MIMO Transmission Schemes for LTE and HSPA Networks

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1 TERMINOLOGY

It is assumed that the reader is familiar with common 3GPP standards terms described in [3]. Terminology that is outside of the scope of [3] is provided below.

Antenna Efficiency	Ratio of radiated power from/to antenna vs. conducted power to/from antenna.
BPD	Branch Power Difference **-** The difference in the efficiencies between the main and diversity (secondary) antenna.
CDD	Cyclic Delay Diversity
CLA	Family of clustered linear antenna configurations such as those resulting from forming clusters of closely spaced antenna elements while separating these clusters either by widely spacing them or by different polarizations.
CL-MIMO	Closed Loop MIMO
CoMP	Coordinated Multipoint Transmission/Reception
Correlation (p)	Cross correlation of received signal power/phase for antennas over space or a traveled route. Generally, as the correlation value increases, the ability of the diversity antenna system to provide any gains decreases. For the SM case, target envelope correlation should be between 0.5 (worst case) and 0.3 (good performance). For simple diversity implementations, target envelope correlation should be < 0.7.
CSI	Channel State Information
CQI	Channel Quality Indication
DFT	Discrete Fourier Transform
DIV	Family of diversity antenna configurations such as those resulting from all elements being widely spaced or separated by different polarizations
EMC	Electromagnetic Compatibility
FDD	Frequency Division Duplex
HAC	Hearing Aid Compatibility
MMSE	Minimum Mean Square Error
MU-MIMO	Multiuser MIMO
OFDM	Orthogonal Frequency Division Multiplexing
OL-MIMO	Open Loop MIMO
RMa	Rural Macrocell deployment type
RRH	Remote Radio Head
SAR	Specific Absorption Rate
SDMA	Space Division Multiple Access
SFBC	Space Frequency Block Coding
SINR	Signal to Interference and Noise Ratio
SM	Spatial Multiplexing
SU-MIMO	Single User MIMO
TDD	Time Division Duplex
TTI	Transmission Time Interval
TXD	Transmit Diversity
ULA	Family of uniform linear array antenna configurations such as those resulting from all elements being uniformly closely spaced.
UMa	Urban Macrocell deployment type
UMi	Urban Microcell deployment type

2 EXECUTIVE SUMMARY

For over a decade universities and wireless research labs have been combining multiple antenna transmission techniques with advanced signal processing algorithms to create what is sometimes called smart-antenna and is also known as multi-input multi-output (MIMO) technology. These schemes are now moving into mainstream communication systems. Indeed, MIMO technologies can already be found in wireless local area network access points (e.g. 802.11n based solutions). This has led to MIMO being standardized in WiMAX as well as in 3GPP Rel-6 and Rel-7 of the UTRAN (HSPA) specifications. Further, Rel-8 of the E-UTRAN (LTE) 3GPP specifications, completed in March 2009, included the most advanced forms of MIMO in any standard in the industry. And even more advanced MIMO enhancements are currently being studied for inclusion in 3GPP Rel-9 and Rel-10.

There are many MIMO schemes standardized in 3GPP systems, and the base station scheduler has the capability to optimally select the MIMO scheme that suits the channel conditions of the mobile. A fundamental MIMO scheme is that of precoded spatial multiplexing (SM) where multiple information “streams” are transmitted simultaneously from the base station to the mobile. These techniques are appropriate in high SINR areas with rich scattering environments, in combination with suitable antenna configurations. Measurements at the base station receiver and feedback signals by the mobile help the base station determine the number of information streams that can be supported across single or multiple users. SM is augmented with techniques such as beamforming and open loop transmit diversity that can be used as the channel conditions become less favorable to spatial multiplexing. The ability to dynamically adapt to the channel optimal MIMO scheme as channel conditions change is a key focus of the LTE Rel-8 specifications.

Antenna configurations at the tower have an impact on the types of MIMO schemes that are available to the base station. Narrowly spaced antennas are ideal for supporting beamforming, while widely spaced or cross pole antennas are ideal for spatial multiplexing and transmit diversity. The choice of antenna at the base station will depend on several factors including the expected performance benefits for the particular deployment environment as well as real estate and cost considerations at the tower. At the terminal, the device form factor as well as operation at lower frequency bands further challenges designers in terms of achieving the required antenna efficiencies. Performance benefits of various MIMO schemes are shown through system simulation results, and demonstrate that both peak throughput as well as system and edge spectral efficiency are increased with MIMO techniques. In the paper, a technology-oriented approach was followed, leaving many real-world deployment and MIMO BS antenna design issues untreated. These include issues ranging from antenna sharing at the tower, to antenna beam design, to wind loading and many others worth of a separate white paper dedicated to this subject.

This paper is organized as follows. In Section 3, we provide the principles behind smart antenna technologies such that the reader will be able to understand the fundamental tradeoffs. We then describe many antenna configurations that can support a wide range of MIMO algorithms at the base station as well as extensively treat the issues behind the antenna configurations at the terminal. Section 4, addresses the specific schemes selected by 3GPP to provide smart antenna capabilities in HSPA and LTE Rel-8. Section 5 focuses on the expected standardization outcome in Rel-9 and Rel-10 and more specifically, in enhancements behind clustered linear arrays (CLA) and collaborative multipoint transmission/reception (CoMP) schemes. Section 6 provides performance results for a wide variety of channel conditions, and antenna configurations for both DL and UL. Closing, Section 7, provides some concluding remarks effectively distilling the performance results of section 6 down to few guiding trends and recommendations.

The 3GPP specifications have already defined and continue to define the most advanced forms of MIMO technology in the industry. We certainly hope that this report increases awareness and helps guide the deployment of MIMO technology in HSPA and LTE networks.

3 PRINCIPLES

3.1 MULTI-ANTENNA-TRANSMISSION BASICS

Roughly speaking, multi-antenna transmission has two partly separate aims:

- *Improving SINR*
- *Sharing SINR*

In principle, the first approach (improving SINR) is mainly targeting low SINR scenarios while the second approach (sharing SINR) is mainly targeting high SINR scenarios.

3.1.1 IMPROVING SINR

The classical technique of using an antenna array for transmitting energy in the direction of the intended receiver falls into the category of improving SINR. Such *classical beamforming* achieves increased SINR by phase adjustments of the signals transmitted on the different antennas with the aim of making the signals add-up *constructively* on the receive side. In a cellular network, this may also cause interference for other users since the transmission is confined to a rather narrow beam as opposed to being uniformly distributed over a whole sector.

Transmit diversity using e.g. the Alamouti space-time block code or space-frequency block codes also strives for improving the SINR, albeit not in the same sense as beamforming. In contrast to beamforming, transmit diversity does not improve the average SINR but rather, due to diversity, reduces the variations in the SINR experienced by the receiver.

3.1.2 SHARING SINR

Compared with improving SINR, the reasons for sharing SINR are a bit less obvious. An improved SINR can be exploited by transmitting with a more aggressive modulation and coding rate, thus achieving a higher link throughput. However, when the SINR level becomes high enough the throughput versus SINR curve saturates, giving diminishing returns for a further increase in the SINR, as illustrated in Figure 1.

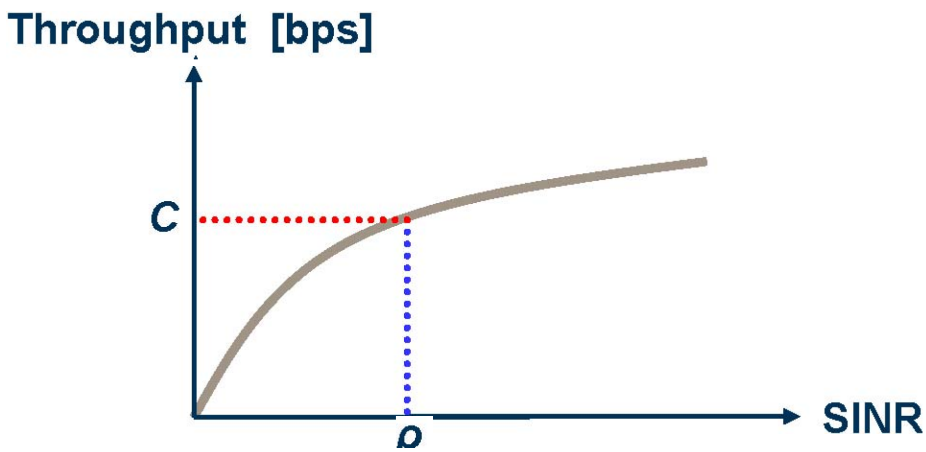


Figure 1. Throughput curve versus SINR saturates at high SINR values.

However, by the use of multiple antennas at both sides (transmitted and receiver) of the radio link, multiple parallel channels can be created. These parallel channels share the overall SINR, thus avoiding the above mentioned throughput saturation. In the simplest of cases, such a multiple-input multiple-output (MIMO) antenna configuration uses two antennas at the transmitter and two antennas at the receiver resulting in a 2x2 MIMO channel. Here, the notation *N*Tx*N*R is taken to mean *N*T transmit antennas (channel *inputs*) and *N*R receive antennas (channel *outputs*). The SINR may be shared by simply encoding and modulating two blocks of information bits separately, and transmitting the resulting two *symbols streams* from different antennas. This is referred to as *Spatial Multiplexing*. In practice, the signal on each receive antenna will be a superposition of the signals stemming from all transmit antennas. Neglecting the inter-stream interference, the 2x2 MIMO link can be modeled as two parallel channels, each having some specific SINR. Keeping the total transmitted power the same (reducing each transmitted stream by 3 dB) and further assuming the two channels have the same amount of noise, that SINR value will be half of the SINR value for a single stream transmission using the same total power of only one antenna. On the other hand, there are now two data pipes to use, offsetting the reduction in the common SINR value. The overall gain depends on where on the throughput curve the operating point is but for sufficiently high SINRs, the throughput can be doubled, just as using twice as much bandwidth can double the throughput. If the two channels are not balanced i.e. their SINR values are different, then a higher overall SINR level is needed to approach a factor of two gain in throughput. In general, a *N*Tx*N*R MIMO channel supports transmissions of at most *r*max = min{*N*R,*N*T} simultaneous symbol streams for sufficiently high SINR values.

However, in practice the inter-stream interference needs to be taken into account. The inter-stream orthogonality largely depends on the actual MIMO channel realization. The number of simultaneously transmitted streams the MIMO channel can support is commonly referred to as the *channel rank* and the actually transmitted number of streams is correspondingly termed *transmission rank*. The transmission rank typically needs to be adapted to suit the current channel characteristics and hence avoid excessive inter-stream interference.

In the most general context, transmission rank can be defined as the number of complex-valued independent modulation symbols transmitted per time-frequency resource. Beamforming, transmit diversity based on Alamouti codes (as defined below) and even single-antenna transmissions are all considered single-rank schemes and naturally fit within the definition of transmission rank. Obviously, spatial multiplexing schemes provide the possibility to use transmission ranks higher than one.

3.1.3 PEAK RATE OR COVERAGE

In a cellular network, not only noise but also interference from other cells disturbs transmissions. The inter-cell interference is typically rather strong on the cell edge and considerably weaker closer to the cell center while the opposite is true for the received energy of the intended transmission. Consequently, improving the SINR by means of beamforming is well-suited for cell-edge users which operate on the lower and linear part of the throughput curve (Figure 1). On the other hand, the cell-center user with high SINR may benefit more from sharing the SINR by means of MIMO transmission with spatial multiplexing. Thus, rank-one transmissions increase the coverage (in terms of cell edge data rates) whereas spatial multiplexing (rank larger than one) improves peak rates. This trade-off between coverage and throughput for single- and multi-rank transmission is illustrated in Figure 2.

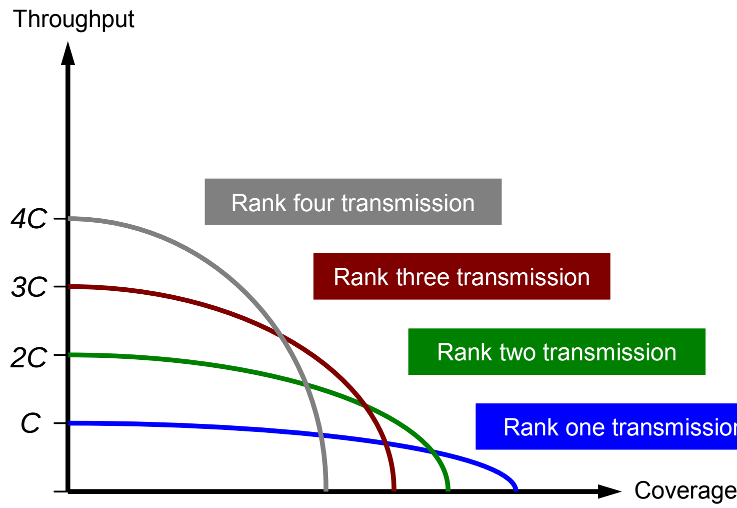


Figure 2. Throughput versus coverage (coverage for a certain minimum requirement on throughput) for a 4x4 MIMO wireless link

3.1.4 PRECODING

There are various ways by which the modulated symbols can be distributed onto the transmit antenna array. In the case of beamforming, a single symbol s_1 is multiplied by a channel dependent weight vector **w** that introduces antenna specific phase adjustments, producing the transmitted vector:

$$\mathbf{x} = \mathbf{w}s_1 = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{N_\mathrm{T}} \end{bmatrix} s_1 . \qquad (1)$$

The phase adjustments are such that the signals from the different antennas add constructively at the receiver side, improving SINR and thus coverage. The achievable SINR improvement increases with the number of transmit antennas. Roughly speaking, the so-called array gain is proportional to the number of transmit antennas implying that a doubling of the number of transmit antennas allows for an up to 3 dB gain in

SINR. How such a gain translates into a throughput increase then depends on e.g. where on the throughput curve the link is operating. The qualitative behavior of the resulting throughput-vs-coverage curves is illustrated in Figure 3.

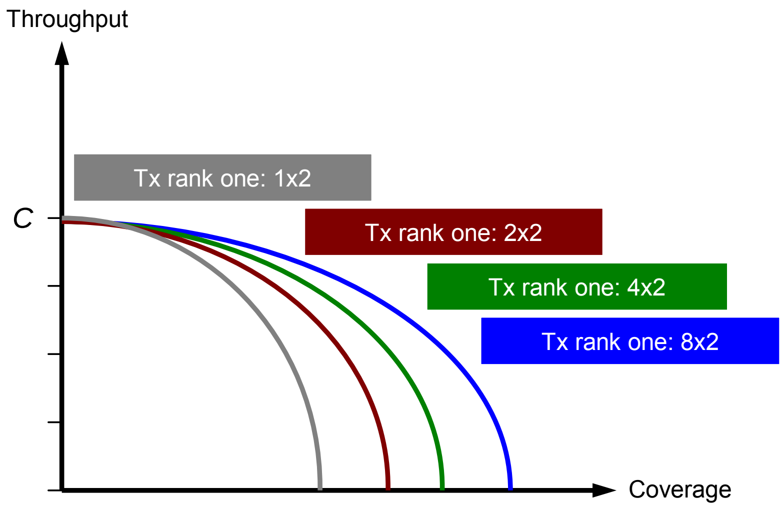


Figure 3. Throughput versus coverage curves illustrating how the array gain from the use of beamforming improves the throughput on the cell edge but not sufficiently close to the cell center

Spatial multiplexing in its simplest form entails transmitting one separately modulated symbol per antenna. The Alamouti code is a block code represented by a 2x2 codeword matrix of the form

$$\mathbf{C} = \begin{bmatrix} s_1 & s_2 \\ s_2^{c} & -s_1^{c} \end{bmatrix} \qquad (2)$$

where the rows correspond to the (transmit) antenna dimension and the columns may be another dimension such as time or frequency and where $(\cdot)^{c}$ denotes complex conjugate.

All the schemes described so far have in common that they fall under the framework of (linear) block based precoding. Such precoding can generally be described by an N_TxL codeword matrix.

$$\mathbf{C} = [\mathbf{x}_1 \quad \mathbf{x}_2 \quad \cdots \quad \mathbf{x}_L] = \sum_{q=1}^{Q} \mathbf{B}_q \operatorname{re}\{s_q\} + \tilde{\mathbf{B}}_q \operatorname{im}\{s_q\} \qquad (3)$$

As seen, a codeword is obtained as a linear combination of the real and imaginary parts of the modulation symbols. This kind of scheme is commonly referred to as linear dispersion coding and the **B***q* matrices are consequently called dispersion matrices, to acknowledge the fact that they distribute each symbol over two different dimensions. Each symbol *sq* corresponds to a certain symbol stream, also known as a layer. The transmission rank can be expressed as $r = Q/L$.

It should be emphasized that the term precoding is a framework that encompasses a large number of widely different transmission schemes. As such, it does not say much about the actual scheme being used and the meaning of precoding thus has to be understood from the context.

The dispersion matrices can either be made dependent or independent of the channel. The Alamouti code is an example of when they are fixed while in beamforming they are adapted according to the channel conditions. Whether to use channel dependent or independent precoding depends on the availability of sufficiently accurate channel information on the transmit side. The degree of mobility is often the most important factor in determining which strategy to use since with high UE velocities it becomes difficult to track the variations of the channel and the channel information is therefore likely to be outdated by the time it is used for the transmission. A common special case of precoding is to perform purely spatial precoding entirely in the complex-valued domain, meaning that L = 1 and $\tilde{\mathbf{B}}_q = j\mathbf{B}_q$. The linear dispersion matrix **C** then becomes a vector and can be written as:

$$\begin{aligned}\mathbf{X} = \mathbf{x}_1 &= \begin{bmatrix}\mathbf{B}_1 & j\mathbf{B}_1 & \cdots\end{bmatrix}\begin{bmatrix}\mathrm{re}\{s_1\} \\ \mathrm{im}\{s_1\} \\ \vdots\end{bmatrix} \\ &= \begin{bmatrix}\mathbf{B}_1 & \mathbf{B}_2 & \cdots & \mathbf{B}_Q\end{bmatrix}\begin{bmatrix}s_1 \\ s_2 \\ \vdots \\ s_Q\end{bmatrix} \\ &= \{\text{let } \mathbf{w}_q = \mathbf{B}_q\} = \begin{bmatrix}\mathbf{w}_1 & \mathbf{w}_2 & \cdots & \mathbf{w}_Q\end{bmatrix}\begin{bmatrix}s_1 \\ s_2 \\ \vdots \\ s_Q\end{bmatrix} = \mathbf{W}\mathbf{s}\end{aligned} \tag{4}$$

Each symbol *sq* is weighted by a specific vector **w**q. If Q = 1, only one symbol is transmitted per resource element and the scheme hence has exactly the same structure as beamforming in (1). Precoded spatial multiplexing is obtained for the case of $Q > 1$ and the transmission rank obviously reduces to $r = Q/L = Q$. In the case of channel dependent precoding, the weighting primarily serves to distribute the transmission into directions (in a vector space) which are “strong” in the sense that much of the transmitted energy reaches the receiver. There is also the possibility to use the precoding operation to improve the separation of the different layers, i.e., reduce the inter-layer interference. However, unless the weighting matrix **W** matches the channel with a high degree of accuracy, this effect is of less importance. For channel independent precoding, transmit diversity could be achieved by varying the weighting matrix over the smallest available scheduling unit.

