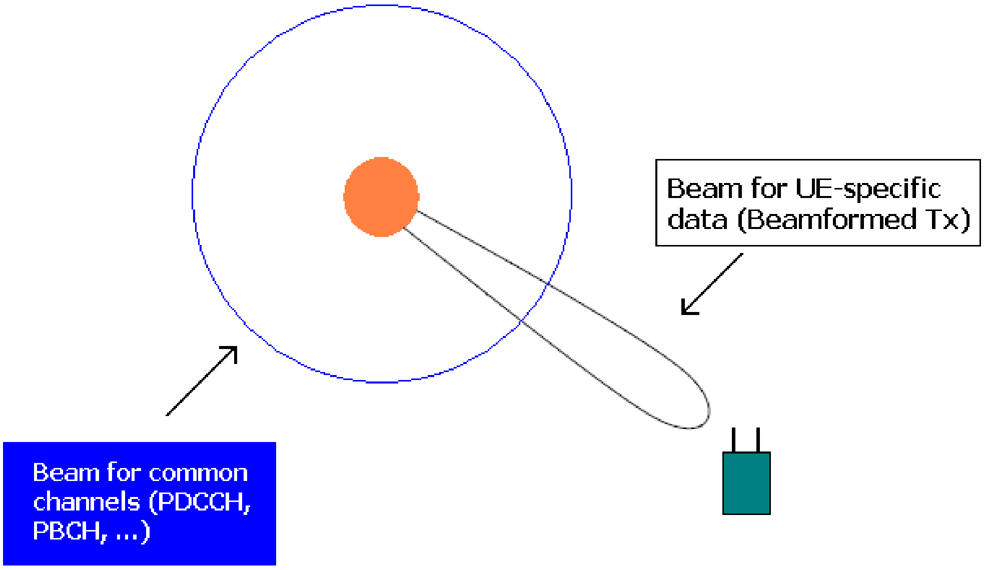


Figure 14: Beamforming in TM 7; use of UE-specific RS; the common channels use transmit diversity

There are different algorithms for calculating the optimum beamforming weightings. For example, it is possible to determine the direction of the received uplink signal (DoA or angle of arrival (AoA)), and from that calculate the beamforming weightings. However, this requires an antenna array with a distance between the individual antenna elements of $\mathbf{d \leq \lambda/2}$. It can be difficult to determine the DoA if the angular spread is not small or if there is no dominant direction in the DoA.

Alternatively, it is possible to determine the optimum beamforming weighting from the channel estimation. Because the uplink and downlink take place on the same frequency in a TD-LTE system, the uplink sounding reference signals can be used directly to estimate the channel, which can then be used to derive the weighting for the downlink beamforming. In this case, the beamforming vector is determined by channel estimation, and not from the DoA calculation.

The beamforming calculation is based on the uplink measurement, making calibration of the antenna array and of the RF frontend a major factor in the accuracy of the beamforming.

LTE does not specify any methods for determining the beamforming parameters. Other methods, such as beamswitching, are also possible. Also the number of antennas and the antenna architecture are left up to implementation.

3.2.8 TM 8 – Dual layer beamforming (antenna ports 7 and 8)

Specification of beamforming in LTE continues. While Release 8 of the LTE specification defines beamforming with one layer (as described in the above section), Release 9 specifies dual-layer beamforming. This will permit the base station to weight two layers individually at the antennas so that beamforming can be combined with spatial multiplexing for one or more UEs.

As in TM 7, UE-specific reference signals (RS) are also used here. Since, as can be seen in Figure 15, the same elements are used, the reference signals must be coded differently so that the UE can distinguish among them.

