White Paper

Maximizing LTE Performance Through MIMO Optimization

Introduction

With applications including social media, high-definition video streaming, mobile banking, and full-featured web browsing, broadband cellular applications provide exciting opportunities for consumers and network operators alike. However, these data-intensive applications also create new bandwidth delivery challenges for mobile operators. In order to expand available wireless network capacity to meet the demands of data-intensive applications, operators have invested heavily in acquiring radio frequency bandwidth. Even so, RF spectrum remains a finite resource, with the industry as a whole facing a spectrum crunch, as acknowledged the United States' Federal Communications Commission chairman, Julius Genachowski.[1] Therefore, network operators must look to new technologies such as LTE to generate more throughput from existing bandwidth. While LTE can provide increased capacity using standard antenna techniques, widespread deployment and optimization of MIMO (Multiple-Input Multiple-Output) antenna techniques can have a multiplicative effect on LTE's data throughput. MIMO techniques, in turn, present their own unique challenges, requiring a new approach to network measurement and optimization.

Terminology	
Channel correlation	The degree to which transmissions on the same channel appear to the Rx to be the same. Low channel correlation indicates the transmissions can be distinguished, allowing multi-layer transmission.
CINR	Carrier to Interference plus Noise Ratio
Closed Loop	Transmissions are configured with detailed feedback from the UE
CN	Condition Number – a measure of channel correlation
CQI	Channel Quality Indicator – overall measurement of channel conditions under a particular transmission mode
eNodeB	LTE's equivalent for a base station
Layer	Data stream to be transmitted over particular time-frequency resources. Transmissions with multiple layers transmit more than one data stream over the same time-frequency resources.
LTE	Long Term Evolution, 3GPP's next-generation wireless protocol.
LTE-Advanced	3GPP Release 10 standard for ITU-Advanced-compliant 4G wireless protocol
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MU-MIMO	Multi-User MIMO
Open Loop	Transmissions are configured with minimal feedback from the UE
Rank	Equal to the number of layers in an LTE spatial multiplexing transmission
RF	Radio Frequency
RI	Rank Indicator – indication of the number of layers that can be supported on a given channel
RS	Reference Signal
Rx	Receive antenna
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SM	Spatial Multiplexing – transmission scheme in which different spatial paths carry different data streams, enabling multi-layer transmissions
SNR	Signal-to-Noise Ratio
SU-MIMO	Single-User MIMO
Tx	Transmit antenna
UE	User Equipment

[1] Brian Stetler, "F.C.C. Chairman: We Need to Auction Off More Spectrum," *Gadgetwise* (blog), *New York Times*, January 7, 2011, http://gadgetwise.blogs.nytimes.com/2011/01/07/fcc-chair-we-need-to-auction-off-more-spectrum/.

This paper will discuss the capabilities of and challenges posed by MIMO in LTE networks. First, it will explain how MIMO increases the capabilities of broadband networks. Second, it will discuss the specific MIMO transmission modes used by LTE. Third, it will outline the key challenges faced when attempting to optimize a network for MIMO transmission. Finally, this article will propose a solution to the challenges of MIMO optimization: real-world RF measurements specifically designed for MIMO LTE networks.

What Is MIMO?

MIMO stands for Multiple-Input Multiple-Output, meaning that MIMO systems use more than one transmit antenna (Tx) to send a signal on the same frequency to more than one receive antenna (Rx). Although MIMO has been deployed for years in WLAN networks,[2] it is a relatively new feature in commercial wireless networks. MIMO technology is a standard feature of next-generation LTE networks, and it is a major piece of LTE's promise to significantly boost data rates and overall system capacity. However, MIMO also represents a new challenge for network operators. Traditional cellular networks generally provide the best service under line-of-sight conditions. MIMO thrives under rich scattering conditions, where signals bounce around the environment. Under rich scattering conditions, signals from different Tx take multiple paths to reach the user equipment (UE) at different times, as shown in **Figure 1**. In order to achieve promised throughputs in LTE systems, operators must optimize their networks' multipath conditions for MIMO, targeting both rich scattering conditions and high SNR for each multipath signal. This optimization process requires accurate measurement of these multipath conditions in order to achieve the best performance for a given environment while avoiding the time and expense of guesswork. With strong measurements, however, an optimized MIMO system can result in massive throughput gains without the expenses associated with adding spectrum or eNodeBs.

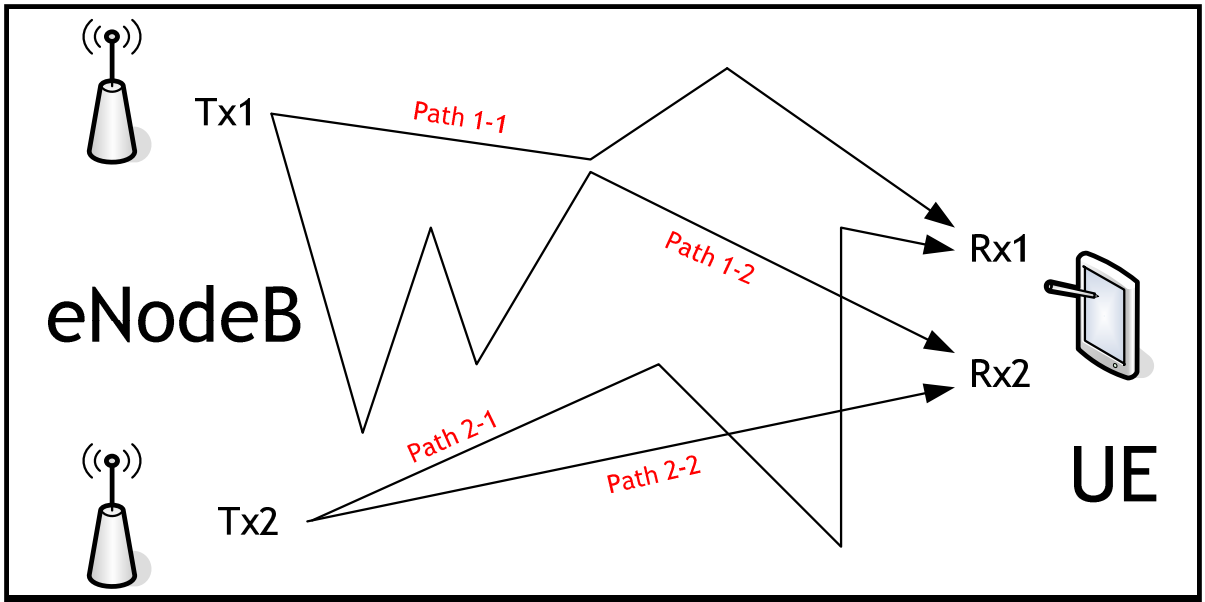


Figure 1 - Multiple Paths from eNodeB to UE in 2x2 MIMO. The first number in the path indicates the Tx, while the second indicates the Rx.

