Introduction

This application note is written for people who need an understanding of Multiple Input Multiple Output (MIMO) radio operation as it applies to Long Term Evolution (LTE). MIMO (otherwise known as spatial multiplexing) is one of several multiple antenna techniques that are being implemented in LTE; however, this application note will primarily focus on MIMO implementations.

Increasing use of high-bandwidth applications (such as streaming video) drives a continued desire for higher throughput or better coverage from wireless systems. To some extent, the use of more complex modulation formats such as Orthogonal Frequency Division Multiplexing (OFDM) and 64 QAM has satisfied this need. Other optimizations have been made through multiple antenna techniques, including the use of more than one antenna, receiver chains that combine multipath signals and multiple base station antennas correlated in phase to shape coverage area.

Further advances are continually being made. Changing the use of the spectrum available is being pursued through several approaches, including MIMO. Release 8 of the 3GPP specifications, which specifies the Long Term Evolution towards 4th generation (4G) systems (LTE), includes new requirements for operation, where a base station and handset communicate using two or more transmit and receive chains and takes advantage of the differences in radio transmission paths between them. The goal is to increase both overall capacity of a cell and the data rate that a single user can expect from the system.

MIMO radios get more from the RF bandwidth they occupy than their single-channel equivalents by exploiting differences in the paths between the transmitter and the receiver inputs. If a conventional single-channel radio system creates one data “pipe” between the transmitter and the receiver, the object of a MIMO radio system is to create multiple such pipes. It does this by creating a mathematical model of the paths from transmitters to receivers and solving the resulting equations, and has to do so as fast as the channel is changing. If the data pipes can be completely separated, the channel capacity increases linearly as more transmitter-receiver pairs are added.

The radio environment does not give up increases in capacity easily. MIMO radio operation relies on the ability to separate the “pipes”. Like a solution to a mathematical puzzle, there have to be enough equations compared to the number of unknowns. This is added to the usual requirements to deal with matters of interference, noise, interoperability, hardware costs and current consumption.

Testing will play an important role in helping to make sure the radios operate correctly, both individually and between the many different vendors’ designs that will be deployed.
In the specifications, the terms “input” and “output” apply to the medium between the transmitters and receivers, including the RF components of both – known as the “channel”. Thus, a base station with two transmitters provides two inputs to the channel, the “MI” part, and a handset with two receive chains takes two outputs from the channel, the “MO” part. This is true only if the data transmitted and received is independent, and is not just a copy of the same data, as explained below.

**Inputs and Outputs**

**Single Input Single Output (SISO)** is the standard transmission mode in most systems, and the objective of more complex systems is capacity, or data rate gain, measured with respect to SISO.

**Single Input Multiple Output (SIMO)** or receive diversity (a single transmitter, and therefore a single data stream), feeds two receiver chains. This aids received data integrity, where signal-to-noise (SNR) ratio is poor due to multipath fading. There is no gain in data capacity except any benefit that comes from better error ratio and consequent reduced retransmission.

**Multiple Input Single Output (MISO)** is a transmit diversity technique. In LTE, Space Frequency Block Coding (SFBC) is used to improve signal robustness under fading conditions. The transmitters send the same underlying user data, but in different parts of the RF frequency space.

**True MIMO**, with two transmitters and two receivers with independent data content, is also known as spatial multiplexing. Each receiver sees the output of the channel, which is a combination of the outputs from the transmitters. Using channel estimation techniques, the receivers use matrix mathematics to separate the two data streams and demodulate the data. In ideal conditions, data capacity would be doubled, though there is a premium to be paid in better SNR requirements than for SISO. Practically, the doubling of data capacity is never achieved, but definite increases in data capacity can be seen.
Five multi-antenna techniques have been defined for LTE to improve the downlink performance:

1. Receive diversity at the mobile
2. Transmit diversity using SFBC at the eNB (evolved Node B)
3. MIMO spatial multiplexing at the eNB, for one or two users
4. Cyclic Delay Diversity (CDD) at the eNB, used in conjunction with spatial multiplexing
5. Beamsteering (user specific)

