Downlink MIMO in 3GPP LTE/LTE-Advanced and IEEE 802.16m

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Abstract

3GPP LTE/LTE-A and IEEE 802.16m have recently been submitted to ITU as IMT-Advanced candidates. MIMO is one of the core technologies that enable both standards to achieve the tough requirements specified by ITU. This paper provides an introduction to the core downlink MIMO features of both standards.

I. Introduction

Two major technologies, i.e. 3GPP LTE/LTE-A and IEEE 802.16m, have recently been submitted to ITU as IMT-Advanced candidates.

The new cellular standard, named Long-Term Evolution (LTE), also referred to as Evolved UMTS Terrestrial Radio Access (E-UTRA), has been initiated in 2004 to replace the UMTS third-generation system. It was completed in September 2008. Since then, 3GPP LTE advanced has been initiated and is the most advanced version of LTE.

LTE targets significant improvements in bit rates with respect to previous 3GPP releases and aims to provide a highly efficient, low-latency, packet-optimized radio access technology offering enhanced spectrum flexibility.

Every layer has been subject to significant modifications in LTE. Similarly to IEEE 802.16, the physical layer in the downlink uses OFDM waveforms in order to avoid the intersymbol interference that typically arises in high bandwidth systems. The uplink on the other hand is based on SC-FDMA. Hence the previous CDMA-based access technology has given way to a radically new time and frequency multiple access. Contrary to its predecessors, MIMO is also nowadays an integral component, and not an add-on feature. The network layer has also been improved by the introduction of a flatter architecture and enables the transition from the existing UTRA network combining circuit- and packet-switching, to an all-IP system. More advanced features using e.g. higher order MIMO, relays and multi-points cooperation are currently being discussed to further boost the performance of LTE systems. Such features will be available in LTE-Advanced release.

IEEE 802.16m on the other hand was initiated in 2006 and provides an advanced air interface (PHY and MAC) as an amendment of the IEEE 802.16 WirelessMAN-OFDMA (more commonly referred as IEEE 802.16e) specification. Similarly to 3GPP LTE/LTE-A, its technology targets to meet the requirements of IMT-Advanced next generation mobile networks. An important requirement of IEEE 802.16m is to support the legacy WirelessMAN-OFDMA equipment.

Similarly to 3GPP LTE/LTE-A, IEEE 802.16m defines TDD and FDD modes, it is based on OFDMA-based downlink access, and MIMO (up to 8x8 on DL and 4x4 on UL) is also

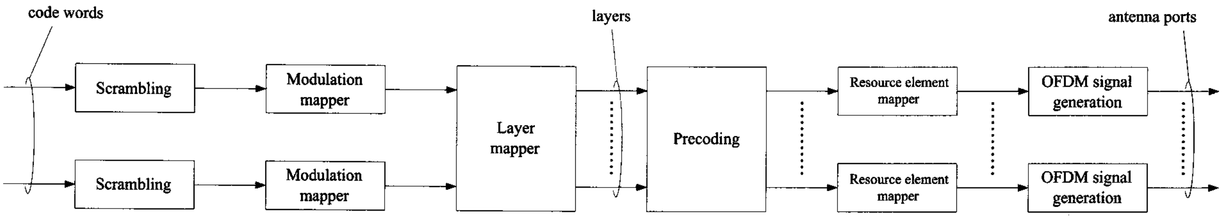

Figure 1: LTE Downlink MIMO physical channel processing

a core component of the system. LTE and 16m distinguish themselves on the uplink. IEEE 802.16m is exclusively based on OFDMA.

Providing an exhaustive comparison of those two standards is beyond the scope of this introductory paper. The objective of our paper is however to provide to the generally knowledgeable person a brief introduction of the MIMO features adopted in 3GPP LTE/LTE-A and IEEE 802.16m.

