Introduction

A common theme in modern wireless communications is the use of multi-antenna techniques, such as beamforming and spatial multiplexing in order to improve the cell capacity and throughput. A common problem encountered by customers today, is the inability to verify and visualize the signal at the RF antenna.

This white paper will summarize multi-antenna techniques, before introducing the concept of beamforming, along with its advantages and specific use within the 3GPP TD-LTE wireless communication system. It will discuss multi-antenna beamforming measurement challenges from an eNB base station test perspective. It will also highlight the importance of calibration when it comes to testing the performance of a beamforming transmission system.

As part of this TD-LTE beamforming discussion an introduction to the Agilent N7109A Multi-Channel Signal Analyzer is provided, along with the Agilent 89600 VSA software installed with the TD-LTE measurement application. Together this test and measurement solution will enable you to verify and visualize your TD-LTE beamforming signals.
A summary of multi-antenna techniques employed by various modern wireless communications systems is shown in Figure 1, which captures the concept of Single-Input Single-Output (SISO), Single-Input Multiple-Output (SIMO), Multiple-Input Single-Output (MISO), and Multiple-Input Multiple-Output (MIMO).

SISO being the most basic radio channel access mode sets the baseline for minimum transmission performance and provides no diversity protection against channel fading.

SIMO provides additional receive antenna redundancy compared to the SISO baseline, allowing the use of receive diversity techniques such as maximum ratio combining in the receiver. This improves SINR observed at the device receiver, and can help improve robustness under channel fading conditions.

MISO provides additional transmit antenna redundancy, allowing the use of transmit diversity techniques such as Alamouti symbol coding, or Space Frequency Block Coding (SFBC) as is the case for LTE. Similar to SIMO this also provides an improvement in the observed SINR at the device receiver, and can again help provide protection against channel fading.

In contrast MIMO provides both additional transmit and receive antenna redundancy. This redundancy can be used to improve the SINR at the device receiver using transmit and/or receive diversity techniques. Alternatively some or all of the potential SINR performance improvement can instead be traded off in order to obtain an improved spectral efficiency, by employing spatial multiplexing transmission techniques. This improved spectral efficiency can be realized either in the form of increased data rate throughput for a single user device using Single-User MIMO (SU-MIMO) techniques, or alternatively in the form of increased system cell capacity using Multi-User MIMO (MU-MIMO) techniques.

In addition to the diversity and spatial multiplexing techniques summarized above, it is possible to use the multi-antenna path redundancy to support transmit and/or receive beamforming techniques to improve system performance, as will be introduced next.
To begin, let’s compare and contrast the basic principles of transmit diversity, spatial multiplexing and beamforming in the context of a multi-antenna transmitter. Figure 2 captures the concept of these three transmission techniques in turn.

In the case of transmit diversity; orthogonally modified redundant copies of an information symbol pair $S_0$ and $S_1$, are transmitted simultaneously in time across the multiple antenna elements, as shown in left of Figure 2 for a subcarrier pair SFBC example. The benefit is improved SINR observed at the device receiver, plus improved robustness to channel fading.

In the case of spatial multiplexing; separate unique information symbols $S_0$ and $S_1$, are transmitted simultaneously in time across the multiple antenna elements, as shown in center of Figure 2. The benefit is improved spectral efficiency observed either as increased individual user throughput or as increased cell capacity.

In the case of beamforming; weighted copies of an information symbol $S_0$, are transmitted simultaneously in time across the multiple antenna elements, as shown in right of Figure 2 where $w_0$ and $w_1$ represent the applied complex per antenna weightings. The benefit is improved SINR observed at the receiver of the primary target device resulting from a coherent signal gain, plus the ability to minimize interference to other devices within the system.

**Beamforming selectivity**

Beamforming techniques are used within many different technologies such as radar, sonar, seismology, radio astronomy, acoustics and wireless communications.

In the general case, transmit beamforming works by exploiting the interference patterns observed whenever the same signal is transmitted from two or more spatially separated transmission points. A similar principle applies whenever the same signal is received from two or more spatially separated reception points, which is exploited by receive beamforming techniques.

As a simple example let’s consider the case of an RF wireless signal transmitted from a single omnidirectional antenna, the resulting signal relative field strength is shown in Figure 3 (a) represented as a solid blue line.
To enable transmit beamforming a second identical omnidirectional antenna element is added, separated from the first element by half the RF carrier wavelength as shown in Figure 3 (b). In this example both antenna elements carry identical copies of the signal information symbol to be transmitted. Immediately it can be seen that in azimuth directions around 0 degree where constructive (or in phase) interference occurs, the combined field strength increases producing an effective coherent signal power gain in those directions. This is in contrast to azimuth directions around +/-90 degree where destructive (or out-of-phase) interference occurs, resulting in a decreased or attenuated combined field strength in those directions.