[2] 3G Americas, *MIMO Transmission Schemes for LTE and HSPA Networks* (3G Americas, June 2009), 5.

MIMO technology has its roots in more widely deployed antenna techniques. MIMO builds on Single-Input Multiple-Output (SIMO), also called receive diversity, as well as Multiple-Input Single-Output (MISO), also called transmit diversity. SIMO techniques have been around for decades, while MISO is used in most advanced cellular networks today. Both of these techniques seek to boost signal-to-noise ratio (SNR) in order to compensate for signal degradation. As a radio frequency (RF) signal passes from Tx to Rx, it gradually weakens, while interference from other RF signals also reduces SNR. In addition, in crowded environments, the RF signal frequently encounters objects which will alter its path or degrade the signal. Multiple-antenna systems can compensate for some of the loss of SNR due to multipath conditions by combining signals that have different fading characteristics, since the path from each antenna will be slightly different. SIMO and MISO systems achieve SNR gain by combining signals that take multiple paths to the Tx and Rx in a constructive manner, taking the best piece of each signal.[3] Because different antennas receive or transmit the same signal, these systems can achieve SNR gains even in line of sight situations. The boost in SNR can then be used to increase the range of the connection or boost data rates by using a modulation scheme such as 16QAM or 64QAM rather than QPSK.

MIMO can work as a combination of SIMO and MISO techniques, resulting in even greater SNR gains, further boosting coverage and data rates. However, when SNR is high, additional throughput gains are minimal, and there is little benefit from further boosting SNR (see **Figure 2**). To achieve throughput gains where SNR is already very high, LTE uses a MIMO technique called spatial multiplexing. In spatial multiplexing, each Tx sends a different data stream to multiple Rx. These data streams are then reconstructed separately by the UE. It may seem counterintuitive that two signals sent at the same time and frequency within the same sector can result in increased throughput rather than interference. However, spatial multiplexing can be compared to conventional spectrum re-use, where signals are transmitted in the same frequency in different cells. For spectrum re-use, the cells must be far enough apart—that is, they must occupy different space—in order to avoid interference. With spatial multiplexing, the signals, instead of occupying a completely different cell, occupy different space-time in the same cell. Good multipath conditions create the signal orthogonality that effectively turns a single cell into multiple cells with respect to the amount of data that can be sent on a particular frequency band.

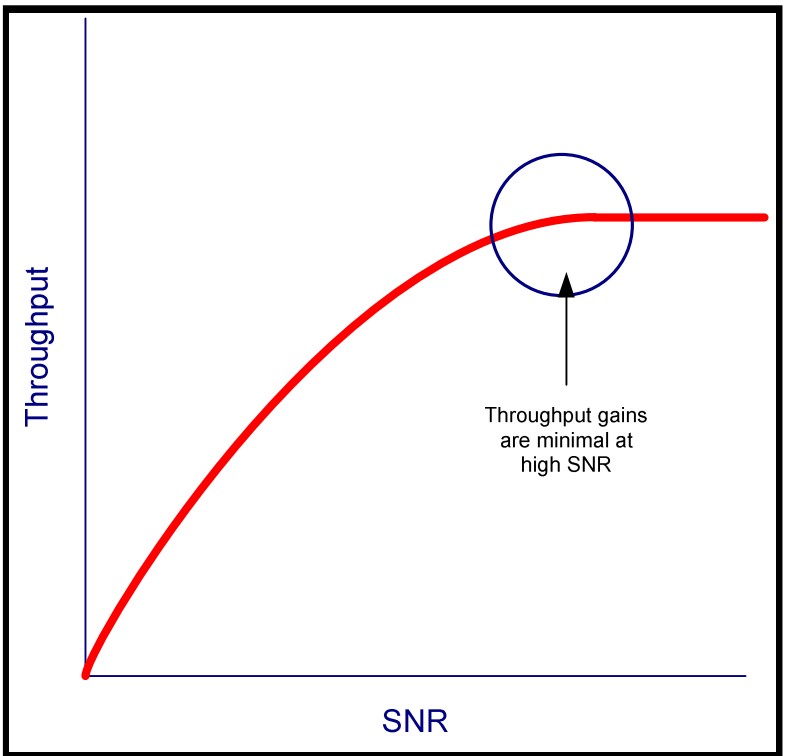


Figure 2 - Diminishing returns of throughput gains from increased SNR

[3] Arunabha Ghosh, Jun Zhang, Jeffrey G. Andrews, and Rias Muhamed, *Fundamentals of LTE* (Boston, MA: Pearson Education, 2010), 168.

In addition to good multipath conditions, spatial multiplexing depends on high SNR to produce large throughput gains. In spatial multiplexing, even though multiple data streams are transmitted, the total power of the transmission remains the same. Essentially, spatial multiplexing distributes the total SNR between these multiple data streams, each of which has a lower power level. The result is that each data stream contains a lower SNR than would be possible with a single data stream. However, because there are diminishing returns for additional SNR when SNR is already high (see **Figure 2**), each of the multiple data streams may be capable of transmitting nearly as much data as a single stream.