Before jumping into the subject, it is worth mentioning that both standards use very different terminologies that could be confusing for the reader. In order to stay inline with the standard specifications, we have chosen to keep in this paper the respective terminologies adopted in IEEE 802.16m and 3GPP LTE. As an example, what is defined as a codeword, a layer and a reference signal in LTE corresponds to a layer, a stream and a pilot in IEEE 802.16m, respectively. Moreover a PMI refers to a precoding matrix indicator in LTE while it refers to a preferred matrix index in 16m.

II. 3GPP LTE/LTE-Advanced

As mentioned in the introduction, LTE/LTE-A [1-6] has adopted various MIMO features as a core technology. This includes transmit diversity, single user (SU)-MIMO, multiuser (MU)-MIMO, closed-loop rank-1 precoding, and dedicated beamforming in LTE and higher order MIMO, advanced MU-MIMO and multi-point transmissions in LTE-A.

The downlink MIMO physical channel processing is illustrated in Figure 1. After channel encoding, interleaving, rate matching, the codeword bits are successively mapped to complex modulation symbols and to the layers as a function of the transmission rank and the transmission mode. The layers are finally precoded and transmitted on the physical antennas.

Antenna configurations from 1x2 (1 transmit antenna and 2 receive antennas) to 8x8 are supported on the downlink with the number of layers varying from 1 to 8 depending on the number of receive antennas and the transmission mode. LTE system supports up to 4x4 configurations with up to 4 layers per user equipment (UE), while LTE-A defines higher order MIMO with up to 8x8 configurations. MU-MIMO in LTE can support a maximum of 2 streams while the maximum number of streams in LTE-A MU-MIMO is still under discussion.

Table 1 summarizes the seven DL MIMO modes defined in LTE.

Mode index	Description
Mode 1	Transmission from a single eNodeB antenna port
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 precoding
Mode 7	Transmission using UE-specific reference signals

The transmit diversity scheme is specified for the configuration with two or four transmit antennas in the downlink. In LTE-A, no transmit diversity is defined for eight transmit antennas. The four transmit antenna diversity scheme is re-used by applying antenna virtualization.

Transmit diversity schemes defined in LTE downlink is based on the well known space-frequency block code (SFBC) if the eNodeB (i.e. Base Station) has two transmit antennas. For the eNodeB with four transmit antennas, a combination of the SFBC and the frequency-switched transmit diversity FSTD (as in Figure 2) is used to provide robustness against the transmit spatial correlation and to simplify the implementation of the UE receiver.

$$\begin{array}{r}\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}\end{array}\overset{\text{Subcarrier}\longrightarrow}{\begin{bmatrix} s_0 & s_1 & 0 & 0\\ 0 & 0 & s_2 & s_3\\ -s_1^* & s_0^* & 0 & 0\\ 0 & 0 & -s_3^* & s_2^*\end{bmatrix}}$$

Figure 2: SFBC + FSTD with four transmit antennas on downlink

It is worth mentioning that LTE transmit diversity is seen as a precoding technique in Figure 1 rather than a MIMO encoding technique as it will be the case in IEEE 802.16m.

The SU-MIMO spatial multiplexing scheme is specified for the configuration with two or four transmit antennas in the LTE downlink and with up to eight transmit antennas in LTE-A downlink. It enables to support transmission of multiple spatial layers with up to four layers to a given LTE User Equipment (UE) and up to eight layers to a LTE-A UE.

Multiple codewords may be mapped to multiple layers depending on the transmission rank scheduled by the eNodeB. Since hybrid automatic repeat request (HARQ) process is operated for each codeword, each HARQ process requires an ACK/NACK feedback signaling on uplink. To reduce the uplink feedback overhead, a maximum of two codewords are transmitted even though more than two layers can be transmitted on downlink in a given subframe, giving rise to the need of defining a rule for mapping a codeword to its layers. In LTE, codewords are mapped to layers according to the following principle. If there is one layer, there is one codeword. If there are two layers, the basic mode of operation is to carry a codeword for each layer. The case of transmitting a single codeword using two layers is only applicable for the eNodeB having four transmit antennas when its initial transmission contained two codewords and a codeword mapped onto two layers needs to be retransmitted. In case of three-layer transmission, the first layer carries the first codeword while the second and the third layers carries the second codeword, in which case the second codeword carries twice the number of modulation symbols as the first codeword. When four layers are scheduled, two codewords are transmitted, each of which is transmitted using two layers. The modulation symbols of a codeword are equally split into two layers when the codeword is mapped to two layers. In the case of eight transmit antennas for LTE-A, the codeword to layer mapping follows a similar rule as in LTE four transmit antennas case, with a maximum of 2 codewords.