The matrix **W** can either be chosen from a fixed and countable set of precoder matrices:

$$W = \{\mathbf{W}_1, \mathbf{W}_2, \square, \mathbf{W}_{K}\} \quad (5)$$

so-called codebook-based precoding, or be chosen without such restrictions correspondingly referred to as non-codebook based precoding. Codebook-based precoding is one of the primary transmission modes in LTE and can be viewed as a sort of channel quantization that facilitates low-rate feedback of channel information from the receiver (UE). In FDD, such channel feedback is a prerequisite for performing channel-dependent precoding that tracks fast fading since measurements from reception of transmissions in the reverse link cannot be used because of the large frequency duplex distance between the forward- and reverse-link carriers. Duplex distance is obviously not a problem in TDD where channel reciprocity may hold if transmit and receive filters are calibrated appropriately. It is therefore potentially easier to use non-codebook-based precoding for tracking fast fading in case of TDD compared to FDD.

3.1.5 MIMO CHANNEL PROPERTIES AFFECTING THE CHOICE OF TRANSMISSION SCHEME

The UE, in most environments, may be modeled as embedded in a cluster of local scatterers (shown as cluster 0 in Figure 4). The local scatterers can be, for example, the body of the user, the ground, or nearby cars. When the base-station (BS) antennas are elevated, the BS may be modeled as being far away from the scatterers. The signal originating from the UE transmitter is reflected by clusters in the far field of the base-station antennas (clusters 1 and 2). Associated with each reflection is a time-delayed and phase-shifted version of the transmit signal that arrives at the mobile via a different direction of arrival (DoA). The locations of scatterers are commonly assumed to be identical between uplink and downlink. This symmetry is fundamental to the operation of many smart-antenna algorithms.

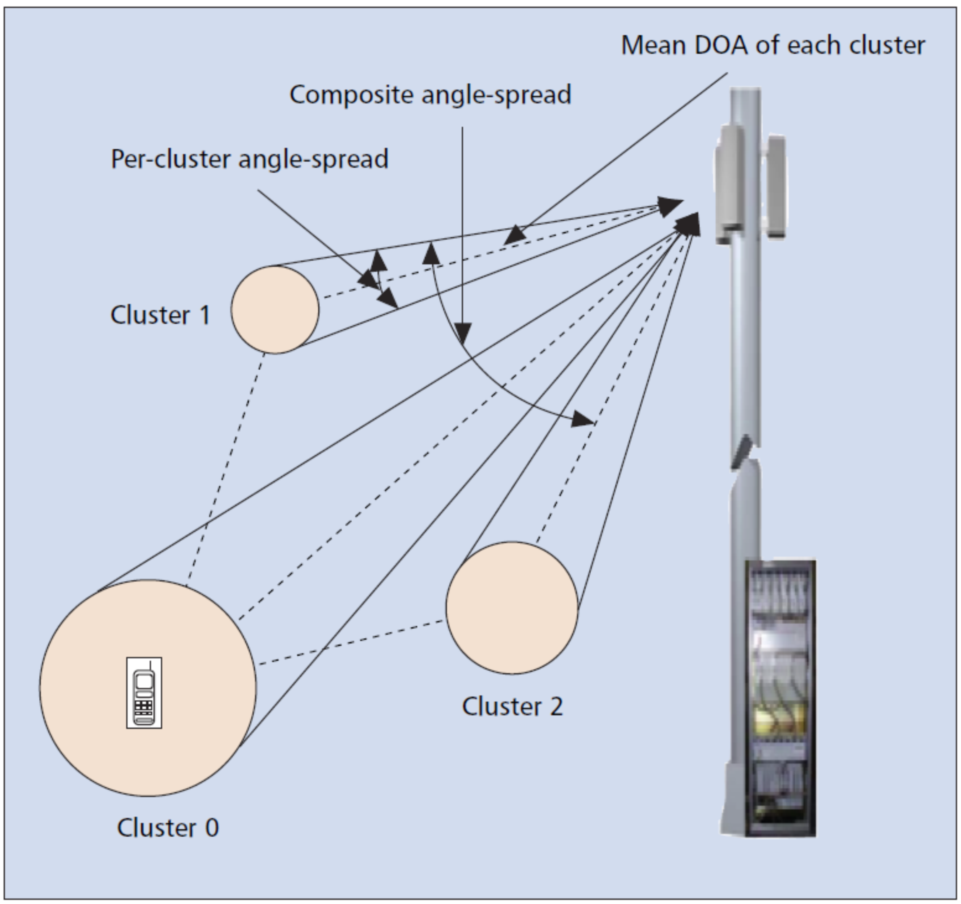


Figure 1. The Mobile Radio Propagation Environment

PDP	Relative power to first path (dB) Relative delay (ns)	Velocity (km/h)	Occurrence prob (%)
Pedestrian A	[0.0, –9.7, –19.2] [0.0, 110.0, 190.0]	3.0	30
Pedestrian B	[0.0, –0.9, –4.9, –8.0, –7.8] [0.0, 200.0, 800.0, 1200.0, 2300.0]	10.0	30
Vehicular A	[0.0, –1.0, –9.0, –10.0, –15.0] [0.0, 310.0, 710.0, 1090.0, 1730.0]	30.0	20
Vehicular B	[0.0, –2.5, –12.8, – 10.0, –16.0] [0.0, 300.0, 8900.0, 12900.0, 20000.0]	120.0 &	10
Single path	[0.0] [0.0]	3.0	10

Figure 5. Examples of Power Delay Profiles (PDP) commonly considered as representative in mobile radio propagation

Apart from the angular spread due to multi-path propagation, the propagation environment affects the properties of the MIMO channel via many factors including UE mobility, path loss, shadow fading and the polarization of the transmitted signal. This in combination with the particular antenna configuration at the transmitter and receiver determines the overall channel characteristics. Some of the key parameters regarding the antenna configuration are the distances between the antenna elements within the multi-antenna configuration array and the polarization direction of the different antenna elements.

A larger inter-antenna distance reduces the correlation between the channels of the different antenna elements for a given fixed angular spread and vice verse. Signals transmitted from antennas with different polarization direction also tend to have reduced correlation. Another important characteristic is that signals transmitted with different polarization directions often remain rather well separated in the polarization "dimension" even when reaching the receiver. Thus, varying inter-antenna distances and polarization can be used to affect the spatial correlation and the isolation between signals. Since a transmission scheme usually works well in a channel with certain properties and less well with other properties, the antenna setup substantially impacts what multi-antenna transmission scheme to use, and vice verse. The previously mentioned transmission schemes are targeting different channel characteristics and hence are suitable together with different antenna setups. Some of the more obvious possible combinations under idealized assumptions regarding the antennas are listed below. They are:

- Beamforming:
    - Strong spatial correlation on the transmitter side, typically due to small inter-antenna distance and co-polarized antennas on transmit side
- Transmit diversity, e.g. using Alamouti coding:
    - Low spatial correlation at least the transmitter side, typically due to orthogonally polarized antennas and/or large inter-antenna distance
- Spatial multiplexing (Single User MIMO):
    - Low spatial correlation on both the transmitter and receiver side and/or good isolation between different transmit/receive antenna pairs provided by either
        - co-polarized antennas on both transmitter and receiver side with large inter-antenna distances on both sides

- orthogonally polarized antennas on transmitter side and receiver side

Note that the meaning of “large” and “small” inter-antenna distance above should be interpreted relative to the angular spread on the intended side of the link and also on the wave length. For a base station mounted above roof tops the angular spread might for example be quite small and “small” may then be taken as half a wavelength and “large” might be 4-10 wavelengths while on the UE side, which typically experiences a much larger angular spread, half a wavelength might be considered “large”.

3.1.6 WHAT DISTINGUISHES BEAMFORMING RELATIVE PRECODING?

Judging from the similar expressions for beamforming in equation (1) and precoding in equation (4), it is natural to pose the question whether there is any difference between (purely spatial) precoding and beamforming for rank-one transmission. From a transmission-structure point of view it is clear that there is no difference and in fact beamforming could be considered as a special case of the extremely generic notion of (channel dependent) precoding. However, it makes sense to attach a more specific meaning to the term “beamforming” since with the classical use of beamforming there is an important difference in how the weight vector is selected and how the properties of the transmission vary over space compared with the newer concept of precoding.

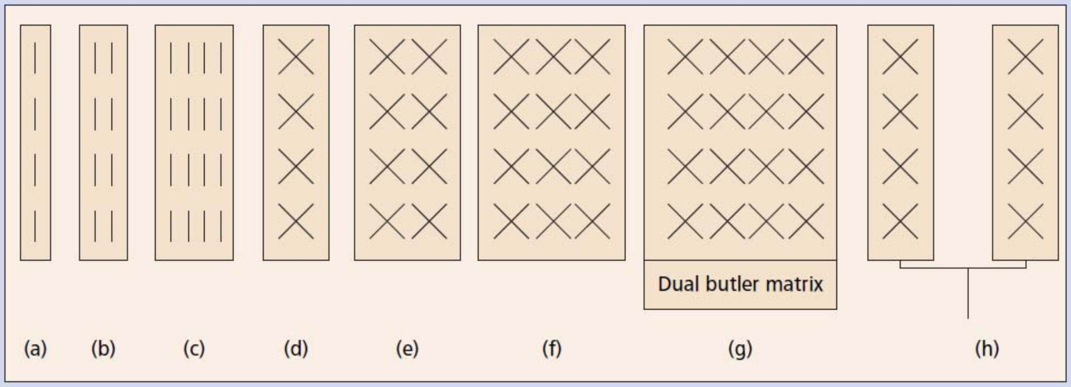
Historically, beamforming relates to forming beams well-localized in the physical space towards a specific point. For this to work, the antennas on the transmit side would be placed using small inter-antenna distances, often using what is often referred to as a *Uniform Linear Array* (ULA) with e.g. half-a-wavelength inter-antenna distance. Thus, the term “beamforming” is taken to mean a component of a transmission scheme and antenna setup that *intentionally* strives to form at least one localized beam in the *physical* space. In contrast, precoding may very well focus energy in different directions but then the direction is with respect to a vector space as opposed to the physical space. Examples of how such a definition affects terminology are:

- Uniform Linear Array (ULA) with e.g. half wavelength inter-antenna distance at transmitter side and purely spatial channel dependent-rank one precoding as in (1) ⇨ “beamforming”
- Diversity (DIV) array with e.g. four wavelengths inter-antenna distance at transmitter side and purely spatial rank-one channel-dependent precoding as in (4) ⇨ “precoding”
- Clustered Linear Array (CLA) with two pairs of cross-polarized antennas spaced half a wavelength apart on transmitter side and purely spatial rank two channel dependent precoding ⇨ “beamforming on each pair of (half-wavelength separated) co-polarized antennas”

Beamforming relies on physical directions which is a property of the channel that varies only on relatively long-term basis. This simplifies the selection of suitable weight vectors and also reduces signaling overhead if the weight vectors need to be fed back from the receiver or if channel reciprocity is exploited in for utilizing channel measurements obtained from reverse link transmissions. Note that directional information in the channel is reciprocal regardless of TDD or FDD so beamforming may be based on reverse-link measurements even in FDD conditioned on the separation of UL and DL carrier frequencies (duplex distance). For similar reason, non-codebook-based beamforming is conceivable even for FDD. The following section provides common antenna configurations that can be deployed in UMTS and LTE-(A) networks constrained by cost and frequency band.

3.2 BS ANTENNA CONFIGURATIONS

Figure 6 shows various antenna configurations for deployments constrained to use twelve or less radio frequency (RF) cables per BS. Twelve RF cables can support four antennas per cell for a three-cell base station and two antennas per sector for a six-cell base station.



Antenna configuration	Fig.	Description
1V	(a)	1 column with vertical polarization (V-pol)
ULA-2V	(b)	2 closely spaced V-pol columns
ULA-4V	(c)	4 V-pol columns
DIV-1X	(d)	1 column with dual-slant polarization (X-pol)
CLA-2X	(e)	2 closely spaced X-pol columns
CLA-3X	(f)	1 X-pol middle column with two closely spaced columns of +45-pol
BM-4X	(g)	4 X-pol columns with dual Butler matrix
DIV-2X	(h)	2 widely spaced X-pol columns

Figure 6. Antenna Configurations for 12 RF cables per BS constraint.

Note that BM-4X is also called a CLA-4X antenna configuration. We now turn our attention to the terminal antenna considerations.

3.3 UE ANTENNA CONFIGURATIONS

Size and battery life are major issues that have a significant impact on the mobile-antenna design. Larger devices such as laptops will not find these constraints as burdensome as handheld form-factor devices. For ease of discussion we will focus on the handheld form factor devices in the following sections.

3.3.1 UE CONSIDERATIONS

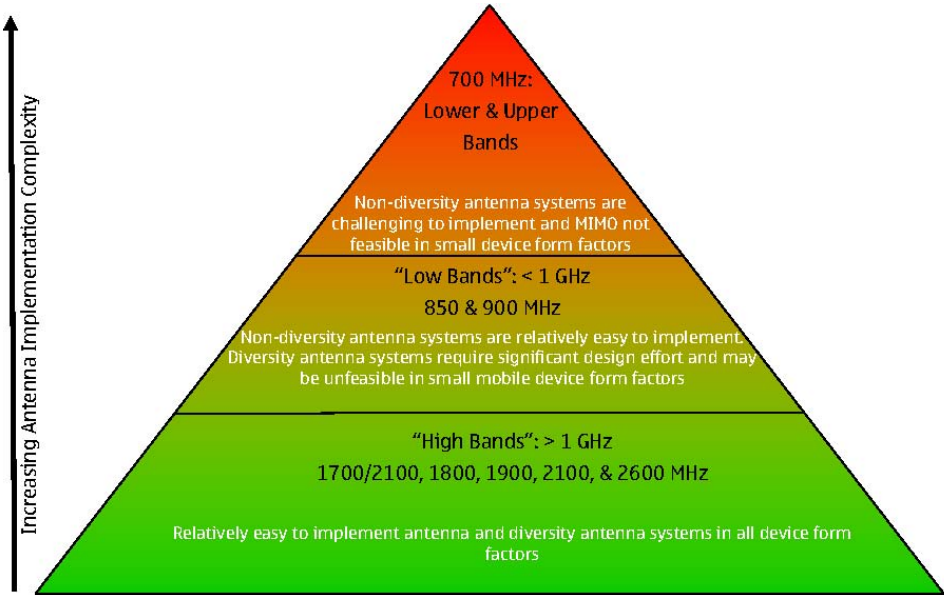
Outside of the areas of antenna volume and battery life that will be discussed later, there are other factors that complicate the antenna design of handheld-form-factor devices. These factors include, but are not limited to:

- RF complexity and placement;
- Correlation with other MIMO antennas;
- Coupling with other MIMO antennas, battery, displays etc.;
- The position and number of other antennas that support 802.11, Bluetooth, GPS, FM Radio, and other cellular services;
- Multiple-band support (e.g., 0.7, 2.1 and 2.6 GHz);
- Polarization, interaction with mechanics (display, battery), ESD and EMC requirements (harmonics), and mass-production limitations all affect antenna design in small, handheld form factors;
- SAR and HAC compliance; and
- Even attenuation caused by hand and head effects can have a large impact on performance.

Two factors addressed by semiconductor vendors are RF and baseband complexity. Both offer considerable engineering challenges; however, they are also thought to be generally manageable. The processing of multiple streams of data in a MIMO transmission will require greater volumes of data that needs to be demodulated. Decoding in this process offers even more challenges. The end result is higher current drain on the battery.

As mobile devices become smaller, antennas for MIMO reception naturally become closer. MIMO is feasible when the antennas can be positioned in the device with approximately 0.5 of a wavelength of the operating frequency in physical separation. This can usually accommodated if higher bands such as 2.6 GHz are the ones targeted for reception; however 700 MHz designs are going to be problematic. A new approach is needed to support multiple antennas in the lower frequency ranges in small form factors.

Some of the challenges faced by UE antenna designers are illustrated in Figure 7. Antenna complexity increases as the frequency band decreases. It is easier to implement multiple antenna systems on high frequency bands (> 1 GHz) than on low bands (< 1GHz) in small, handheld form factor devices. The 850 and 900 MHz bands used in the US and globally (respectively) present definite challenges, while the 700 MHz band introduces the greatest challenge of all.



NOTE: Implementation complexity refers to integrated antennas for a multi-band handheld mobile device

Figure 7. Antenna Complexity and Frequency Band

As the antennas become closer in small, handheld-form-factor devices, coupling becomes greater and antenna patterns begin to distort. As coupling increases, antenna efficiencies decrease and correlation is impacted. Correlation must be considered in more than one context. There is the normal path correlation that can be determined by decompositions of the estimated channel. Also, there is antenna correlation which adds to the problem. As antennas become closer the antenna correlation tends to increase. These effects are often combated with forms of diversity that will be discussed in below. A summary of the challenges for various network/channel conditions is given in Table 1 below.

Table 1: Summary of UE Challenges in UE-MIMO Implementations

Network Scenario	Relative Difficulty	Device Antenna Parameters	Practical Effects on the Mobile Device
Interference Mitigation in interference limited scenarios with strong to medium signal levels.	Low	• Envelope Correlation < 0.7 • Antenna BPD in the range of 10dB (quite "loose")	Small increase in antenna volume in device (e.g. ~ 10-25 %). Diversity antenna does not have to perform nearly as well as the "main antenna"
MIMO usage in strong to medium signal level environments.	Medium/ High	• Envelope Correlation < 0.3 for good MIMO "gain" • Envelope Correlation < 0.5 in worst case • "Medium" to low "BPD" is required	Difficult to implement in low (< 1 GHz bands) in small handheld devices. Device antenna volume increase from ~ 30% - 100%
SNR improvements in noise-limited weak signal environments (e.g. range extension).	High	• Low BPD is needed (ideally 0 dB) – the main and diversity antennas need to have the same performance	Device antenna volume doubles. Diversity antenna performance gets closer to that of the main antenna.

BPD: See terminology section

Mobile devices are filled with electronics, a large battery, displays and multiple antennas to support the several radios contained in size. These create additional coupling problems and, hence, efficiency degradations. The problem may only get worse as the number of radios supported continues to grow. Not only does the mobile antenna designer have to worry about GPS, Bluetooth and WiFi, he/she has to contend with the multiple bands and even radio technologies that are needed to support wide area network cellular communications.

Finally, the antenna designer must comply with regulations regarding specific absorption rate (SAR) and hearing aid compatibility (HAC) compliance. Given that coupling distorts the antenna patterns, the directionality of the resulting pattern(s) can have a direct impact on SAR and HAC.

3.3.2 IMPACT OF MULTIPLE ANTENNAS ON SIZE

The impact of multiple antennas on coupling and correlation has been considered. Size is also a major consideration. If we focus on the 700 MHz band for a moment and note that the dimensions of an antenna is inversely proportional its frequency operation. It is easy to calculate that a length of a quarter of wavelength monopole antenna to be approximately 11 cm. This would be longer than many handhelds on the market now.

