Keysight Technologies
Design and Verification Challenges: Beamforming

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This section briefly recaps multi-antenna techniques before introducing the concept of beamforming, its advantages, and its use within modern wireless communications systems such as LTE.

Multi-antenna beamforming measurement challenges are discussed from an eNB test perspective, and the importance of calibration is highlighted when it comes to testing the performance of a beamforming transmission system.

6.9.1 Multi-Antenna Techniques Summary

Various multi-antenna techniques employed by LTE are introduced in Section 2.4. These radio access techniques are illustrated in Figure 2.4-1, 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 is the most basic radio channel access mode and sets the baseline for minimum transmission performance. However, SISO does not provide any diversity protection against channel fading.

SIMO provides additional receive antenna redundancy compared to the SISO baseline, which allows the use of receive diversity techniques such as maximum ratio combining in the receiver. This flexibility improves signal to interference noise ratio (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, MISO also provides an improvement in the observed SINR at the device receiver which helps protect 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 receive diversity techniques. Alternatively some or all of the potential SINR performance improvement can instead be traded off 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 receive beamforming techniques to improve system performance, as will be introduced next.

6.9.2 Introduction to Beamforming

The basic principles of transmit diversity, spatial multiplexing, and beamforming are compared in the context of a multi-antenna transmitter. Figure 6.9-1 illustrates the basic concepts.

![Comparison of transmit diversity, spatial multiplexing and beamforming](image)

In the case of transmit diversity, orthogonally modified redundant copies of an information symbol pair, S0 and S1, are transmitted simultaneously in time across the multiple antenna elements. The example at the far left of Figure 6.9-1 shows SFBC transmit diversity for a subcarrier pair. The symbols S0 and S1 are transmitted on different subcarriers on Tx0 and the complex subjugate of the symbols (denoted by *) is transmitted on Tx1, with S1 also being negated. The benefit is improved SINR, observed at the device receiver, plus improved robustness to channel fading.
In the case of spatial multiplexing, separate and unique information symbols, S0 and S1, are transmitted simultaneously in time across the multiple antenna elements, as shown in the center example of Figure 6.9-1. The benefit is improved spectral efficiency observed as either increased individual user throughput or increased cell capacity.

In the case of beamforming, weighted copies of an information symbol, S0, are transmitted simultaneously in time across the multiple antenna elements, as shown in the example at the far right of Figure 6.9-1. In this example w0 and w1 represent the applied complex per antenna weightings. The benefits are 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.

6.9.2.1 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.

A simple example is the case of an RF wireless signal transmitted from a single omnidirectional antenna. The resulting signal relative field strength is shown in Figure 6.9-2 (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 6.9-2 (b). In this example both antenna elements carry identical copies of the signal information symbol to be transmitted. However, in the azimuth directions around 0 degrees azimuth, where
constructive (or in phase) interference occurs, the combined field strength increases, producing an effective coherent signal power gain in those directions. In contrast the azimuth directions around ±90 degrees, where destructive (or out-of-phase) interference occurs, result 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 6.9-2 (c). In this 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 to the ULA broadside can clearly be seen. This main lobe region 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.

Finally, adding a fourth antenna element to the ULA further improves the main lobe selectivity as shown in Figure 6.9-2 (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 located on the ULA antenna axis line. 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 also by the effects of the relative magnitude and phase weightings applied to each information symbol copy transmitted on each antenna element.

This sensitivity of the lobe to power and phase changes can be demonstrated by now introducing a +90 degrees 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 6.9-2 (e). Note that the null and side lobe locations have also been affected by the new weighting values.

With careful design of the beamforming antenna array geometry and accurate control of 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 the power null azimuth locations and side lobe levels.

### 6.9.2.2 Beamforming Gain

At this stage it is important to note that the combined beam pattern in Figure 6.9-2 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. The next example considers how adding more antenna elements affects the effective power gain of the resultant beam pattern observed at a target device receiver.