In the closed-loop spatial multiplexing mode, the eNodeB applies the spatial domain precoding on the transmitted signal taking into account the precoding matrix indicator (PMI) reported by the UE. The closed-loop spatial multiplexing with Mt layers and Nt transmit antennas (Nt $\geq M_t$)writes as $\mathbf{z}=\mathbf{W}\mathbf{x}$ where $\mathbf{x}$ is the modulation symbol vector and $\mathbf{z}$ is the complex symbol vector transmitted on the N_t physical antennas. $\mathbf{W}$ is selected by the UE in a 2-bit (resp. 4-bit) CL SU MIMO codebook if the eNodeB has 2 transmit antennas (resp. 4 transmit antennas).

To support the closed-loop spatial multiplexing in the downlink, the UE needs to feedback the rank indicator (RI), the PMI, and the channel quality indicator (CQI) in the uplink. The RI indicates the number of spatial layers that can be supported by the current channel experienced at the UE.

The eNodeB may decide the transmission rank, M_t, taking into account the RI reported by the UE.

In the open-loop spatial multiplexing, the feedback consists of the RI and the CQI. In contrast to the closed-loop spatial multiplexing, the eNodeB only determines the transmission rank and a fixed set of precoding matrices are applied cyclically across all the scheduled subcarriers in the frequency domain. On the i^{th} complex modulation symbol, the precoding for the open-loop spatial multiplexing mode is defined by

$$y(i) = W(i)D(i)Ux(i)$$

where $\mathbf{W}(i)$ is of size N_t x M_t defined by the identity matrix for two transmit antennas and by a codeword of the closed loop SU-MIMO codebook for four transmit antennas, $\mathbf{U}$ is a M_t x M_t DFT matrix and the matrix $\mathbf{D}(i)$ of size M_t x M_t provides the large delay cyclic delay diversity (CDD). When multiple layers are transmitted, $\mathbf{D}(i)\mathbf{U}$ effectively makes the modulation symbols of a single codeword to be mapped onto different layers for each i in a cyclic manner with period M_t as the index i increases, so that a codeword can experience all the transmitted layers.

The closed-loop MU-MIMO scheme allows allocation of different spatial layers to different users in the same time-frequency resource. If a UE is configured to be in the MU-MIMO transmission mode, only rank-1 transmission can be scheduled to the UE. The eNodeB can schedule multiple UEs, which are configured to be in the MU-MIMO transmission mode, in the same time-frequency resource using different rank-1 precoding matrices. The precoding matrices used for transmission are constrained to be included in the rank-1 codebook used by the UE for quantization and feedback. Given the presence of cell-specific reference signals in LTE, the UE has to be informed about its own precoding matrix. The scheduled UE decodes the information data utilizing the common reference signal together with the precoding information obtained from the control signaling.

The UE generates the PMI/CQI feedback without any knowledge about other simultaneously scheduled UEs. Hence, there could be mismatch between the UEs CQI report and the actual CQI experienced due to lack of knowledge of interference caused by other UEs scheduled simultaneously.

An important constraint of LTE is the use of common reference signals for transmission modes 1 to 6. Those reference signals are used at the UE for measurements and feedback as well as for demodulation. Hence reference signals are common for all UEs belonging to the cell and cannot be precoded. Due to such constraint, MU-MIMO defined in LTE is clearly sub-optimal.