The first two are relatively conventional diversity methods. The third and fourth methods make use of space frequency coding mechanisms to spread data across multiple antennas. Cyclic delay diversity introduces deliberate delays between the antennas to create artificial multipath. It is applied more dynamically in LTE than in other radio systems. The techniques are applied differently, depending on the type of physical signal or physical channel. Both SIMO and MISO are employed in 3rd generation (3G) cellular systems, and will be rolled out in LTE networks. Their purpose is to improve the integrity of connections and to improve error rates, particularly where the connection suffers poor SNR (for example, at the edge of a cell). Conventional phased-array beamsteering introduces phase and amplitude offsets to the whole of the signal feeding each transmitting antenna. The intention is to focus the signal power in a particular direction. The same technique of applying phase and amplitude offsets can be used on the receiving antennas to make the receiver more sensitive to signals coming from a particular direction. In LTE, the amplitude and phase of individual resource blocks can be adjusted, making beamsteering far more flexible and user-specific. Beamsteering does not increase data rates but has an effect similar to diversity in terms of increasing signal robustness. The effectiveness of beamsteering increases with the number of transmitting antennas, which allows for the creation of a narrower beam. The gains possible with only two antennas are generally not considered worthwhile; thus, beamsteering is generally only considered for the four-antenna option.

User Equipment (UE) diversity reception (SIMO) is mandatory for the UE. It is typically implemented using maximum ratio combining. In a cellular environment, the signal from a single receive antenna will suffer level fluctuations due to various types of fading. With the wider nature of the LTE channel bandwidths there may also be a noticeable frequency dependency on the signal level. By combining the signal received from two antennas, the UE can recover a more robust signal. Receive diversity provides up to 3 dB of gain in low SNR conditions.
Consider an instant in time, at a single frequency, and model the channel as a black box with fixed components inside. If we add two completely different signals at the input, they will be mixed together in a defined way, dependant on the values of Z1 to Z4. If we send a training signal that’s unique to each input and measure the outputs we know how they got coupled, and therefore how to uncouple them. Everything, data and training signals, will be coupled in the same way, so what we learned from the training signal can be applied to real data. Noise and interference limit the modulation that can be used, along with the ability to uncouple the outputs. The worst case would be if Z1 to Z4 are all the same, when both outputs would be the same and MIMO would not work. The best case is if the outputs are equal in magnitude and opposite in phase, when capacity would theoretically double.

Equation 1. The long-form version of the channel capacity theorem can be written as:

\[
C = B \left[ \log_2 \left( 1 + \left( \frac{\sigma}{N} \right) \rho_1 \right) + \log_2 \left( 1 + \left( \frac{\sigma}{N} \right) \rho_2 \right) \right]
\]

where \( C \) = channel capacity in bits per second, \( B \) = occupied bandwidth in Hz, \( \sigma/N \) = signal to noise ratio and \( \rho \) = a singular value of the channel matrix

The potential increase in instantaneous system capacity can be derived from the ratio of singular values of the channel matrix \( H \), also known as the condition number. The condition number can also be used to indicate the increase in SNR needed to recover the MIMO signal, relative to the SISO case.

Figure 6. Overall system performance is improved since MIMO can potentially double the data capacity.
With the channel constantly changing due to fading and multipath effects, and Doppler frequency shift due to handset movement, amongst others, condition number versus frequency changes constantly across the RF-channel spectrum as illustrated in Figure 7.

Reference signals (or pilots) at regular frequency locations in the output of each transmitter provide a way for the receivers to estimate the channel coefficients. In general, each data “pipe” will not have the same performance. LTE uses feedback mechanisms known as pre-coding and eigenbeamforming – both forms of “closed-loop MIMO”, where the handset requests changes to the cross-coupling of the transmitter outputs to give the best match to the channel characteristics.

The terms codeword, layer, and precoding have been adopted specifically for LTE to refer to signals and their processing. Figure 8 shows the processing steps to which they refer. The terms are used in the following ways:

- **Codeword**: A codeword represents user data before it is formatted for transmission. One or two codewords, CW0 and CW1, can be used depending on the prevailing channel conditions and use case. In the most common case of Single User MIMO (SU-MIMO), two codewords are sent to a single handset UE, but in the case of the less common downlink Multi-User MIMO (MU-MIMO), each codeword is sent to only one UE.

- **Layer**: The term layer is synonymous with stream. For MIMO, at least two layers must be used. Up to four are allowed. The number of layers is always less than or equal to the number of antennas.

