The Seven Modes of MIMO in LTE

White Paper

This whitepaper describes the seven modes of MIMO defined in the Long Term Evolution (LTE) of the universal mobile telecommunication systems (UMTS), which is developed by the 3rd Generation Partnership Project (3GPP). Particular attention is given to the applicability of these modes in different radio channels.

Long Term Evolution[1] (LTE) systems make the promise of delivering large data rate to users, on the order of several tens of megabits per second, which is substantially larger than what the current 3G systems offer (order of megabits per second). This is a challenging proposition as wireless networks are subject to interference, multipath and poor propagation channel characteristics that limits data rates. MIMO techniques have emerged as a solution to provide higher data rates by exploiting the multipath characteristics of the wireless channel. This is accomplished by using several antennas to transmit and receive signals thereby leveraging the spatial dimension resulting from using multiple spatially distributed antennas (hence the term multiple input multiple output: MIMO). When the signals are combined properly at the receiver, the signal quality or data rate for each MIMO user will be improved.

MIMO Basics

A key factor to the performance of MIMO is the number of "spatial layers" of the wireless channel which determines the ability to improve spectral efficiency. Spatial layers are born out of the multipath and scattering environment between transmitters and receivers. Another factor is the number of transmit and receive antennas. The increase in data rate of a MIMO system is linearly proportional with the minimum number of transmit and receive antennas subject to the limit of the "rank" of the propagation channel estimate. The "rank" is a measure of the number of independent spatial layers. Hence, a 4 Tx/2 Rx antenna MIMO system provides double the data rate (i.e., min(4,2) = 2) provided that there are two spatial layers (rank = 2) in the wireless channel. In line-of-site conditions, the channel matrix rank is one; hence, even with 4 antennas we cannot increase the spectral efficiency of the channel.

MIMO Modes in LTE

Seven MIMO modes for the downlink path are defined in LTE [1]. These are:

Mode 1 – Single-antenna port; Port 0: This is analogous to most current wireless systems where a single data stream (code word) is transmitted on one antenna and received by either one (SISO: Single Input Single Output) or more antennas (SIMO: Single Input Multiple Output; receive diversity). Figure 1 shows the different antenna access schemes in modern wireless communication networks.

Mode 2 – Transmit diversity: This mode involves the transmission of the same information stream on multiple antennas (LTE supports the option of two or four antennas). The information stream is coded differently on each of the antennas using so-called "Space-Frequency Block Codes." Unlike the Alamouti "Space-Time Block Codes" where data symbols are repeated in time, SFBC repeats data symbols over different subcarriers on each antenna.

This mode is used in LTE by default for the Common Channels as well as for control and broadcast channels. Since it is a "single-layer transmission" it does not improve the peak rate. Rather, the signal quality becomes more robust and lower signal to interference plus noise ratio (SINR) is required to decode the signal.

Mode 3 – Open loop spatial multiplexing (OL-SM): In this case, two information streams (two code words) are transmitted over two or more antennas (up to 4 in LTE). There is no explicit feedback from the user equipment (UE), although a "Transmit Rank Indication" (TRI) transmitted by the UE is used by the base station to select the number of spatial layers.

[1] The formal name for this 3GPP project is Evolved UMTS Terrestrial Radio Access (EUTRA) and Evolved UMTS Terrestrial Radio Access Network (E-EUTRAN).

As multiple code words are transmitted, OL-SM provides much better peak throughput than transmit diversity. It is also simpler to implement and is considered to be one of the main modes of MIMO to be implemented in LTE systems.

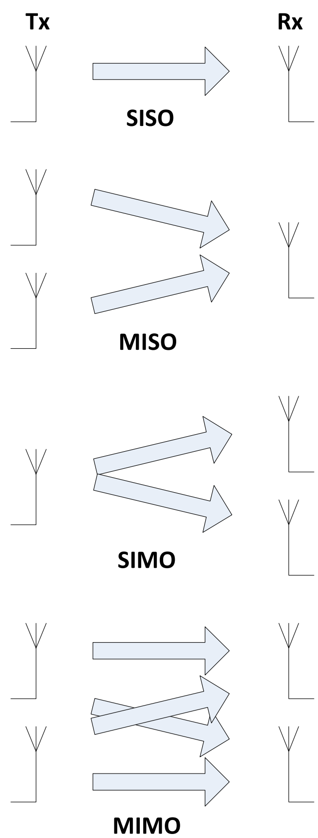

FIGURE 1 MULTIPLE ANTENNA ACCESS SCHEMES.