Given the fact that MU-MIMO has been shown to be a core feature to achieve IMT-Advanced requirement, LTE-A has put much efforts on introducing and defining new user specific reference signals in order to enable the use of more advanced MU-MIMO schemes (e.g. ZFBF, joint leakage suppression, etc). In such advanced MU-MIMO, the transmit precoding is not constrained to be included in the UE codebook used for feedback. Along with the user-specific reference signals, CSI reference signals are defined to allow the UEs to measure the MIMO channel and to report the channel state information to the eNodeB. Those CSI reference signals act as a midamble in IEEE 802.16, as we will wee later. Hence LTE-A system will have three types of reference signals: the user-specific reference signals, the cell-specific reference signals (to enable legacy with LTE users) and the CSI reference signals.

This advanced MU-MIMO scheme in LTE-A is currently being designed in such a way that it can enable dynamic switching with SU-MIMO, can be more transparent from a UE perspective and can enable multiple streams transmissions per UE. Moreover more advanced feedback mechanisms are currently being proposed. The feedback of short time covariance matrix or multiple PMIs in order to better estimate the null space of each user channel has been shown to provide some benefits over a single PMI-based feedback. Enhancements of feedback by combining short term channel state information with long term statistics or with differential codebook feedback are also under discussion.

The closed-loop rank-1 precoding scheme is used to improve data coverage utilizing SU-MIMO technology based on the cell-specific common reference signal while introducing a control signal message that has lower overhead.

The dedicated beamforming scheme in LTE is used for data coverage extension when the data demodulation based on dedicated (i.e. UE-specific) reference signal is supported by the UE. LTE specifies only one UE-specific reference signal.

The uplink feedback for support of downlink data transmission consists of the RI, the PMI, and the CQI. Wideband RI is reported as it was observed that frequency-selective RI reporting did not provide significant performance benefit. On the contrary, the reporting of PMI and CQI can be either wideband or frequency-selective. The PMI is calculated conditioned on the associated RI, and the CQI is calculated conditioned on the associated RI and PMI. In case of the frequency-selective PMI/CQI reporting, the UE reports a PMI/CQI for each subband. For the non-frequency-selective wideband PMI/CQI reporting, the UE reports a single wideband PMI/CQI corresponding to the whole bandwidth.

In addition to meeting the peak spectrum efficiency by enabling higher order MIMO and the average cell throughput by enhancing downlink MU-MIMO, further improvement of the cell edge performance is also an important aspect of the LTE-advanced study. Coordinated multipoint transmission/reception (referred as CoMP) is a candidate technology where antennas of multiple cell sites are utilized in a way such that the transmit antennas of the serving cell as well as the neighboring cells can contribute in improving quality of the received signal at the UE, as well as in reducing the co-channel interferences from neighboring cells. Two major kinds of CoMP techniques are under discussion: coordinated beamforming/scheduling (CS/CB) and joint processing (JP). CS/CB assumes exchange of channel state information among eNodeB to perform interference mitigation. JP on the other hand assumes data and CSI exchange in order to increase the beamforming gain on top of performing interference mitigation.

III. IEEE 802.16m

Advanced multi-antenna techniques based on single and multi-user MIMO (spatial multiplexing and beamforming), and transmit diversity schemes are core features of IEEE 802.16m [7].

The downlink MIMO transmitter structure is shown in Figure 3. The encoder block contains the channel encoder, interleaving, rate-matching, and modulation blocks per layer. A layer is defined as an encoding and modulation input path to the MIMO encoder and corresponds to the codeword in LTE. The resource mapping block maps the complex-valued modulation symbols to the corresponding time-frequency resources. The MIMO encoder block maps the layers onto the streams, which are further mapped to the physical antennas by the beamforming/precoding block according to the selected transmission MIMO mode. The OFDMA symbol construction block maps antenna-specific data to the OFDMA symbols. The feedback block contains feedback information such as channel quality indicator (CQI) or channel state information (CSI) from the mobile station.