The increased data capacity that results from sharing SNR between multiple data streams means that, while spatial multiplexing may be used to encode the same data differently and boost SNR of the recombined data streams, it can also be used to send completely different data through each Tx. In LTE, each set of data sent through the antennas in a spatial multiplexing operation is called a **layer**. Under ideal conditions, each layer of a spatial multiplexing transmission will contain as much data as a single-Tx LTE transmission. The result is that spatial multiplexing can theoretically multiply throughput by the transmission rank.

This multiplicative effect on throughput means that MIMO technology is essential for achieving the full benefits of LTE. With the 2x2 (2 Tx and 2 Rx) antenna configuration expected to be deployed initially, effective use of MIMO could nearly double throughput both for individual users and for each cell as a whole. However, these throughput gains depend on three factors: maximizing rich scattering conditions within a cell, configuring the eNodeB to properly match MIMO settings to real-world conditions, and ensuring that UEs can take full advantage of the multipath conditions that are present. Scanning receivers that can provide accurate real-world measurements of multipath conditions and potential throughput are essential tools for evaluating the performance of all three of these factors. With these measurements, mobile operators can maximize the data rates and reliability of LTE networks, resulting in a premium return on their LTE equipment investments while improving customer satisfaction.

How LTE MIMO Works

LTE Downlink Transmission Modes

This section discusses the basic MIMO features and techniques available in LTE downlink operations. Because network conditions and UE capabilities can vary greatly, MIMO systems must be highly flexible in order to maximize gains in throughput. Since each eNodeB can be configured differently in terms of how it adapts transmissions in real time, it is important to understand the key transmission modes available in LTE, as well as the conditions under which they are most useful. Network operators can then compare scanning receiver measurements to UE-reported data logged by the network to determine if the eNodeB is effectively adapting transmissions to the RF environment.

Transmission Mode	Downlink Transmission Scheme
Mode 1	Single Antenna Port (SISO or SIMO)
Mode 2	**Transmit Diversity**
Mode 3	**Open-Loop Spatial Multiplexing**
Mode 4	**Closed-Loop Spatial Multiplexing**
Mode 5	Multi-User MIMO
Mode 6	**Closed-Loop Rank-1 Spatial Multiplexing**
Mode 7	Single Antenna Port Beamforming
Mode 8	Dual-Layer Beamforming[4]

Table 1 - Downlink Transmission Modes for LTE Release 8[5]
Bold *indicates MIMO modes expected to be widely used in early LTE deployments.*

As shown in **Table 1**, LTE Release 8 supports seven different transmission modes, with an eighth available in Release 9. These modes are designed to take the best advantage of different channel and multipath conditions and eNodeB antenna configurations, as well as differences in UE capabilities and mobility. Modes 2, 3, 4, and 6 are **Single-User MIMO (SU-MIMO)** modes. These modes form the core of LTE's MIMO operations, in which more than one antenna at the eNodeB communicates with more than one antenna at a single UE. Selection of the correct SU-MIMO mode depends on factors such as mobility, SNR, and channel correlation, where low correlation indicates signal orthogonality. The relative potential throughputs of the SU-MIMO modes for different SNRs at low channel correlation are illustrated in **Figure 3.** All four SU-MIMO modes will be discussed in detail below.

[4] 3GPP, *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 9)* (3GPP, September 2010), TS 36.213 V9.3.0, 21.
[5] 3GPP, *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 8)* (3GPP, September 2009), TS 36.213 V8.8.0, 20.