Adding a third antenna element, separated along the same axis as the first two elements by half the RF carrier wavelength improves the spatial selectivity of the combined relative field strength as shown in Figure 3 (c). In our example the array elements are co-polarized, correlated and uniformly separated along a single antenna element axis, creating a Uniform Linear Array (ULA) antenna system. The formation of a single main lobe in the azimuth direction of 0 degrees relative the ULA broadside can clearly be seen. This is where maximum constructive (or in phase) interference occurs, producing a power gain maximum within the combined field strength beam pattern. The formation of two distinct power attenuation nulls, one either side of the main lobe located at +/-42 degrees azimuth can now be observed. These two power minimum locations represent the azimuth directions in which maximum destructive (or out-of-phase) interference occurs within the combined field strength beam pattern.

Figure 3. ULA Beamforming examples
Finally adding a fourth antenna element to the ULA further improves the main lobe selectivity as shown in Figure 3 (d). The number of power nulls has also increased from two to three. Two nulls are now located at +/-30 degrees azimuth, with the third is located on the ULA antenna axis line. The formation of two distinct power side lobes are now clearly observed, located at +/-50 degrees azimuth. Both side lobes appear at reduced power levels relative to the main lobe.

The resultant beam pattern is determined not only by the ULA physical geometry and element separation, but is also affected by the relative magnitude and phase weightings applied to each information symbol copy transmitted on each antenna element. This can be demonstrated by now introducing a +90 degree relative phase shift weighting across each of the four antenna elements. The result is a shift of the main beam location from 0 degrees azimuth to -30 degrees azimuth as shown in Figure 3 (e). Note that the null and side lobe locations have also been affected by the new weighting values.

By careful design of the beamforming antenna array geometry, plus accurately controlling the relative magnitude and phase weightings applied to each of the antenna elements it is possible to control not only the selectivity shape and azimuth direction of main lobe power transmissions, but also possible to control the power null azimuth locations and side lobe levels.

**Beamforming gain**

At this stage it is important to note that the combined beam pattern in Figure 3 focuses on the spatial selectivity improvements, and as such the main lobe peak powers of plots (b) through (e) are shown normalized to the single antenna plot (a) case.

Let’s now separately consider the impact of adding additional antenna elements on the effective power gain of the resultant beam pattern observed at a target device receiver.

In Figure 3 plot (b) a second antenna element was added, which transmitted an exact symbol copy of what was being transmitted on the first antenna element. In this case, the constructive in-phase signal summation would result in a 6 dB coherent power gain improvement observed by a target device receiver positioned at the 0 degree azimuth main beam location. Therefore if plot normalization were not applied, the main lobe maximum of Figure 3 plot (b) two antenna case would in theory be twice the main lobe maximum of plot (a) single antenna case.

This 6 dB coherent gain improvement can be considered as the beamforming gain improvement observed at the target device receiver, due to using two spatially separated antenna elements relative to a single antenna transmission.

In practice the symbol power levels transmitted on each of the two antenna elements may be reduced by 3 dB to half the original single antenna symbol power level, maintaining the same total transmitter power as the single antenna case. Even so, this would still result in a 3 dB beamforming gain observed at the target device receiver relative to a single antenna transmission.
**Beamforming advantages**

The use of multi-antenna beamforming transmission is very attractive in modern wireless communication systems due to the combined advantages of beamforming selectivity, interference management and coherent signal gain.

Let’s summarize some important aspects and terminology used to describe beamforming transmissions in the context of Figure 4.

- **Main Lobe:** the primary maximum transmission power lobe, usually directed at the target device or a transmission path that will reach the target device by reflections in the radio propagation channel.
- **Side Lobe:** the secondary power transmission lobes which can potentially produce unwanted interference to other user devices within the serving or adjacent cells.
- **Power Null:** locations of minimum power within the transmission beam pattern which the system may choose to exploit and control in order to mitigate interference to other devices within the serving or adjacent cells.
- **Main Beam Width (Φ):** selectivity of the main lobe transmission measured as the degree azimuth spread across the 3 dB points of the main lobe.
- **Main Lobe to Side Lobe Levels:** the selectivity power difference of the desired main lobe transmission power relative to the unwanted side lobe transmission power.
Figure 5 illustrates two practical scenario examples which both exploit the advantages of beamforming to improve performance within a modern cellular wireless communication system.