Antenna configurations from 2x2 to 8x8 are supported on the downlink with the number of streams varying from 1 to 8 depending on the number of receive antennas and the transmission mode. While SU-MIMO can support up to 8 steams to a single-user (if the user can support it), a maximum of 4 streams is sent in MU-MIMO with 4 and 8

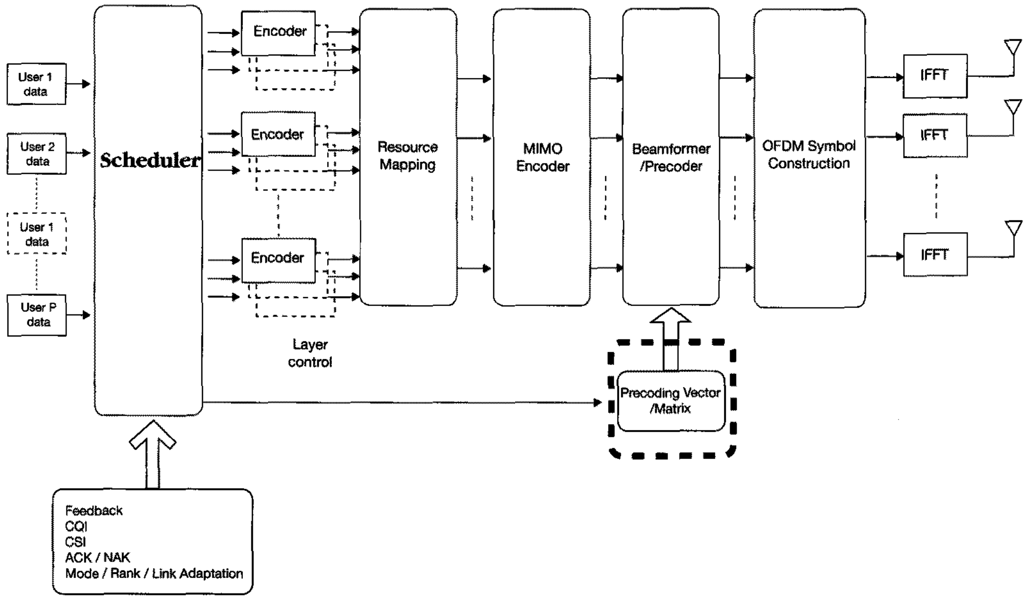

Figure 3: Downlink MIMO Structure

transmit antennas.

Table 2 summarizes the 6 DL MIMO modes defined in IEEE 802.16m with the corresponding encoding format and the type of precoding.

Table 2: Downlink MIMO Modes

Mode index	Description	MIMO encoding format	MIMO precoding
Mode 0	OPEN-LOOP SINGLE-USER-MIMO	SFBC (Tx diversity)	non-adaptive
Mode 1	OPEN-LOOP SINGLE-USER-MIMO	Spatial Multiplexing Vertical encoding	non-adaptive
Mode 2	CLOSED-LOOP SINGLE-USER-MIMO	Spatial Multiplexing Vertical encoding	adaptive
Mode 3	OPEN-LOOP MULTI-USER-MIMO	Spatial Multiplexing Horizontal encoding	non-adaptive
Mode 4	CLOSED-LOOP MULTI-USER-MIMO	Spatial Multiplexing Horizontal encoding	adaptive
Mode 5	OPEN-LOOP SINGLE-USER-MIMO	Conjugate data repetition (Tx diversity)	non-adaptive

For SU-MIMO, vertical encoding (i.e. a single layer) is utilized, whereas for MU-MIMO horizontal encoding (i.e. multiple layers) is employed at the base station. Hence if M modulated symbols are to be transmitted, they would belong to the same layer in SU-MIMO and to M different layers in MU-MIMO. Given that ML decoder can be implemented nowadays in practical handset, vertical encoding was chosen to simplify the UL control channel design and reduce the UL overhead by feeding back a single ACK/NACK.