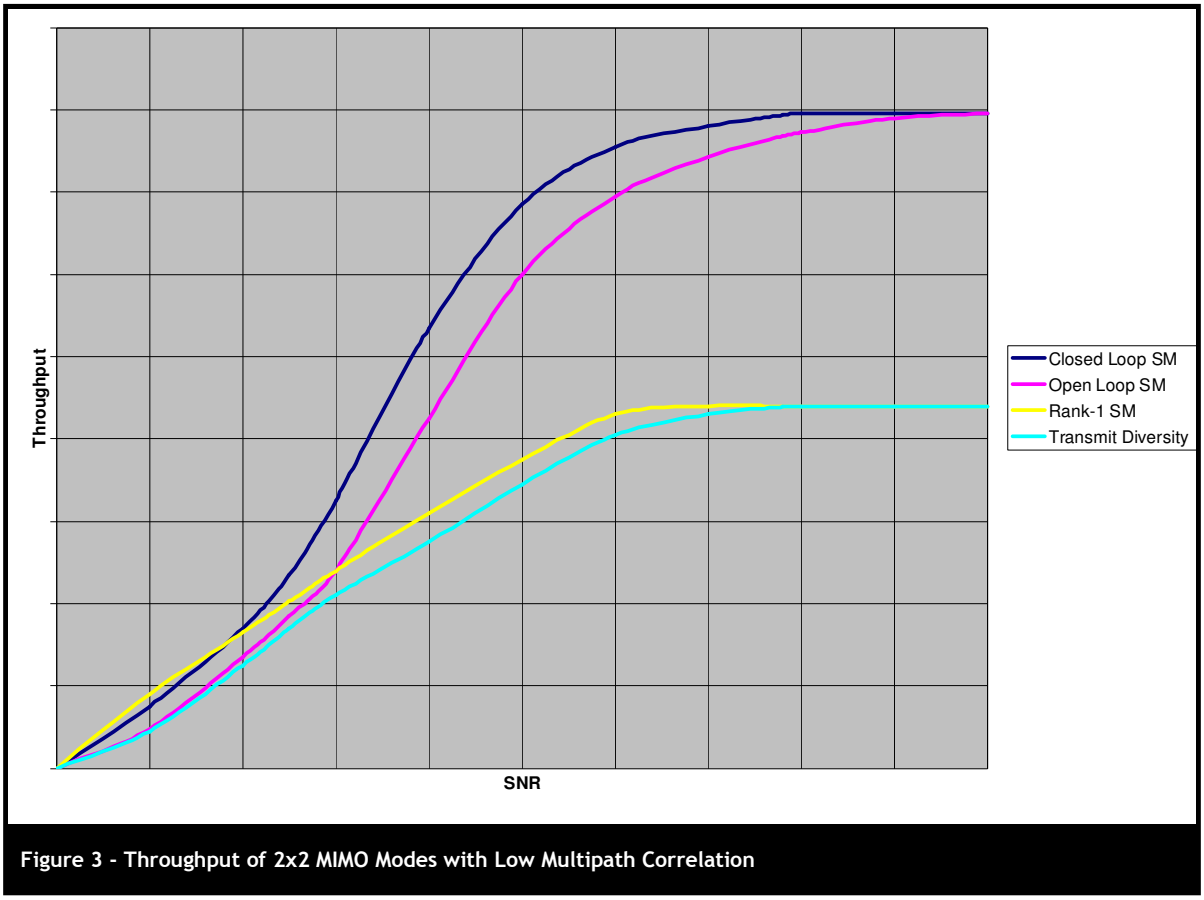


Figure 3 - Throughput of 2x2 MIMO Modes with Low Multipath Correlation

The remaining modes are less relevant to current LTE MIMO techniques. Modes 1 and 7 represent non-MIMO-based antenna techniques. Single Antenna Port (Mode 1), for SISO or SIMO operation, gives LTE networks an option when the UE or eNodeB is unable to support MIMO operations. Single Antenna Port Beamforming (Mode 7) generally requires a different antenna configuration from MIMO operations. Modes 5 and 8 are early versions of antenna techniques that are expected to be used minimally in early LTE deployments, but more robust versions of these techniques are planned for LTE-Advanced. Multi-User MIMO (Mode 5) uses multiple Tx antennas to send data to Rx antennas that are located at different, spatially separated UEs. Dual-Layer Beamforming (Mode 8), available only in LTE Release 9 and later, combines beamforming with 2x2 MIMO spatial multiplexing capabilities. Mode 8 can be used for either MU-MIMO or SU-MIMO. It requires deployment of beamforming antenna arrays as well as special configuration of eNodeBs and UEs. This paper will briefly discuss MU-MIMO, but since neither Mode 5 nor Mode 8 are expected to be used widely until the release of LTE-Advanced, the focus of this discussion will be the four SU-MIMO modes.

SU-MIMO and MU-MIMO

In SU-MIMO (Modes 2, 3, 4, and 6), multiple Tx antennas send data to multiple Rx antennas located at the same UE. Depending on reported channel conditions and the UE's ability to quickly send detailed updates on these conditions, the eNodeB selects between SU-MIMO modes. These modes include **Transmit Diversity**, as well as three spatial multiplexing modes: **Closed-Loop Rank-1 Spatial Multiplexing**, **Open-Loop Spatial Multiplexing**, and **Closed-Loop Spatial Multiplexing**. In spatial multiplexing, **rank** refers to the number of data streams transmitted over the same time-frequency resource, corresponding to the number of layers.

Transmit Diversity and Closed-Loop Rank-1 Spatial Multiplexing use multiple antennas to boost SNR at the UE. Closed- and Open-Loop Spatial Multiplexing, by contrast, are capable of transmitting multiple layers. Multiple-layer transmissions can greatly increase capacity in a channel with high SNR and rich scattering conditions. Regardless of SNR and multipath conditions, the four SU-MIMO modes provide the eNodeB with a choice between a closed loop (Closed-Loop Rank-1 or Closed-Loop SM) or open loop (Transmit Diversity or Open-Loop SM) transmission mode. The choice of a closed or open loop transmission mode depends on whether the UE is able to provide detailed and timely information on its channel conditions.

In MU-MIMO, separate data streams are sent to spatially separated UEs over the same sub-channel, with each UE serving as one of the multiple Rx antennas. This increases overall system capacity, though it does not increase throughput for individual UEs over single-antenna techniques. Like SU-MIMO, MU-MIMO is dependent on rich scattering conditions for each UE to decode the data stream meant for that UE. Measures of signal orthogonality as well as SNR of individual data streams are therefore crucial for optimizing MU-MIMO.

In LTE Rel-8, MU-MIMO has lower expected performance than SU-MIMO or single-antenna beamforming.[6] As a result, MU-MIMO is not expected to be widely deployed at this stage. Because of the limitations and additional capital expenditures associated with Mode 8 and MU-MIMO in LTE Rel-8 and 9, SU-MIMO optimization is the primary focus of operators attempting to maximize throughput gains in first- and second-generation LTE networks. Achieving this optimization requires an understanding of LTE's four SU-MIMO modes, including the difference between open and closed loop SU-MIMO operations.

Closed Versus Open Loop Operations

LTE's four SU-MIMO modes include two open loop modes (Transmit Diversity and Open-Loop Spatial Multiplexing) and two closed loop modes (Rank-1 Closed-Loop Spatial Multiplexing and Closed-Loop Spatial Multiplexing). Open loop and closed loop modes differ in the level of detail and frequency with which channel conditions are reported by the UE. In turn, the eNodeB relies on detailed and timely information from the UE in order to apply the best antenna and data-processing techniques for the existing channel conditions. Depending on the UE's data-processing speed as well as the quality of its connection to the eNodeB in both uplink and downlink, LTE will operate in either closed loop or open loop mode. The eNodeB communicates with a UE in open loop when the UE is moving too fast to provide a detailed report on channel conditions in time for the eNodeB to select the precoding matrix. Other factors, such as UE processing speed or uplink data capacity (which may also be affected by UE specifications), may result in open loop operations even when the UE is moving relatively slowly. The UE's capabilities are therefore crucial for achieving the best results from particular multipath conditions.

In open loop operations, the eNodeB receives minimal information from the UE: a **Rank Indicator (RI**), the number of layers that can be supported under the current channel conditions and modulation scheme; and a **Channel Quality Indicator (CQI)**, a summary of the channel conditions under the current transmission mode, roughly corresponding to SNR. The eNodeB then uses the CQI to select the correct modulation and coding scheme for the channel conditions. Combined with this modulation and coding scheme, CQI can also be converted into an expected throughput. The eNodeB adjusts its transmission mode and the amount of

[6] 3G Americas, *3GPP Mobile Broadband Innovation Path to 4G: Release 9, Release 10 and Beyond: HSPA+, LTE/SAE and LTE-Advanced* (3G Americas, February 2010), 68.

resources devoted to the UE based on whether the CQI and RI reported by the UE matches the expected values, and whether the signal is being received at an acceptable error rate.

