MIMO Techniques in WiMAX and LTE: A Feature Overview

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ABSTRACT

IEEE 802.16m and 3GPP LTE-Advanced are the two evolving standards targeting 4G wireless systems. In both standards, multiple-input multiple-output antenna technologies play an essential role in meeting the 4G requirements. The application of MIMO technologies is one of the most crucial distinctions between 3G and 4G. It not only enhances the conventional point-to-point link, but also enables new types of links such as downlink multiuser MIMO. A large family of MIMO techniques has been developed for various links and with various amounts of available channel state information in both IEEE 802.16e/m and 3GPP LTE/LTE-Advanced. In this article we provide a survey of the MIMO techniques in the two standards. The MIMO features of the two are compared, and the engineering considerations are depicted.

INTRODUCTION

The IEEE 802.16e (WiMAX Profile 1.0) and Third Generation Partnership Project (3GPP) Evolved Universal Terrestrial Radio Access (E-UTRA) Long Term Evolution (LTE) (Releases 8 and 9) standards have been developed and are part of the IMT-2000 third generation (3G) technologies [1]. IEEE 802.16m (WiMAX Profile 2.0) [2] and 3GPP E-UTRA LTE-Advanced (LTE-A) (Release 10) [3] are still being developed primarily to meet or exceed the requirements of the International Telecommunication Union (ITU) for IMT-Advanced fourth generation (4G) technologies. In this article we use 802.16m for IEEE 802.16m, LTE for 3GPP releases 8 and 9, LTE-A for 3GPP release 10, and E-UTRA for releases 8 to 10. With limited spectrum resources, multiple-input multiple-output (MIMO) techniques are paramount for achieving the minimum target cell spectral efficiency, peak spectral efficiency, and cell edge user spectral efficiency defined by the ITU [4].

This article provides an overview of the design challenges and the specific MIMO solutions developed in these standards, in terms of MIMO configuration and reference signals (RSs) along with enhancements of open-loop (OL) and closed-loop (CL) MIMO operation. Key techniques in MIMO downlink (DL) and the MIMO system capabilities are summarized in Tables 1 and 2, respectively, and introduced in more detail later in this article. Space-frequency block coding (SFBC), frequency-switched transmit diversity (FSTD), and cyclic delay diversity (CDD) are OL transmit diversity techniques. Multicell MIMO and uplink MIMO techniques are defined in 802.16m and under discussion in LTE-A. 3GPP release 8 features are supported in 3GPP release 9, and all of them are supported in 3GPP release 10.

MIMO CONFIGURATIONS

802.16m and E-UTRA target MIMO schemes for the same sets of antenna configurations: 2, 4, or 8 transmit antennas and a minimum of 2 receive antennas in the DL, and 1, 2, or 4 transmit antennas in the uplink with a minimum of 2 receive antennas. Terminologies in 802.16m and E-UTRA are not matched, and as such could be confusing to the reader. Table 3 gives the equivalence between the terminologies used in both standards. The MIMO systems can be configured as single user MIMO (SU-MIMO), multi-user MIMO (MU-MIMO), and multicell MIMO; their DLs are illustrated in Fig. 1.

SU-MIMO

SU-MIMO transmissions occur in time-frequency resources dedicated to a single-terminal advanced mobile station/user equipment (AMS/UE), and allow achieving the peak user spectral efficiency. They encompass techniques ranging from transmit diversity to spatial multiplexing and beamforming. These techniques are supported in 802.16e/m and LTE, with a most noticeable difference in the approach taken for spatial multiplexing.