The MIMO encoder takes M modulated symbols as an input and provides as an output an M_t x N_f space-time coding matrix where M_t is the number of spatial streams and N_f is the number of adjacent subcarriers in 1 OFDM symbol. Over each subcarrier, the MIMO precoder determines the stream to antenna mapping and maps M_t space-time coded symbols (representing M_t streams and expressed as a [M_t x 1] vector $\mathbf{x}$) to Nt physical antennas after being precoded by the beamforming vector $\mathbf{W}$ as follows $\mathbf{z}=\mathbf{Wx}$.

It is important to note that for all transmission modes, the data and the pilots are precoded by $\mathbf{W}$. This is a major difference with LTE where reference signals are not precoded by $\mathbf{W}$. As mentioned in previous section, the introduction of user-specific reference signals in LTE-A enables however to precode the reference signals by $\mathbf{W}$.

In open loop SU-MIMO, **W** is unitary taken from the open loop codebook subset and pre-defined per subband. In Tx diversity modes, **x** is a 2x1 vector for SFBC and 1x1 in CDR and vertical encoding. In spatial multiplexing, **x** is a [M_t x 1] vector where M_t can be adaptively changed as a function of the rank feedback.

In closed loop SU-MIMO, **W** is a unitary precoding matrix that is vendor-specific or chosen from a codebook. It is an implementation choice given the presence of dedicated pilots. **W** is derived from the feedback. Similarly to open-loop MIMO, **x** is a [M_t x 1] vector where M_t can be adaptively changed as a function of the rank feedback.

In multi-user MIMO, data and pilots are precoded by **W** and a maximum of 4 users are scheduled with 1 stream per user.

In open-loop MU-MIMO, **W** is unitary taken from the open-loop codebook subset and pre-defined per subband. Users feedback the best stream for the preferred subbands. Base stations pairs users with different streams for the same precoding matrix.

In closed-loop MU-MIMO, **W** is vendor-dependent or chosen from a codebook for the same reason as in CL SU MIMO. Unitary (e.g. PU2RC) and non-unitary (e.g. ZFBF) precoding can be supported by the implementation. **W** is derived from the feedback and the number of streams can be adaptively modified by the base station.

An optional open-loop region has been added in IEEE 802.16m to prevent dynamic interference. The open loop region is a resource in the frequency partition with reuse 1 open-loop transmissions with 1 or 2 streams. That resource is aligned for all cells and sectors. A fixed precoding in all cells and sectors is applied to prevent dynamic interference and enabling accurate link adaptation. To do so, rank adaptation in an open-loop region is prohibited.

The usage of the DL MIMO modes has been defined for each kind of resource allocation. In subband based localized allocation, only MIMO modes 1 to 4 are allowed. In diversity allocation with distributed minibands (i.e. distributed Resource blocks), MIMO modes 0, 1, 2 and 4 are allowed. For MIMO mode 2, only rank 1 transmission (M_t=1) is allowed to perform wideband SU beamforming. MIMO mode 4 enables to perform wideband MU beamforming. In diversity allocation with distributed subcarriers, MIMO mode 0 and 1 are allowed with a constraint on 2 streams (M_t=2) for mode 1 due to the presence of the control channels transmitted using MIMO mode 0.

To perform closed-loop MIMO, measurements are done on a midamble (a set of common pilots per transmit antennas available every subframe). The feedback modes need to be specified in order to report the channel state information and perform adaptive precoding. Codebook-based feedback (for TDD and FDD) and uplink sounding (for TDD) are supported in IEEE 802.16m. The feedback information may contain the subband selection, the STC rate (commonly referred to as the rank) to perform rank adaptation, the CQI (wideband or sub-band) for link adaptation, preferred matrix index PMI (wideband or subband, for serving cell and/or neighboring cell, for SU and MU MIMO) for computing the adaptive precoder, the preferred stream index (for OL MU MIMO), the quantized correlation matrix (in the transformed codebook based feedback mode), the preferred operation mode (diversity/localized).