In closed loop operations, the UE analyzes the channel conditions of each Tx, including the multipath conditions. The UE provides an RI as well as a **Precoding Matrix Indicator (PMI)**, which determines the optimum precoding matrix for the current channel conditions. Finally, the UE provides a CQI given the RI and PMI, rather than basing CQI on the current operation mode. This allows the eNodeB to quickly and effectively adapt the transmission to channel conditions. Closed loop operations are particularly important for spatial multiplexing, where MIMO offers the greatest throughput gains.

Transmit Diversity and Closed-Loop Rank-1 Spatial Multiplexing

Transmit Diversity and Closed-Loop Rank-1 Spatial Multiplexing are used to boost SNR. These modes are most useful near the cell edge or in other low-SNR or poor multipath conditions. In Transmit Diversity mode, MIMO functions much like a MISO system. The same data are sent from both Tx, coded to minimize co-channel interference. The use of multiple spatially differentiated signals increases the chances that data lost due to poor SNR will be different from each channel. The UE receives the signals from both Tx at both Rx and reconstructs a single data stream from all multipath signals. In Closed-Loop Rank-1 Spatial Multiplexing, the eNodeB similarly sends only one set of data for both Tx. However, Closed-Loop Rank-1 Spatial Multiplexing uses a linear precoding matrix to improve multipath conditions for spatially multiplexed signals. When decoded, these signals contain the same data. The precoding matrix works by shaping and directing the signal coming from each Tx in order for them to combine constructively at the UE. Matching the precoding matrix to the UE's channel conditions therefore results in greater overall SNR. Because this transmission mode operates in closed loop, the eNodeB is able to receive detailed information on channel conditions from the UE and choose the best among the four precoding matrices defined for 2x2 MIMO. Compared to more conventional Transmit Diversity techniques, Closed-Loop Rank-1 Spatial Multiplexing increases the likelihood that MIMO antenna schemes will result in significant SNR increases. This can further extend range and throughput potential at cell edges.

Open-Loop and Closed-Loop Spatial Multiplexing

Open-Loop and Closed-Loop Spatial Multiplexing are the keys to SU-MIMO's great leap in throughput potential. By sending different data on each antenna, these modes come close to multiplying peak throughput by the transmission rank, which is equal to the number of separate data streams or layers transmitted. LTE supports up to rank-2 transmissions for 2x2 or 4x2 antenna configurations, and up to rank-4 for 4x4 antenna configurations. Throughput gains from Closed-Loop and Open-Loop rank-2 transmissions can be seen in **Figure 3**. These spatial multiplexing modes, however, require rich scattering of multipath signals and high SNR so that all data can be successfully decoded. Under the right conditions, a UE can separate the signals from two Tx, identified by their different Reference Signals, and reconstruct two separate data streams in the same frequency block.

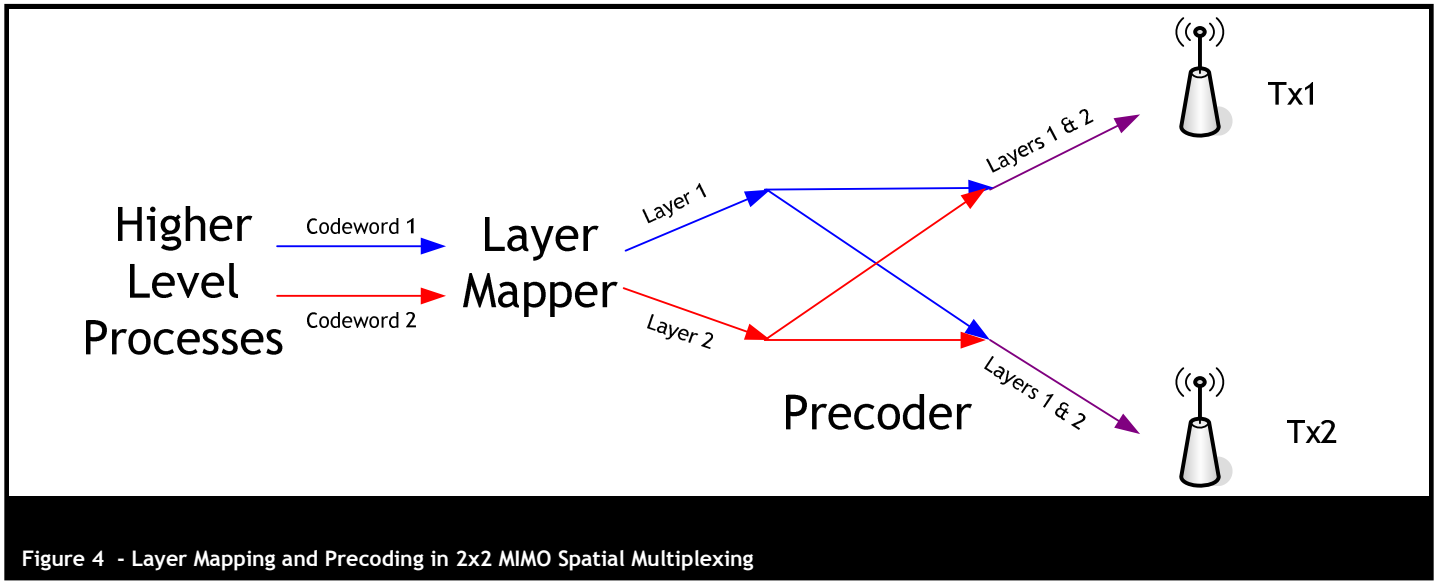
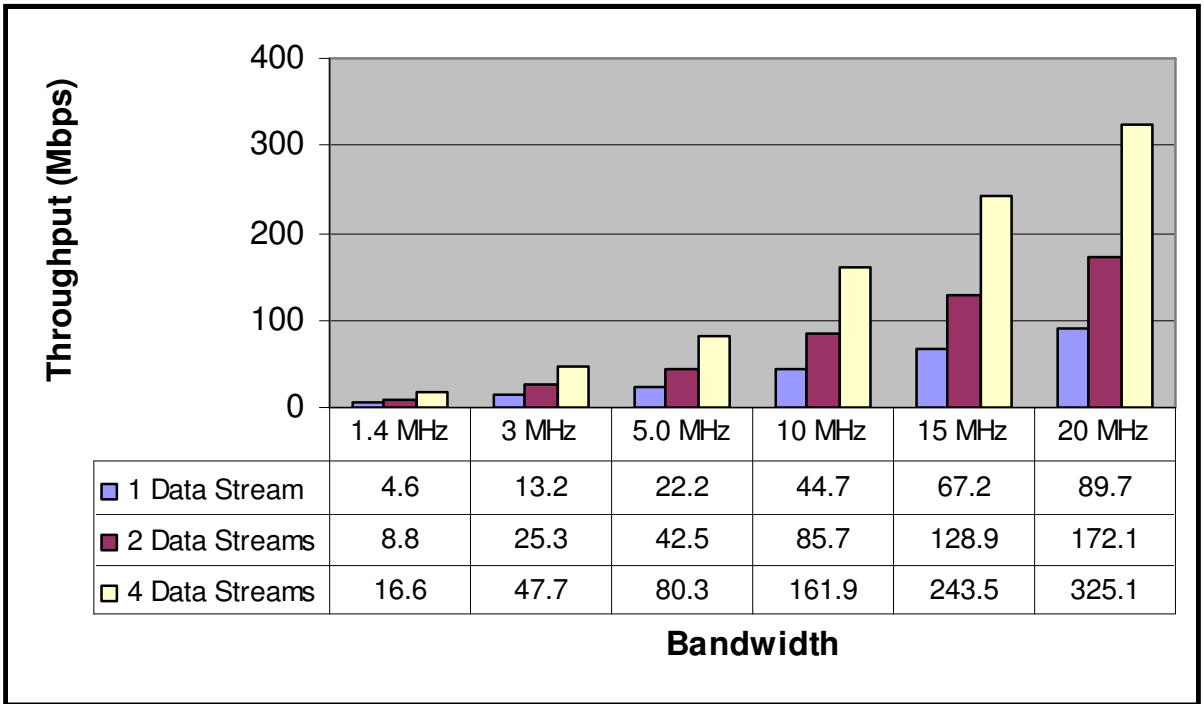