Spatial multiplexing (SM) is a recognized technique for increasing the peak user throughput by sending multiple spatial streams through

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Key downlink MIMO techniques	802.16m	LTE	LTE-A
Open-loop transmit diversity	SFBC with precoder cycling	SFBC, SFBC+FSTD	Inherited from LTE
Open-loop spatial multiplexing	Single codeword with precoder cycling	Multiple codewords with large delay CDD	Inherited from LTE
Closed-loop spatial multiplexing	Advanced beamforming and precoding	Codebook-based precoding, UE-specific RS based beamforming	Advanced beamforming and precoding (under development)
Multi-user MIMO	Closed-loop and open-loop MU-MIMO	Closed-loop MU-MIMO	Closed-loop MU-MIMO (under development)

Table 1. *Key techniques in MIMO downlink.*

Key downlink MIMO techniques		802.16m	3GPP E-UTRA		
			LTE		LTE-A
			Release 8	Release 9	Release 10
DL	SU-MIMO	Up to 8 streams	Up to 4 streams	Up to 4 streams	Up to 8 streams
	MU-MIMO	Up to 4 users (non-unitary precoding)	Up to 2 users (unitary precoding)	Up to 4 users (non-unitary precoding)*	Under development
UL	SU-MIMO	Up to 4 streams	1 stream	1 stream	Up to 4 streams
	MU-MIMO	Up to 4 users	Up to 8 users	Up to 8 users	Under development

*Release 8 unitary precoding for up to 2 users is still supported in Releases 9 and 10.

Table 2. *MIMO capabilities.*

multiple antennas, and separating these streams at the receiver by spatial processing [5]. The design of SM techniques in 802.16m and LTE emphasizes trade-offs determined in part by backward compatibility constraints and different assumptions on advanced receiver complexity. While a linear minimum mean square error (LMMSE) receiver is the baseline for performance evaluation, the design should account for the availability of more complex terminals as technology evolves. Design choices for SM also have effects on forward error correction (FEC) encoding coupled with hybrid automatic repeat request (HARQ), feedback mechanisms, and DL control. One of the fundamental choices is the transmission of one or multiple FEC codewords through multiple spatial streams.

802.16m has evolved from VE transmission adopted in the WiMAX profile Release 1.0. Behind this choice is the assumption that advanced receivers would be better implemented with an optimal two-stream maximum likelihood detector (MLD) than with a successive interference cancellation (MMSE-SIC) detector. This view was continued in 802.16m, relying on promising advances in near MLD techniques such as QRM-MLD [6] or sphere detectors [7] for more than two spatial streams. The usage of VE also facilitates the design and implementation of HARQ processes and requires only a single report of channel quality indicator (CQI) for all the multiplexed layers. Uplink SU-MIMO in 802.16m follows the same design as the DL.

On the other hand, LTE has opted for multiple codewords (MCW) on the DL, while uplink SU-MIMO is still being discussed in LTE-A. MCW allows link adaptation for each FEC codeword in CL SU-MIMO. An MMSE-SIC receiver may cope with the interference between FEC codewords that are spatially multiplexed. CL SU-MIMO with MCW requires one CQI report and one HARQ process for each FEC codeword. By contrast, layer permutation at the transmitter in OL SU-MIMO with MCW has the effect of averaging the signal-to-noise ratio (SNR) experienced by the two codewords so that a single CQI can be reported, although both codewords still need separate HARQ processes. Note that each FEC codeword in the layer permutation experiences the same channel quality as VE when an LMMSE receiver is used. Therefore, the layer permutation in MCW is equivalent to single codeword (SCW) in some sense. Challenges for accurate modeling of the effective SNR per codeword at the output of an MLD also played a role in the decision to favor MCW with an LMMSE or MMSE-SIC receiver in LTE. Extensive studies during both standardization processes on SCW vs. MCW taken as a part of the whole system under various operation conditions have emphasized the merits of each scheme and led the two standards to develop in their own way.