- **Precoding**: Precoding modifies the layer signals before transmission. This may be done for diversity, beamsteering or spatial multiplexing. The MIMO channel conditions may favor one layer (data stream) over another. If the base station (eNB) is given information about the channel (e.g. information sent back from the UE), it can add complex cross-coupling to counteract the imbalance in the channel. In a 2*2 arrangement, LTE uses a simple 1-of-3 precoding choice, which improves performance if the channel is not changing too fast.

- **Eigenbeamforming** (some times known simply as “beamforming”) modifies the transmit signals to give the best carrier to interference and noise ratio (CINR) at the output of the channel.

![Figure 7. Condition number as a function of sub-carrier frequency](image)
Single User and Multi-User MIMO

Figure 9 shows how both codewords are used for a single user in the downlink. It is also possible for the codewords to be allocated to different users to create multiple user MIMO (MU-MIMO). Depending on the channel information available at the eNB, the modulation and the precoding of the layers may be different to equalize the performance.

Figure 9. Codebook for transmission on antenna ports 0, 1
The precoding choices are defined in a lookup table known as the codebook. A codebook is used to quantize the available options and thus limit the amount of information fed back from the receiver to the transmitter. Some of the precoding choices are straightforward; for example, Codebook Index (CI) 0 is a direct mapping of codewords to layers and CI 1 applies spatial expansion.

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>Number of layers</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>$\frac{1}{\sqrt{2}} [1]$</td>
<td>$\frac{1}{\sqrt{2}} [1]$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$\frac{1}{\sqrt{2}} [-1]$</td>
<td>$\frac{1}{\sqrt{2}} [1]$</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>$\frac{1}{\sqrt{2}} [1]$</td>
<td>$\frac{1}{\sqrt{2}} [-1]$</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>$\frac{1}{\sqrt{2}} [1]$</td>
<td>$\frac{1}{\sqrt{2}} [-1]$</td>
</tr>
</tbody>
</table>

Table 1. Codebook for transmission on antenna ports 0,1

Table 1 shows the codebook choices for one and two layers. Note only the two-layer case employs spatial multiplexing. Precoding with one layer is limited to a 0 °, ± 90 ° or 180 ° phase shift.

In operation, the UE sends a message to the eNB scheduler with the codebook index most closely matching the channel, although the system can be configured for multiple codebook values, one for each resource block group. To use this information while it is still valid, the scheduler has to respond rapidly, within milliseconds, depending on the rate of change of the channel. If the UE is instructed to provide channel information more regularly, the information will be more accurate but the proportion of resources used for signalling will increase and place higher demands on the eNB.
SU-MIMO is within the scope of LTE but at the time of this writing has not yet been fully defined. To implement SU-MIMO the UE would require two transmitters. This is a significant challenge in terms of cost, size and battery consumption, and for these reasons SU-MIMO is not currently a priority for development. Also, the increased data rates in the uplink that might be possible from SU-MIMO are not as important as they are in the downlink due to asymmetrical traffic distribution. Lastly, if the system is deployed to be uplink-performance-limited, it may be impractical to increase the transmit power from the UE sufficiently to achieve the SNR needed at the eNB receivers.

Although a UE typically has a single transmitter in its baseline configuration, it is still capable of supporting a novel form of MIMO. Unlike the receive function, MIMO does not require that the transmitters are in the same physical device or location. It follows that uplink MIMO can be implemented using two transmitters belonging to two different UEs. This creates the potential for an increase in uplink capacity — although an individual user will see no increase in data rates.

The fact that the transmitters are physically separate has two consequences. First, there is no possibility of precoding since the source data cannot be shared between the two UEs to create the necessary cross-coupling of the data streams. This reduces the potential gains that co-located transmitters may have had. Second, the separation of the transmitters increases the probability that the radio channels seen by the eNB will be uncorrelated. Indeed, when the eNB has to select two UEs for pairing with MU-MIMO, the primary criteria will be the presence of de-correlated channels. Any potential gains lost through lack of precoding will be more than compensated for by the gains likely from better channel de-correlation; therefore, MU-MIMO could be a valuable technique for improving uplink capacity.

Signal recovery in LTE is tolerant of small timing and frequency errors. Normal uplink operation will result in each UE adjusting its frequency quite precisely to that of the eNB. The eNB will also instruct the UE to adjust its timing and power so that all signals arrive at the eNB receiver at approximately the same level and time. With the antennas located in different devices, the transmit paths are assumed to be uncorrelated. These conditions give the eNB scheduler the opportunity to control two UEs to transmit data simultaneously using the same subcarriers.