Now add the fact that there will be more than one of these antennas for a MIMO application, it is easy to see that there will be pressure to increase the size of the devices. A 700 MHz MIMO implementation could increase the form factor volume by up to 30% depending on the reference device (without MIMO) selected for comparison. However, if marketing holds sway, the designer will have to sacrifice efficiency and correlation for size. This must be accounted for in a link budget analysis to make sure that the efficiency losses do not overwhelm the gains that you would receive by using the more propagation friendly 700 MHz band. Finally, the impact on handheld device size worsens as the number of frequency bands supporting MIMO increases.

3.3.3 BATTERY CONSUMPTION OF MULTIPLE ANTENNAS

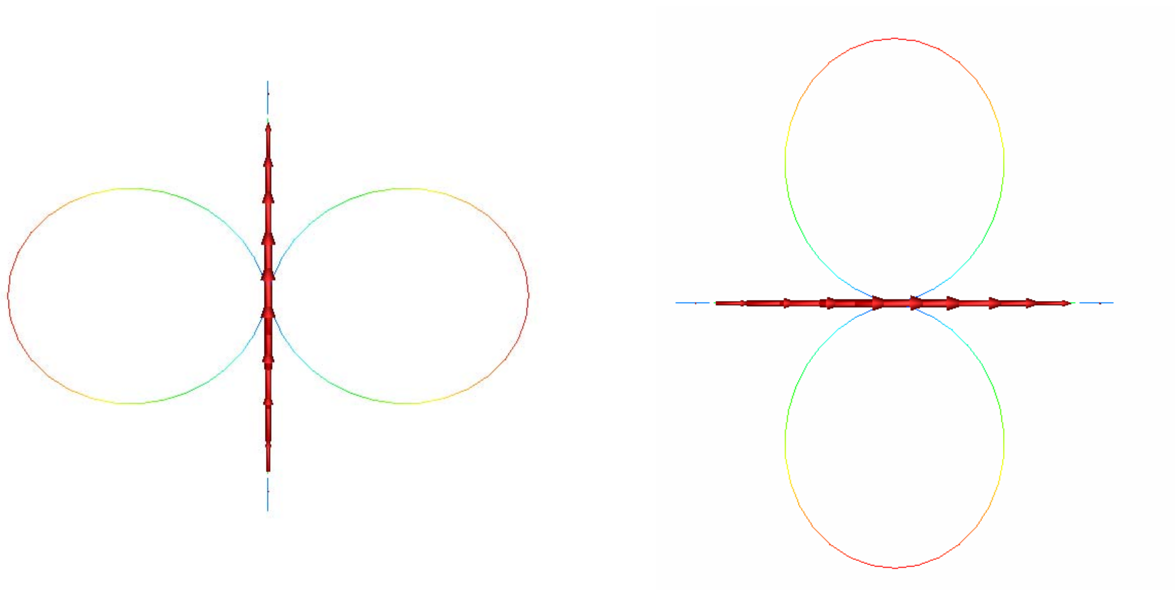
Increased battery consumption is another factor in assessing the cost/benefit of multiple antennas in mobile devices. Each antenna in a multi-antenna implementation requires dedicated components, resulting in separate RF processing chains. These chains and components require energy to operate, which increases battery consumption. For example, in a simple receiver diversity implementation, battery consumption can increase up to 25%. This increase in battery consumption would also be expected in MIMO implementations. This condition worsens as the number of frequency bands supporting MIMO increases. Also in the context of Rx diversity, the impact on current consumption is different for the coverage versus capacity case.

3.3.4 ADVANCED-ANTENNA CONCEPTS FOR UE APPLICATION

It was mentioned above that as the multiple antennas become closer their patterns distort. Due to the limited size of the handheld, it is difficult to employ spatial diversity to combat path correlation. This generally leads the antenna designer to view other forms of diversity to combat correlation and coupling. There are several types of diversity that the designer can consider. Two of the most popular are pattern (including phase) and polarization diversity.

Pattern diversity uses the fact that each antenna is directional and can be position such that they point in different directions. It sometimes thought that the designer might make the patterns orthogonal which in practice can only be approximated and leads to a decrease in amount of energy (multipath signals) being received. The directionality helps with coupling since the antennas "point" in different directions.

Polarization diversity exploits the rich scattering environment. A transmitted signal, even if it is vertically polarized, finds itself reflected in ways that the incoming signals whose polarization is not highly correlated. Cross-polarized antennas also have beneficial coupling properties. Figure 8 provides a simple illustration of pattern and polarization diversity. It shows the antenna patterns of two half-wavelength of dipoles. The arrows in the middle of each pattern indicate the polarity of the antenna. Hence, by conceptually placing two dipoles in a handheld device in this manner allows for both polarization and pattern diversity.



(a) (b)

Figure 8. A simple illustration of pattern and polarization diversity obtained by using two orthogonal half-wavelength dipoles.

4 CURRENT MIMO TRANSMISSION SCHEMES

This section addresses MIMO transmission schemes that have already been standardized and therefore currently deployable in HSPA and LTE networks. We start the discussion with LTE as it offers a superset of algorithmic capabilities compared to HSPA.

4.1 INTRODUCTION TO LTE REL-8 MIMO ALGORITHMS

LTE Release 8 (Rel-8) supports downlink transmissions on one, two, or four cell-specific *antenna ports*, each corresponding to one, two, or four cell-specific *reference signals*, where each reference signal corresponds to one antenna port. An additional antenna port, associated with one *UE-specific* reference signal is available as well. This antenna port can be used for conventional beamforming, especially in case of TDD operation.

An overview of the multi-antenna related processing including parts of the UE is given in Figure 9. All bit-level processing (i.e., up to and including the scrambling module) for the n^{th} transport block in a certain subframe is denoted codeword *n*. Up to two transport blocks can be transmitted simultaneously, while up to *Q* = 4 layers can be transmitted for the rank-four case so there is a need to map the codewords (transport blocks) to the appropriate layer. Using fewer transport blocks than layers serves to save signaling overhead as the HARQ associated signaling is rather expensive. The layers form a sequence of *Q*x1 symbol vectors:

$$\mathbf{s}_n = \begin{bmatrix} s_{n,1} & s_{n,2} & \cdots & s_{n,Q} \end{bmatrix}^{\mathrm{T}}, \quad (5)$$

which are input to a precoder that in general can be modeled on the form of a linear dispersion encoder. From a standard point of view, the precoder only exists if the PDSCH (Physical Downlink Shared CHannel) is configured to use cell-specific reference signals, which are then added after the precoding and thus do not undergo any precoding. If the PDSCH is configured to use the UE specific reference signal, which would then also undergo the same precoder operation as the resource elements for data, then the precoder operation is transparent to the standard and therefore purely an eNB implementation issue.

The precoder is block based and outputs a block:

$$\mathbf{X}_n = \begin{bmatrix} \mathbf{x}_{nL} & \mathbf{x}_{nL+1} & \cdots & \mathbf{x}_{nL+L-1} \end{bmatrix} \quad (6)$$

of precoded *N*Tx1 vectors for every symbol vector **s***n*. The parameter *N*T corresponds to the number of antenna ports if PDSCH is configured to use cell specific reference signals. If a transmission mode using UE specific reference signals is configured, then, similarly as to above, *N*T is standard transparent and entirely up to the eNB implementation. But typically it would correspond to the number of transmit antennas assumed in the baseband implementation.

The vectors **x***k* are distributed over the grid of data resource elements belonging to the resource block assignment for the PDSCH. Let *k* denote the resource element index. The corresponding received *N*Rx1 vector **y***k* on the UE side after DFT operation can then be modeled as:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{e}_k \quad (7)$$

where **H***k* is an *N*Rx*N*T matrix that represents the MIMO channel and **e***k* is an *N*Rx1 vector representing noise and interference. By considering the resource elements belonging to a certain block **X***n* output from the precoder and making the reasonable assumption that the channel is constant over the block (the block size *L* is small and the used resource elements are well-localized in the resource element grid), the following block based received data model is obtained:

$$\begin{aligned}\mathbf{Y}_n &= \begin{bmatrix}\mathbf{y}_{nL} & \mathbf{y}_{nL+1} & \cdots & \mathbf{y}_{nL+L-1}\end{bmatrix} \\ &= \mathbf{H}_{nL}\begin{bmatrix}\mathbf{x}_{nL} & \mathbf{x}_{nL+1} & \cdots & \mathbf{x}_{nL+L-1}\end{bmatrix} + \begin{bmatrix}\mathbf{e}_{nL} & \mathbf{e}_{nL+1} & \cdots & \mathbf{e}_{nL+L-1}\end{bmatrix} \\ &= \mathbf{H}_{nL}\mathbf{X}_n + \mathbf{E}_n\end{aligned} \quad (8)$$

with obvious notation being introduced. The transmission rank is per definition given by the average number of complex valued symbols per resource element. Thus, since *Q* symbols are transmitted over *L* resource elements, the transmission rank *r* is obtained as *r* = *Q*/*L*.

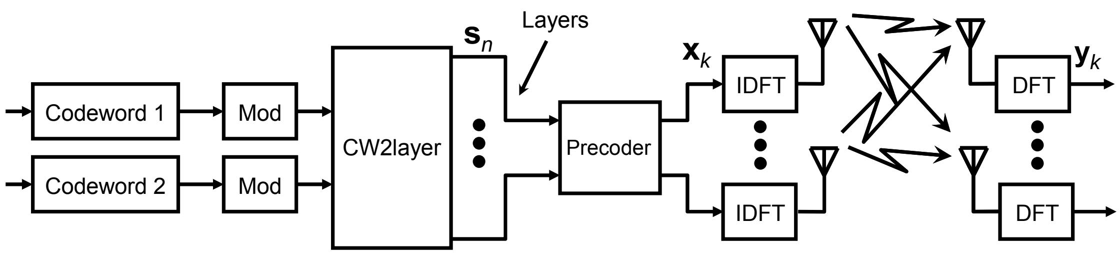


Figure 9. Overview of multi-antenna related processing in LTE for the transport channel on the PDSCH.

4.2 DL SU-MIMO AND TRANSMIT DIVERSITY (TXD)

LTE Rel-8 support rank-1 transmit diversity by means of Alamouti based linear dispersion codes. The coding operation is performed over space and frequency so the output block **X***n* from the precoder is confined to consecutive data resource elements in a single OFDM symbol. Single-codeword transmission is assumed, so the modulated symbols of a single codeword are thus mapped to all the layers. Transmit diversity for two and four cell-specific antenna ports is supported.

Note that the two transmit-diversity schemes to be presented next are also used for the BCH (Broadcast CHannel), PDCCH (Physical Downlink Control CHannel) and the PCFICH (Physical Control Format Indicator CHannel). Furthermore, the number of cell-specific antenna ports used to encode the BCH is the same as the total number of configured cell-specific antenna ports and all these are used for all other control channels as well. Thus, *all UEs* must support up to four cell-specific antenna ports and the corresponding transmit-diversity schemes.

4.2.1 TRANSMIT DIVERSITY FOR TWO ANTENNA PORTS

For the case of two antenna ports, the output from the precoder is:

$$\mathbf{X}_n = \begin{bmatrix} s_{n,1} & s_{n,2} \\ s_{n,2}^{c} & -s_{n,1}^{c} \end{bmatrix} \quad (9)$$

where the rows corresponds to the antenna ports and the columns to consecutive data resource elements in the same OFDM symbol. Alamouti in the frequency domain is the result, more commonly referred to as space-frequency block coding (SFBC) in 3GPP. This obviously corresponds to single rank transmission since

$r = Q/L = 2/2 = 1$.

4.2.2 TRANSMIT DIVERSITY FOR FOUR ANTENNA PORTS

When four antenna ports are configured, a combination of SFBC and frequency switching is employed. The output from the precoder is:

$$\mathbf{X}_n = \begin{bmatrix} s_{n,1} & s_{n,2} & 0 & 0 \\ 0 & 0 & s_{n,3} & s_{n,4} \\ s_{n,2}^{c} & -s_{n,1}^{c} & 0 & 0 \\ 0 & 0 & s_{n,4}^{c} & -s_{n,3}^{c} \end{bmatrix} \qquad (10)$$

The code is seen to be composed of two SFBC codes which are transmitted on antenna ports 0, 2 and 1, 3, respectively. The reason for distributing a single SFBC code in such an interlaced fashion on every other antenna port instead of consecutive antenna ports is related to the fact that the first two cell-specific antenna ports have a higher reference signal density than the two last, and hence provide better channel estimates. Interlacing ensures a more balanced decoding performance of the two SFBC codes which has been shown to be overall (slightly) beneficial. The rapid switching of which pair of antenna ports to use, from one pair of data subcarriers to the next, serves to gain additional spatial diversity when used together with the outer coding on the bit level. The scheme is in 3GPP known as SFBC plus frequency switched transmit diversity (SFBC+FSTD). Also in this case is the transmission rank $r = Q/L = 4/4 = 1$.

4.2.3 PRECODED SPATIAL MULTIPLEXING FOR LTE

In order to reach high peak rates, LTE supports multi-rank transmission through the use of channel dependent, purely spatial precoded spatial multiplexing. The transmission scheme is actually a special case of cyclic delay diversity (CDD) combined with spatial multiplexing. It is therefore in 3GPP referred to as zero-delay CDD with precoded spatial multiplexing. But the delay parameter is zero, rendering the CDD operation transparent so CDD related aspects can for now be ignored.

Pure spatial precoding means L = 1 and the precoder hence, multiplies the symbol vector sk = sn with a channel dependent precoder NTxr matrix Wk, resulting in the transmitted vector:

$$\mathbf{x}_k = \mathbf{W}_k \mathbf{s}_k \qquad (11)$$

The transmission is here denoted by r and up to r = NT layers can be transmitted. The precoder matrix is selected by the eNB from a codebook of precoder elements with scaled orthonormal columns, so-called unitary precoding. Recommendations on transmission rank and which precoder matrix to use may be obtained via feedback signaling from the UE, together with the reporting of CQI. This guides the eNB in adapting the transmission rank, as well as the precoder and the coding rate and modulation to the current channel conditions. However, the eNB can override the UE recommendations.

CQI provides a form of SINR measure for each codeword but in fact more precisely corresponds to a UE recommended transport format giving a first transmission BLER rate close to 10%. It is important to realize that the CQI is computed conditioned on a certain recommendation of precoder and rank, thus these quantities are all dependent on each other.

The rank recommendation from the UE represents the “average” (not to be confused with a linear average) rank over all the feasible[1] set of subbands for scheduling. The average rank is, at least conceptually, determined by the UE so as to maximize predicted throughput if the UE were to be scheduled over the entire feasible set of subbands. In contrast to the single rank report, frequency-selective precoding is supported, meaning that the precoder matrix can vary from one subband to another and that the UE can report such recommendations containing one precoder per subband.

Currently, the subband size is either the full carrier bandwidth for frequency-nonselective precoding, also referred to as wideband precoding, or for most carrier bandwidths a strict function of the carrier bandwidth. A subband size of four consecutive resource blocks may for example be configured for a 20 MHz system. Also the precoders are determined by the UE to maximize predicted throughput. Conceptually, the UE hence performs a brute force search over all the possible precoder and rank hypotheses and conditioned on each hypothesis it predicts the throughput and then selects the rank and precoders giving the highest throughput. It can then compute the CQIs for the selected rank and precoders and report everything to the eNB.

4.2.3.1 PRECODED SPATIAL MULTIPLEXING FOR TWO ANTENNA PORTS

When two antenna ports are configured, the number of codewords equals the transmission rank and codeword *n* is mapped to layer *n*. Thus the codeword to layer mapper becomes trivial and there is a maximum of two codewords (transport blocks) and two layers. The precoder matrix is selected from the codebook in Table 2.

Table 2: Precoder codebook for 2 antenna port configuration.

Tx Rank	Precoder matrix			
1	$\begin{bmatrix}1\\1\end{bmatrix}/\sqrt{2}$	$\begin{bmatrix}1\\-1\end{bmatrix}/\sqrt{2}$	$\begin{bmatrix}1\\j\end{bmatrix}/\sqrt{2}$	$\begin{bmatrix}1\\-j\end{bmatrix}/\sqrt{2}$
2	$\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}/\sqrt{2}$	$\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}/2$		$\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}/2$

Note how the rank-one precoders are column subsets of the rank two precoders. This facilitates support of rank override at the eNB since even if a rank two precoder was recommended by the UE, the eNB can make a reasonable rank one precoder choice by performing precoding using one of the columns/layers and thus in many cases be guaranteed to have at least as high channel quality on the single selected layer as the original CQI for that layer computed assuming the presence of both layers. The four last rank-one precoders correspond to the columns of two DFT matrices of size 2. As such they are particularly well-suited for beamforming in that they keep constant amplitude over the antenna ports but vary the phase of the second antenna port relative to the first. From these four elements, and after adding an additional phase shift on the second antenna port for all resource elements including the reference signal, four beams covering different parts of the sector can be generated, if two closely spaced antennas (i.e. half a wavelength apart) are used. The normal precoder reporting mechanism can be used to perform such beamforming, just as short-term

[1] Feasible set of subbands as determined by eNB semi-statically configuring a set of subbands over which a UE should report feedback information (such as CQI, Precoder matrices and rank).

channel dependent precoding is naturally supported in scenarios where the spatial correlation on the eNB side is low. The latter could be achieved by deploying either two eNB antennas spaced sufficiently far apart or a pair of cross-polarized antennas.

4.2.3.2 PRECODED SPATIAL MULTIPLEXING FOR FOUR ANTENNA PORTS

The four antenna port case is very similar in principle to its two antenna port counterpart. The maximum transmission rank (i.e., number of layers) is now $r = 4$ and another codebook is used. The codebook now contains a total of 64 precoders, sixteen per transmission rank. The increased number of precoders naturally reflects the fact that a channel with more dimensions now needs to be quantized. Also in this case is there a set of rank one precoder taken as columns of a DFT matrix. In fact, two different DFT matrices are represented so that codebook based beamforming using eight beams in a sector can be performed.

The codeword-to-layer mapping is no longer transparent. A fixed set of codeword to layer mappings as depicted in Figure 10 is used. Note that for simplicity each modulator has in the figure been absorbed into its respective codeword. Note also how sometimes a codeword is mapped to two different layers. This provides some improved diversity but limits the use of successive interference cancellation (SIC) type of receivers since such a receiver can no longer decode and cancel each layer separately when a transmission rank of three or four has been used. It can also be claimed that there should be a degradation compared with using one codeword per layer due to the inability to vary the modulation between layers using the same codeword. But in practice such fine-granular adaptation seems to be of limited value.