Figure 5 (a) depicts two adjacent cells each communicating with a respective UE located at the boundary between the two cells. The illustration shows eNB1 is communicating with target device UE1, with the eNB1 transmission using beamforming to maximize the signal power in the azimuth direction of UE1. At the same time it can be observed that eNB1 is attempting to minimize interference to UE2 by steering the power null location in the direction of UE2. Similarly eNB2 is using beamforming to maximize reception of its own transmission in the direction of UE2, whilst minimizing interference to UE1. In this scenario, it is clear that the use of beamforming can provide considerable performance improvements particularly for cell edge users. The beamforming gain can also be used to increase the cell coverage where required.

Figure 5 (b) depicts a single cell (eNB3) communicating simultaneously with two spatially separated devices (UE3 and UE4). Since different beamforming weightings can be applied independently to each of the spatial multiplexing transmission layers, it is possible to use Space Division Multiple Access (SDMA) in combination with MU-MIMO transmissions in order to deliver an improved cell capacity.
Beamforming implementation techniques

Two different beamforming implementation techniques are illustrated in Figure 6. Figure 6 (a) shows an example of a fixed conventional switched beamformer consisting of an eight-port Butler matrix beamforming network. This network implementation consists of a matrix of different selectable fixed time or phase delay paths, implemented using a combination of 90° hybrid couplers and phase shifters.

The number of fixed transmission beams produced is equal to the number of antenna elements N used to form the Butler matrix network. (The example shown uses eight antennas, producing eight selectable beams.) This is sometimes also referred to as a “grid of beams” beamforming network, and supports selection of any individual or combination of the N fixed transmission beams in order to maximize the SINR at the device receiver.

In a wireless network, optimal eNB downlink transmission beam selection would primarily be driven by some knowledge of the UE position within the cell. This knowledge can readily be obtained directly through measurement of the uplink signal Angle of Arrival (AoA) across the eNB receive antenna array, or indirectly derived from uplink control channel quality feedback information.

Figure 6 (b) shows an example of an adaptive beamformer. As the name suggests, an adaptive beamformer has the ability to continually adapt and re-calculate the optimum applied transmission beamforming complex weighting values in order to best match the channel conditions.

Because the adaptive beamformer weightings are not fixed, it can not only optimize the received SINR at the target UE, but also better adapt the selectivity and power null positioning to minimize interference to other users.
In a wireless network, the eNB would typically estimate the optimum weightings through direct measurement of the received uplink reference signals observed across the eNB receiver array. This information can be then be used to calculate the uplink Angle of Arrival (AoA) as well as decompose the channel characteristic matrix.

For the case of a Frequency Division Duplex (FDD) system, where both downlink and uplink use different RF carrier frequencies, the applied beamforming transmission complex weightings will be primarily driven by measured AoA information derived for both the target UE, as well as knowledge of any other UE’s within the cell. Weighting estimation may also be aided by channel feedback information reported by the UE on the uplink.

For the case of a Time Division Duplex (TDD) system, since downlink and uplink share the same RF carrier frequency, channel reciprocity may be assumed. The applied beamforming transmission complex weightings may therefore be chosen to best match the decomposed channel characteristic matrix eigenvectors, as derived from the eNB received signal. These channel-matched beamforming weightings can help optimize the SINR observed at the target UE receiver. For this reason beamforming in a TDD system can outperform what is possible in an FDD system. Note that for TDD case, the eNB is not reliant on channel feedback information supplied by the user device on the uplink, although in practice, channel feedback may still be used in the eNB beamforming weighting estimation process.
One of the biggest challenges in any modern wireless cellular communications system is the performance at the cell edge. With this in mind it is obvious why beamforming technology has a key role to play in delivery of services within LTE. This section will now specifically focus on the use of beamforming within LTE.

**LTE Downlink transmission mode support for beamforming**

LTE defines many downlink transmission modes, as shown in Figure 7.

![Figure 7. LTE downlink transmission modes](image)

<table>
<thead>
<tr>
<th>3GPP Release 8</th>
<th>3GPP Release 9</th>
<th>3GPP Release 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM1: SISO single antenna transmissions</td>
<td>TM8: Dual Layer Beamforming on Ports 7 &amp; 8</td>
<td>TM9: Up to 8 layer transmissions using Ports 7 to 14</td>
</tr>
<tr>
<td>TM2: Tx Diversity using 2 or 4 antennas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM3: Open-loop SU-MIMO (spatial multiplexing)</td>
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<tr>
<td>TM4: Closed-loop SU-MIMO</td>
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<tr>
<td>TM5: Closed-loop MU-MIMO</td>
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<td>TM6: Rank 1 Spatial Multiplexing</td>
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<tr>
<td><strong>TM7: Single Layer Beamforming on Port 5</strong></td>
<td><strong>3GPP Release 9</strong></td>
<td><strong>3GPP Release 10</strong></td>
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Of particular interest from a beamforming point of view are Transmission Modes 7, 8 and 9. Release 8 introduced TM7, single layer beamforming on antenna port 5. Release 9 added TM8, dual layer beamforming on antenna ports 7 and 8. Finally, Release 10 added TM9, supporting up to eight layer transmission on antenna ports 7 to 14.