802.16m	E-UTRA
Advanced base station (ABS)	Enhanced NodeB (eNB)
Advanced mobile station (AMS)	User equipment (UE)
Transmit antenna	Antenna port
Layer	Codeword
Stream (i.e., spatial stream)	Layer (i.e., spatial layer)
Pilot	Reference signal (RS)
Preferred matrix index (PMI)	Precoding matrix indicator (PMI)
Dedicated pilots	UE-specific reference signals
Vertical encoding (VE)	Single codeword (SCW)
Multilayer encoding	Multiple codewords (MCW)
Resource unit (RU)	Resource block (RB)
Uplink collaborative spatial multiplexing	Uplink MU-MIMO
Uplink sounding	Sounding reference signal

Table 3. *IEEE 802.16m and 3GPP LTE terminologies.*

MU-MIMO

MU-MIMO [8] has become the key technique to fulfill IMT-Advanced requirements. MU-MIMO allocates multiple users in one time-frequency resource to exploit multi-user diversity in the spatial domain, which results in significant gains over SU-MIMO, especially in spatially correlated channels. In configurations such as DL 4 × 2 (four transmit antennas and two receive antennas) and uplink 2 × 4, single-user transmission only allows spatially multiplexing a maximum of two streams. On the other hand, linear MU-MIMO schemes allow sending as many as four spatial streams from four transmit antennas, or receiving as many as four spatial streams with four receive antennas, by multiplexing four spatial streams to or from multiple users. MU-MIMO techniques provide large sector throughputs in areas experiencing heavy data traffic.

The different nature of DL demodulation pilots/reference signal (RS) has induced the use of different precoding techniques in 802.16m and E-UTRA. With non-precoded common RSs in LTE, the enhanced NodeB (eNB) needs to signal the index of the precoder to the terminal via a DL control channel. This constrains the precoder to belong to the codebook used to report the precoding matrix indicator or preferred matrix index (PMI). Even though the choice of the actual precoder eventually belongs to the eNB, a simple way of building a precoder is to form a matrix from orthogonal PMIs reported by different users, which leads to unitary precoding.

On the other hand, 802.16m, LTE release 9, and LTE-A have chosen to use DL precoded dedicated pilots (UE-specific RS) even for multiple streams per terminal so that the advanced base station (ABS)/eNB can employ any precoder as long as the same precoder is applied to both RS and data symbols. Both linear and nonlinear MU-MIMO schemes [8] have been considered in the early phase of the two standards. Nonlinear MU-MIMO with dirty paper coding theoretically offers the best performance, but there are many practical limitations to its implementation, so linear MU-MIMO has been adopted in both standards for its simplicity and good performance. Zero-forcing MU-MIMO [9] is one linear MU-MIMO technique commonly assumed in both standards, where the precoding matrix at the transmitter is not unitary. Non-unitary precoding techniques offer significant performance enhancements over unitary precoding, especially in asymmetric antenna configurations (e.g., DL 4 × 2). A scheduler selects several users with good spatial separation and performs pseudo inversion of the combined channel matrix in order to obtain the precoding matrix. The CQI reported by each user is then adjusted at the ABS/eNB to fit the channel quality after precoding. The rank-1 PMI that best approaches the principal eigenvector of the channel matrix and the corresponding CQI need to be reported by the terminal.

When the terminal estimates the rank-1 PMI and CQI, it does not know which other terminal it will be paired with by the scheduler. In 802.16m the AMS estimates the rank-1 PMI and CQI assuming that the paired AMS reports an orthogonal vector. With this approach, inter-user interference is somewhat taken into consideration for MU-MIMO scheduling. From a different perspective, LTE emphasizes the transparent UE operation between SU-MIMO and MU-MIMO in terms of CQI feedback, thereby adopting SU-MIMO feedback for MU-MIMO scheduling.

In the DL 802.16m also introduced OL MU-MIMO, where a unitary precoding matrix is preset for each frequency-domain resource. Each AMS selects the preferred stream (column of the matrix) for each resource, and reports the corresponding CQI. This technique shows promising performance with limited feedback in uncorrelated and semi-correlated channels. It is suitable for urban areas where user density is high and the channel is typically non-line-of-sight.