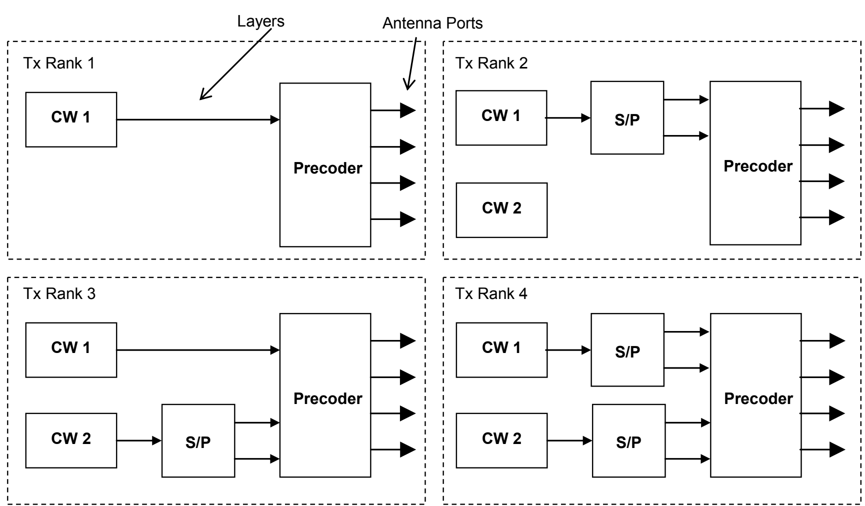


Figure 10. Fixed set of codeword to layer mappings.

4.2.3.3 CDD WITH PRECODED SPATIAL MULTIPLEXING

Originally, CDD was conceived as an alternative way of performing single-rank transmit diversity along the lines of delay diversity, but tailored for OFDM based transmissions. In CDD, the same signal is transmitted from all antennas except that different delays are used. Because of the use of OFDM, the delays are in fact made cyclic. A cyclic delay of Δ samples in the time domain corresponds to a linearly increasing phase shift in the subcarrier domain of $\exp(j2\pi\Delta m / N)$, where m is the subcarrier index in the DFT of size N. As a consequence, each symbol is precoded by a NTx1 weight vector:

$$\mathbf{w}_m = \left[\exp(j2\pi\Delta_1 m / N) \quad \exp(j2\pi\Delta_2 m / N) \quad \cdots \quad \exp(j2\pi\Delta_{N_T} m / N)\right]^T \qquad (12)$$

Typically a constant delay increase from one antenna port to the other is used. Without loss of generality, the vector can be normalized with its first element and hence can then be written on the form:

$$\mathbf{w}_m = \left[1 \quad \exp\left(j2\pi\Delta m/N\right) \quad \cdots \quad \exp\left(j2\pi\Delta(N_T - 1)m/N\right)\right]^T \quad (13)$$

CDD can obviously also be viewed as channel independent frequency-selective precoding and it is this view that most easily explains the behavior of CDD. The precoder sometimes matches the channel and thus gives increased SINR and sometimes emits substantial energy into the null-space of the channel matrix leading to decreased SINR. Thus, CDD induces variations in the channel quality over the bandwidth. In other words, it spreads the transmission in many different “directions” (or more precisely subspaces) over the *N*Tx1 dimensional vector space that serves as input to the channel matrix. Sometimes the channel’s nullspace is nearly hit, leading to fading dips and sometimes the transmission is along a subspace that is matched to the channel (i.e., matched to the strong parts of the row space of the channel) so that much energy reaches the UE and a fading peak is obtained.

The characteristics of CDD are entirely different depending on the value of the delay parameter Δ. Diversity on the link is achieved if the UE is scheduled over a bandwidth sufficiently large to see many of these induced variations and an outer code with sufficiently low code rate is used to capitalize on the resulting frequency diversity. Naturally, limited gains will be obtained if the channel already is sufficiently frequency-selective. It is important to be able to guarantee that there are sufficient variations even over the smallest possible resource allocation. Thus, the delay parameter needs to be set to a high value. The highest possible value is $\Delta = N/N_T$ and this is a reasonable choice that introduces maximum SINR variations over a given bandwidth and would guarantee sufficient variations over even a single RB (Resource Block).

CDD can be extended to handle spatial multiplexing as well by performing the CDD operation after applying a fixed unitary precoder to distribute all layers onto all antennas. This is illustrated in Figure 11. The frequency domain representation of CDD combined with spatial multiplexing thus becomes:

$$\begin{aligned}\mathbf{x}_m &= \mathrm{diag}\left(1, \exp\left(j2\pi\Delta m/N\right), \cdots, \exp\left(j2\pi\Delta(N_T - 1)m/N\right)\right)\left[\mathbf{u}_1 \quad \mathbf{u}_2 \quad \cdots \quad \mathbf{u}_r\right]\mathbf{s}_m \\ &= \Lambda_m \mathbf{U}_{N_T \times r}\mathbf{s}_m\end{aligned} \quad (14)$$

where there is a slight abuse of notation in that the resource element index *k* has been replaced by the subcarrier index *m*. Each layer is now precoded using a combination of the corresponding vector $\mathbf{u}q$ and the frequency-selective phase shifts. Thus, *r* orthogonal and frequency-selective precoder vectors are used to convey the *r* different layers. The scheme works much as in the single-rank case, with the same qualitative behavior with respect to the delay parameter.

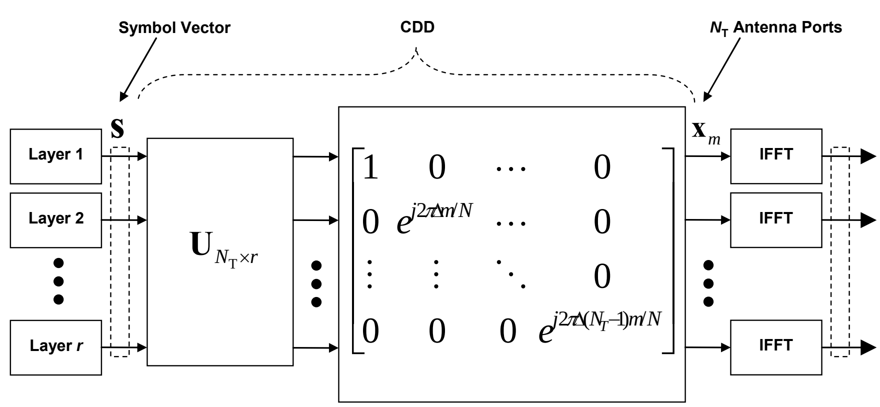


Figure 11. CDD combined with spatial multiplexing.

4.2.3.3.1 LARGE DELAY CDD WITH PRECODED SPATIAL MULTIPLEXING FOR LTE

LTE supports a variant of large delay CDD with spatial multiplexing where the CDD operation is combined with channel-dependent purely-spatial precoding. The setup is depicted in Figure 12. The symbol vector undergoes a large-delay CDD operation. The task of CDD is to mix all the *r* layers together and distribute them in equal proportion on what is here referred to as *r* virtual antennas. The notion of virtual antennas is used to describe the input to the channel dependent precoder and is motivated by the fact that the precoder together with the physical channel can be viewed as forming a new effective channel where the virtual antennas serve as input.

The mixing means all layers see the same channel quality, assuming the UE uses a linear MMSE equalizer. Compared with the previously described zero-delay CDD spatial multiplexing scheme, such an averaging is beneficial since it provides the opportunity to minimize signaling overhead by avoiding the need to adapt various parameters depending on the quality of a particular layer. For example, only a single CQI needs to be fed back and DL control signaling can also be reduced as there is no need to reallocate HARQ retransmissions on different layers. Averaging also provides increased robustness against imperfect link adaptation, a situation which may be very common in practice due to bursty inter-cell interference, feedback delay and CQI estimation noise.

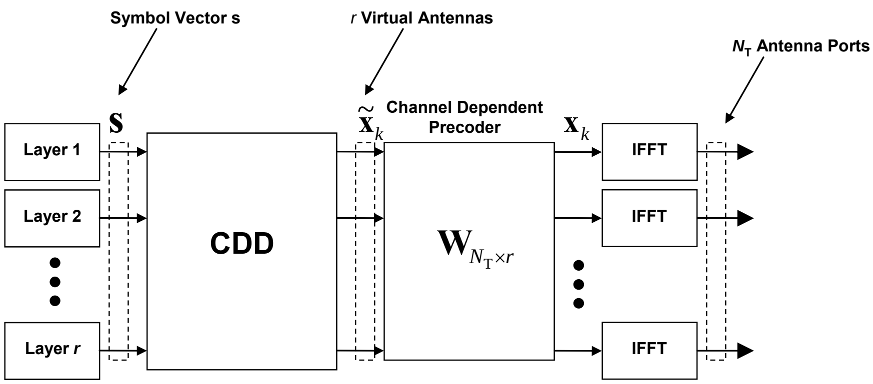


Figure 12. Large delay CDD combined with spatial multiplexing and channel dependent precoding.

The virtual antenna signals in:

$$\tilde{\mathbf{x}}_k = \mathbf{\Lambda}_k \mathbf{U}_{rxr} \mathbf{s}_k \quad (15)$$

resulting from the CDD operation are subsequently mapped onto the *N*T antenna ports by means of a channel dependent *N*T x *r* precoder matrix **W***k*. Prior to the IDFT, the antenna port signals for resource element *k* are thus described by

$$\mathbf{x}_k = \mathbf{W}_k \mathbf{\Lambda}_r \mathbf{U}_{rxr} \mathbf{s}_k \qquad (16)$$

where

$$\mathbf{\Lambda}_r = \mathrm{diag}\left(1, \exp\left(j2\pi\Delta k / N\right), \cdots, \exp\left(j2\pi\Delta(r-1)k / N\right)\right), \quad \Delta = N / r \quad (17)$$

and **U** is a DFT matrix of size *r* x *r*. With this choice of delay parameter and $\mathbf{U}_{rxr}$, it is easy to check that the CDD operation carries the interesting property that $\mathbf{\Lambda}_r \mathbf{U}_{rxr}$ for some *k* = *k*' may be obtained as a cyclic shift of the columns of $\boldsymbol{\Lambda}_r\mathbf{U}_{rxr}$ for some other $k = k'' \neq k'$. Thus, the whole CDD operation is equivalent to instead shifting the layers within $\mathbf{s}_k$ and keeping a fixed $\boldsymbol{\Lambda}\,\mathbf{U}_{\mathbf{rxr}}$ corresponding to some fixed k value.

The described large-delay CDD scheme is supported in LTE both for two and four antenna ports. All in all, it is in many respects very similar to its zero delay counterpart. It can in fact be viewed as a more robust (with respect to CQI link adaptation impairments caused by high mobility and/or bursty interference) version of channel dependent precoded spatial multiplexing offering reduced requirements on signaling overhead.

4.3 DL-MIMO IN HSPA

HSPA supports closed-loop MIMO where the UE can receive one or two transport blocks per TTI as shown in Figure 13. If a transmission is rank-1 the precoder control indication (PCI) value transmitted in the UL direction via the HS-DPCCH channel, is used to determine the precoder weight. If a transmission is rank-2 then the first stream is using the PCI value to determine the weight while the second stream is using an orthogonal weight to that of the first stream.

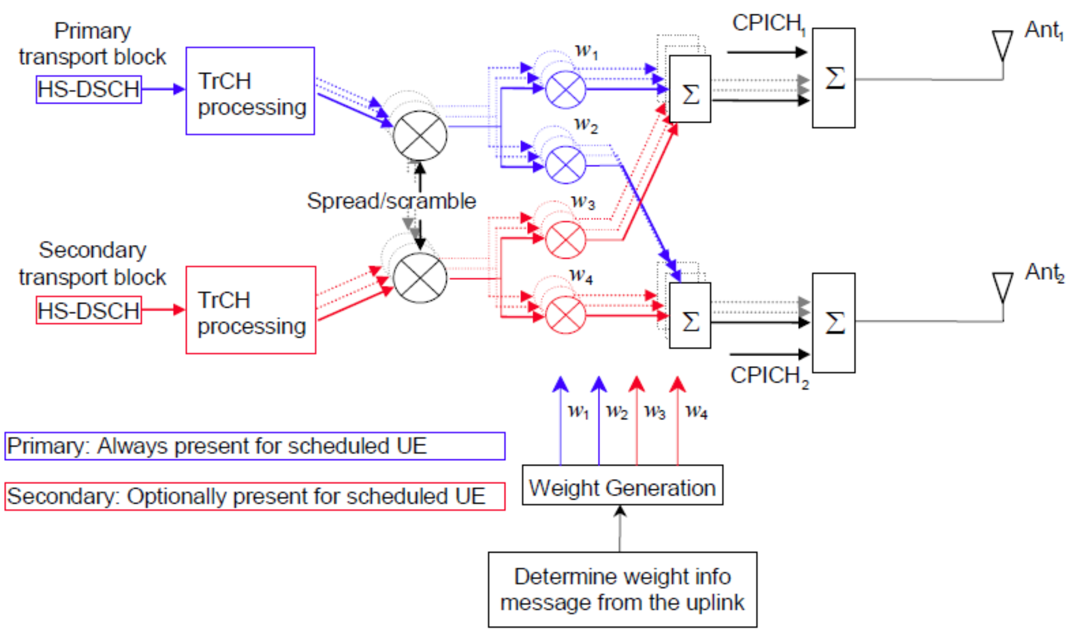


Figure 13. Node-B Transmission for supporting MIMO in HSPA

The UE effectively signals single stream or dual stream CQI depending on its rank determination algorithm. The Node-B signals via the HS-SCCH channel the decision as to the number of transport blocks (primary only if a single stream (rank-1) transmission and primary plus secondary for rank-2 transmission), the block size(s), the channelization code information (codes are reused for rank-2 transmission) as well as the index of the primary precoder weight vector. The later is important as it provides the capability for the Node-B to use different precoder weights to the ones recommended by the UE.

The UE-MIMO receiver requires two receive antennas to distinguish the MIMO streams. Many UE vendors implement the receiver architecture shown in Figure 14.

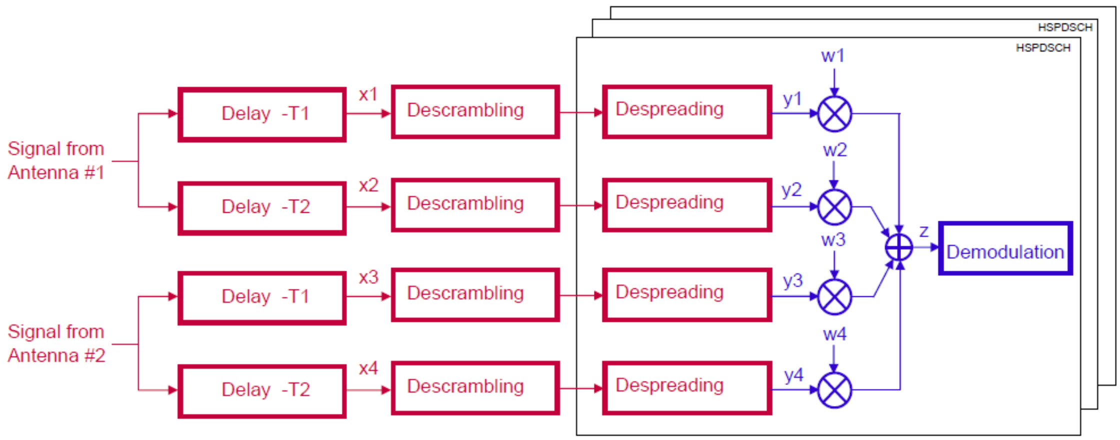


Figure 14. MMSE Space-Time Receiver for HSPA UEs

The detailed description of the UE receiver is outside the scope of this report but essentially is a MMSE equalizer in space and time. Compared to a RAKE, this receiver chooses the delays and the number of fingers to minimize error rate instead of matching the number and location of the channel multipath. Also, compared to a RAKE, the finger weights are chosen to minimize the Mean Squared Error (MSE) instead being matched to the conjugate of the channel estimates. The combining results in suppression of multipath interference from the serving cell.

4.4 DL MULTIUSER MIMO

The schemes described so far are concerned with transmissions to a single user (UE). The spatial domain is exploited to obtain improved SINR. Spatial multiplexing shares SINR among several layers in high geometry situations to provide peak rates to a single user. But the same principle of sharing high SINR by means of spatial multiplexing can also be used for transmitting to several UEs at once. In fact, sectorization and the simultaneous transmission of several users on the same resource elements, albeit from different cells, can be viewed as one form of spatial multiplexing. 3GPP has however agreed to also offer some rudimentary support for spatial multiplexing to different UEs in the same cell. The scheme resembles classical space-division multiple access (SDMA) but is commonly referred to as multi-user MIMO (MU-MIMO) in 3GPP. MU-MIMO is in contrast to single-user MIMO (SU-MIMO) as previously described. The objective is to support SDMA for compatible antenna configurations i.e., configurations that include antennas spaced half a wavelength apart on the eNB side, resulting in highly correlated channels. By co-scheduling several UEs that are located in sufficiently well-separated physical directions and focusing the transmission in a narrow beam towards each UE, the interference caused by other coscheduled UEs in the same cell can be kept low. Since the channel is highly correlated, each UE is served by single-rank beamforming. Clearly, this is targeting scenarios with small angular spread on the eNB side.

Much of the functionality needed for such classical SDMA is already present in LTE. Nothing prevents several UEs to be assigned the same resource blocks. Codebook based beamforming is supported by means of channel dependent precoding for rank one transmission. So the UEs can be configured for the single-rank channel-dependent precoding scheme and report precoder vectors accordingly to the eNB. It appears that the only really critical MU-MIMO specific additional functionality is the need of the UEs to be able to derive the power ratio between the reference signals and the power per data resource element and antenna that is applied for its own transmission in order to assist in the demodulation. The issue of power ratio is important since multiple UEs share the same resources and thus may share the finite power of the PAs. This can result in power fluctuations at subframe speed of the transmission to a particular UE. Since the UE is not mandated to blindly estimate this power ratio for all different modulations, the power fluctuations somehow need to be signaled to the UE. For QPSK transmissions, it is agreed that the UE cannot rely on knowing the power ratio, but for higher modulation (64QAM and 16QAM) it is assumed that the UE is informed about the power ratio, however probably not every subframe.

A fundamental problem in MU-MIMO is that UEs can only be co-scheduled if their preferred beams are sufficiently well-separated. This becomes an additional restriction on the scheduler that needs to match UEs that have data to send, have reported compatible beams and have sufficiently high geometry. Thus, in order for MU-MIMO to be beneficial, the system load should be high with many active UEs requesting data in each subframe. This enables the scheduler to find sufficiently many UEs that can be coscheduled on beams which will result in limited intra-cell interference.

4.4.1 SINGLE-LAYER DEDICATED BEAMFORMING IN LTE

As previously mentioned, it is possible to configure a transmission mode where a single UE specific reference signal is utilized for the demodulation. Since the UE is guaranteed that the reference signal is processed in the same manner as the data resource elements, the UE sees an effective channel with a single input (c.f. single antenna transmission) and is unaware of any possible precoding operation performed on the eNB side. It is up to the eNB implementation to determine how to utilize this mode, but a likely use is to provide support for beamforming using four antennas or more. Using, for example, eight instead of four antennas can potentially double the array gain and hence the SNR. The inter-cell interference may also decrease because more narrow beams can be formed with a larger antenna array. Consequently, for low geometry UEs that operate on the linear part of the throughput curve, such a 3 dB boost in SNR translates to a 100% improvement of throughput. System simulations under idealized conditions indicate that in coverage limited situations with sufficiently large cells, the throughput gains on the cell edge even surpass 100% because of improved array gain and reduction in inter-cell interference. Similar arguments can be made for a transition from two to four antenna arrays. However, some common control channels are not beamformed and thus there may be the coverage limiting factor.