It should be noted that the ports mentioned above are all virtual antenna ports. The physical geometry and number of antenna elements is not defined in the LTE specifications. In practice each virtual port’s physical realization may comprise of four or more spatially separated physical antenna elements.

Note that the remainder of this LTE beamforming discussion will focus on transmission modes 7 & 8, which are the main development focus for initial TD-LTE market deployments at the time of this writing.
A summary of the defined downlink signal processing flow for transmission modes 7 & 8 is shown in Figure 8.

As with other transmission modes, the PDSCH data transport block information is channel encoded and rate matching applied, producing either 1 or 2 codewords, which are then mapped onto layers.

But note that for transmission modes 7 & 8 the precoding block is non-codebook based. And so it is left up to the base station to determine the optimum beamforming precoding to apply. This can be derived by the base station from direct measurement of the received UL Sounding Reference signal, plus can include the use of any configured UE channel feedback (CQI / PMI / RI) information. Also note that beamforming precoding can be dynamic, and vary on a per subframe and resource block basis to adapt to changing channel conditions.

For demodulation purposes, transmission TM7 and TM8 include the mapping of UE-specific reference signal (UE-specific RS), also known as demodulation reference signals (DM-RS) in each PDSCH resource block.

It is important to note that the UE-specific RS undergo the same beamforming precoding as the associated PDSCH. This concept is shown in Figure 8. The beamforming precoding is primarily calculated to maximize the SINR observed by the target UE device, but will also attempt to minimize interference to other UE within the serving or adjacent cells.

As well as producing user specific beam patterns, the base station also has the capability of shaping a desired sector wide broadcast beam pattern for common control channel content, which is received by all user devices within the cell. This is possible when the number of beamforming antenna elements is greater than the number of configured Cell-specific RS Ports. This concept is also shown in Figure 8.
LTE UE-specific reference signals structure

In order to support beamforming for TM7, 8 and 9, UE-specific RS are defined for port 5 and ports 7 through 14. The physical structure of the UE-specific RS is shown in Figure 9 for TM7 and 8 cases.

Transmission Mode 7 supports only single layer beamforming transmissions. For this purpose port 5 UE-specific RS resource element mappings are defined in time and frequency within each scheduled PDSCH resource block assignment as shown in Figure 9. Since the UE-specific RS undergo the same beamforming weight precoding as the associated PDSCH data, it is possible for the target UE to directly demodulate the precoded PDSCH using the similarly precoded UE-specific RS as the reference.

Transmission Mode 8 extends beamforming to dual layer spatial multiplexing. For this purpose ports 7 & 8 UE-specific RS resource element mappings are defined. Each port corresponds with a different spatially multiplexed MIMO transmission layer. It is worth noting that the same physical resource elements are used by both port 7 and port 8. In order that the UE can correctly separate these simultaneously transmitted UE-specific RS, orthogonal UE-specific RS sequences are used.

The UE-specific RS resource mappings for Ports 7 & 8 are further extended using a combination of orthogonal frequency (FDM) and code (CDM) resources in order to support ports 9 through 14 required for TM9.

From a test point of view, it is essential that the UE-specific RS content for TM7, 8 and 9 is verified for baseband correctness, as well as relative magnitude and phase weighting accuracy observed at the calibrated RF output of the antenna element array.
This section introduces a typical TD-LTE eNB antenna configuration and system test setup used to verify performance of downlink beamforming and spatial multiplexing signals used for TM7 and TM8.

It demonstrates how the use of a phase coherent multi-channel signal analyzer along with appropriate measurement application software can be invaluable in the beamforming signal verification process, as well as enabling visualization of the beamforming signal at the RF antenna array. The importance of calibration when it comes to verifying the performance of a beamforming transmission system is also given special attention.

**TD-LTE eNB antenna configuration**

Let’s initially consider a typical eNB RF antenna configuration as shown in Figure 10, which is used within TD-LTE cellular networks supporting Transmission Mode 7, 8 & 9 MIMO beamforming signals.

![Figure 10. Typical eight-antenna configuration for TD-LTE TM7, 8 and 9](image)

The example is an eight-element physical antenna, configured with two groups of antenna elements. Each group is orthogonally cross-polarized at 90 degrees to the other group. Antenna group 0 consists of antenna elements 1 through 4, polarized at plus 45 degrees. Antenna group 1 consists of antenna elements 5 through 8, polarized at minus 45 degrees.