Figure 4 - Layer Mapping and Precoding in 2x2 MIMO Spatial Multiplexing

Spatial multiplexing works by creating separate data streams on multiple antennas. In spatial multiplexing, the eNodeB divides the data to be sent to a given UE on a given sub-channel into data streams, called layers. The number of layers is the same as the rank of the transmission. Transmission rank is determined according to channel conditions at the UE, as well as other considerations such as available resources at the eNodeB. In the simplest case for spatial multiplexing, a rank-2 spatial multiplexing transmission on a 2x2 MIMO antenna configuration will transmit one layer from each Tx. In this case, the paths 1-1 and 1-2 shown in **Figure 1** represent Layer 1, while paths 2-1 and 2-2 represent Layer 2. Each layer reaches each Rx along a different path. The UE then reconstructs the layers using information from both antennas.

With multiple-layer transmissions, data arrives from higher level processes in one or more codewords, as shown in **Figure 4**. Each codeword is then mapped onto one or more layers. In 2x2 MIMO, each codeword corresponds directly to a layer. Each layer is then mapped onto one or more antennas using a precoding matrix. When the UE detects a similar SNR from both Tx, the precoding matrix will map each layer onto a single antenna. However, when one Tx has a high SNR and another has a low SNR, the precoding matrix will divide the layers between the Tx in an effort to equalize SNR between the layers, as shown in **Figure 4**. In this case, the paths 1-1 and 1-2 in **Figure 1** would not represent a single layer, but data streams that contain information from both Layer 1 and Layer 2. Since maximum throughput using a given modulation scheme increases linearly at low SNR but logarithmically at high SNR, increasing the SNR of the low-SNR layer at the expense of the high-SNR layer increases total throughput. At a basic level, however, the goal is to ensure that each layer can be decoded at an acceptable error rate of 10% or less, allowing the UE to take advantage of the spatial multiplexing.



	1.4 MHz	3 MHz	5.0 MHz	10 MHz	15 MHz	20 MHz
1 Data Stream	4.6	13.2	22.2	44.7	67.2	89.7
2 Data Streams	8.8	25.3	42.5	85.7	128.9	172.1
4 Data Streams	16.6	47.7	80.3	161.9	243.5	325.1

Figure 5 - Peak LTE Downlink Throughput with Single and Multiple Data Streams
Source: Harri Holma and Antti Toskala, *LTE for UMTS: OFDMA and SC-FDMA Based Radio Access* (Chichester: John Wiley & Sons, 2009), 214.

Open-Loop Spatial Multiplexing uses a fixed set of precoding matrices to enable multiple-layer spatial multiplexing for fast-moving UEs. However, the greatest potential gains in throughput come from Closed-Loop Spatial Multiplexing, up to the peak rates shown in **Figure 5**. Because of the detailed information received from the UE, Closed-Loop Spatial Multiplexing is able to tailor the precoding matrix and modulation scheme to the real-world conditions of the UE, allowing throughput to approach the theoretical limits set by the multipath conditions and SNR. Therefore, LTE will achieve the greatest gains in throughput when multipath conditions and UE capabilities allow for spatial multiplexing, and when the UE is capable of providing the data needed by the eNodeB to closely match the existing channel conditions. A well-tuned network will provide the best chance for a UE to operate in Closed-Loop Spatial Multiplexing mode, but UEs must also have the antenna placement and processing capabilities to take advantage of this mode when conditions present themselves.