It should also be pointed out that as an alternative to using eight element antenna arrays, higher order sectorization may be utilized to use four antennas in twice as many sectors. Such a setup is transparently supported by the standard and also provides some MU-MIMO capability since UEs may be scheduled simultaneously in the different sectors. However, for low load situations in coverage limited scenarios, then the approach of doubling the number of sectors is theoretically 3 dB worse than using twice as many antennas per sector. Many additional factors need to be taken into account in choosing between these two approaches including the size of the antenna installation and typical traffic situation.

4.5 UL MULTIUSER MIMO

Similar to the DL, UL multi-user MIMO is feasible. In Release 8, the UE supports only one transmit antenna and multiple receive antennas. As such, single user MIMO (SU-MIMO) cannot be supported on UL but the UL can support multi-user MIMO transparently. It may be noted that the support of multiple transmit antennas at the UE is being considered for LTE-Advanced. When the spatial channel between UE 1 and the eNB is significantly different from that between UE 2 and the eNB, both the UE's may use the same resource blocks. This multi-antenna technique is called MU-MIMO. In Figure 15, an example of uplink MU-MIMO involving UE 1 and UE 2 is shown. MU-MIMO is beneficial when there are many users in a sector (e.g. VoIP users) and the number of receive antennas at the base station is greater than or equal to 2.

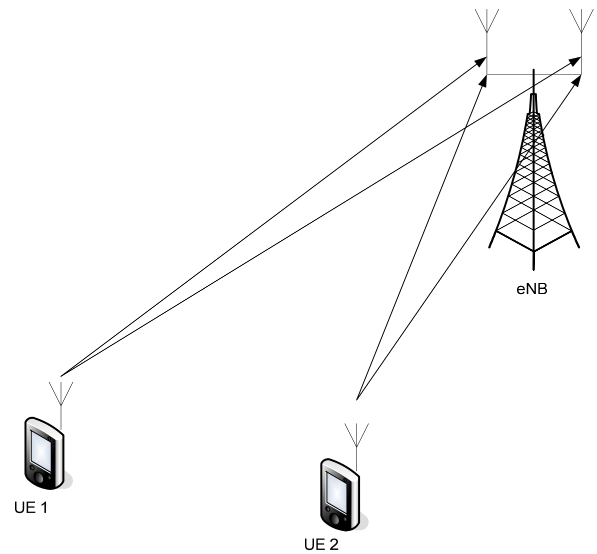


Figure 15. UL Multiuser MIMO

To support MU-MIMO, the reference signals for users involved should be distinct and should have good cross-correlation property. If two or more UEs in one sector are assigned to the same resource blocks, their reference signals are derived from the same sequence with “cyclic shift” in the time domain. In LTE, the cyclic shifts for a UE's reference signal can take eight different values. These eight values ideally can support UL MU-MIMO with 2 to 6 UEs. But in practice, only 2 users are paired for modest receiver complexity. It may be noted that the length of the reference signals are based on the number of RB’s allocated to a user. Generally, reference signals of length 36 or more are based on extended ZC (Zadoff-Chu) sequences while reference signals of length 12 and 24 are computer generated sequences.

The interference seen by a user’s signal comes from two parts: the intra-cell interference due to other users’ involved in the uplink MU-MIMO and intercell interference due to users in other sectors. As UEs in a sector can operate at different MCS levels and multipath can create null and peaks in one transmission, the intercell interference due to these UEs seen at neighboring sectors can be quite un-even in the frequency domain. One can choose to estimate the spatial pattern of the intercell interference over one or multiple resource blocks. As presented section, there are a number of uplink MIMO receiver algorithms which can be used for LTE uplink MIMO. Using MU-MIMO, two UE’s transmit on same frequency subcarriers and at the same time. Thus there are cross user interference between these two UE’s. With MMSE receiver at BS, the interference between these two UE’s can be significantly reduced.

In Figure 16, an example is provided for uplink MIMO receive processing with an MMSE receiver for a 10 MHz system.

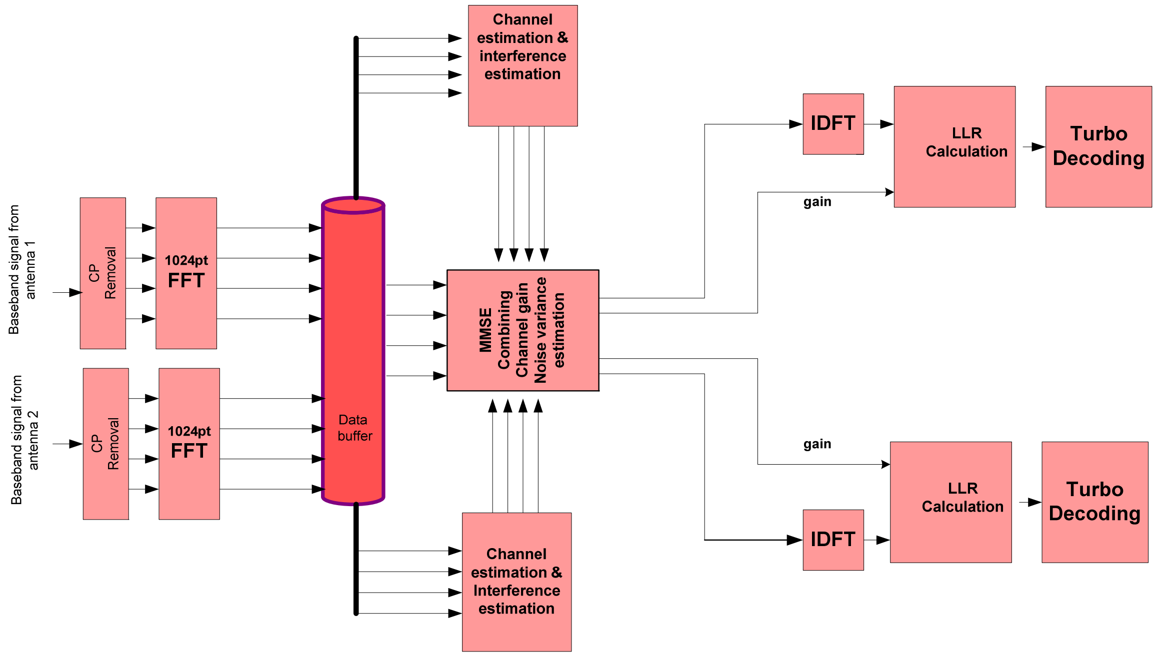


Figure 16. MMSE Receiver for UL MU-MIMO

The radio frequency signal at each receive antenna is converted to a baseband signal. After removing cyclic prefixes, selected samples of the baseband signal which correspond to the data symbols and reference symbols in the uplink MIMO transmissions are passed to a1024 point FFT for a 10-MHz system. From the reference symbols, the interference patterns and power level are estimated to build the pre-whitening matrices. As discussed above, depending on the assumed or detected variation in interference pattern and power level, multiple pre-whitening matrices may be needed. At the same time, the channel responses for UEs involved in the uplink MIMO transmissions are estimated. The combining weights for each UE are then derived. Finally, the likelihood ratio is found from the gain and DFT de-spread data symbols for each UE and fed to the turbo decoder.

The decision to select two or more UEs for MU-MIMO may be based on various factors such as, spatial correlation of reference signals, sounding reference signals, demodulated data symbols from different UEs etc. One of the simplest algorithms that can be used is called random pairing, where two UE's are selected randomly to share the same resource blocks.

4.6 ALGORITHM ADAPTATION

The many algorithms addressed in this section, require the base station scheduler to make adaptation decisions for each user. The introduction section clearly explained the tradeoff between coverage and throughput in selecting the rank of the transmission scheme. At lower speeds the UE recommendations for both rank and precoder weights can be trustworthy. Higher speeds and urban environments with short shadowing de-correlation lengths, i.e. where multipath components can change quickly in both direction and power, pose quite a number of challenges for the base station vendors. Adapting to the channel conditions is a fundamental capability and often a source of vendor differentiation.

5 EMERGING MIMO TRANSMISSION SCHEMES

In order to meet the diverse requirements of advance applications that will become common in the wireless market place in the foreseeable future, a further evolution of LTE, sometimes also referred to as "LTE-Advanced", is currently under study within 3GPP. This evolution will further lower the CAPEX and OPEX of LTE-based broadband wireless networks and also targets full compliance with all the requirements for so-called *IMT-Advanced* radio access as defined by ITU.

This section will discuss the MIMO transmission techniques currently considered as technology components for the evolution of LTE. The organization of the discussion is as follows: *dual-layer beamforming,* which is a direct extension of the single-layer beamforming supported already in Release-8 LTE, will first be discussed. Uplink single-user MIMO, extended downlink single-user and multi-user MIMO, and coordinated multipoint transmission (CoMP), all considered as technology components for the further evolution of LTE ("LTE-Advanced") will then be discussed.

5.1 DOWNLINK DUAL-LAYER BEAMFORMING

Downlink single-layer beamforming is already supported in LTE Release 8. For LTE Release 9, this feature is considered to be extended with the support of dual-layer beamforming. This enhancement will primarily improve the throughput of users that are experiencing good channel conditions. The objectives of this enhancement are as follows:

- Support single-user dual-layer beamforming using UE-specific reference signals for both TDD and FDD.
- The design of the UE-specific demodulation reference signals and the mapping of physical data channel to resource elements should aim for forward compatibility with LTE-Advanced demodulation reference signals.
- Principles exploiting channel reciprocity shall be considered in the feedback design where applicable. The need for additional feedback shall be assessed.
- All new enhanced features and capabilities shall be backward compatible with networks and UEs compliant with LTE Release 8, and also should aim to be as an extension of the beamforming in Release 8.

The support for dual-layer beamforming for single-user MIMO with fast-rank adaptation is currently being developed. The extension to MU-MIMO is currently under discussion.

5.2 UPLINK SINGLE-USER MIMO

The current IMT-Advanced requirements in terms of uplink peak spectral efficiency imply that the LTE uplink must be extended with the support for uplink MIMO (multi-layer) in order to be fully IMT-Advanced compliant. The extension of the uplink currently under study within 3GPP can be classified into roughly two categories: techniques relying on channel reciprocity and techniques not relying on channel reciprocity. Among the techniques that take advantage of channel reciprocity are Beamforming (BF) and multi-user MIMO (MU-MIMO). With these techniques, the enhanced Node-B (eNB) uses a sounding reference signal from the UE to determine the channel state and assumes that the channel as seen by the eNB is the same as that seen by the UE (channel reciprocity) and forms transmission beams accordingly. It should be noted that since the transmitter has information about the channel, the transmitter may use this information for beamforming including generation of weights for antenna weighting/precoding. These techniques are especially suited in case of TDD.

The channel non-reciprocity techniques can be further separated into open-loop MIMO (OL-MIMO), closed-loop MIMO (CL-MIMO) and multi-user MIMO (MU-MIMO). OL-MIMO is used in the case where the transmitter has no knowledge of the channel-state information (CSI). Since the UE has no knowledge of the CSI from the eNB, these techniques cannot be optimized for the specific channel condition seen by the eNB receiver but they are robust to channel variations. Consequently, these techniques are well suited to high-speed mobile communication. OL-MIMO can be classified into transmit diversity (TXD) and spatial-multiplexing (SM) techniques. The TXD techniques will increase diversity order which may result in reduced channel variations and improved system. These techniques include transmit antenna switching (TAS), space-frequency block coding (SFBC), cyclic delay diversity (CDD) and frequency shift transmit diversity (FSTD), etc. The SM techniques allow multiple spatial streams that are transmitted sharing the same time-frequency resource.

In the case where the eNB sends CSI to the UE, CL-MIMO can be used to significantly increase spectral efficiency. CL-MIMO utilizes the CSI feedback from the eNB to optimize the transmission form specific UE's channel condition. As a result of this feedback, it is vulnerable to channel variations. In general, it can be said that CL-MIMO has better performance than OL-MIMO in low-speed environments but has worse performance than OL-MIMO in high-speed environments. SM techniques can also be used to significantly increase the spectral efficiency of CL-MIMO. The multiple spatial streams are separated by an appropriate receiver (e.g. using successive interference cancellation). This will increase peak data rates and potentially the capacity, benefiting from high SINR and uncorrelated channels. The spatial-multiplexing techniques can be classified into single-codeword (SCW) and multiple-codewords (MCW) techniques. In the former case, the multiple streams come from one turbo encoder, which could achieve remarkable diversity gain. In the latter case, the multiple streams are encoded separately, which can use the SIC receiver to reduce the co-channel interference between the streams significantly.

For SU-UL-MIMO, spatial multiplexing of up to four layers will be considered. DFT-spread OFDM (DFT-S-OFDM) has been agreed upon in 3GPP as the transmission scheme used for the PUSCH both in the absence and presence of spatial multiplexing. In the case of carrier aggregation, where multiple component carriers are aggregated together for bandwidth extension, there is one DFT per component carrier. In terms of resource allocation, both frequency-contiguous and frequency-non-contiguous resource allocation is supported on each component carrier. Also under intense study are MIMO techniques that are compatible with low PAPR such as STBC-II scheme, joint MCW spatial multiplex with TAS, cell-edge enhancement techniques via single-rank beamforming, etc.

5.3 EXTENDED DOWNLINK SINGLE-USER MIMO

In order to improve the spatial efficiency of the downlink, extension of LTE downlink spatial multiplexing to up to eight layers is considered as part of the LTE evolution. In the case where carrier aggregation is used, spatial multiplexing with eight layers per component carrier will be supported.

5.4 MU-MIMO

In the case where there are a large number of UEs in a cell, the cell spectral efficiency can be further increased through the use of MU-MIMO. It should be noted that the terms MU-MIMO and SDMA (space division multiple access)) are sometimes used interchangeably in the literature. With MU-MIMO, unlike single-user MIMO (SU-MIMO) where one user uses a radio resource, multiple users share the same radio resource. To some extent, MU-MIMO is already supported in the first release of LTE. However, support for downlink MU-MIMO can be further improved. As an example, the lack of interference signaling in the downlink makes it more difficult to apply high-performance interference-suppressing receivers. Moreover, it can be seen from Figure 17 that the sum-rate performance of the 3GPP LTE codebook is significantly inferior to that of the zero-force bound [1] [2]. For comparison, the performance of the Grassmanian code book and random code books of various sizes are also shown. The Grassmanian code book is a beamforming codebook that is derived based upon subspace packing on a Grassmanian manifold while the random code book is based upon random beamforming vectors. It can be seen that the gap between the LTE codebook and the zero forcing bound may be recaptured by increasing the size of the code book. Consequently, for LTE-Advanced, MU-MIMO is a technology with strong potential to increase system throughput by supporting multiple user transmissions over the same radio resource for both OL and CL-MIMO. It provides higher system throughput by exploiting multi-user diversity gain and joint signal processing to reduce the inter-stream interference among different users in the spatial domain with attractive performance-complexity trade-off.

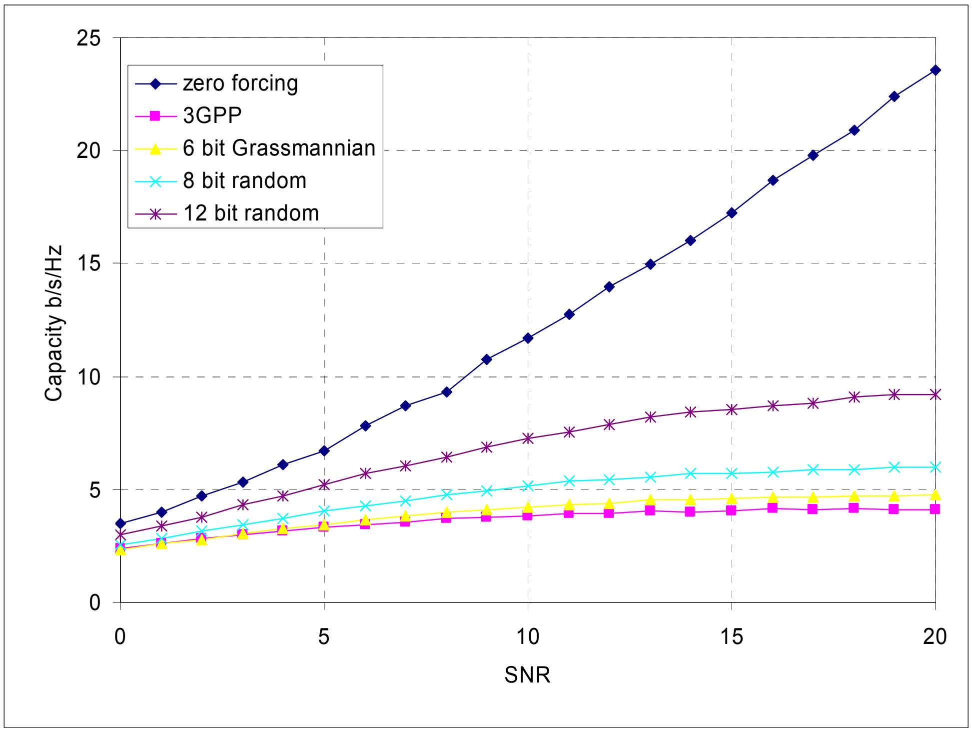


Figure 17. Sum capacity performance of MU-MIMO with the number of users equal to the number of transmit antenna = 4 for the Grassmanian, random and 3GPP LTE base codebooks [2].

For downlink MU-MIMO, the techniques that are currently under study in 3GPP can be roughly classified into two categories: fixed beam and user-specific beams. For fixed beam MU-MIMO, the base station will be configured to transmit multiple beams steadily while the scheduler allocates an individual user to a suitable beam to achieve best performance. This scheme is suitable for high-mobility UEs and can operate without dedicated pilots. With more closely spaced antenna elements, it could provide improved performance via sharper pointed beams.

In the case of user specific beams, the beams are generated for each user adaptively based on individual user's CSI. The user specific beams can provide better performance than static fixed-beams because of improved SINR (better beam pointing and interference suppression) but it requires that the UE feeds back the CSI to the eNB and that the channel changes insignificantly between the CSI measurement and the transmission. Consequently, this scheme is suitable for low-to-moderate mobility scenarios. User specific MU-MIMO techniques currently under study can be classified into unitary codebook based and non-unitary codebook based techniques. The unitary code book based MU-MIMO forms the beam from an optimal unitary codebook. The performance of unitary codebook MU-MIMO is generally worse than that of the non-unitary codebook based MU-MIMO because the channel seen by the UE does not exactly match the unitary codeword. This will cause inter-user interference and degrade performance. For non-unitary codebook based MU-MIMO, the beams can be formed exactly in the direction of the UE and in the case of zero-forcing beamforming, the set of beams that are used for the transmission can be made exactly orthogonal. However, since user specific non-unitary codebook based beams are used, a user specific reference signal is needed for channel estimation. Although the MU-MIMO schemes discussed so far are codebook based, it should be noted that MU-MIMO schemes based upon non-codebook type feedback are also possible.