Each of the elements within a given group are spatially separated by approximately half the RF carrier wavelength. This provides a high degree of antenna element correlation within the antenna group, which is good for coherent beamforming.

And since each of the two groups are cross-polarized relative to each other, there is a low correlation between each of the two antenna groups, which is good for spatial multiplexing.

In summary, a typical TD-LTE eNB RF antenna physical configuration attempts to satisfy the desirable but conflicting correlation requirements for MIMO spatial multiplexing and coherent beamforming.
TD-LTE eNB test system configuration

Now let’s consider a typical TD-LTE MIMO beamforming transmission mode 7 & 8 eNB test configuration as shown in Figure 11.

Starting from the center-left the main eNB blocks are illustrated, comprising of Base Band (BB) and Remote Radio Head (RRH). The RRH provides eight antenna feeds which are connected for test purposes to an RF antenna calibration coupler unit. Note that calibration of the RF antenna elements is achieved using a dedicated calibration port, between the RRH and the RF antenna calibration coupler.

The RRH is capable of generating a known calibration signal to be used as a common magnitude and phase reference. This calibration signal is periodically injected via the calibration port into the RF antenna network. The eNB is then able to measure the RF coupled calibration signal observed on each of the eight receiver ports of the RRH. This allows the eNB to monitor and correct for per antenna magnitude and phase variations inherent in the system due to the antenna feed cabling and coupler variations. The periodicity of eNB in-service calibration measurements can vary, and will depend on environmental operating conditions. Verification of the eNB calibration performance is a very important aspect of beamforming test.

The calibration coupler output is typically fed into an RF downlink channel emulator, shown here in an 8x2 configuration, to emulate the downlink channel characteristics. The two RF outputs of the channel emulator are connected to the UE.

In our example, the UE transmits the uplink signal on two output ports, which can be connected to an uplink RF channel emulator in a 2x8 configuration, to emulate the uplink channel characteristics.

Finally, to complete the UE feedback loop, the eight RF outputs from the uplink channel emulator are coupled back into the eNB’s eight receive antenna ports using RF circulators.
Beamforming measurement challenges

One of the main test challenges is the ability to verify and visualize the beamforming signal performance at the physical RF antenna array. This is important in order to validate:

- eNB RF antenna calibration accuracy
- Baseband encoded beamforming weighting algorithm correctness
- MIMO single and dual layer EVM at the RF antenna

One solution to this test challenge is the Agilent N7109A Multi-Channel Signal Analyzer, along with the 89600 VSA software installed with the TD-LTE measurement application. The N7109A Multi-Channel Signal Analyzer can support eight phase-coherent RF measurement channels, and using appropriate RF splitters and attenuators, can easily be integrated into a typical TD-LTE base station test setup, as shown in Figure 11.

The Agilent 89600 VSA software, provides a correction wizard for the N7109A which can be used along with an Agilent MXG or ESG-C signal generator and appropriate high quality calibration two-way RF power splitter in order to correct for all the RF cabling and connectors used within the test system. Note that the quality of the corrections will be determined by the quality of the power splitter and any connectors required between the power splitter and your measurement cables. The signal generator is used to create a broadband calibration reference signal output which is connected to the input of the two-way power splitter. The desired beamforming measurement verification point in Figure 11 is indicated by a dotted line at the output of the RF antenna calibration coupler. It is therefore essential to compensate for any magnitude and phase mismatch inherent in the measurement cables, connectors, splitters and attenuators used between the RF antenna calibration coupler eight output ports and the N7109A eight input channels.

Under the guidance of the correction wizard, the user is prompted to connect the N7109A channel 1 measurement cable (located on dotted line) to the first output port of the two-way calibration splitter. Note all cross channel characterization measurements will be made referenced to channel 1. The user is then prompted to connect each of the remaining channels 2 through 8 measurement cables (located on dotted line) one at a time to the second output port of the two-way calibration splitter. In this way the correction wizard is able to characterize the cross channel corrections required to compensate N7109A beamforming measurements for all mismatch effects inherent in the measurement cables, connectors, splitters and attenuators. This allows direct, corrected measurements of the antenna beamforming performance observed at the RF antenna output.

The importance of test system calibration of magnitude and phase variations due to RF cabling and connectors cannot be overstated. Calibration is covered in more detail within “Calibration of the beamforming test system” section on Page 23.
Verification and visualization of MIMO beamforming signals

This section discusses some of the useful verification measurements that can be made using the test system shown in Figure 11.