Figure 6.9-2 plot (b) shows the addition of a second antenna element, which transmits an exact symbol copy of what is being transmitted on the first antenna element. In this case, the constructive in-phase signal summation results in a 6 dB coherent power gain improvement, observed by a target device receiver positioned at the 0 degrees azimuth main beam location. If plot normalization had not been applied, the main lobe maximum of the plot (b) two antenna case would in theory be twice the main lobe maximum of the plot (a) single antenna case.
The 6 dB coherent gain improvement is considered to be the beamforming gain improvement observed at the target device receiver and is the result of 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, the result will still be a 3 dB beamforming gain observed at the target device receiver relative to a single antenna transmission.

**6.9.2.3 Beamforming Advantages**

The use of multi-antenna beamforming transmission is very attractive in modern wireless communication systems because it offers the advantages of beamforming selectivity, interference management, and coherent signal gain. Some important concepts and terminology used to describe beamforming transmissions are summarized below and illustrated in Figure 6.9-3.

- **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 lobes**: the secondary power transmission lobes which can produce unwanted interference that affects 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.

![Beamforming terminology](image)

Figure 6.9-3. Beamforming terminology
Figure 6.9-4 shows two practical scenarios, both of which exploit the advantages of beamforming to improve performance within a modern cellular wireless communication system.

Figure 6.9-4 (a) depicts two adjacent cells, each communicating with a UE located at the boundary between the two cells. The illustration shows that eNB1 is communicating with target device UE1. The eNB1 transmission is using beamforming to maximize the signal power in the azimuth direction of UE1. At the same time 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 while 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 6.9-4 (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 to deliver an improved cell capacity.
6.9.2.4 Beamforming Implementation Techniques

Two different beamforming implementation techniques are illustrated in Figure 6.9-5.

Figure 6.9-5 (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 degree 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 it 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 be driven primarily by some knowledge of the UE position within the cell. This knowledge can be directly obtained 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.

In contrast, Figure 6.9-5 (b) shows an example of an adaptive beamformer. As the name suggests, an adaptive beamformer has the ability to continually adapt and recalculate the optimal applied transmission beamforming complex weighting values in order to best match the channel conditions.

Because the adaptive beamformer weightings are not fixed, they can both optimize the received SINR at the target UE and 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 optimal 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 AoA as well as decompose the channel characteristic matrix.

For the case of a frequency division duplex (FDD) system, in which both the downlink and the uplink use different RF carrier frequencies, the applied beamforming transmission complex weightings will be driven primarily by measured AoA information derived for both the target UE, as well as any other UEs within the cell. In addition, weighting estimation can be aided by channel feedback information reported by the UE on the uplink.

For the case of a time division duplex (TDD) system, since the 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 the 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.
6.9.3 Beamforming in LTE

One of the biggest challenges in any modern wireless cellular communications system is the performance at the cell edge. This is a major reason why beamforming technology has a key role to play in delivering LTE services.

6.9.3.1 LTE Downlink Transmission Mode Support for Beamforming

LTE defines many downlink transmission modes, which are listed in Table 2.4-1. Of particular interest from a beamforming point of view are transmission modes 7, 8, and 9. Release 8 introduced TM7, which supports single layer beamforming on antenna port 5. Release 9 added TM8, which supports dual layer beamforming on antenna ports 7 and 8. Finally, Release 10 added TM9, which supports 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 representing particular configurations of reference signals. The physical geometry and number of antenna elements are not defined in the LTE specifications. In practice each virtual port’s physical realization may comprise four or more spatially separated physical antenna elements.

The following examples focus on TM7 and TM8, which are the focus of development for initial TD-LTE market deployments.

6.9.3.2 Signal Processing for TM7 and TM8

A summary of the defined downlink signal processing flow for TM7 and TM8 is shown in Figure 6.9-6. As with other transmission modes, the PDSCH data transport block information is channel-encoded and has rate matching applied, producing either one or two code words, which are then mapped onto layers.

It’s worth noting that for TM7 and TM8, the precoding block is not codebook based. It is left up to the eNB to determine the optimal beamforming precoding to apply. This coding can be derived by the eNB from direct measurement of the received uplink sounding reference signal, and can include the use of any configured UE channel feedback (CQI/PMI/RI) information. Also worth noting is that the beamforming precoding can be dynamic and vary on a per subframe and resource block basis to adapt to changing channel conditions.