Mode 4 – Closed loop spatial multiplexing (CL-SM): Similar to OL-SM, two information streams are transmitted over two code words from N antennas (up to 4). The difference is "Pre-coding Matrix Indicator" (PMI) which is fed back from the handset to the base station. This feedback mechanism allows the transmitter to pre-code the data to optimize transmission over the wireless channel so the signals at the receiver can be easily separated into the original streams. This mode is expected to be highest performing mode of MIMO in LTE.

Mode 5 – Multi-User MIMO: This mode is similar to CL-SM, but the information streams are targeted at different terminals. Hence, multiple users share the same resources. While each user experiences the same data rate, the overall network data rate is improved. It is expected that linear antenna arrays be used for this mode in practice as opposed to multiple spatially distributed antennas.

The number of users is limited by the number of spatial layers: the limit is one user per spatial layer. The users are separated in the space domain and can be uncorrelated due to individual beam-forming patterns. In case the layers are not completely orthogonal, each user will experience interference from other users. This mode is generally interesting when LTE networks become heavily loaded and is not expected to be a main feature driver in initial deployments.

Mode 6 – Closed loop Rank 1 with pre-coding: This case represents the scenario when a single code word transmitted over a single spatial layer. Many consider this case to be a fall-back scenario of CL-SM and it has been associated with beamforming.

Mode 7 – Single-antenna port; Port 5: This is a beamforming mode where a single code word is transmitted over a single spatial layer. A dedicated reference signal forms an additional antenna port (i.e. Port 5) and allows transmission from more than 4 antennas. The terminal estimates the channel quality from the common reference signals on antennas 1-4. Linear antenna arrays are expected to be used for this mode.

MIMO in Practice

A key characteristic of MIMO is that its performance depends on a number of factors such as the state of the wireless channel (e.g. low vs. high scattering), the signal quality (as measured by SINR), the speed of the mobile terminal, and the correlation of the received signals at the receiver antennas. Therefore, certain MIMO modes will be more effective than others depending on these critical factors. This opens the door widely for different types of practical implementation of MIMO which could differentiate vendors' products.

The benefits of open and closed loop spatial multiplexing schemes are achieved when the received signal quality (as measured by SINR) is at its highest (as a rule of thumb, the benefits of SM schemes kick in at about SINR = 15 dB and higher when the correlation is low). At the cell edge, a weak signal strength and high signal-to-noise ratio reduce the benefits of spatial multiplexing modes. Closed-loop rank 1 or transmit diversity become more attractive. Transmit diversity is also more attractive than CL-SM and OL-SM in environment where signal scattering is low (e.g. rural areas). Switching between these modes as the mobile terminal moves away from the cell center or as the scattering environment changes is a way to optimize the system performance.

The speed of the mobile terminal impacts the performance of closed loop MIMO systems. In general, CL-SM mode provides better spectral efficiency than OL-SM mode as the channel parameters are fed back to the transmitter from the receiver and used to code the data stream. However, as the speed of the mobile terminal increases and channel conditions change more rapidly, CL-SM looses much of its advantage over OL-SM which is simpler to implement. Transmit diversity is also robust to speed while its performance in low scattering environment and high SINR does not degrade as that of OL-SM. Therefore, for a vehicle moving at high speed along a highway with a clear line of sight to the base station, transmit diversity would provide the better spectral efficiency while OL-SM would be preferred when the terminal is moving at high speed in a rich multipath environment and high SINR.

Spatial multiplexing schemes perform best when the signals have low correlation coefficient. As the signal correlation increases the performance of SM schemes decrease. Signal correlation is related to the scattering environment of the base station and terminal device. The higher the signal scattering, the more effective spatial multiplexing techniques become. In high-scattering environments where the received signal has a relatively large angular spread such as in dense urban areas is where spatial multiplexing schemes are expected to perform at their best.