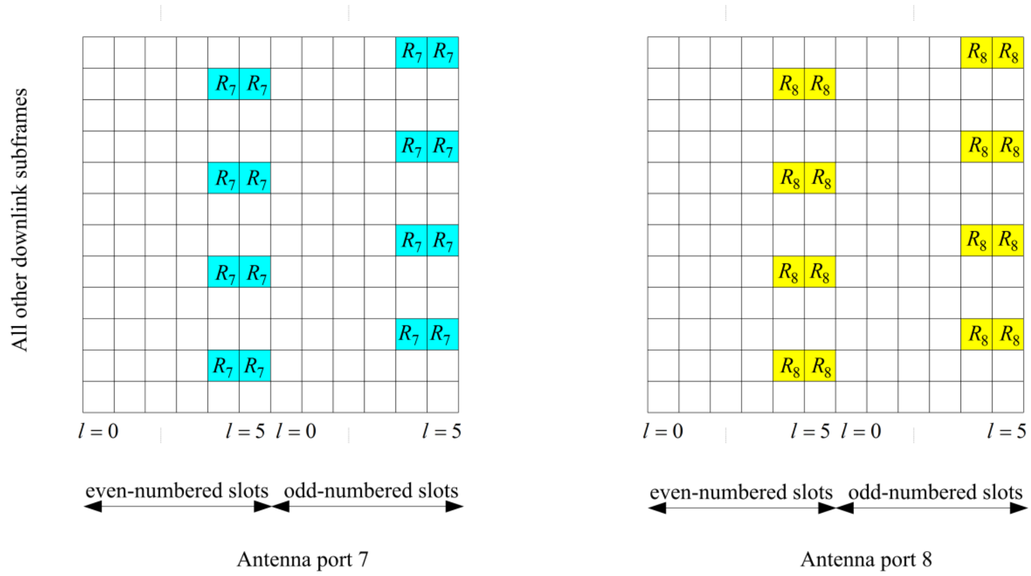


Figure 15: Distribution of reference signals for transmission mode 8 (antenna ports 7 and 8) [1]

Because two layers are used, both layers can be assigned to one UE (single-user MIMO, Figure 16), or the two layers can be assigned to two separate UEs (multi-user MIMO, Figure 17).

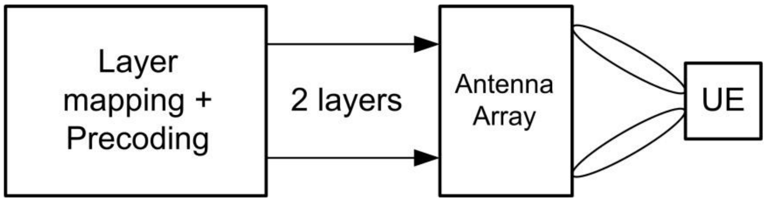


Figure 16: Dual-layer beamforming with SU-MIMO: Both beamformed data streams benefit the same UE.

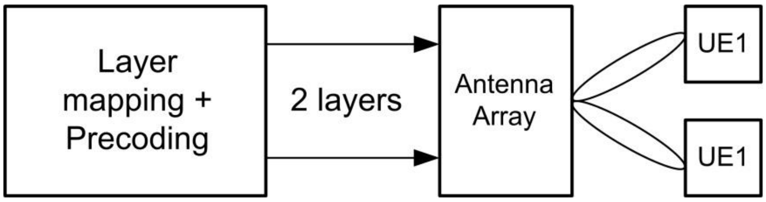


Figure 17: Dual-layer beamforming with MU-MIMO: The individual beamformed data streams each benefit a different UE.

3.2.9 TM 9 – Up to 8 layer transmission (antenna ports 7 - 14)

Release 10 adds Transmission Mode 9. In this mode up to eight layers can be used, so up to eight physical transmit antennas are needed, this leads to up to 8x8 MIMO configurations. The number of used layers may be defined dynamically. The virtual antenna ports 7…14 are used.

Both single user (SU) and multi user (MU) MIMO is possible, dynamic switching between both modes is possible without special signaling by higher layers.