For demodulation purposes, TM7 and TM8 include the mapping of UE-specific reference signals (UE-specific RS), also known as demodulation reference signals (DMRS) in each PDSCH resource block. The UE-specific RS undergo the same beamforming precoding as the associated PDSCH. This concept is shown in Figure 6.9-6 where the UE-specific RS feed into the precoding block. The beamforming precoding is calculated primarily to maximize the SINR observed by the target UE, but the precoding will also attempt to minimize interference to other UE within the serving or adjacent cells.
In addition to producing user-specific beam patterns, the base station has the ability to choose a different sector-wide broadcast beam pattern for common control channel content, which is received by all UE within the cell. This beamforming of the control channels is possible when the number of beamforming antenna elements is greater than the number of configured cell RS ports, as shown in Figure 6.9-6.

### 6.9.3.3 LTE UE-specific Reference Signals Structure

To support beamforming for TM7, TM8, and TM9, 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 6.9-7 for the TM7 and TM8 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 6.9-7. 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 and 8 UE-specific RS resource element mappings are defined. Each port corresponds to 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 orthogonality of UE-specific RS resource mappings for ports 7 and 8 are further extended using a combination of frequency division multiplexing (FDM) and code division multiplexing (CDM) resources in order to support ports 9 through 14 as required for TM9. From a test point of view, it is essential that the UE-specific RS content for TM7, TM8, and TM9 be verified for baseband correctness as well as for relative magnitude and phase weighting accuracy observed at the calibrated RF output of the antenna element array.
6.9.4 TD-LTE MIMO Beamforming Test Setup

This section introduces a typical TD-LTE eNB antenna configuration and system test setup used to verify the performance of downlink beamforming and spatial multiplexing signals used for TM7 and TM8.

Examples are included that demonstrate how a phase-coherent multi-channel signal analyzer along with appropriate measurement software can be used in the beamforming signal verification process, 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.

6.9.4.1 TD-LTE eNB Antenna Configuration

Figure 6.9-8 shows a typical eNB RF antenna configuration used in TD-LTE cellular networks that support TM7, TM8, and TM9 MIMO beamforming signals.

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 −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. 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. Thus 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.

6.9.4.2 TD-LTE eNB Test System Configuration

A typical configuration for testing a TD-LTE MIMO beamforming TM7 and TM8 eNB is shown in Figure 6.9-9. Starting at the left, the two main eNB blocks are shown: the baseband (BB) and the 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, located 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, which are 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 an 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 this 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 allow emulation of 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.

### 6.9.4.3 Beamforming Measurement Challenges

One of the main test challenges for beamforming is the need to verify and visualize the beamforming signal performance at the physical RF antenna array, in order to validate the following:

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

![Typical TD-LTE beamforming test system configuration](image)
CHAPTER 6 | Design and Verification Challenges

This test challenge can be met using the Agilent N7109A Multi-Channel Signal Analyzer and the Agilent 89600 VSA software installed with TD-LTE measurements. The multi-channel signal analyzer can support eight phase-coherent RF measurement channels and, along with the appropriate RF splitters and attenuators, can easily be integrated into a typical TD-LTE base station test setup, as shown in Figure 6.9-9.

In this example, the 89600 VSA software provides a correction wizard for the signal analyzer that is used along with an Agilent MXG or ESG-C signal generator and an appropriate high quality calibration two-way RF power splitter 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 the measurement cables. The signal generator is used to create a broadband calibration reference signal output that is connected to the input of the two-way power splitter. The desired beamforming measurement verification point in Figure 6.9-9 is indicated by a dotted line at the output of the RF antenna calibration coupler. It is 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’s eight output ports and the signal analyzer’s eight input channels.