With the 89600 VSA software and N7109A Multi-Channel Signal Analyzer combination it is useful to start by viewing the time-synchronized RF signal capture from all eight antenna elements as shown in Figure 12. Any fundamental RF power or timing performance impairments can be quickly identified early on, prior to attempting the more advanced demodulation measurements.

Using the 89600 VSA Spectrogram feature, provides useful insight into the frequency resource activity as shown in Figure 13. This allows a quick picture to be built up of RF activity on a per subframe basis for user specific resource block scheduling, as well as on a per symbol basis for common control channels and signals. Note this feature does not require demodulation and so is a very simple and useful debugging tool when investigating unexpected RF or scheduling related issues, especially when those issues impair normal demodulation of the signal.

Figure 12. Time-synchronized capture of eight-antenna transmission

Figure 13. Spectrogram of eight-antenna transmission
Prior to demodulating the TD-LTE signal it is important to properly configure the 89600 VSA software Antenna Group parameter with the appropriate number of elements and spacing used to match our physical RF Antenna configuration as shown in Figure 14.

As mentioned earlier, the beamforming weightings can be changing on each resource block, therefore the UE-specific weighting results may either be viewed per resource block, or alternatively per user allocation.

The 89600 VSA software TD-LTE measurement application provides a rich set of demodulation results to help you verify and visualize your downlink MIMO beamforming signals. These include IQ constellations, EVM result metrics, detected resource allocations, UE-specific RS weights, Cell-specific RS weights and impairments as well as UE-specific and common broadcast antenna beam patterns. A closer look will now be taken at some of these measurements.

The demodulated IQ Constellations are displayed per spatial multiplexing layer as shown in Figure 15 traces A and L, and provide a quick visual indication of the signals modulation quality correctness.
The frame summary shown in Figure 15 trace D provides access to individual EVM and power metrics associated with each channel and signal type. It also provides a color key for all channel type results, which is reused throughout the VSA traces.

The detected allocations displayed in Figure 15 trace B lets you visualize the resource block allocations for each user specific transmission, plus resource allocations used by common control channels.

Measured UE-specific RS weights are presented in table format for each of the eight antenna elements as shown in Figure 16 Trace A. Weightings can be evaluated in both magnitude and phase down to the individual resource block allocations associated with each user transmission. Separate UE-specific RS weights traces are available for each spatial multiplexing layer.
To help you visualize the beamforming performance, the VSA software also presents the resulting combined beam pattern trace associated with each antenna group. Measured UE-specific RS weights from the first four channels are used to compute the antenna group 0 beam pattern as shown in Figure 16 trace L. This process is repeated using the second four channels producing the antenna group 1 beam pattern results as shown in Figure 16 trace B. Note that a separate beam pattern trace can be visualized for each resource block associated with each user device.

Similar to the way the IQ Constellation provides a quick visual health check of modulation quality, the antenna group beam pattern trace provides a quick visual health check of beamforming baseband encoding and RF calibration quality. Any identified anomalies can be investigated in detail using the UE-specific RS metrics.

Channel frequency, magnitude and phase response traces can be viewed simultaneously for all eight antenna elements, along with the VSA common tracking error trace as shown in Figure 17 traces A, L and B respectively.

The common tracking error trace is particularly useful to understand and compare each of the eight transmit antennas common Cell-specific RS (CRS) magnitude and phase performance stability over time.
Figure 18. MIMO info display and Cell-specific RS broadcast beam pattern

The VSA MIMO Info trace shown in Figure 18 reports Cell-specific RS (CRS) metrics and impairments measured for all eight antenna elements. The reported metrics include CRS power, EVM, timing, phase, symbol clock and frequency error, enabling verification of the common broadcast beam pattern weightings associated with each antenna element.

The VSA software also extracts these relative antenna weightings in order to produce the CRS derived, sector wide broadcast beam pattern results. These broadcast beam pattern results are displayed as the blue colored pattern results in Figure 18 traces L and D, associated with antenna groups 0 and 1 respectively.

The user-specific and common broadcast beam pattern results can be viewed in either IQ polar format or log magnitude (dB) format as shown in Figure 19 traces A and L respectively. Both formats support markers for easy tracking of main lobe peak levels and azimuth locations during live measurement updates. Markers can also be used to read out various beam pattern characteristics like null depth, azimuth locations, and main lobe to side lobe levels.
It is worth highlighting that for this specific example signal, the channel frequency magnitude response derived from the CRS content varies by as much as 0.6 dB across the 20 MHz transmission bandwidth as can be observed in Figure 17 trace A. This magnitude response variation is due to the transmission filtering used, and so it equally applies to all channel types including UE-specific RS weights and associated PDSCH content. This magnitude response variation is also observed in the user-specific and common broadcast beam pattern results of Figure 19 trace A. Each beam pattern corresponds to a different resource block allocation, and just as the channel frequency magnitude response is attenuated at the transmission bandwidth lower and upper edges, so the per resource block beam pattern magnitudes are also attenuated at the transmission bandwidth lower and upper edges.