Low signal correlation is also dependent with the placement of the antennas. The larger the distance between multiple antennas at each of the transmitter and receiver, the lower the correlation. This place certain restrictions on mobile handset design since space is limited. Beamforming techniques are alternatively effective in high correlation environments where the signal comes with a low angular spread such as in rural environments.

Table 1 summarizes the decision matrix to select the MIMO mode most suitable for the usage scenario. As the scenario changes along with the wireless channel characteristics, it is possible to "dynamically adapt" between certain modes.

TABLE 1 DECISION MATRIX FOR THE MAIN LTE MIMO MODES.

MIMO Mode	Signal Quality (SINR)	Scattering	Speed	Dynamic Adaptation
Transmit Diversity	Low	Low	High	None
Open-Loop Spatial Multiplexing	High	High	High	Transmit Diversity
Closed-Loop Spatial Multiplexing	High	High	Low	Transmit Diversity, or CL Rank=1
Closed-Loop Rank=1 Precoding	Low	Low	Low	Transmit Diversity

Application of Modes in Practice

With the advent of MIMO techniques, adaptive modulation and many other innovations introduced into wireless networks, it is certain that the design of 4G broadband wireless networks will be more challenging than that of the current 2G and 3G networks. There are many factors that impact the network design and it becomes important to define the applications, services and other offerings that the carrier plans to provide so a proper network design is planned and implemented. This complexity allows for product differentiation on both the equipment vendors and service providers.

In the case of MIMO techniques, the performance will depend on many factors and it is clear that there is no single mode that universally provides superior performance in all usage scenarios. However, it is possible for a subset of modes to be implemented and the system configured to intelligently switch among them to optimize performance. The leading modes are transmit diversity, which is a very robust implementation, and OL-SM and CL-SM because of the improvement in spectral efficiency required to deliver on the promise of LTE data rates. The manner in which these modes are implemented and the higher level algorithms to optimize performance are one area for product differentiation that equipment vendors have been investing in. Other areas of differentiation in related to the design of terminal devices where space is at a premium and it becomes more challenging to achieve low correlation between signals received by the diversity antennas.

Network operators, on the other hand, need to be cognizant of how effective MIMO techniques will be in achieving their service objectives. In this case, the use case and deployment scenarios have to be clearly defined since the performance is impacted by the surrounding environment (e.g. urban vs. rural) and use case (e.g. fixed vs. mobile). Spectrum requirements are also important since frequency reuse factor determines the interference level and signal quality that affect the performance of MIMO systems.

Conclusions

Broadband wireless systems implement MIMO technologies to increase spectral efficiency and data rates. There are different implementations of MIMO techniques whose performance depend on the characteristics of the wireless propagation channel. Although there are seven modes of MIMO defined in LTE, a subset will be used in actual systems. Equipment vendors can differentiate their product offering by developing higher level algorithms to take advantage of the changing wireless channel to adapt between MIMO modes and wireless operators need to carefully consider the deployment scenarios and applications when selecting MIMO-capable equipment.

References

[1] 3GPP TS36.213: "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures" version 8.5.0

Abbreviations and Acronyms

3GPP: third generation partnership project
CL: closed loop
E-EUTRAN: evolved UMTS terrestrial radio access network
EUTRA: evolved UMTS terrestrial radio access
LTE: long term evolution
MIMO: multiple input multiple output
MISO: multiple input single output
OL: open loop
PMI: pre-coding matrix indicator
Rx: Receiver
SFBC: space-frequency block codes
SIMO: single input multiple output
SINR: signal to interference plus noise ratio
SISO: single input single output
SM: spatial multiplexing
STBC: space-time block codes
TRI: transmit rank indication
Tx: Transmitter
UE: user equipment
UMTS: universal mobile telecommunication systems
UTRA: UMTS terrestrial radio access

More Information

For more information about the 3GPP and LTE specifications visit 3GPP home page
http://www.3gpp.org/

3GPP Specification home page
http://www.3gpp.org/specs/specs.htm

3GPP Series 36 (LTE) specifications
http://www.3gpp.org/ftp/Specs/archive/36_series

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