The correction wizard guides the calibration process, prompting the user to connect the signal analyzer channel 1 measurement cable to the first output port of the two-way calibration splitter at the injection point represented by a dotted line in Figure 6.9-9. Note that 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 the signal analyzer beamforming measurements for all mismatch effects inherent in the measurement cables, connectors, splitters, and attenuators. As a result direct, corrected measurements of the antenna beamforming performance can be 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 in Section 6.9.4.5.

6.9.4.4 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 6.9-9.

The 89600 VSA software and multi-channel signal analyzer are first used to display the time-synchronized RF signal capture from all eight antenna elements as shown in Figure 6.9-10. Any fundamental RF power or timing performance impairments can be identified quickly, before the more advanced demodulation measurements are attempted.

The 89600 VSA software spectrogram feature provides useful insight into the frequency resource activity as shown in Figure 6.9-11. Spectrograms allow a quick picture to be built up of RF activity on a per subframe basis for user-specific resource block scheduling, and on a per symbol basis for common control channels and signals. This feature does not require demodulation and so is a very simple and useful debugging tool for investigating unexpected RF or scheduling related issues, especially when those issues might prevent measurements that rely on demodulation of the signal.
Figure 6.9-10. Time-synchronized capture of eight-antenna transmission

Figure 6.9-11. 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 the physical RF antenna configuration shown in Figure 6.9-12.

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

The 89600 VSA software TD-LTE measurement application provides a rich set of demodulation results for verifying downlink MIMO beamforming signals. These include IQ constellations, EVM result metrics, detected resource allocations, UE-specific RS weights, cell-specific RS weights and impairments, and UE-specific and common broadcast antenna beam patterns.

The demodulated IQ constellations are displayed per spatial multiplexing layer, as shown in Figure 6.9-13 traces A and L, and provide a quick visual indication of the signal's modulation quality correctness.

The frame summary shown in Figure 6.9-13 trace D provides access to individual EVM and power metrics associated with each channel and signal type. It also provides a color key (not shown here) for all channel type results, which is reused throughout the 89600 VSA software traces.

The detected allocations displayed in Figure 6.9-13 trace B shows 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 6.9-14 trace E. 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 give a picture of beamforming performance, the 89600 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 6.9-14 trace L. This process is repeated using the second four channels, producing the antenna group 1 beam pattern results shown in Figure 6.9-14 trace B. Note that a separate beam pattern trace can be shown for each resource block associated with each user device.

Similar to the way the IQ constellation provides a quick visual check of modulation quality, the antenna group beam pattern trace provides a quick visual 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 89600 VSA software common tracking error trace shown in Figure 6.9-15 traces A, L, and B, respectively.

The 89600 VSA software MIMO Info traces A and B shown in Figure 6.9-16 reports cell 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, and these metrics make it possible to verify the common broadcast beam pattern weightings associated with each antenna element.

The 89600 VSA software also extracts these relative antenna weightings in order to produce the CRS-derived, sector wide broadcast beam pattern results. The broadcast beam pattern results are shown in Figure 6.9-16 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 next in Figure 6.9-17 traces A and L. Both formats support markers for easy tracking of the main lobe peak levels and azimuth locations during live measurement updates. Markers can also be used to read out various beam pattern characteristics such as null depth, azimuth locations, and main lobe to side lobe levels.

For the signal in these examples, 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 6.9-15 trace A. The magnitude response variation is caused by the transmission filtering used, and so it applies equally 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 6.9-17 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 that is shown in Figure 6.9-17 trace B. This trace reports the dB difference between each UE-specific beam pattern and the common CRS broadcast beam pattern, producing 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.
6.9.4.5 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 investigates the reasons why, using the simple calibration setup illustrated in Figure 6.9-18.

The calibration test system in this example 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 N7109A signal analyzer, which is controlled by the 89600 VSA software.

As mentioned in Section 6.9.4.3, the 89600 VSA software provides a correction wizard utility program for the signal analyzer that can be used to correct for magnitude and phase delay variations observed between each of the analyzer's RF input channels. These magnitude and phase variations are in part due to slight performance variations within each of the analyzer's multi-channel phase coherent receiver paths. Perhaps more importantly these variations may be the result of magnitude and phase delay variations associated with the RF cabling, splitters, and adaptors used between the RF antenna calibration reference point and the signal analyzer RF input ports.
The 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 signal analyzer 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 software fixed equalization feature, it is possible to compensate and correct all 89600 VSA software results for the relative channel-by-channel magnitude and phase response offset variations.