Optimizing MIMO

The goal of optimizing a MIMO system is to achieve the highest throughput and connectivity possible in a given environment by leveraging the multipath potential of the environment. Optimization is necessary for successful rollout of MIMO systems, while continued optimization of active networks helps maintain return on investment as multipath environments change and UEs evolve. The first part of MIMO optimization is configuration of antennas at the eNodeB to create the best multipath conditions possible. This may involve altering the placement, tilt, or selection of antenna equipment. Second, MIMO optimization includes evaluating UEs to ensure that they have the processing power and antenna configurations necessary to take

advantage of multipath conditions created by the interaction between the environment and antenna configuration. Finally, LTE MIMO systems must optimize the algorithms the eNodeB uses to select the best MIMO mode given UE capabilities and multipath conditions.

All three elements of MIMO optimization require accurate, UE-agnostic measurements of real-world multipath conditions. Without these measurements, operators have no way of knowing whether antenna configurations have produced the expected multipath conditions throughout the sector. Furthermore, only real-world, UE-agnostic measurements allow operators to determine whether MIMO mode selection and UE capabilities are successfully meeting the throughput potential of existing multipath conditions.

Real-world MIMO measurements should include power and quality measurements of each multipath signal, as well as indications of signal orthogonality and the overall throughput potential of the multipath environment. Together, these measurements allow operators to evaluate each multipath signal as they would a single transmitted signal, and also evaluate how well the multiple transmitted signals are working together to create multipath conditions. Test mobiles provide real-world data, but can only estimate achievable throughput for that particular UE. Mobiles also lack the scan speeds or dynamic range necessary to achieve an accurate picture of the variations in multipath conditions throughout a given sector. Data collected by the eNodeB is similarly limited by the capabilities of the UEs active within the sector. Furthermore, eNodeB data may be unavailable or inadequate when no or few MIMO-capable UEs are in use, or when UEs operate in open loop mode. Only high-powered scanning receivers with the capability to simultaneously receive and analyze multiple signals using optimally placed multiple antennas can provide the complete and accurate multipath data necessary for full MIMO optimization.

PCTEL SeeGull Scanning Receiver MIMO Measurements

PCTEL's MIMO-capable SeeGull Scanning Receivers feature a variety of parameters designed to provide a complete real-world picture of the SNR and multipath characteristics of LTE MIMO propagation in the downlink. SeeGull accomplishes this by simultaneously decoding the Reference Signals (RS) originating from multiple Tx antennas in the same sector. SeeGull then provides a standard set of LTE measurements on each Tx in the sector, giving operators the information they need to maximize SNR from each antenna. In addition, SeeGull provides data on multipath conditions, giving operators the information they need to maximize the orthogonality of Tx signals in a sector. Finally, SeeGull provides an overall estimate of the maximum throughput given the measured channel conditions, which can be used to judge eNodeB and UE performance. See **Table 2** for definitions and ranges of SeeGull's MIMO-specific parameters.

Standard LTE measurements provided for each RS include, but are not limited to, Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Delay Spread. RSRP is a total power measurement, while RSRQ is a direct measurement of SNR. Delay Spread measures the difference between the first and last multipath signal received for that Tx. SeeGull also provides **Reference Signal Carrier to Interference plus Noise Ratio (RS CINR)**, which provides a more consistent measure of SNR, since RSRQ can be affected by the amount of traffic on the channel. Together, these measurements provide an accurate reading of channel conditions. With the help of optimization tools, operators can use these measurements to diagnose problems and maximize SNR for each Tx.

MIMO Parameter	Definition	Range
Condition Number (CN)	Indication of channel correlation. Lower values are better. Available for both wideband and individual subbands.	0-50 dB
Estimated Channel Quality Indicator (ECQI)	Indication of overall channel efficiency. Calculated for each MIMO transmission scheme and layer. Available for both wideband and individual subbands.	0-15
Estimated Throughput	Estimation of overall wideband channel throughput, given channel conditions, bandwidth, and typical overhead. Calculated for each MIMO transmission scheme and layer.	Value in Mbps; maximum varies according to bandwidth.

Table 2 - SeeGull MIMO Parameters

Furthermore, SeeGull provides a **Condition Number (CN),** an indication of channel correlation, given in dB. At lower CNs, the signals from the two Tx produce independent channels which, if SNR is high enough, can be separately decoded. Therefore, CN can be used to determine if the channel is capable of supporting multi-layer spatial multiplexing in high SNR conditions. Lower values are better for CN, with a value of less than 13 dB generally required to support spatial multiplexing. **Table 3** includes general guidelines for the interpretation of different CN levels. However, CN alone should never be used to determine whether conditions are sufficient to support a particular MIMO transmission scheme, such as multi-layer spatial multiplexing, or a particular level of throughput. Between individual RS measurements and CN, SeeGull provides complete information on MIMO channel conditions, allowing operators to distinguish between problems caused by poor multipath conditions (high CN) from those caused by more conventional propagation issues.

CN	Channel Correlation
0 dB	Completely Independent Channels
<13 dB	Low Channel Correlation – *Large MIMO Throughput or SNR gains; Multi-Layer Spatial Multiplexing Possible at High SNR*
13-19 dB	Medium Channel Correlation – *Significant MIMO Throughput or SNR gains; Multi-Layer Spatial Multiplexing May Sometimes Be Possible at Very High SNR*
>19 dB	High Channel Correlation – *Little to No MIMO Throughput Gains; No Multi-Layer Spatial Multiplexing*

Table 3 – Channel Correlation at Different CNs (Approximate)

In addition to measuring the specific components of channel and multipath conditions that determine MIMO performance potential, SeeGull also produces overall estimations of channel quality and throughput. When a UE reports to the eNodeB, it includes a **CQI** for one transmission mode, which the eNodeB uses to determine how much data can be sent to the UE. CQI values range from 0 to 15. A CQI of 1 represents a channel efficiency of 0.15 b/s/Hz, while a CQI of 15 represents 5.55 b/s/Hz.[7] Actual user channel efficiency for data throughput will be reduced due to channel overhead, including handshaking and synchronization.

[7] 3GPP, *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 8)* (3GPP, September 2009), TS 36.213 V8.8.0, 48.