For uplink MU-MIMO, both standards allow multiple users to transmit simultaneously in the same uplink resource. The ABS/eNB distinguishes the signals from these terminals through the pilots/RSs allocated to each terminal, and separates them with an advanced receiver, which can be an MLD receiver in the 802.16m orthogonal frequency-division multiple access (OFDMA) uplink, or a turbo MMSE receiver in the LTE single-carrier FDMA uplink.

Reference Signal for Multi-Antenna Operation

An RS, or pilot, is defined in 802.16m and E-UTRA to allow measurements of the spatial channel properties and facilitate coherent demodulation at the terminal. An RS can be a dedicated RS (DRS), which is targeted for a specific terminal, or a common RS (CRS), which is shared among a group of terminals. The RS can be further classified into precoded or non-precoded RS. DRSs are transmitted via virtual antenna ports with a spatial precoding weight to exploit beamforming gain while keeping low RS overhead when the number of virtual antenna ports is smaller than the number of physical antenna ports. CRSs are transmitted via physical antenna ports without a spatial precoder to allow for channel measurements of the non-precoded MIMO channel.

A lot of commonalities exist in 802.16m and E-UTRA in terms of RS usage on the uplink, although exact details are different. For instance, the sounding RS is employed as a non-precoded DRS in both standards for the purpose of uplink spatial channel adaptation, including beam selection and scheduling, as well as for measuring the DL channel by exploiting channel reciprocity in time-division duplex systems. In addition, a precoded DRS is also employed for coherent demodulation in uplink.

In contrast, different designs have been adopted for the DL pilots. Non-precoded common pilots, or midamble, and precoded dedicated pilots are both used in 802.16m for channel measurements and coherent demodulation supporting up to eight transmit antennas. Although the midamble can be used for demodulation in a specific transmission mode such as OL SU-MIMO, it mainly provides fine channel measurements with low pilot overhead because it is transmitted in a wideband manner to enable measurements of the whole frequency band with a small duty cycle. In addition to the midamble, precoded dedicated pilots up to eight streams, which allow flexible beam generation at the ABS side, have been defined for contiguous resource units (RUs) in 802.16m irrespective of the transmission mode. For distributed RUs supporting only two streams, common pilots precoded by predefined matrices are utilized.

On the other hand, non-precoded CRSs supporting up to four antenna ports have been defined for channel measurements and coherent demodulation purposes in LTE Release 8. With the use of non-precoded CRS, the spatial precoder used in the DL signal should be indicated to a terminal in each transmission assignment. LTE Release 8 also supports single-layer beamforming using rank-1 precoded DRS in addition to the CRS, which has been extended to two UE-specific RSs to support dual-layer beamforming in LTE Release 9, and for which the spatial precoder does not need to be indicated to the terminal. To further enhance the peak and average throughputs, eight antenna port transmissions supporting up to eight layers have been adopted in LTE-A. Precoded DRSs supporting up to eight layers and non-precoded CRSs (i.e., LTE-A channel state information [CSI]-RS) with a low duty cycle for eight antenna ports' measurement are utilized on top of the LTE CRS, which are kept in LTE-A for the continuing support of LTE terminals.