Figure 6.9-19 shows the uncorrected magnitude and phase response plots for measurement channels 2, 3, and 4, all displayed relative to the reference measurement channel 1. In this example the uncorrected relative channel magnitude responses can vary as much as −0.95 dB, as is the case for channel 3 relative to channel 1, shown in trace C. The uncorrected relative phase variation between channels is expected to fall anywhere between ±180 degree range, as indicated by the spread of uncorrected relative phase results in Traces F, G, and H.
Figure 6.9-20 shows the equivalent corrected magnitude and phase response plots for measurement channels 2, 3, and 4 relative to reference channel 1. As shown the corrected relative channel magnitude and phase responses now appear as flat responses in contrast to the uncorrected results. The maximum magnitude response variation has dropped to around −0.02 dB, and the maximum phase response variation has dropped to <0.1 degree after applying the 89600 VSA software cross-channel corrections.
Using Agilent N7625B Signal Studio for 3GPP LTE TDD application software, it is possible to generate and download a 20 MHz TD-LTE downlink signal configured for a single user scheduled with TM7 (port 5) PDSCH plus associated UE-specific RS resource allocations in subframes 0 and 5. Figures 6.9-21 and 6.9-22 show the resulting uncorrected and corrected 89600 VSA software demodulation results for comparison purposes.
Figure 6.9-21 shows the uncorrected results. The antenna group 0 beam pattern results in trace H are not what might be expected given the simple test setup in which the MXG output RF source is split directly to each of the four signal analyzer input channels. Theoretically a main lobe should appear at 0 degrees azimuth, as was the case in Figure 6.9-2 plot (d). Also, the power null depth is around 25 dB down from main lobe level. The reality is that the uncorrected variations in relative per channel magnitude and phase responses of the RF splitters, cabling, adaptors, and analyzer receiver paths all affect the reported UE-specific RS magnitude and phase results shown in trace C. These per channel response variations also affect the derived antenna group 0 beam pattern results shown in traces H and L.

The 89600 VSA software per-channel fixed equalization feature produces the corrected demodulation results shown in Figure 6.9-22. The results now align very well with the theoretical results of Figure 6.9-2 plot (d), and it is now possible to identify a distinct power main lobe at 0 degree azimuth. Also, the power null depths are much improved at > 40 dB down from main lobe level.
Beamforming measurement results are sensitive to any uncalibrated changes to the test setup. To illustrate this fact, two physical test setup changes are made to the original test setup in Figure 6.9-18 that has just been calibrated.

First a short N-type male-to-female extension adaptor is added to the signal analyzer input channel 3 N-type cable connection. The effect of this change is to introduce a −85 degree phase shift impairment to the channel 3 UE-specific RS results shown in Figure 6.9-23 trace C.

The result of this phase shift impairment is seen in 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 and the power null depths observed in trace L are degraded.
Next, the original calibrated 1 meter N-type RF cable for signal analyzer channel 3 is replaced with an uncalibrated 4 meter cable. This introduces a 165 degree phase shift impairment to the channel 3 UE-specific RS results as shown in Figure 6.9-24 trace C. Again the effect of this phase shift impairment is seen clearly in the antenna group 0 beam pattern results of traces H and L. However, 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 contain 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 is reduced to 160 degrees for RB5. This changing phase error can be explained by the fact that introducing a longer RF cable to channel 3 in effect introduced a fixed time delay impairment to the channel 3 reported results. This fact 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 results in a different phase shift for each resource block. The effect on the combined antenna beam pattern trace is a distinct spreading of the observed beam pattern results corresponding to each frequency resource as seen in Figure 6.9-24 trace H.
The key point here is that in order to make accurate measurements of 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 be included within the calibration correction procedure. Also the calibration should be repeated whenever the physical configuration of the measurement setup is changed.
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