For the UL, joint processing could be done on base station for MU-MIMO. The MMSESIC is the optimal scheme to reach MU-MIMO upper-capacity regions. Furthermore, recent advances in optimization procedures have shown that numerical efficient implementation of this scheme may now be possible.

5.5 CoMP

Coordinated multi-point transmission/reception (CoMP) is considered by 3GPP as a tool to improve coverage, cell-edge throughput, and/or system efficiency.

5.5.1 PRINCIPLE

The main idea of CoMP is as follows. When an UE is in the cell-edge region, it may be able to receive signal from multiple cell sites and the UE's transmission may be received at multiple cell sites. Given that, if we coordinate the signaling transmitted from the multiple cell sites, the DL performance can be increase significantly. This coordination can be simple as in the techniques that focus on interference avoidance or more complex as in the case where the same data is transmitted from multiple cell sites. For the UL, since the signal can be received by multiple cell sites, if the scheduling from the different cell sites, the system can take advantage of this multiple reception to significantly improve the link performance. In what follows, the COMP architecture will first be discussed follow by the different schemes proposed for CoMP.

5.5.2 COMP ARCHITECTURE

CoMP communications can occur with intra-site or inter-site CoMP as shown in Figure 18. With intra-site CoMP, the coordination is within a cell site. The characteristics of each CoMP architecture are summarized in Table 3. An advantage of intra-site CoMP is that significant amount of exchange of information is possible since this communication within a site and does not involve the backhaul (connection between base stations). Inter-site CoMP involves the coordination of multiple sites for CoMP transmission. Consequently, the exchange of information will involve a backhaul. This type of CoMP may put additional burden and requirement upon the backhaul design.

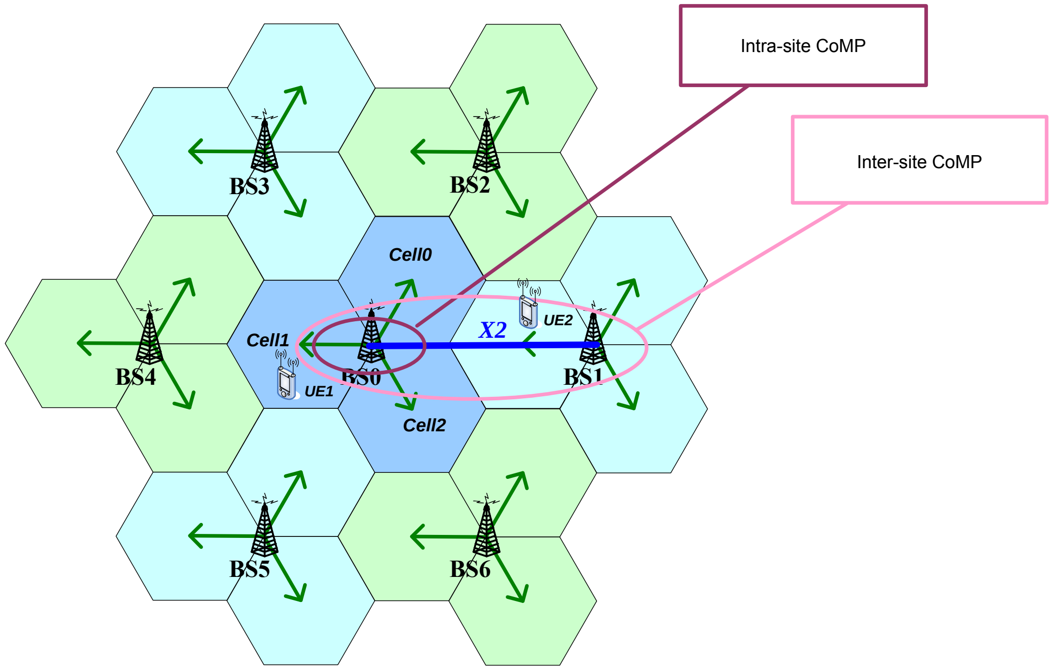


Figure 18. An illustration of the inter-site and intra site CoMP.

Table 3: Summary of the characteristics of each type of CoMP architecture

	Intra-eNB Intra-site	Intra-eNB Inter-site	Inter-eNB Inter-site (1)	Inter-eNB Inter-site (2)
Information shared between sites	Vendor Internal Interface	CSI/CQI, Scheduling info	CSI/CQI, Scheduling Info	Traffic + CSI/CQI, Scheduling Info
CoMP Algorithms	Coordinated Scheduling, Coordinated Beamforming, JP	Coordinated Scheduling, Coordinated Beamforming, JP	Coordinated Scheduling, Coordinated Beamforming	Coordinated Scheduling (CS), Coordinated Beamforming, JP
Backhaul Properties	Baseband Interface over small distances provides very small latencies and ample bandwidth	Fiber-connected RRH provides small latencies and ample bandwidth	Requires small latencies only.	Requires small latencies. Bandwidth dominated by traffic.

An interesting CoMP architecture is the one associated with a distributed eNB depicted in Figure 19. In this particular illustration, the radio remote units (RRU) of an eNB are located at different locations in space. With this architecture, although the CoMP coordination is within a single eNB, the CoMP transmission can behave like inter-site CoMP instead.

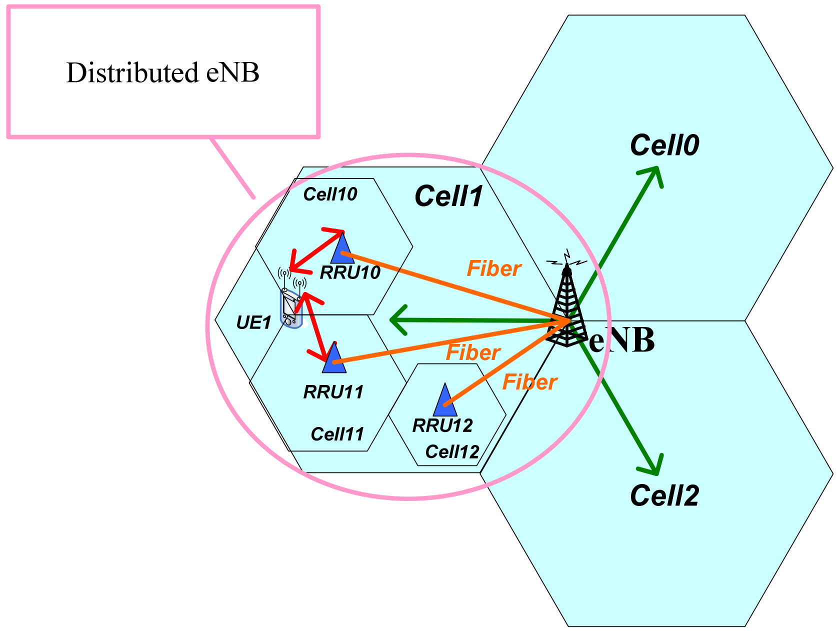


Figure 19. An illustration of intra eNB CoMP with a distributed eNB.

5.5.3 DL COMP

In terms of downlink CoMP, two different approaches are under consideration: *Coordinated scheduling and/or beamforming*, and *joint processing/transmission*. In the first category, the transmission to a single UE is transmitted from the serving cell, exactly as in the case of non-CoMP transmission. However, the scheduling, including any beam-forming functionality, is dynamically coordinated between the cells in order to control/reduce the interference between different transmissions. In principle, the best serving set of users will be selected so that the transmitter beams are constructed to reduce the interference to other neighboring user, while increasing the served users' signal strength.

For joint processing/transmission, the transmission to a single UE is simultaneously transmitted from multiple transmission points, in practice cell sites. The multi-point transmissions will be coordinated as a single transmitter with antennas that are geographically separated. This scheme has the potential for higher performance, compared to coordination in the scheduling only, but comes at the expense of more stringent requirement on backhaul communication.

Network and collaborative MIMO have been proposed for the evolutions of LTE. Their application depends on the geographical separation of the antennas, coordinated multipoint processing method and the coordinated zone definition. Depending on if the same data to a UE is shared at different cell sites, collaborative MIMO includes single-cell antenna processing with multi-cell coordination, or multi-cell antenna processing. The first technique can be implemented via precoding with interference nulling by exploiting the additional degrees of spatial freedom at a cell site. The latter technique includes collaborative precoding and CL macro diversity. In collaborative precoding, each cell site performs multi-user precoding towards multiple UEs, and each UE receives multiple streams from multiple cell sites. In CL macro diversity, each cell site performs precoding independently, and multiple cell sites jointly serve the same UE.

5.5.4 UL COMP

Uplink coordinated multi-point reception implies reception of the transmitted signal at multiple geographically separated points. Scheduling decisions can be coordinated among cells to control interference. It should be noted that in different instances, the cooperating units can be separate eNB's remote radio units, relays, etc. Moreover, since UL CoMP mainly impacts the scheduler and receiver, it is primarily an implementation issue. Consequently, the evolution of LTE will likely define only the signaling needed to facilitate multi-point reception.

6 SYSTEM PERFORMANCE

6.1 MAPPING MIMO ALGORITHMS TO ENB AND UE ANTENNA CONFIGURATIONS

The aim of this section is to establish a compatibility matrix between antenna configurations and MIMO algorithms for the three main deployment environments identified in Section 1. There are, overall, many permutations, some of which are either not feasible or, even if they are, have performance issues that arise forcing some combinations to be preferred over others. Table 4 summarizes the compatibility matrix of antenna configurations in terms of the deployment environment.

Table 4: Compatibility Matrix of Antenna Configurations

	Urban Micro	Urban Macro	Rural Macro
DIV-1X	H	M	L
DIV-2X	H	H	L
ULA-4V	L	M	H
CLA-2X	L	H	M
CLA-4X	L	H	H

Three levels of high (H), medium (M) and low (L) preferences are defined, attempting to provide some form of relative ranking. This report selects a few representative antenna configurations based on the constraints of twelve RF cables per three-cell base station. It also presents the configuration CLA-4X that violates the constraint and represents an upper limit in the size/performance tradeoff.

Figure 20 captures some of the features offered by these antenna configurations. Note that in this draft version the maximum spectrum efficiency (SE) axes numbers have not been captured. The features of interest include:

- The resource reuse factor also known as multi-user multiplexing factor or SDMA factor. Note that for ULA configurations, SDMA benefits across orthogonal beams are only captured.
- The suitability for the three major deployment environments as captured by Table 4.
- The suitability of the antenna configuration to support adaptation across multiple MIMO algorithms. This includes primarily Doppler-spread robustness that results in performance guarantees across a wide range of propagation conditions.
- A relative OPEX figure that results from the increase in leasing costs for the base station site with the assumption that the larger the physical dimensions of the antennas the higher the recurring expense that operators pay the tower vendors.

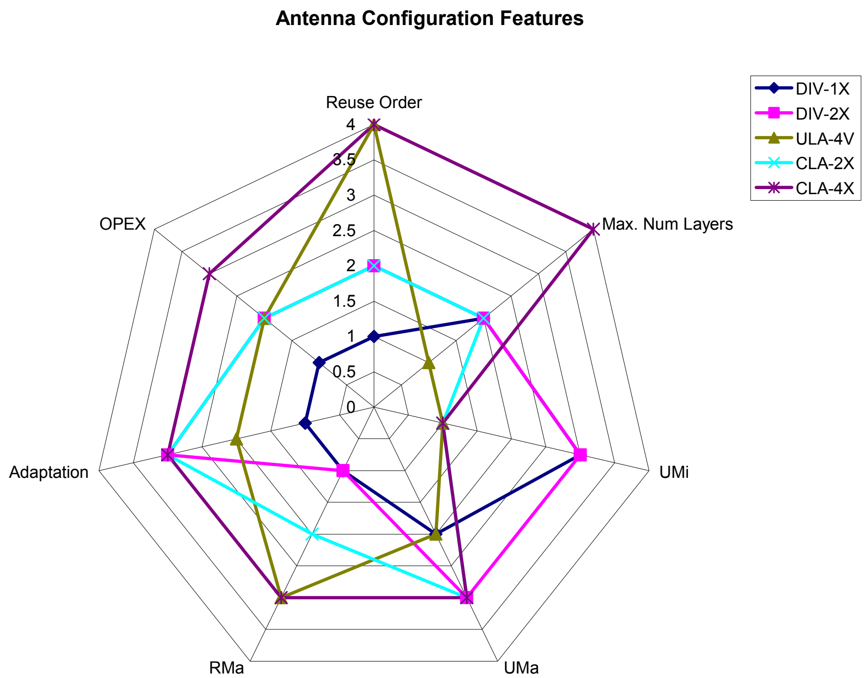


Figure 20. Radar chart with the qualitative ranking of antenna configurations against various features

6.1.1 ALGORITHM MAPPINGS

Table 5: Algorithm Mappings

Antenna Configuration	Supported Algorithm	Comments
DIV-1X	• TxD with SFBC/CDD • DL OL and CL SM with up to two streams. • UL MU-MIMO with reuse factor of two.	• Scheduling algorithm uses UE mobility information to adapt the transmit precoder weights.
DIV-2X	• TxD with SFBC/CDD • DL OL and CL SM with up to four streams • UL MU-MIMO with reuse factor of four	• Scheduling algorithm uses UE mobility information to adapt the transmit precoder weights
CLA-2X	• TxD with SFBC/CDD • DL OL and CL-MIMO with up to two streams (in R9) • UL MU-MIMO with reuse factor of four.	• Robustness to UE mobility due to beamforming capability.
ULA-4V	• DL OL and CL SM with a single stream. • DL MU-MIMO with reuse factor of four • UL MU-MIMO with reuse factor of four	• Robustness to UE mobility due to beamforming capability.
CLA-4X	• TxD with SFBC/CDD • DL OL and CL-MIMO with up to two streams (in R9) • UL MU-MIMO with reuse factor of four.	• Sizable antenna array, 24-RF cables per base station.

6.2 DL SYSTEM PERFORMANCE

6.2.1 THE BASELINE CASE (1V)

This report assumes that many 3G Americas operators will elect to initiate LTE services using the DIV-1X antenna configuration at the eNB. It is, however, instructive to observe the so-called baseline case of a single vertical column at the eNB transmitter (1V) such that the relative benefits of DIV-1X can be best understood. The performance of the 1V baseline antenna configuration is shown in Figures 21 to Figure 23. Note that a dual carrier HSPA system is presented and also, the notation for system bandwidth is that of FDD i.e. 2 x K MHz.

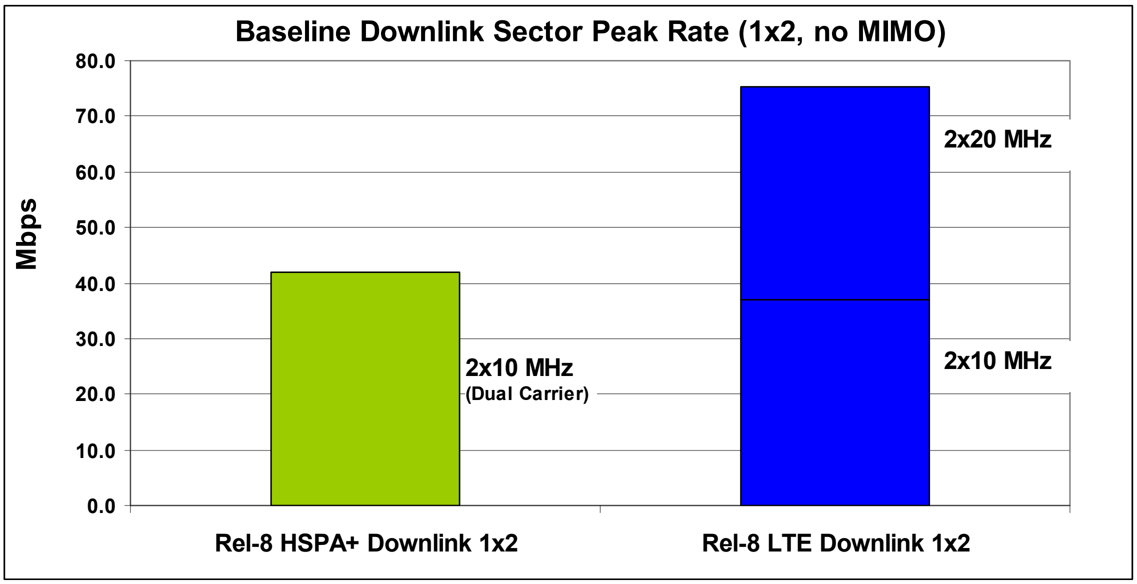


Figure 21. DL peak rate per sector (Baseline)

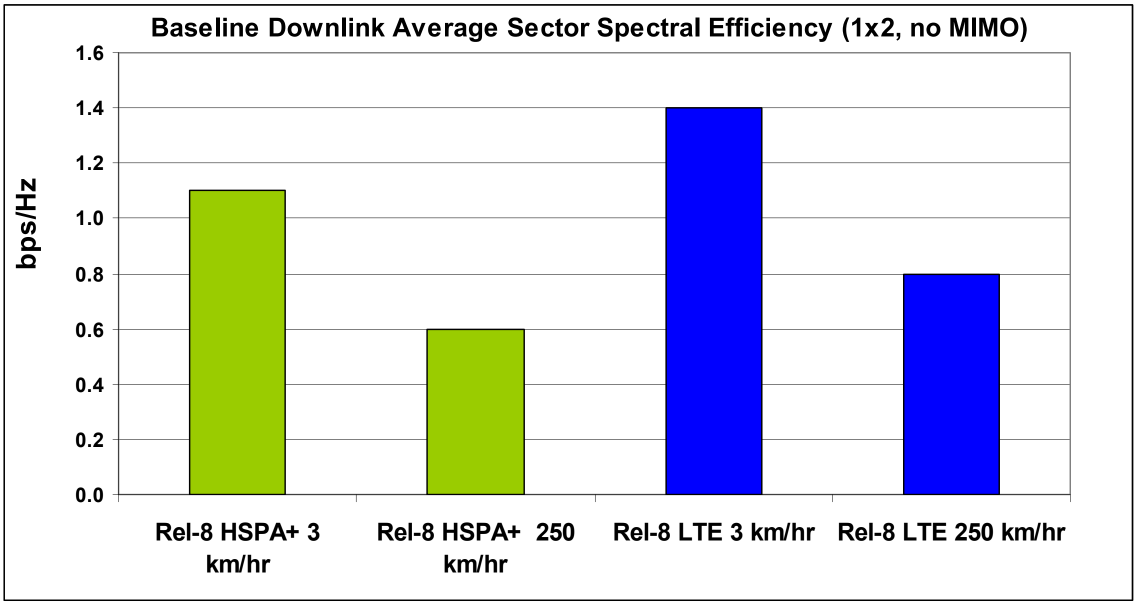


Figure 22. DL average SE per sector (Baseline)

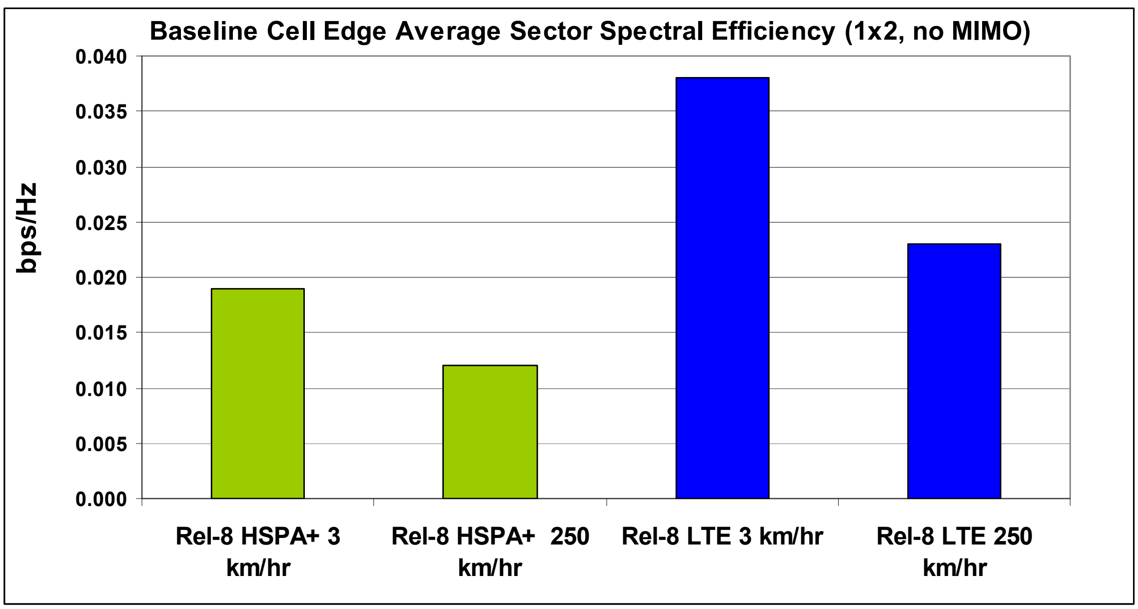


Figure 23. DL cell edge SE (Baseline)

LTE Release 8 seems to offer significant performance gains over HSPA for the baseline scenario. Average cell SE gain is on the order of 30% with cell-edge SE gain in the order of 100%.