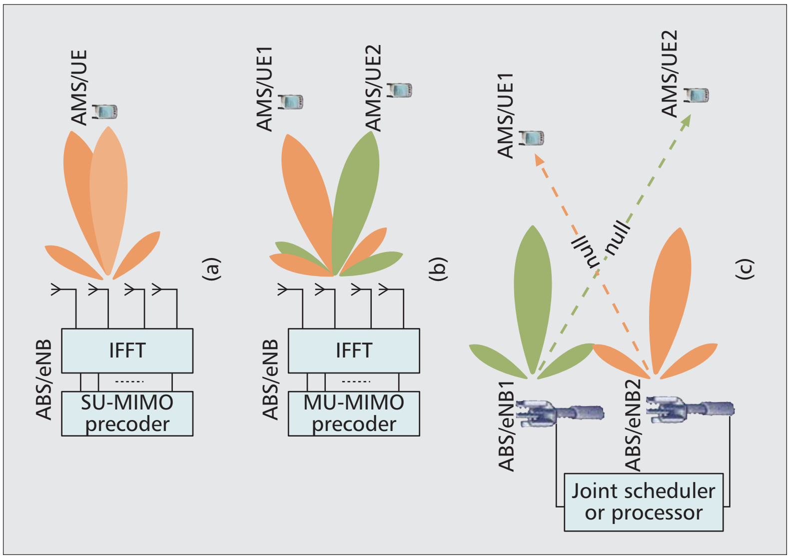

Figure 1. *MIMO configurations.*

Open Loop Techniques

In general, OL techniques are designed for high mobility or limited feedback capability. OL techniques mainly provide robustness for the link adaptation considering terminal mobility with infrequent CSI feedback exploiting long-term channel statistics rather than short-term fading information. Therefore, CQI may represent short-term or long-term channel information. As a special case, opportunistic beamforming is also classified as an OL technique since no information relative to the spatial transmit weights is reported, while short-term CQI is used for the adaptation of modulation and coding rate. Two different types of OL techniques have been considered, space-time coding and random beamforming, and these techniques are optimized differently in each standard.

Space Time/Frequency Code

Transmit diversity techniques provide spatial diversity gain, which translates into higher link margin than single-transmit-antenna techniques. For a configuration with two transmit antennas, both standards have adopted the frequency domain version of the Alamouti code [10] as the basic transmit diversity MIMO mode, where pairs of adjacent subcarriers are coded together instead of two adjacent time slots. Because fast changing channel in the time domain would destroy the orthogonality of the code, an SFBC outperforms an STBC in high-speed scenarios. Application of the SFBC with more than two transmit antennas necessitates the application of a precoder to convert four or eight physical antennas into two virtual antennas. Both techniques adopted in 802.16m and LTE limit the transmission of SFBC to a pair of subcarriers while making effective use of all spatial degrees of freedom over a set of subcarriers in order to provide robustness against spatial correlations in the channel. The receiver can use the same decoding process independent of the number of physical transmit antennas.

CL-MIMO exploits CSI at the transmitter (CSIT) for increasing coverage or throughput. In CL-MIMO, the transmitter acquires the CSI from feedback or channel sounding, and then forms a beamforming or precoding matrix. The major challenges lie in efficiently obtaining the CSI.

The usages of the precoders in 802.16m and LTE are slightly different, due to the difference in the design of DL demodulation pilots, but they target the same objective. While 802.16m chose a combination of precoder cycling and SFBC with precoded pilots, LTE opted for a combination of FSTD and SFBC with non-precoded CRS. The precoder cycling creates a fixed set of two virtual antennas across all subcarriers within an RU and changes the virtual antennas by using different precoder weights across RUs, while FSTD cycles transmissions over pairs of transmit antennas across subcarriers within an RU. These designs also incur different constraints on the channel estimation at the receiver, with a trade-off between the reduced overhead offered by precoded pilots in 802.16m vs. the wider range of interpolation available in the frequency domain with non-precoded pilots for finer channel estimation in 3GPP LTE.

Random Beamforming/Precoder Cycling

As described above, space-frequency codes exploit spatial diversity so that the variance of the CQI is reduced as the diversity order increases, which allows for robust transmission with infrequent CSI feedback. However, although the robustness of space-frequency codes is superior to other OL schemes, their limited design flexibility led both standards to additionally employ random beamforming. Random beamforming artificially increases the channel selectivity by changing beams within allocated time/frequency resources, and strong FEC codes (e.g., turbo codes) enjoy this artificial frequency diversity gain.