A key metric to be verified in TD-LTE beamforming transmissions is beamforming gain. The 89600 VSA software has a beamforming gain results trace for this purpose as shown in Figure 19 trace B. This trace reports the dB difference between each UE-specific beam pattern, and the common CRS broadcast beam pattern, to produce a beamforming gain trace result for each user allocation. The beamforming gain results can be viewed for each individual resource block associated with each user’s allocation.

Figure 19. User-specific and cell broadcast beam patterns in polar and log magnitude format plus beamforming gain

A key metric to be verified in TD-LTE beamforming transmissions is beamforming gain. The 89600 VSA software has a beamforming gain results trace for this purpose as shown in Figure 19 trace B. This trace reports the dB difference between each UE-specific beam pattern, and the common CRS broadcast beam pattern, to produce a beamforming gain trace result for each user allocation. The beamforming gain results can be viewed for each individual resource block associated with each user’s allocation.
Calibration of the beamforming test system
The importance of correcting measured beamforming results for all RF cabling and connectors used in the test setup cannot be overstated. This section will now visually illustrate that importance in detail using the simple calibration setup illustrated in Figure 20.

The example calibration test system consists of an Agilent MXG RF signal generator, connected via a 1 to 4 way RF splitter network to the four RF inputs of an Agilent N7109A Analyzer, which is controlled by the Agilent 89600 VSA software application.

As mentioned within the “Beamforming measurement challenges” section on Page 16, the 89600 VSA software provides a Correction Wizard utility program for the N7109A which can be used to correct for magnitude and phase delay variations observed between each of the N7109A RF input channels. These magnitude and phase variations will in part be due to slight performance variations within each of the N7109A multi-channel phase coherent receiver paths. But perhaps more importantly these variations will also be due to any magnitude and phase delay variations observed between the RF cabling, splitters, and adaptors used between the RF Antenna calibration reference point and the N7109A RF input ports.

The N7109A Correction Wizard can directly control the MXG to generate an appropriate wideband modulated calibration signal to exercise the frequency band of interest. The wizard also directly controls the 89600 VSA software to measure the Cross Channel Frequency Response trace results for all RF input channels relative to channel 1, which is used as the reference channel. In this way the correction wizard can measure and characterize both the magnitude and phase response variations between each of the N7109A RF input channels (including measurement cabling, splitters and adaptors) at the RF carrier measurement frequency and band of interest. By loading the per channel characterized magnitude and phase responses into the 89600 VSA Fixed Equalization feature, it is then possible to compensate and correct all 89600 VSA results for the relative channel by channel magnitude and phase response offset variations.
Figure 21 (a) screenshot shows the uncorrected magnitude and phase response plots for measurement channels 2, 3 and 4, all displayed relative to the reference measurement channel 1. It can be seen that in our example the uncorrected relative channel magnitude responses can vary as much as minus 0.95 dB, as is the case for channel 3 relative to channel 1 shown in trace C. It would also be expected that the uncorrected relative phase variation between channels could fall anywhere between +/- 180 degrees range, as indicated by the spread of uncorrected relative phase results in our example in traces F, G and H.

Figure 21 (b) screenshot shows the equivalent corrected magnitude and phase response plots for measurement channels 2, 3 and 4 relative to reference channel 1. As can be seen the corrected relative channel magnitude and phase responses now appear as flat responses compared with the uncorrected results. The maximum magnitude response variation has dropped to around minus 0.02 dB, and also the maximum phase response variation has dropped to less than 0.1 degrees after applying the VSA cross channel corrections.

Using the Agilent N7625B Signal Studio for 3GPP LTE TDD application software, it is possible to generate and download a 20MHz TD-LTE downlink signal configured with a single user scheduled with Transmission Mode 7 (Port 5) PDSCH plus associated UE-specific RS resource allocations in subframes 0 and 5. Figure 22 shows the resulting uncorrected and corrected 89600 VSA demodulation results for comparison purposes.
Figure 22 (a) screenshot shows the uncorrected results. It can immediately be observed that the antenna group 0 beam pattern results in trace H are not as one might initially expect given the simple test setup where the MXG output RF source is being split directly to each of the four N7109A input channels. Theoretically one might expect to see a main lobe appearing at 0 degree azimuth, as was the case in Figure 3 plot (d). Also it can be noted that the power null depth is around 25 dB down from main lobe level. But of course in practice the uncorrected variations in relative per channel magnitude and phase responses of the RF splitters, cabling, adaptors and N7109A receiver paths will all contribute to effect the reported UE-specific RS magnitude and phase result metrics shown in trace C. These per channel response variations will then also affect the derived antenna group 0 beam pattern results of traces H and L.