The reference signals (RS) structure is enhanced from Release 8:

- UE-specific (DM-RS) for demodulation of PDSCH. This is an extension of the beamforming concept of TM7 and TM8 to support more layers.
- In addition CSI-RS allows the UE downlink channels state information (CSI) measurements. They are cell-specific.

The same elements are used for ports 7,8,11,12 (noted as Rx, blue) and 9,10,13,14 (noted as Ry, green), the reference signals must be coded differently so that the UE can distinguish among them (Figure 18).

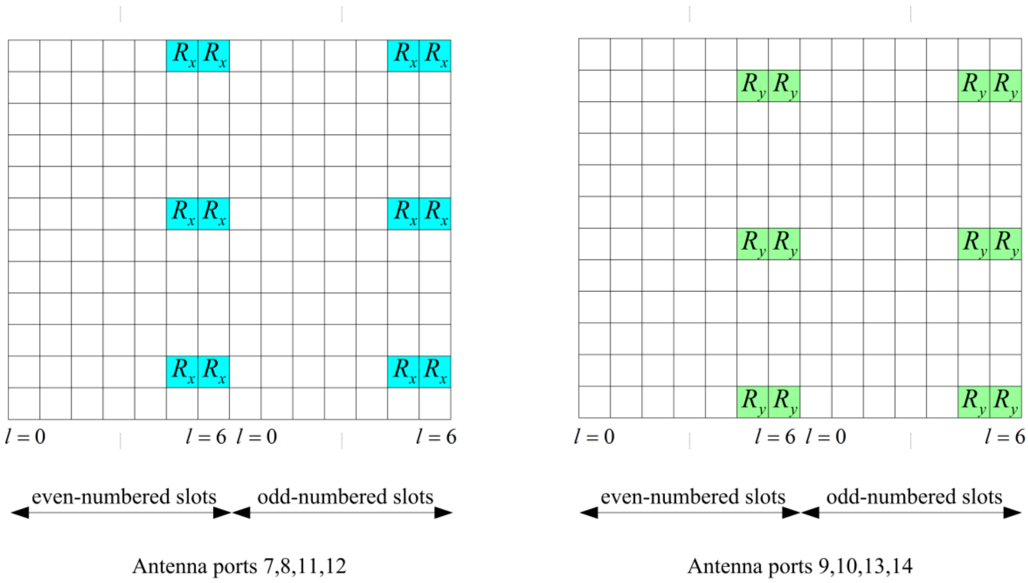


Figure 18: Distribution of reference signals for transmission mode 9 (antenna ports 7…14) [1]

The UE-specific DM-RS is applied to the data streams before the precoding. That means the UE receives the known RS which is precoded and transmitted via the channel. Thus the receiver does not need to know the used precoding in advance. There is no need to use special codebooks anymore, the UE does not send back the the PMI. In other words the spatial multiplexing is able to use the full range of weighting (precoding) for beamforming now, not only discrete precoding via the codebook like in TM3…6.