6.2.2. OL-MIMO WITH DIV ANTENNA CONFIGURATIONS

Multiple stream transmission increases the peak rate of LTE Rel-8. OL-MIMO is not available for HSPA, effectively though a peak rate increase for HSPA is provided via dual-carrier transmission. Two cases are presented: with SM, where the transmission rank is higher than 1 and without SM where we have rank 1 transmission.

Compared to baseline, SE gains for OL-MIMO with DIV-1X are small due to the interference limited simulated scenario; gains could be much higher in an isolated cell. Note that the notation N_{TX} x N_{RX} in this report assumes diversity (DIV) antenna configuration at the base station and the terminal.

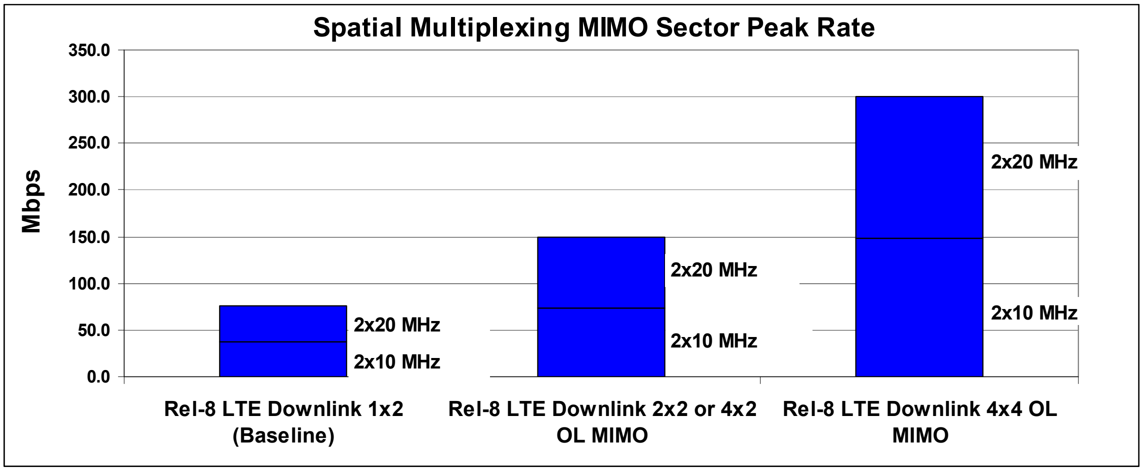


Figure 24. DL peak rate with DIV antenna configuration

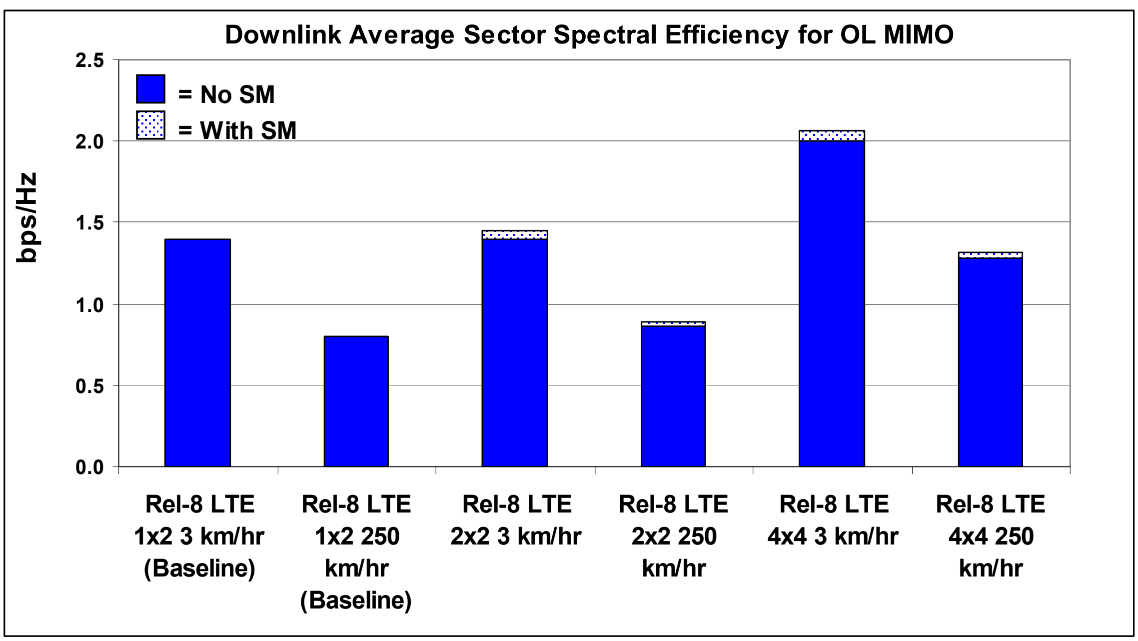


Figure 25. DL average sector SE with DIV antenna configuration

Figure 26 shows only rank -1 results as transmission with rank >1 were not observable at the cell edge.

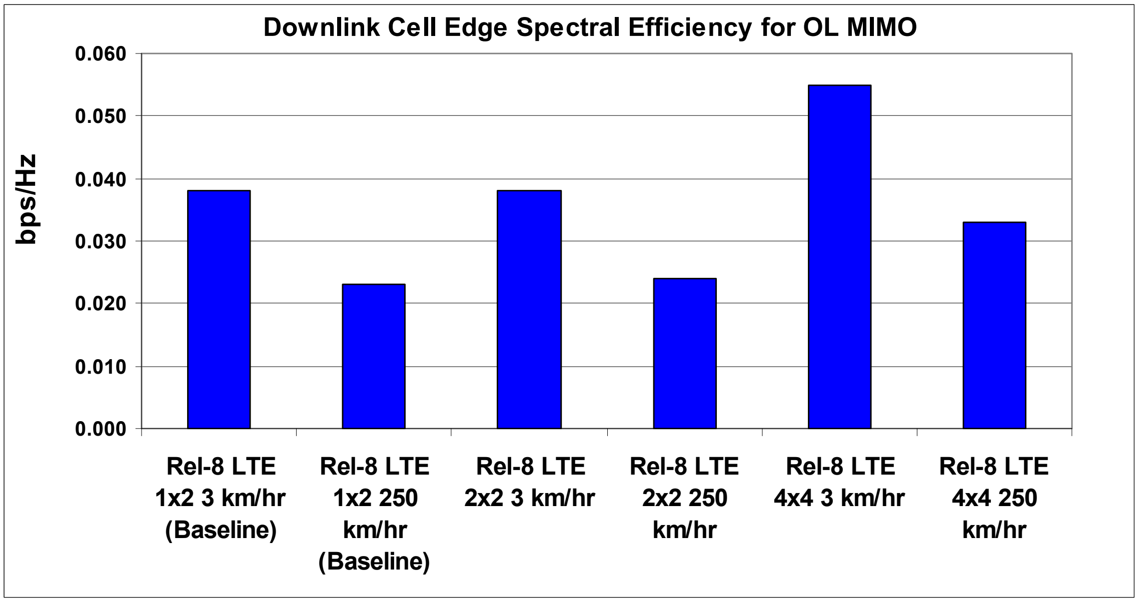


Figure 26. DL cell edge SE with DIV antenna configuration

6.2.3. CL-MIMO WITH DIV ANTENNA CONFIGURATIONS

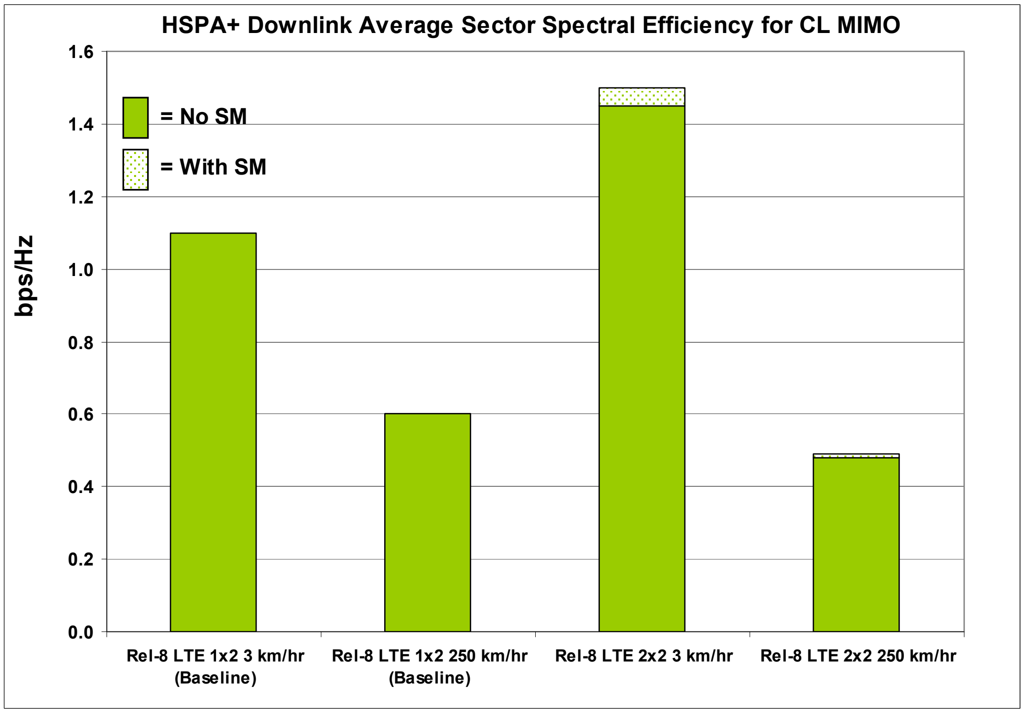


Figure 27. HSPA DL average sector SE with DIV-1X antenna configuration

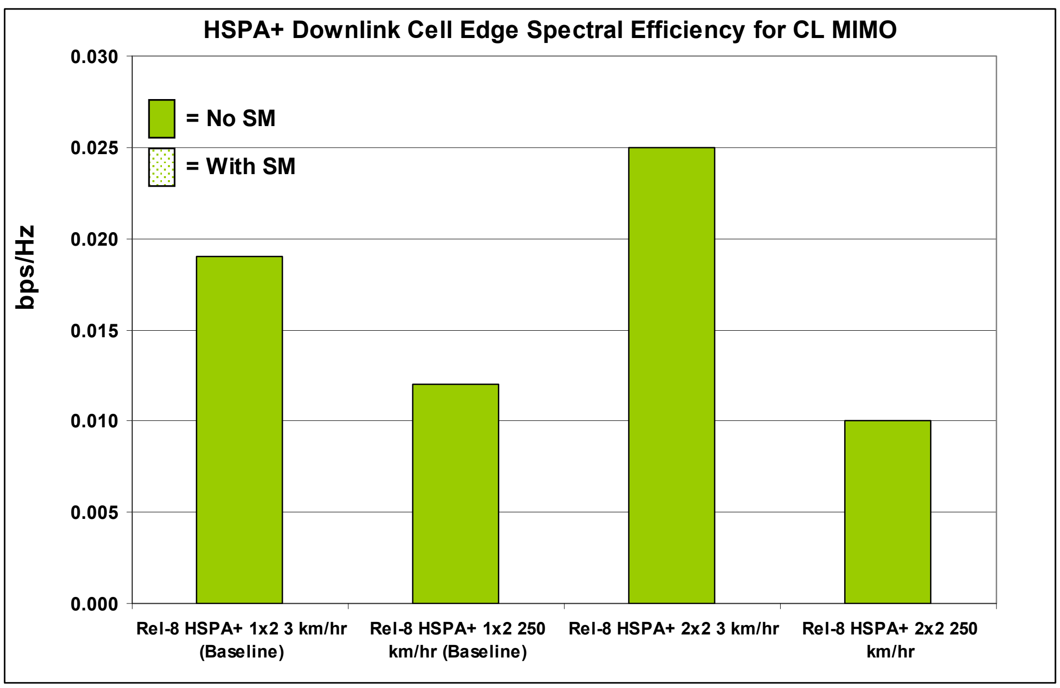


Figure 28. HSPA DL cell edge SE with DIV-1X antenna configuration

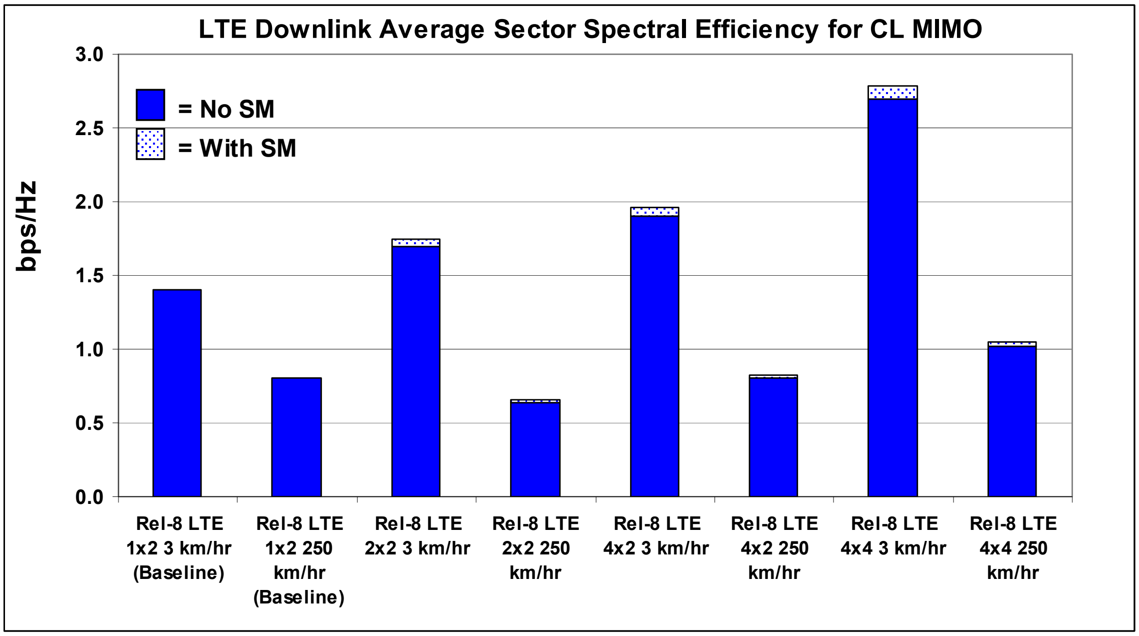


Figure 29. LTE DL average sector SE with DIV antenna configuration

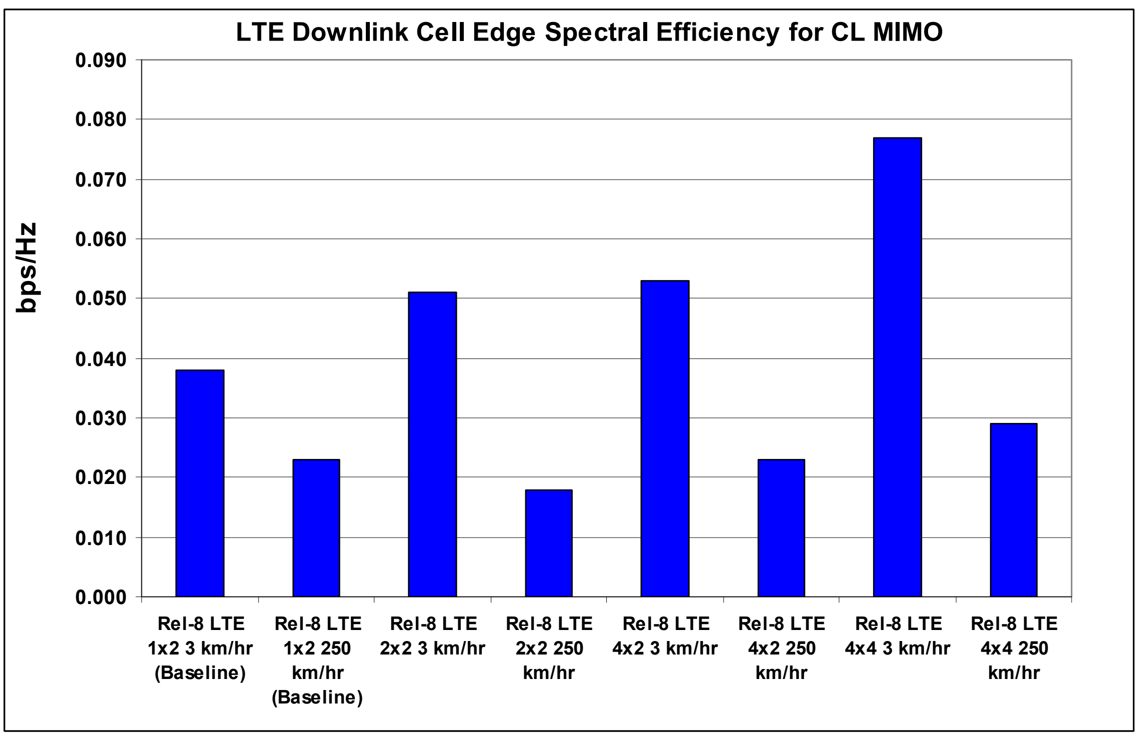


Figure 30. LTE DL edge SE with DIV antenna configuration

6.2.4. MIMO WITH ULA-4V

With the ULA-4V antenna configuration, SDMA benefits are evident for macro-cellular deployments. The Doppler-spread tolerance is also evident due to the long-term beamforming. At the cell edge, ULA-4V helps with increasing SNR with rank-one transmission as well as improved SIR statistics due to SDMA scheduling in the interfering base stations.