Multi-user MIMO involves the simultaneous transmission of codewords via layers from different UEs at the same time and frequency. The use of normal radio management techniques will ensure adequate frequency, timing and power alignment of the signals received at the eNB. Aligning the received power from the UEs at the eNB will be the most difficult thing to control if the potential capacity gains are to be realized.
LTE Transmitter and Receiver Design and Test

LTE already requires fundamental changes in base station and handset design and test due to the higher data rates, wider allowable signal bandwidths, and increasing integration and miniaturization in the handset, for example:

- The requirement to handle 6 different channel bandwidths from 1.4 to 20 MHz and both Frequency Division (FDD) and Time Division Duplex (TDD) modes.
- Flexible transmission schemes and virtually infinite operating permutations in which the physical channel configuration has a large impact on RF performance.
- Handset components complying with the multi-gigabit DigRF v4 standard, which removes the potential communication bottleneck between the baseband and radio frequency integrated circuits (RFICs), require cross-domain (digital in, RF out) measurement capability. A digital test source must emulate both data traffic and the encapsulated protocol stack within the digital interface that controls RFIC functionality.
- The DigRF high-speed digital serial interface in the handset must be treated as a transmission medium where analog impairments can degrade quality and degrade bit error rate (BER), and care must be taken connecting test equipment to avoid disturbing signal flow.
- Information transfers between the handset RF and baseband ICs must comply with strict timing constraints. Therefore it is important for the test environment to measure precisely when each frame is sent from one IC to the other and provide real-time detection of timing violations.

Added to these are the specific challenges resulting from the need to support multi-antenna techniques including diversity, beamsteering and MIMO.
The main objective of receiver testing is to make performance measurements on the entire receiver. However, many factors can influence receiver performance, so the basic receiver sub-blocks must be verified first and uncertainty contributions eliminated or quantifiably reduced. Where multiple receivers are used, it is necessary to make these basic measurements on each receive chain separately before attempting to verify MIMO performance. The principles discussed here apply to both frequency division duplex (FDD) and time division duplex (TDD) access modes although the examples here are FDD. A simplified block diagram of a typical LTE handset radio is shown in Figure 11.

Modern receivers utilize the same building blocks as classic designs; however, today there is a higher degree of integration with single components performing multiple functions, particularly in handsets where space is at a premium (meaning there will likely be fewer places where signals can be injected or observed for testing).
Here we will focus on a subset of receiver design and test considerations, specifically: open and closed loop operation, wide bandwidths, cross-domain signal analysis, affects of the channel, and finally precoding and the LTE codebook.

Open-loop and close-loop operation

Open-loop testing, where the receiver under test does not send feedback information to the source, is sufficient to test the fundamental characteristics of the individual components in the receiver and also is a first step in validating the demodulation algorithms in the baseband section. However, full verification of the overall receiver performance in real-world conditions requires closed-loop testing through a faded channel. In closed-loop testing lost packets are retransmitted using incremental redundancy based on real-time packet acknowledgement feedback from the receiver. The modulation and coding used for transmission are similarly based on real-time feedback from the receiver. This feedback may be optimized for sub bands within the overall channel bandwidth to enable frequency-selective scheduling.

Wide bandwidths

Next, we consider that one of the unique aspects of LTE is that it supports six channel bandwidths ranging from 1.4 MHz to 20 MHz. To simplify system operation and roaming, handsets must support all of these bandwidths, even though actual deployment in any one area may be restricted to fewer bandwidths. The LTE 20 MHz bandwidth is significantly wider than the maximum bandwidths of today’s other cellular systems; therefore, special attention to phase and amplitude flatness is required during receiver design. Filters, amplifiers and mixers in particular now have to operate correctly over multiple channel bandwidths. The LTE signal structure contains Reference Signals (RS) that are spread in both frequency and time over the entire LTE signal. The UE and eNB receivers can use these signals along with Digital Signal Processing (DSP) techniques to compensate for amplitude and phase-linearity errors in the receiver. Flatness needs be tested across each supported bandwidth and band, particularly at the band edges where the duplex filter attenuates the edge of the signal.