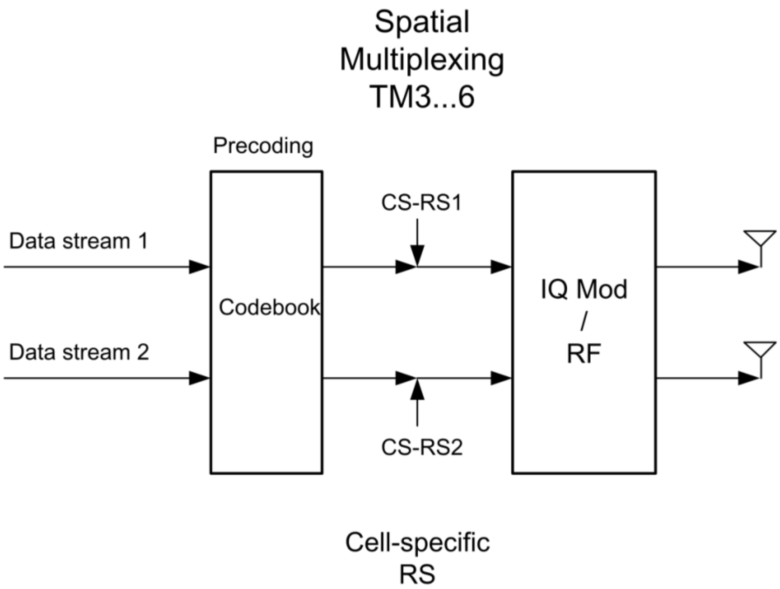


Figure 19: TM3…6: The cell-specific RS is applied after the precoding. The UE reports back the wanted codebook index. Only discrete beamforming patterns are used (see 3.2.4 and 3.2.6).

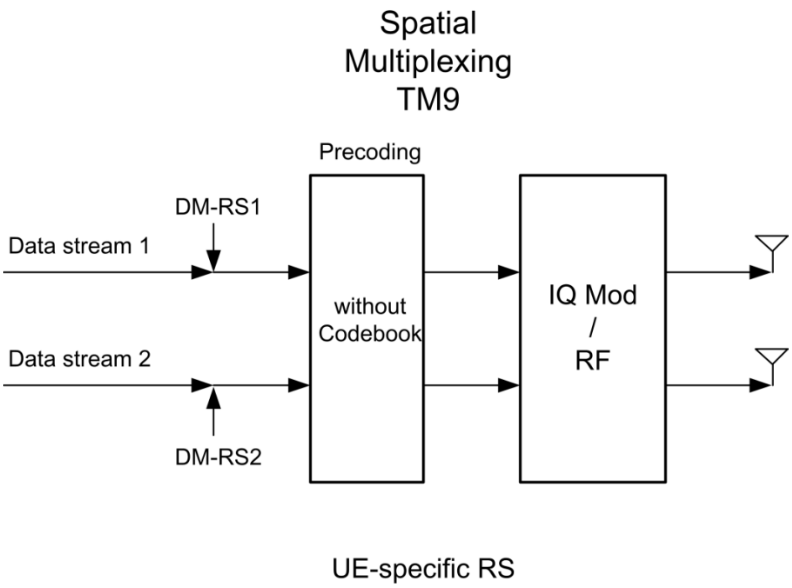


Figure 20: TM9: The UE-specific RS is applied before the precoding. This enables non-codebook based precoding. So the full range of beamforming patterns can be used.

3.2.10 TM 10 – Up to 8 layer transmission (antenna ports 7 - 14)

Release 11 adds Transmission Mode 10. This mode is similar to TM9 (see 3.2.9). Again, up to eight layers can be used, so up to eight physical transmit antennas are needed, this leads to up to 8x8 MIMO configurations. The number of used layers may be defined dynamically. The virtual antenna ports 7…14 are used. TM10 uses the same reference signals like TM9, see figure 18.

The main difference to TM9 is the used DCI format (2D). With TM10 Coordinated Multi Point Transmission (CoMP, see [10]) is supported. CoMP uses in principle the same MIMO technique like TM9, but the transmit antennas may be physically on different base station sites. DCI format 2D allows to tell the UE, that it can assume a quasi co-location of the antenna ports with respect to Doppler shift, Doppler spread, average delay, and delay spread.

3.3 Transmission modes (TM) in LTE uplink

To keep the UE complexity low, Releases 8/9 do not specify a true MIMO in the uplink for LTE. Receive beamforming in the uplink can be carried out dependent on the base station implementation.

Since Release 10, LTE supports MIMO with up to four layers in the uplink, so up to four antennas are supported. For this a new transmission mode in the uplink has been introduced.

Uplink Transmission modes in LTE Release 12			
Transmission modes	**Description**	**DCI** (Main)	**Comment**
1	Single transmit antenna	0	single antenna port (port 10)
2	Closed-loop spatial multiplexing	4	2 or 4 antennas (ports 20 and 21) (ports 40,41,42,43)

Table 6: The two uplink transmission modes in LTE Release 12.