By enabling the 89600 VSA per channel fixed equalization feature, the improved corrected demodulation results are observed as shown in Figure 22 (b) screenshot. As can be seen, the results now align very well with the theoretical results of Figure 3 plot (d). Now it is possible to identify a distinct power main lobe at 0 degree azimuth and the power null depths are much improved at greater than 40 dB down from main lobe level.
To better understand the sensitivity of the beamforming measurement results to any uncalibrated changes to the test setup let’s consider the effect of making two different physical test setup changes to the original test setup in Figure 20 which has just been calibrated.

First, let’s add a short N-type male-to-female extension adaptor to the existing N7109A input channel 3 N-type cable connection. In our example the effect of this change is to introduce a minus 85 degree phase shift impairment to channel 3 UE-specific RS results as shown in Figure 23 (a) screenshot trace C. The effect of this phase shift impairment is clear to see from the antenna group 0 beam pattern results of traces H and L. The main lobe power has been reduced from 12.04 dB to 10.34 dB as reported by the trace L marker readouts. Also the left side lobe power level is greatly increased, as well as degrading all the power null depths observed in trace L.

Second, let’s replace the original N7109A input channel 3 calibrated 1 meter length N-type RF cable, with an un-calibrated 4 meter length cable. In our example the effect of this change is to introduce a 165 degree phase shift impairment to channel 3 UE-specific RS results as shown in Figure 23 (b) screenshot trace C. Again the effect of this phase shift impairment is clear to see from the Antenna Group 0 Beam Pattern results of traces H and L.
But in this case there also appears to be a distinct azimuth spreading of the reported beam pattern trace results. To explain this, it is first important to understand that trace H and L actually contains a separate beam pattern trace result plot for each of the UE device PDSCH resource block allocations. The UE-specific RS results for each separate resource block are reported within trace C as a separate column entry. It can be observed from trace C that the input channel 3 phase error is actually changing slightly for each measured resource block. The 165 degree error reported for RB0, has reduced to 160 degree for RB5. This changing phase error can be explained by the fact that by introducing a longer RF cable to channel 3, this in effect introduced a fixed time delay impairment to channel 3 reported results. This is confirmed by the “RSTiming” metric, reported in MIMO Info trace K as 17 ns for input channel 3. Since each resource block occupies a different carrier frequency region, the fixed time delay impairment will result in a different phase shift for each RB. The effect on the combined antenna beam pattern trace is a distinct spreading of the observed beam pattern results corresponding to each frequency RB as seen in Figure 23 (b) screenshot trace H.

The key point here is that in order to make accurate measurements of your eNB MIMO beamforming signal performance and eNB beamforming calibration accuracy, it is essential that all the physical cabling, adaptors, splitters and attenuators used in the measurement test setup are included within the calibration correction procedure. Also the calibration should be repeated whenever the measurement setup physical configuration is changed.
Summary

The performance demands placed on any modern wireless cellular communications system like LTE are highest at the cell edge. This is the region where user devices experience the most degraded signal to noise conditions as well as highest levels of inter-cell interference.

In order to meet those most challenging demands the use of multi-antenna beamforming transmission technology has a key role to play. The combined benefits of beamforming selectively, interference management and coherent signal gain can help ensure a more consistent end-user experience, with delivery of key services at an acceptable performance level throughout the entire cellular network.

From an eNB development perspective, the use of multi-antenna beamforming transmission presents some specific test challenges. This includes the need to verify correct implementation of eNB baseband receive/transmit algorithms used to generate beamforming weightings, as well as accurate validation of eNB calibration performance observed at the RF Antenna. When testing a beamforming transmission system the importance of calibration cannot be overstated, and care must be taken to correct for the physical measurement configuration setup used. In addition, since beamforming is combined with spatial multiplexing techniques there is a need to verify EVM performance of each MIMO layer observed at the RF Antenna.

Agilent’s N7109A multi-channel signal analyzer and 89600 VSA software are ideally suited for LTE multi-antenna beamforming measurements. Additional information, including demonstration videos, can be found at http://www.agilent.com/find/N7109A.

An accompanying video to this application note can also be found at http://www.youtube.com/watch?v=mj58aSOZ1Kc or by scanning the following QR code.
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