In SISO transmissions, CQI corresponds directly to CINR, but in MIMO transmissions CQI varies according to other aspects of the channel conditions such as CN. CQI also varies according to the specific MIMO transmission mode selected. SeeGull therefore calculates a different **Estimated CQI (ECQI)** for measured conditions under each of the four major 2x2 SU-MIMO modes: Transmit Diversity, Closed-Loop Rank-1 Spatial Multiplexing, Open-Loop Spatial Multiplexing, and Closed-Loop Spatial Multiplexing. For Closed and Open-Loop Spatial Multiplexing, SeeGull provides a separate ECQI for each of the two layers in a 2x2 MIMO spatial multiplexing transmission. SeeGull converts each ECQI to an **Estimated Throughput** in Mb/s, taking into account typical overhead as well as channel conditions and bandwidth. ECQI and Estimated Throughput are key factors in the actual throughput experienced by users and can provide a baseline for a wide variety of optimization and modeling tasks.

All of SeeGull's MIMO parameters are available for LTE channels of variable bandwidths, ensuring that the scanner does not miss interference or bad multipath conditions that occur on only some sub-channels. Additionally, SeeGull allows the user to select individual sub-channels for parameter. This allows operators to precisely diagnose problems with MIMO signal generation and propagation, as well as frequency-selective interference problems in the LTE channel. Finally, SeeGull's fast scan rates and high dynamic range ensure a complete assessment of all signals and potential sources of interference throughout the network. Together, SeeGull's MIMO measurements give operators an accurate picture of their MIMO LTE networks. Not only does this picture allow operators to optimize their current networks, but it also provides a baseline against which achieved throughputs can be gauged.

Conclusion

MIMO is a key component of next-generation wireless technologies and provides the bulk of LTE's peak throughput gains when compared with older technologies. However, MIMO gains can only be realized on a fully optimized network. MIMO optimization requires a different approach to traditional network optimization, with assessment of multipath conditions playing a key role in determining the potential throughput provided by a MIMO-enabled LTE network. Optimizing an LTE network for MIMO therefore requires a new set of scanning receiver parameters, including multipath CINR measurements, CN, and CQI for all key MIMO modes. PCTEL's SeeGull Scanning Receivers provide high-quality data for all of these MIMO parameters, enabling network operators to construct an accurate picture of MIMO LTE networks.

Operators can use the knowledge gained from analyzing scanning receiver MIMO data to improve conditions in the current network through antenna and eNodeB adjustments. Scanning receiver data can also be used to evaluate the performance of UEs and eNodeB MIMO mode selection. Finally, accurate data on multipath conditions in existing LTE networks can lead to better planning of future MIMO-capable networks. This knowledge will become increasingly valuable as more users depend on LTE to provide the data rates they need for wireless applications from mobile banking to high-definition video streaming. Operators that maximize the performance of MIMO in their LTE networks will be able to provide the best service to these users with the smallest amount of infrastructure investment, providing a clear competitive advantage in both price and quality of service.

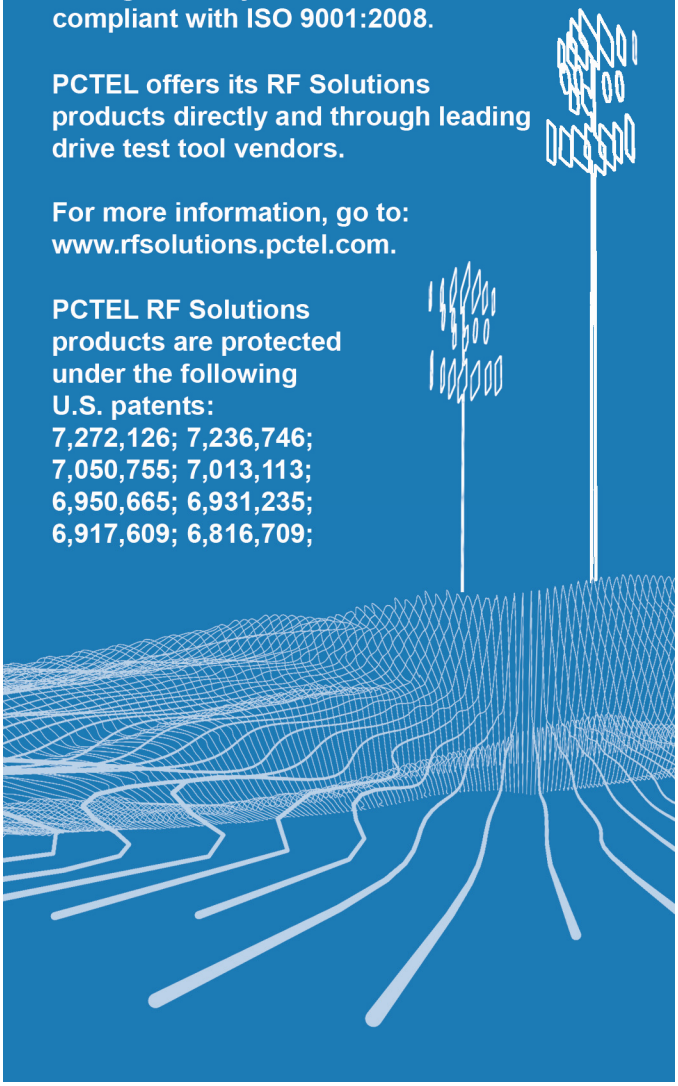
About PCTEL RF Solutions

PCTEL, Inc. is a recognized leader in high performance RF data collection components and systems used worldwide by leading drive test system OEMs, network operators, and engineering services companies to measure, monitor and optimize wireless networks. Its SeeGull® line of multi-standard demodulating Scanning Receivers, CLARIFY® Interference Management System, SeeHawk™ Wireless Drive Test Suite, and InSite® Data Collection software provide a diverse set of tools that allow RF engineers to measure and optimize Radio Access Networks for all leading wireless technologies. PCTEL RF Solutions Quality Management System has been certified to be compliant with ISO 9001:2008.

PCTEL offers its RF Solutions products directly and through leading drive test tool vendors.

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PCTEL RF Solutions products are protected under the following U.S. patents: 7,272,126; 7,236,746; 7,050,755; 7,013,113; 6,950,665; 6,931,235; 6,917,609; 6,816,709;



Rev. B April 2011
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