The basic principle is the same like the downlink spatial multiplexing (TM4). Table 7 shows as an example the codebook indices for the use with two antennas. The tables for four antennas are in [1].

Spatial multiplexing uplink		
Codebook index	Number of layers υ	
	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 7: Codebook indices for spatial multiplexing in the uplink with two antennas [1]

3.4 Test requirements in 3GPP Release 12

3GPP conformance test specifications for UEs contain a lot of tests with regards to verification of functionality and performance of the different MIMO modes. However, only few tests address beamforming with transmission modes 7, 8 and 9. This is even more true for the base station side. Because many beamforming parameters and algorithms are not specified in LTE, there are only a limited number of prescribed tests that directly affect beamforming. Additional tests, such as phase measurements, are described in [6].

3.4.1 Base station test

No special beamforming measurements are specified for the transmitter or receiver tests at the base station. Section 6.5.3 [7] of 36.141 (Base Station Conformance Tests) specifies only the time offset between the antenna ports for the transmitter.

3.4.2 UE test

For the UE receiver, several performance (TS 36.521-1, Section 8 [8]) tests are specified under MIMO configurations.

A couple of tests apply for TDD mode with user-specific RS, thus Beamforming TMs 7 and 8 (Section 8.3 with B.4, [8]); however, discrete beamforming settings with precodings CB0….CB3 randomly selected from codebook table (Table 4) are used. The UE must achieve a minimum throughput under fading conditions.

3.5 Summary

LTE Release 8 defines seven different transmission modes. Release 9 adds TM 8, dual-layer beamforming. TMs 7 and 8 use "classical" beamforming with one or two layers using UE-specific reference signals. Release 10 extends the dual layer mode of TM8 to TM9 with up to eight layers. Release 11 adds TM10 with up to eight layers for Downlink CoMP.

The “classical” beamforming modes require a special antenna array with a distance of $d \leq \lambda/2$. Feedback from the UE is not necessary. Different algorithms are available for determining the optimum weighting. Beamforming for TD-LTE is especially attractive because the same frequency is used in both the uplink and the downlink so that the channel reciprocity can be exploited.

4 Appendix

4.1 Literature

[1] Technical Specification Group Radio Access Network; **Physical Channels and Modulation**, Release 10; **3GPP TS 36.211 V 12.5.0**, March 2015

[2] Rohde & Schwarz: **UMTS Long Term Evolution (LTE) Technology Introduction**, Application Note 1MA111, September 2008

[3] Rohde & Schwarz: **Introduction to MIMO**, Application Note 1MA142, July 2009

[4] R. O. Schmidt, **Multiple emitter location and signal parameter estimation,** in *Proc. RADC Spectral Estimation Workshop*, Rome, NY, 1979, pp. 243–258.

[5] A. Paulraj, R. Roy, and T. Kailath, **A subspace rotation approach to signal parameter estimation**, *Proc. IEEE*, vol. 74, pp. 1044–1046, Jul. 1986.

[6] Rohde & Schwarz: **LTE Beamforming Measurements**, Application Note 1MA187, September 2011

[7] Technical Specification Group Radio Access Network; **Base Station Conformance Testing**, Release 10; **3GPP TS 36.141 V 12.5.0**, September 2014

[8] Technical Specification Group Radio Access Network; **UE conformance specification**, Release 10; **3GPP TS 36.521-1 V 12.5.0**, March 2015

[9] Rohde & Schwarz: **LTE-Advanced (3GPP Release 11) Technology Introduction**, White Paper 1MA169, July 2013

[10] Rohde & Schwarz: **LTE-Advanced (3GPP Release 12) Technology Introduction**, White Paper 1MA252, June 2014

4.2 Additional information

Please send your comments and suggestions regarding this white paper to

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