Cross-domain signal analysis

On the topic of cross-domain analysis, we note that traditionally, the signal from a receiver RF section can be demodulated into the I and Q components using analog techniques. Today however, the down-converted IF signal is usually digitized by an ADC and then fed to the baseband section for demodulation and decoding. Measuring the output of the ADC poses a challenge because the output is now in the digital domain. One solution is to analyze the digital bits from the ADC directly using a logic analyzer to capture the digital data. The difficult part of this solution is processing the data into a meaningful result since most logic analyzer applications are not focused on generating RF metrics. Using the Keysight Technologies, Inc. 89601A Vector Signal Analysis (VSA) software is one way to solve this challenge.
The VSA software can be run in a number of Keysight spectrum analyzers, logic analyzers and oscilloscopes for demodulating various modulation formats, and offers a unique way to analyze the ADC performance by being able to make traditional RF measurements directly on digital data. This approach gives a designer the ability to quantify the ADC contribution to the overall system performance and compare it to RF measurements made earlier in the block diagram (shown in Figure 11) using the same measurement algorithms.

If the RFIC has analog IQ outputs, these can be analyzed using an oscilloscope or Keysight MXA signal analyzer. If the RFIC interface uses DigRFv3 or v4, the signal can be captured with the Radio Digital Cross Domain (RDX) tester.

These digital or analog IQ signals can then be analyzed with the same 89601A VSA software. For the baseband developer, hardware probes are available for analog IQ and DigRF interfaces. The VSA software provides numerical EVM performance measurements for verification, as well as more detailed graphical information useful during product development to isolate the source of signal impairments. If Gaussian noise is added to the signal as the impairment, a relationship can be drawn between EVM and the raw BER. Alternatively, the captured IQ signals can be fed into a simulated receiver such as the Keysight design software for LTE. The precise design of a receiver determines the performance, so the results may differ depending on a vendor’s specific implementation.

Affects of the Channel

For our next topic, looking at affects of the channel, consider that the base station receiver faces many of the same MIMO challenges that the UE receiver faces, but in addition has to simultaneously receive data from multiple users. From the point of view of MU MIMO, each signal comes from a separate UE, therefore each signal has a completely independent channel, somewhat different power levels, and different timing. These characteristics can be emulated using the Keysight N5106A MIMO receiver tester (PXB) in conjunction with RF signal generators.

The receiver test configuration for the eNB is different from the configuration for the UE. The UE normally sends packet error reports on the uplink back to the test system, whereas the base station hardware is more likely to make a suitable demodulated signal output available.

Remember that MIMO channel recovery involves the separation of multiple signal components in the presence of noise and interference. When the signals are transmitted they are orthogonal, but by the time the signals reach the multiple receivers the coupling in the radiated path can reduce the difference between the signals.
In normal operation the receiver will have to deal with a complex and continuously changing channel, but using such a fading channel means testing is not repeatable when looking to ensure that the basic baseband operation is correct. A fading channel, built from simple phase and timing differences between paths, provides a deterministic signal that can be designed to verify the receiver’s performance limits. Adding noise to such a channel can readily create a test signal in which some subcarriers are more difficult to demodulate than others. For dual-source testing the standard RF phase and baseband timing alignment that can be achieved using a common frequency reference and frame synchronization signal is sufficient for most purposes.

Where fading is required, a configuration such as that shown in Figure 12 provides multiple independent continuously faded paths with analog or digital outputs using the Keysight N5106A MIMO receiver tester.

For directly mapped, open-loop MIMO testing, the phase relationship between the test signals does not affect the performance of the receiver because orthogonal signals have to be coupled twice for vector addition to take place. In closed-loop systems, the phase between test signals needs to be constant during the period when the channel is sampled, allowing any coupling coefficients to be calculated and applied. This may require the system to be stable rather than phase-locked. The channel condition number can be used to determine the SNR needed to achieve a specific performance at the demodulator. The condition number gives a measure of the composite channel performance. Each layer of the MIMO signal may actually have a different performance.
Precoding and the LTE codebook

Our final topic is precoding. The plots in Figure 13 show the demodulated signals from a single frame of an LTE signal. The channel was flat-faded (no frequency selectivity). The two constellations at the top of the figure show the two layers of the MIMO signal. It is clear that the constellation on the left is tighter, which would result in a lower BER in a real receiver.