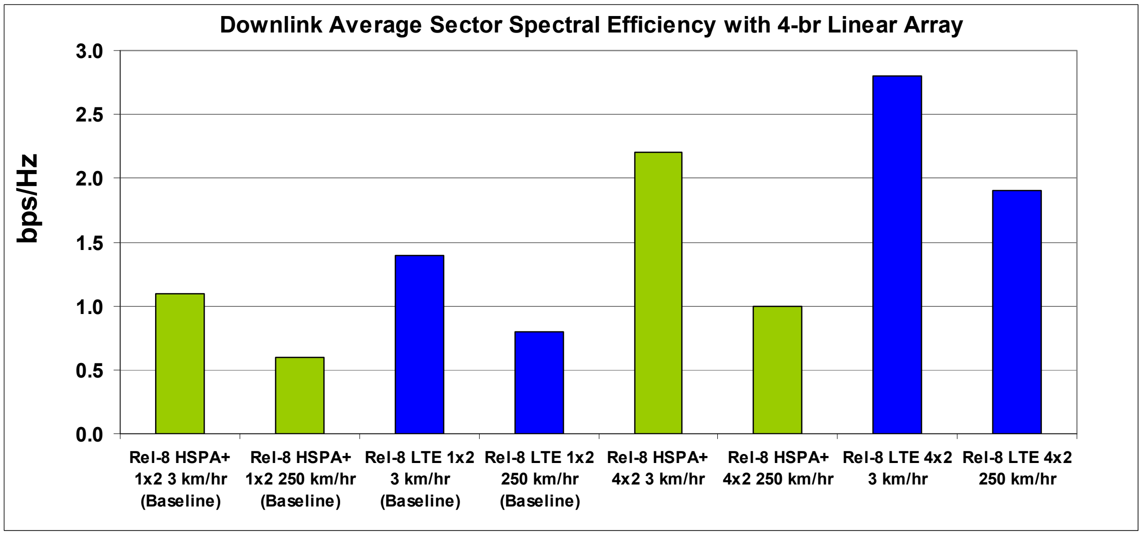


Figure 31. LTE DL average sector SE with ULA-4V antenna configuration

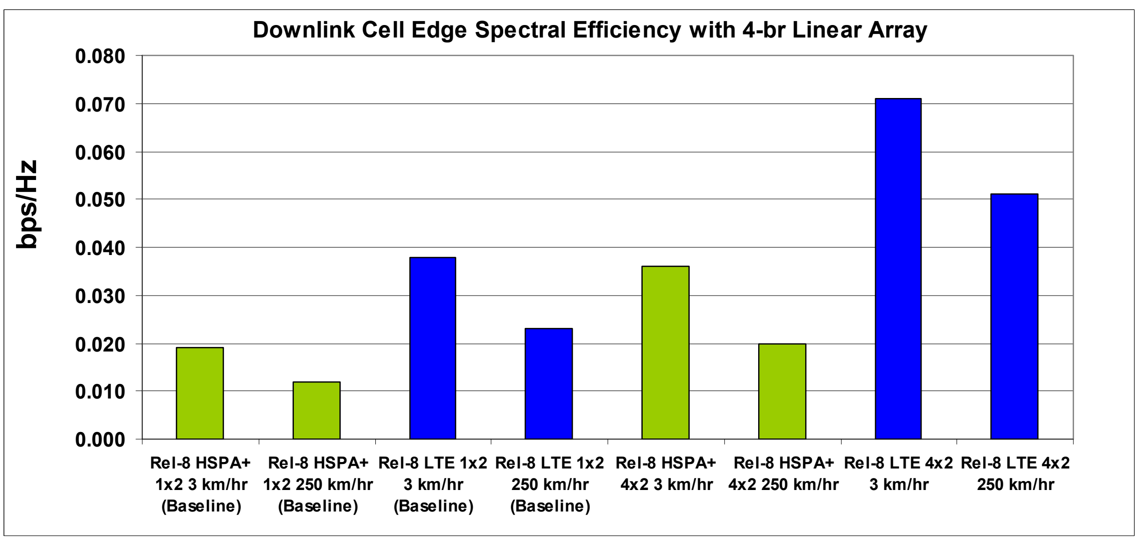


Figure 32. LTE DL edge SE with DIV antenna configuration

6.3 UL SYSTEM PERFORMANCE

6.3.1 THE BASELINE CASE WITH DIV-1X

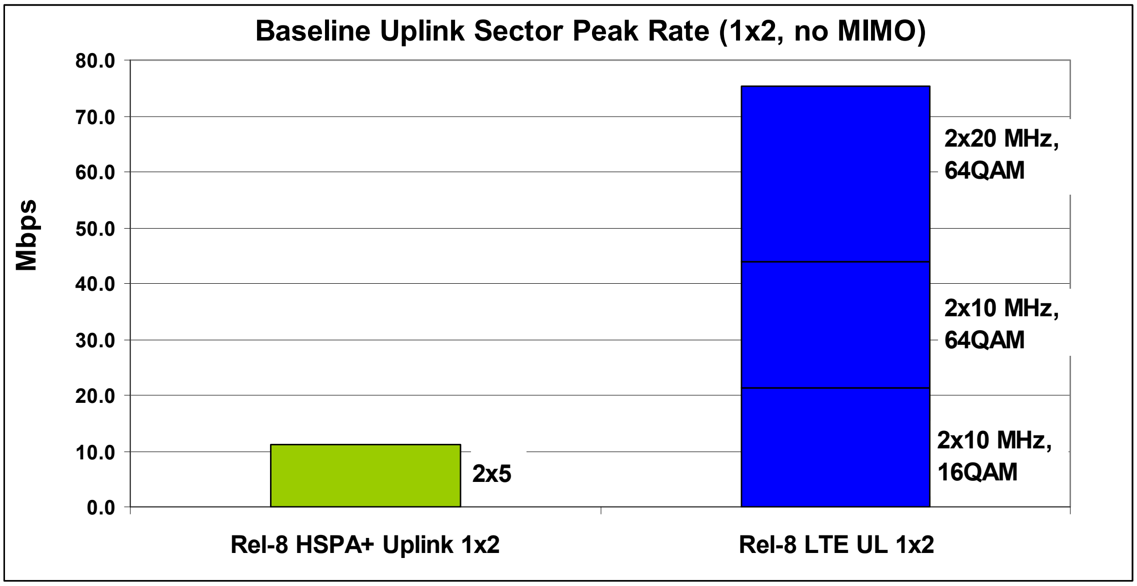


Figure 33. UL peak rate with DIV-1X (Baseline)

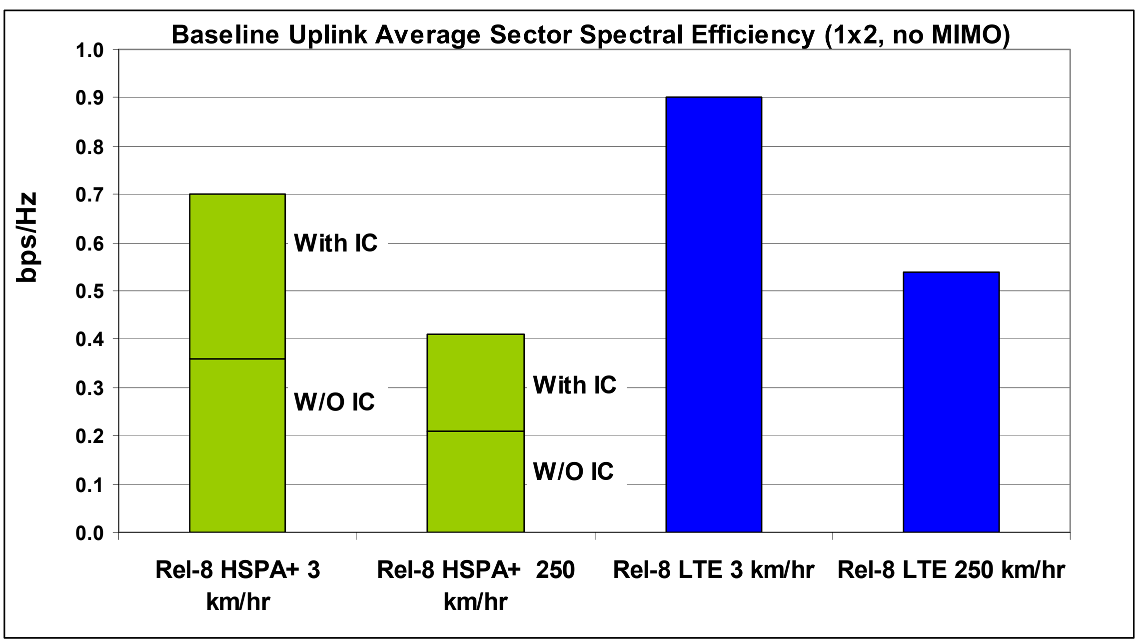


Figure 34. UL sector average SE (Baseline)

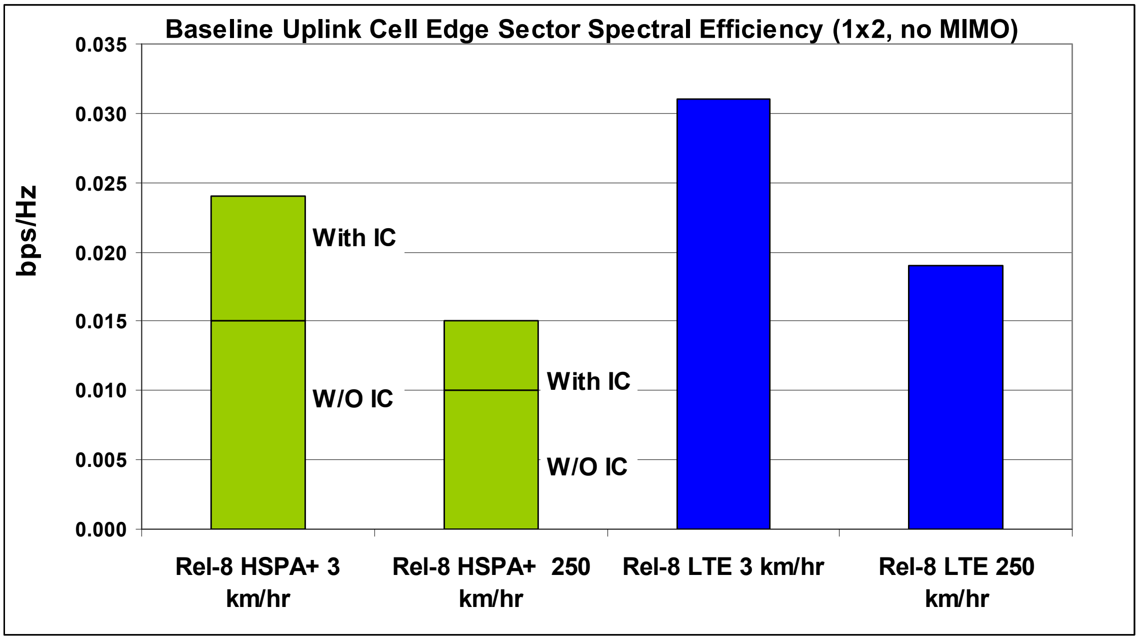


Figure 35. UL edge average SE (Baseline)

6.3.2 UL MU-MIMO WITH DIV-1X

UL MU-MIMO with DIV-1X exhibits some moderate gains over the baseline of the order of 10%. Limiting factors include the small number of receive antenna elements, the receiver technology with SIC outperforming MMSE, the traffic distribution. The later affects the scheduler capability in identifying two simultaneous UEs with target SINRs that allow MIMO detection/separation. The results below were performed with 10 users per cell; the presence of more users will likely increase the benefits.

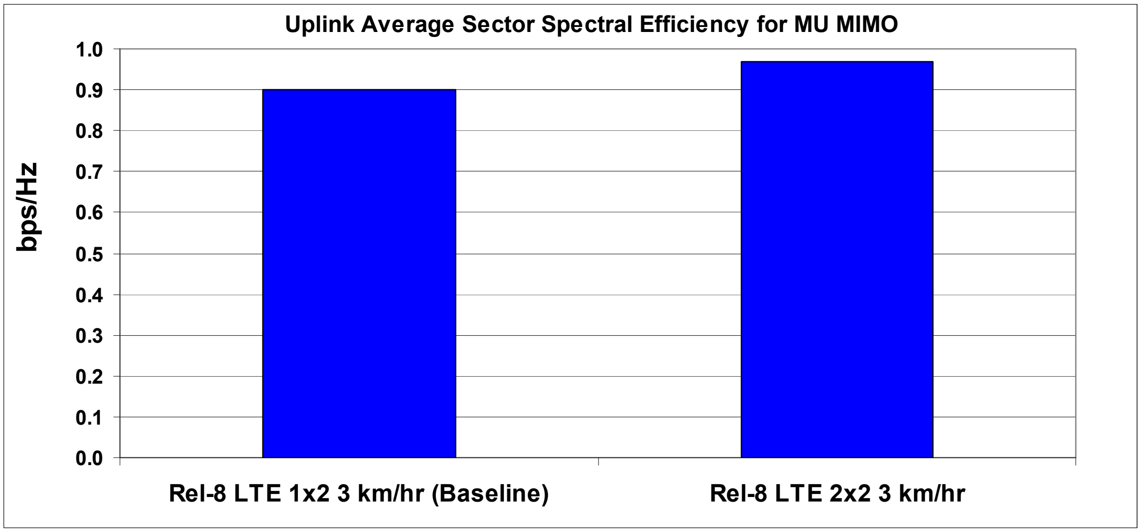


Figure 36. UL MU-MIMO sector SE with DIV-1X

At the cell edge, maintenance of the IoT target constraints even further reduces the performance benefits since it leads to suppression of the Tx PSD as a result of the simultaneous transmission by more than one UE on the same set of resources.

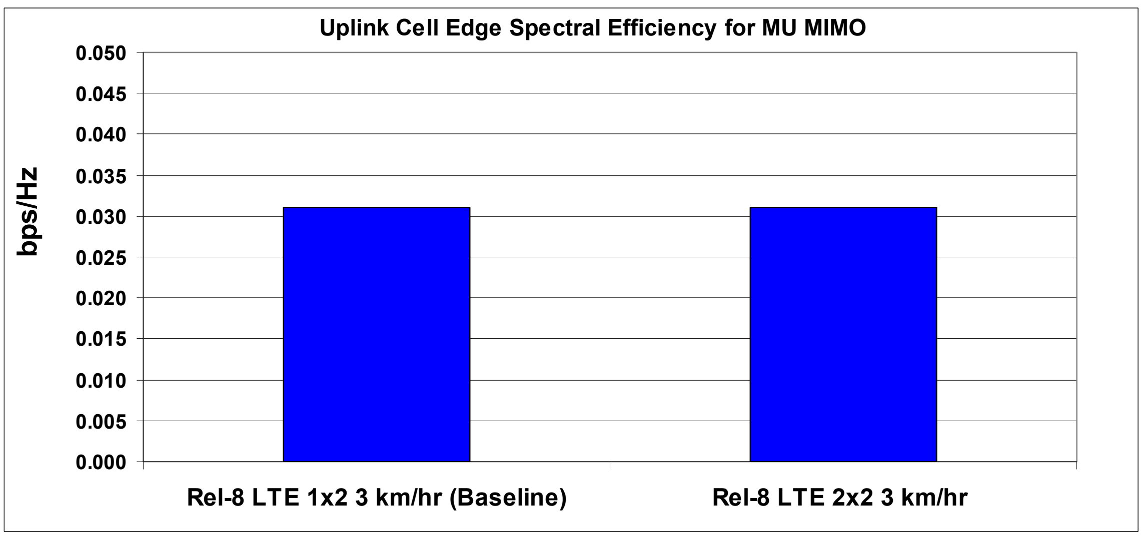


Figure 37. UL MU-MIMO edge average SE

7 CONCLUDING REMARKS

This report provided an overview of current and emerging MIMO techniques that increase significantly the performance of HSPA and LTE networks. Based on simulation results presented in this report, it was shown that the relatively simple MIMO transmission scheme based on 2x2 CL SM, at low user equipment (UE) speeds can increase by 20% the DL sector spectral efficiency relative to a single antenna transmission, as well as increase the cell edge efficiency by approximately 35%. More advanced antenna configurations can provide benefits that are significant for both good geometry users as well as cell edge users.

At the base station, the migration path from DIV-1X to more complicated arrays is critical.

- Uniform linear array configurations are more suitable for rural environments where the size of the cells in combination with the propagation characteristics provide a compatible match to the capacity-coverage tradeoff curve as outlined in the Principles section. In the DL, cell-edge users get an SINR boost in the more efficient linear capacity region, and even more so with DL CoMP, while users with higher geometries get SDMA benefits. Doppler-spread tolerant beamforming algorithms provide a good match to the expected user mobility patterns. In the UL, SDMA benefits all users that pay a diversity penalty relative to DIV antenna configurations. On the other hand, per-beam IoT control allows for better granularity in managing UL load balancing, useful for the mostly non-uniform traffic distributions of larger cells.

- Diversity antenna configurations are more suitable for urban microcell and urban macrocell environments. For microcells, the cost, antenna size and "in-the-clutter" location in combination with user mobility patterns, can make extensive usage of closed-loop feedback MIMO capabilities that benefit low-speed single user and multi-user transmissions.

- Clustered antenna configurations are more suitable for urban macrocell environments. Such hybrid antenna arrays manage to support most, if not all, of MIMO algorithmic alternatives and together with mode adaptation match well the more unpredictable environments of urban macrocells. In the DL and for the same antenna elements, they trade reduced SDMA performance relative to uniform linear arrays, with increased UL robustness due to the presence of diversity elements. They also offer increased DL robustness for high speed users and for common control channels that cannot be beamformed.

At the terminal, the challenges faced by UE designers in creating handheld devices are numerous. The effect on battery life needs to be considered. Small form factors will force design compromises, some of which that can be alleviated through advanced antenna designs. However, these designs will have effects whose impact on MIMO system performance should be well understood.

The 3GPP has already defined and continues to standardize the most advanced forms of MIMO technology in the industry. It is the intention of this report to increase awareness and offer guidance on the deployment of MIMO technology in HSPA and LTE networks.

8 REFERENCES

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9 ACKNOWLEDGEMENTS

The mission of 3G Americas is to promote, facilitate and advocate for the deployment of the GSM family of technologies including LTE, throughout the Americas. 3G Americas' Board of Governor members include Alcatel-Lucent, America Móvil, AT&T (USA), Cable & Wireless (West Indies), Ericsson, Gemalto, HP, Huawei, Motorola, Nokia Siemens Networks, Nortel, Openwave, Research In Motion (RIM), Rogers (Canada), T-Mobile USA and Telefónica.

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