Precoder cycling, in which predefined precoders are cyclically allocated to a group of contiguous subcarriers, is utilized in both standards as a random beamforming technique. The predefined set of precoders is selected from the precoding codebook as a subset, which has a good Chordal distance property so that diversity order can be maximized. Precoder cycling is used for providing beam diversity gain and beam selection gain in 802.16m. To obtain the beam diversity gain, resources are distributed within a wide frequency band where predefined precoders in each localized frequency band form different beams; hence, the aggregated resources at the receiver may enjoy the beam diversity gain. To enable the beam selection gain, on the other hand, a localized resource is allocated to a terminal based on the CQI feedback for its preferred subbands. Since the predefined precoders are cyclically changed according to the subbands, opportunistic beamforming gain can be achieved by allocating the preferred subbands as reported by a terminal. Since non-precoded CRSs are employed in LTE, the predefined precoders can be changed every few subcarriers within each RB so that the beam diversity gains are fully exploited even in a single RB allocation. Layer permutation is performed along with precoder cycling in E-UTRA to further increase diversity gain from virtual antennas with MCW transmissions. The combination of precoder cycling and layer permutation is called large-delay CDD and was adopted as an OL SM technique in E-UTRA.

Closed Loop Techniques

CL-MIMO exploits CSI at the transmitter (CSIT) for increasing coverage or throughput. In CL-MIMO the transmitter acquires the CSI from feedback or channel sounding, and then forms a beamforming or precoding matrix. The major challenges lie in efficiently obtaining the CSI. For accurate CSIT, frequent update is required for mobile terminals. However, overhead and delay limit CSIT accuracy. First, the frame structure inherently sets a delay between the channel measurement and the actual beamforming transmission. Any channel variation during the delay degrades the performance. Second, the overhead for acquiring CSIT becomes burdensome as the number of reporting terminals and mobility increase. On one hand, the CSI of multiple terminals is collected, but only a few favorable terminals are scheduled for transmission. Unfortunately, this selection gain increases logarithmically with the number of reporting terminals. On the other hand, the feedback/sounding overhead increases linearly with the number of reporting terminals. Therefore, efficient feedback/sounding techniques are essential.

Feedback Mechanisms

Feedback is required when channel reciprocity is unavailable (e.g., in frequency-division duplex systems). The major challenge lies in how to report the preferred beamforming matrix (directions), which is used for the transmitter to compute the actual precoder over a limited feedback bandwidth. For overhead reduction, the whole beamforming matrix is quantized by a matrix or vector codebook. The index of the selected quantization codeword (the PMI defined in Table 3) is fed back. An L bit codebook consists of 2^L codewords, where L is the required number of bits for indexing each codeword. In this section the term codeword means the quantization codeword in the quantization codebook. In the DL, after measuring the channel, the terminal searches for the best codeword in the codebook for optimizing the performance and reports the PMI to the ABS/eNB. After receiving the PMI, the ABS/eNB looks up the codeword and computes a precoder. Three feedback types are devised, called *base codebook*, *adaptive* (or *transformed*) *codebook*, and *differential codebook*, respectively. The base codebook has the least signaling overhead, and the other two have better performance with additional signaling overhead.

The engineering considerations of the base codebook design comprise performance gain, overhead, robustness, complexity, and power amplifier imbalance. First, 802.16m defines 3-bit for 2-transmit antennas (2-Tx) as well as 4-bit and 6-bit feedbacks for 4-transmit antennas (4-Tx), while LTE defines 2-bit and 4-bit feedbacks for 2-Tx and 4-Tx, respectively. Besides the preferred beamforming matrix, an indication of the preferred number of spatial streams is also defined. In addition, 802.16m has 4-bit feedback for 8-transmit antennas (8-Tx) and an enhanced 6-bit feedback for 4-Tx. Second, codewords with a rotated block diagonal structure are explicitly employed in 802.16m and LTE for dual-pole antennas. Third, base codebooks can be dynamically generated from a few parameters for reducing storage complexity. In addition, the codeword entries of all LTE base codebooks and most of the 802.16m codebooks are selected from quaternary phase shift keying (QPSK) and 8-PSK constellations for reducing the storage requirement and computational complexity. Furthermore, the high-rank codewords with more columns include the low rank codewords with a few columns as a subset. This reduces the complexity of searching for the best number of spatial streams. Finally, each LTE codeword and most of the 802.16m codewords load transmission power evenly on each antenna for lowering the power amplifier cost.