If the channel characteristics are known (e.g. by the UE sending channel state information to the eNB) the mismatch in performance can be dealt with in either of two ways. The layer with better performance can be loaded with a higher order modulation, or precoding can be applied to equalize the performance of the two layers, as seen in the lower plots.
In LTE, the codebook index method is used to facilitate channel precoding, with a small number of codes used to minimize the system overhead in signalling. This means that the codebook index provides an approximation to the channel, implying some level of residual error. Figure 14 shows that once a codebook is chosen to equalize the EVM, the actual EVM still depends on the phase match between the transmitters.

The rectangular block at the center of Figure 14 represents the region in which codebook 1 would be chosen as the best fit. The diagonal lines show how the EVM of each stream varies with phase error. EVM is used as a performance metric, but BER could be also used. In the best circumstance, the codebook exactly fits the channel state and the performance of both layers is made the same.

As the phase between the transmitters varies — indicating that a mismatch in the codebook choice or variation in the channel occurred after the channel station information was provided — the layer performance separates. At extremes, the performance of the layers can be swapped. For receiver measurements, the significance of precoding errors shows the need for a fixed RF phase relationship at the output of the signal generators being used for a test. The term phase coherence is used to signify that the RF phase at the outputs of two or more generators is being maintained at a specified frequency. When it is necessary to guarantee that phase will not change versus frequency, a test configuration such as shown in Figure 15 can be used.
From the perspective of the RF engineer, LTE promises a dauntingly wide range of design and measurement challenges, arising from a number of factors:

- The requirement to handle six channel bandwidths from 1.4 to 20 MHz
- The use of different transmission schemes for the downlink orthogonal frequency division multiplexing (OFDMA) and uplink single carrier frequency division multiplexing (SC-FDMA)
- Flexible transmission schemes in which the physical channel configuration has a large impact on RF performance
- Specifications that include both FDD and TDD transmission modes
- Challenging measurement configurations resulting from the spectral, power and time variations due to traffic type and loading
- Further challenges resulting from the need to support multi-antenna techniques such as TX diversity, spatial multiplexing (MIMO) and beamsteering
- The need for making complex tradeoffs between in-channel, out-of-channel and out-of-band performance

As with the development of other modern communication standards, the design task involves troubleshooting, optimization and design verification with an eye toward conformance and interoperability testing.

The next section discusses general challenges of transmitter design and some basic verification techniques, starting with basic characteristics and then moving on to LTE-specific aspects, specifically: output power and power control, out-of-channel and out-of-band emissions, power efficiency, high-peak power including crest factor and predistortion, and phase noise.
Output power and power control

Beginning with a look at output power and power control, we note that accurate average power measurement of time-invariant signals is not a major challenge for LTE. Accurate broadband power measurements can be made using power meters, signal and spectrum analyzers or VSAs. However, due to the nature of the downlink and uplink signal characteristics, the more typical case for LTE involves output power measurements that are much more specific. These involve measurement all the way down to the Resource Element (RE) level, which is one OFDMA or SC-FDMA symbol lasting 66.7 μs on one subcarrier. For such measurements a power meter is of no value, but a spectrum or signal analyzer or a VSA is essential. In particular, power measurements associated with specific portions of the signal often require the digital demodulation capabilities of VSAs.

Out-of-channel and out-of-band emissions

Next, we consider that out-of-band emissions are regulated to ensure compatibility between different radio systems. The primary requirement is for control of spurious emissions from very low (9 kHz) frequencies to very high (13 GHz) frequencies. LTE in this respect is no different than any other radio system and spurious emissions will not be discussed further. LTE gets more interesting at the band edges where the signal has to meet the out-of-channel requirements as well as the out-of-band requirements, which are often tighter. With LTE supporting channel bandwidths up to 20 MHz, and with many bands too narrow to support more than a few channels, a large proportion of the LTE channels are also at the edge of the band.