Three types of codebook-based feedback have been defined:

1. The standard mode using a PMI feedback from a base codebook (3 bits in 2Tx, 6bits and a 4bits subset in 4Tx, 4bits in 8Tx) optimized for uncorrelated, correlated and dual-polarized configurations.
2. The transformation mode for rank 1 PMI only enabling to transform the base codebook using the wideband long-term quantized spatial correlation matrix.
3. The differential mode using a rotation-based differential codebook enabling progressive refinement of the channel state information at the base station in low mobility scenarios.

On top of single-cell processing, multi-base station MIMO techniques are also under consideration for improving sector and cell-edge throughput. Among those techniques, we can find DL single base station processing with PMI coordination among base stations (using e.g. PMI restriction and recommendation), DL multiple base station joint transmission to multiple users (closed-loop macro diversity with SU-MIMO transmission, cooperative MIMO with MU-MIMO transmission).

IV. Performance evaluation to ITU

Table 3 summarizes performance of LTE/LTE-A and IEEE 802.16m in environments defined by ITU for submissions as IMT-Advanced candidates [8-9]. While not specifically indicated in the table, performance of IEEE 802.16m standard has been conducted assuming MU-MIMO with transformation mode based feedback. Results of both standards converge to say that MU-MIMO based on user-specific reference signals (i.e. dedicated pilots) is the core technology to achieve ITU requirements. Additional advanced features like coordinated beamforming and scheduling or joint processing are not strictly required to achieve the goals fixed by ITU. Such technologies may however be necessary to achieve the goal specified by 3GPP LTE-A requirements.

V. Conclusions

This paper provides an introduction to the MIMO features standardized in 3GPP LTE/LTE-A and IEEE 802.16m. Both standards have recently been submitted to ITU as IMT advanced candidate systems. It is shown that both

Table 3: Performance evaluation results for the ITU-R submission (IIII refers to 4 closely space single polarized antennas, I I I I refers to 4 largely spaced single polarized antennas, XXXX refers to 8 dual-polarized antennas)

environments	ITU requirements		3GPP LTE-A with 3 OFDM symbols overhead			IEEE 802.16m	
	cell av. [b/s/Hz/cell]	cell edge [b/s/Hz]	scheme and antenna configuration	cell av. [b/s/Hz/cell]	cell edge [b/s/Hz]	cell av. [b/s/Hz/cell]	cell edge [b/s/Hz]
Indoor Hotspot	3	0.1	Rel-8 SU-MIMO 4 X 2, I I I I	4.1	0.19	5.9	0.255
			MU-MIMO 4 x 2, IIII	5.5	0.22		
Urban Micro	2.6	0.075	MU-MIMO 4 x 2, IIII	2.9	0.087	3.13	0.096
			MU-MIMO 4 x 2, I I I I	2.8	0.099		
			CS/BF-CoMP 4 x 2, IIII	3	0.089		
			JP-CoMP 4 x 2, IIII	3.7	0.12		
			MU-MIMO 8 x 2, IIIIIIII/XXXX	3.5	0.13		
Urban Macro	2.2	0.06	MU-MIMO 4x2, IIII	2.4	0.066	2.44	0.068
			CS/CB-CoMP 4x2, IIII	2.4	0.067		
			JP-CoMP 4x2, I I I I	2.5	0.066		
			CS/BF-CoMP 8 x 2, IIIIIIII	3.2	0.085		
Rural Macro	1.1	0.04	Rel-8 SU-MIMO 4 X 2, IIII	1.9	0.069	3.12	0.092
			Rel-8 SU-MIMO 4 X 2, I I I I	1.8	0.057		
			MU-MIMO 4 x 2, IIII	3.2	0.09		
			MU-MIMO 8 x 2, IIIIIIII	3.4	0.11		

technologies can achieve ITU requirements in all scenarios and that MU-MIMO based on user-specific reference signals (or also called dedicated pilots) is the core technology to achieve ITU requirements.

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약력

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