Since the optimal codebook varies with the deployment scenario, adaptive codebook is defined in 802.16m. The adaptive codebook changes its codeword distribution according to long-term channel statistics captured in the transmit covariance matrix, which characterizes the spatial correlations across transit-side antennas. Using that matrix, each vector codeword of the rank-1 base codebook is linearly transformed and normalized for generating a codeword in the adaptive codebook. Effectively, more codewords are steered around the directions where the ideal beamforming direction likely appears. As a result, the overall quantization error is reduced. This gain increases with antenna correlation, which increases as the antenna spacing and the angle spread of departing signals at the ABS/eNB decrease. Since MU-MIMO has higher gains in highly correlated channels, the adaptive codebook is most beneficial for MU-MIMO. Antenna configurations, inaccurately calibrated transceiver chains, and propagation channel properties are inherently captured in the measured covariance matrix, making the adaptive codebook robust in a wide range of scenarios. The adaptive codebook, however, requires additional signaling and feedback overhead for reporting the covariance matrix that is needed once for the whole frequency band and for a period greater than 20 ms.

For overhead reduction, the correlation between consecutive beamforming reports is also exploited by differential codebooks in 802.16m. Instead of depicting the preferred beamforming matrices in full, each differential feedback only specifies the incremental change between the current and previous matrices. Because the change is usually within a small range, fewer codewords are needed to cover the small range than the whole beamforming space covered by the base codebook. The reduction of codebook size not only saves feedback overhead but also reduces the quantization complexity. 2-bit, 4-bit, and 4-bit codebooks are defined in 802.16m for 2-Tx, 4-Tx, and 8-Tx, respectively. The down side of differential codebook is the error propagation effect. That is, once an error occurs, that error corrupts the subsequent feedback reports until the differential process is reset.

Uplink Sounding

In time-division duplex systems, the transmitter can learn about the DL channel from sounding on the uplink channel by exploiting the reciprocity of the propagation channel. To achieve full reciprocity, calibration of the transceiver RF chains is needed at the ABS/eNB. Both 802.16m and LTE provide sounding mechanisms for estimating the uplink channel on a subband or wideband scale. In 802.16m, the uplink sounding channel is inherited from 802.16e with some enhancements. In LTE the ABS/eNB assigns different training sequences to multiple terminals for sharing the same training resources simultaneously. Finally, channel estimation error due to noise and intercell interference limits the performance of uplink sounding.

Long-Term Beamforming

Long term beamforming applies a rough precoder for the whole frequency band and over a period of several frames. This reduces the density of feedback and sounding multiple times. The rough beamforming direction corresponds to a dominant multipath component. Furthermore, in line-of-sight scenarios with closely spaced antennas, the beam pattern is wide in space, and thus allows the beam to cover a high-speed terminal for several time frames. Both 802.16m and LTE support PMI feedback for long-term beamforming. In addition, 802.16m also allows using the reported transmit covariance matrix to derive the precoder.

Long term beamforming applies a rough precoder for the whole frequency band and over a period of several frames. This reduces the density of feedback and sounding by multiple times. The rough beamforming direction corresponds to a dominant multipath component.

Concluding Remarks

In this article we have reviewed the MIMO techniques adopted or under development in IEEE 802.16m and 3GPP LTE/LTE-Advanced. We have emphasized the design trade-offs considered during both standardization processes and outlined some of the implementation challenges.

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