Controlling transmitter performance at the edge of the band requires careful filter design to trade-off the required out-of-band attenuation without affecting the in-channel performance of the channels near the band edge. This trade-off must also consider costs (in terms of financial cost, power or power efficiency, physical space, etc.), which must be balanced with optimization of the in-channel and out-of-band performance and the location in the transmitter block diagram where this trade-off is achieved. Requirements for out-of-channel emissions are covered by Adjacent Channel Leakage Ratio (ACLR) and Spectrum Emission Mask (SEM) measurements, as was the case for Universal Mobile Telecommunications Service (UMTS). These measurements are generally made with spectrum or signal analyzers using built-in routines for ACLR and SEM. The measurements can be done using either swept analysis in a signal or spectrum analyzer or using FFT analysis in a VSA. The swept approach offers higher dynamic range and faster measurements.

Power efficiency

Next, power efficiency is a critical design factor for both eNB and UE transmitters and the design must meet power consumption targets while ensuring that the transmitter meets the outputpower, modulation quality, and emission requirements. There are no formal requirements for power efficiency, although this may change in the future with increased environmental awareness. Instead, power efficiency remains an ever-present design challenge to be met through design choices and optimization.
Strategies for handling high-peak power

With high-peak power, we observe that OFDMA signals can have a high Peak-to-Average Power Ratio (PAPR) and eNB power amplifiers must have a high degree of linearity to avoid producing out-of-channel distortion products. Power amplifiers with high linearity for the eNB are expensive and modest in their power efficiency. Two complementary methods exist to counteract this challenge: Crest Factor Reduction (CFR), which attempts to limit the signal peaks, and predistortion, which attempts to match the signal to the non-linear characteristics of the amplifier.

CFR was first widely used with CDMA signals and is also an important technique for LTE, although the specifics of the implementation will be somewhat different. CFR is distinct from predistortion in that it attempts to limit the peaks in the signal before it reaches the amplifier rather than shaping the input signal to compensate for amplifier nonlinearity. As such, CFR is a general technique that can be applied to any amplifier design. CFR improves headroom at the cost of degraded in-channel performance. OFDM signals without CFR have RF power characteristics similar to that of Additive White Gaussian Noise (AWGN), with peak power excursions more than 10 dB above the average power. It is impractical to design and operate power amplifiers with this level of headroom. Careful use of CFR can substantially reduce peak power requirements while maintaining acceptable signal quality. The effectiveness of CFR can be evaluated using the Complementary Cumulative Distribution Function (CCDF) applied to a series of instantaneous power measurements.

Predistortion enables the use of amplifier technologies that are both more power-efficient and less costly, although predistortion also adds design and operational complexity. Predistortion is a more advanced power management technique than CFR because it requires tight coupling to a specific amplifier design. Predistortion maintains the in-channel performance while operating in the non-linear region of the amplifier. This minimizes signal compression so that out-of-channel performance does not degrade at the higher operating level. A number of analog and digital predistortion techniques are available, from analog predistortion to feed-forward techniques and the full adaptive-digital predistortion used in the latest generations of more power-efficient base stations requiring digital-in, RF-out test functionality.

Finally, consider that optimizing designs for sufficient phase noise performance is particularly challenging in OFDM systems for two reasons. First, excessive phase noise degrades the orthogonality of the closely spaced subcarriers causing frequency domain Inter-Carrier Interference (ICI) leading to impaired demodulation performance. Second, phase noise reduction can be expensive in terms of system cost and power efficiency. Relatively, these costs are a larger issue for the UE as opposed to the eNB.
Analysis of MIMO signals has to be a multi-step process to ensure we find a root cause of any problems in the transmitters. When complex digitally modulated signals are verified and optimized, it is tempting to go directly to advanced digital demodulation measurements using vector signal analysis. However, it is usually more productive and sometimes necessary to follow a verification sequence that begins with basic spectrum measurements and continues with vector measurements (combined frequency and time) before switching to digital demodulation and modulation analysis, as shown in Figure 16.

Each of the verification sequence stages are represented below with example measurements, beginning with RF spectrum measurements (Figure 17), then proceeding to vector measurements (Figure 18), and finally to digital demodulation (Figure 19). The latter shows:

- Trace A – the IQ constellation (which shows the analyzer has locked to and demodulated the signal)
- Trace B – power and frequency from a single FFT
- Trace C – the error vector spectrum
- Trace D – the error summary
- Trace E – the EVM in the time domain as a function of symbol
- Trace F – the frame summary

Figure 17. Spectrum of 5 MHz downlink showing power, OBW, and center frequency
Figure 18. CCDF measurements of uplink signals: from left to right, QPSK, 16QAM, 64QAM and the AWGN reference curve

Figure 19. Example analysis of digitally demodulated 5 MHz LTE downlink signal using Keysight 89601A VSA software
While many transmitter measurements are a straightforward matter of connecting the transmitter RF output directly to an RF signal analyzer input and measuring signal characteristics and content, some measurements will require connecting, probing and measuring at early or intermediate points in the transmitter signal chain. Figure 20 shows a typical transmitter block diagram and the possible ways in which signals can be injected or probed at different points.

Figure 20. Stimulus and analysis of different point in the UE block diagram
In the case of MIMO transmission, it may be possible to isolate and measure each transmitter separately, while it may also be that the only access point is to the coupled, precoded signals. When deciding on the measurement method, it’s important to choose the test configuration that will give the most accurate results. Table 2 shows which measurements require single or dual analyzer inputs.

<table>
<thead>
<tr>
<th>Device configuration and analyzer connection</th>
<th>Analyzer Configuration</th>
<th>Measurement steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single input measurement</td>
<td>Using the same analysis configuration steps as SISO signal</td>
<td>Measure power versus time and gated spectrum to ensure each channel has the expected power level and spectrum</td>
</tr>
<tr>
<td>Connect to each transmitter output separately</td>
<td>Start with Demodulator OFF</td>
<td>Record signal and use spectrogram</td>
</tr>
<tr>
<td>TX Diversity or spatial multiplexing ON</td>
<td>Use Hanning window with gate time = 1 symbol (67 us)</td>
<td></td>
</tr>
<tr>
<td>Codebook index = 0</td>
<td>Turn Demodulator ON</td>
<td>Sync to P-SS or RS</td>
</tr>
<tr>
<td></td>
<td>Display RS, P-SS, and S-SS (which may not be configured for all transmitters)</td>
<td>Check constellation and EVM of uncoupled signal elements</td>
</tr>
<tr>
<td></td>
<td>Shared Channel and Control Channel Precoding ON</td>
<td>Check constellation and EVM of diversity and SM signals</td>
</tr>
<tr>
<td>Combine signals using a power coupler</td>
<td>Two or four transmitter ports active</td>
<td>Check all RS based measurements</td>
</tr>
<tr>
<td>Codebook index = 0</td>
<td>Allows precise measurement of relative power, timing and phase</td>
<td></td>
</tr>
<tr>
<td>Measure signals using a two-input analyzer</td>
<td>Two inputs needed to remove the effect of coupling between the transmitters (e.g. precoding)</td>
<td>Check shared channel constellations and EVM with all codebook values</td>
</tr>
<tr>
<td>All codebook values</td>
<td>Allows measurement of the residual error that will be seen by the UE receiver</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. A basic structure for diagnosing multi-transmitter signal impairments
Today’s design techniques center around system simulation to avoid costly hardware iterations and speed up the overall design process. Keysight offers design tools which, later in the design process, can be interfaced with test instrumentation to provide a mixed hardware and simulation environment, so that engineers can functionally test completed components and subsystems in a system context. Figure 21 shows a complete transmitter and receiver with a faded MIMO channel using Keysight SystemVue software.

As shown in Figure 21, combining simulation with test offers a number of benefits. Simulation is a powerful and flexible way to model both baseband and RF design elements as well as RF path impairments and the creation of pre-coded MIMO channels. As the design is turned into functioning physical blocks, combining simulation with test instrumentation allows stimulation and analysis of the blocks in a “real-world” environment.

One powerful example is to create a MIMO dual-transmitter source and perform coded BER measurements on a complete MIMO dual-receiver and baseband combination. The transmitter payload can be either digital or analog IQ data, combined with control and pre-coding, with real-time error analysis provided by comparing the receiver data output with the sent data. Stress-testing the receivers by applying known fading and channel coupling scenarios, while measuring real-time BER, builds confidence that the design will work correctly in the real-world. The block diagram of such a system is shown in Figure 22.
Conclusion

This overview of MIMO and LTE has shown some of the engineering challenges associated with implementing spatial multiplexing and other system features of LTE. This knowledge can help receiver and transmitter designers improve their designs through insight gained from key measurements.

Evolving Since 1939

Our unique combination of hardware, software, services, and people can help you reach your next breakthrough. We are unlocking the future of technology.

From Hewlett-Packard to Agilent to Keysight.