Overview of Full-Dimension MIMO in LTE-Advanced Pro

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Abstract

Multiple-input multiple-output (MIMO) systems with large number of basestation antennas, often called massive MIMO systems, have received much attention in academia and industry as a means to improve the spectral efficiency, energy efficiency, and also processing complexity. Mobile communication industry has initiated a feasibility study to meet the increasing demand of future wireless systems. Field trials of the proof-of-concept systems have demonstrated the potential gain of the FD-MIMO and 3rd generation partnership project (3GPP) standard body has initiated the standardization activity for the seamless integration of this technology into current 4G cellular carrier frequency. A study item, process done before a formal standardization process, has been completed in June 2015 and the follow up (work item) process will be initiated shortly for the formal standardization of Release 13. In this article, we provides an overview of the FD-MIMO system, with emphasis on the discussion and debate conducted on standardization process of Release 13. We present key features for FD-MIMO systems, summary of the major issues for the standardization and practical system design, and performance evaluation for typical FD-MIMO scenarios.

1 Introduction

Multiple-input multiple-output (MIMO) systems with large number of basestation antennas, often referred to as *massive MIMO systems*, have received much attention in academia and industry as a means to improve the spectral efficiency, energy efficiency, and also processing complexity [1]. The wisdom behind the massive MIMO systems is that when the number of basestation antennas goes to infinity, multiuser interference caused by the downlink user co-scheduling and uplink multiple access approaches to zero, resulting in a dramatic increase in the throughput with relative simple transmitter and receiver operations. While massive MIMO technology is key enabler for the next generation cellular systems, there are many practical challenges down the road to the successful commercialization. These include design of low-cost and low-power basestation with acceptable antenna space, increase in the backhaul capacity between radio devices and control unit, acquisition of high dimensional channel state information (CSI), and many others. Recently, 3rd generation partnership project (3GPP) standard body initiated the standardization activity for the massive MIMO systems with an aim to satisfy the spectral efficiency requirement of future cellular systems [2, 3]. Considering the implementation cost and complexity, and also the timeline to the real deployment, the standard body decided to use tens of antennas with two dimensional (2D) array structure as a starting point for the standardization. Full-Dimension MIMO (FD-MIMO), an official name for massive MIMO for 3GPP, targets the systems utilizing up to 64 antennas at the transmitter side. Recently, field trials of the proof-of-concept FD-MIMO systems have been conducted successfully [4, 5]. A study item, process done before a formal standardization process, has been completed in June 2015 and the follow up process (work item) will soon be initiated for the formal standardization of Release 13.[1]

The purpose of this article is to provide an overview of the FD-MIMO systems with emphasis on the discussion and debate conducted on standardization process of Release 13. Specifically, we describe key features for FD-MIMO systems, summarize the main issues for the standardization and practical system design, provide performance evaluation results for typical scenarios, and also make some comments for the future direction.

[1] LTE-Advanced Pro is the LTE marker that is used for the specifications from Release 13 onwards by 3GPP.

2 Key Features of FD-MIMO Systems

One of the main feature of FD-MIMO systems distinct from the MIMO systems of the current LTE standards (up to Rel.12) is that a large number of antennas in the form of 2D antenna array are employed at basestation.[2] In theory, as the number of basestation antennas N_T increases, cross-correlation of two random channel realizations goes to zero [1]. As a result, the interuser interference in the downlink can be controlled via a simple linear precoder and multiuser interference in the uplink can be eliminated via a simple receive combiner. Such benefit, however, can be realized only when the perfect CSI is available at the basestation. While the CSI acquisition in TDD systems is relatively simple due to the channel reciprocity, such is not the case for FDD systems. Basically, channel is measured in FDD systems via the donwlink pilots and then sent back to the basestation after the quantization. Even in TDD mode, one cannot solely rely on the channel reciprocity because the measurement at the transmitter does not capture the downlink interference from neighboring cells or co-scheduled UEs. As such, pilots are still required to capture channel quality indicator (CQI) for the TDD mode and thus the downlink pilot transmission and CSI feedback are essential ingredients for both duplex scenarios. Identifying the potential issues of CSI acquisition and developing the proper solutions is, therefore, of great importance for the successful commercialization of FD-MIMO systems. Two major problems related to the CSI acquisition process are as follows.

- **Degradation of CSI accuracy**: One of the well-known problems for the MIMO systems, in particular for FDD-based systems, is that the quality of CSI is affected by the limitation of feedback resources. As the CSI distortion increases, quality of the MU-MIMO precoder to control the interuser interference is degraded and hence the performance of FD-MIMO systems will be affected [6]. In general, the amount of CSI feedback, determining the quality of CSI, needs to be scaled with the number of antennas to control the quantization error so that the overhead of CSI feedback would be a concern for FD-MIMO systems.

- **Increase of pilot overhead**: An important problem related to the first one yet to be discussed separately is the pilot overhead problem.

[2] In what follows, we will use LTE terminology exclusively. We use enhanced node-B (eNB) for basestation, user equipment (UE) for the mobile terminal, and reference signal (RS) for pilot signal.

UE performs the channel estimation using the reference signal (RS) transmitted from the basestation. Since RSs are assigned in an orthogonal manner, RS overhead grows linearly with the number of antennas. For example, if $N_T = 64$, approximately 48% of resource will be used for RS in the current LTE systems.Clearly, this overhead is undesirable since the RS eats out the uplink resources for the data transmission.

Another interesting feature of the FD-MIMO system is an introduction of the active antenna with 2D planar array. In the active antenna-based systems, gain and phase are controlled by the active components such as power amplifier (PA) and low noise amplifier (LNA) attached to each antenna element. Also, when the antenna array has 2D structure, one can control the radio wave on both vertical (elevation) and horizontal (azimuth) direction so that the control of the transmit beam in three dimension space is possible. This type of wave control mechanism is often referred to as the *3D beamforming*. Another benefit of 2D planar array is that it can accommodate a large number of antennas without increasing the space. For example, when 64 linear antenna arrays are deployed in a horizontal direction, under the common assumption that the antenna spacing is half wavelength ($\frac{\lambda}{2}$) and the system is using LTE carrier frequency (2 GHz), it requires a horizontal room of 3 m. Due to the limited space on rooftops or mast, this space would be burdensome for most of cell sites. In contrast, when antennas are arranged in a square array, relatively small space is required (e.g., 1.0×0.5 m with dual-polarized 8×8 antenna array).

When basic features of the FD-MIMO systems are given, the next step is to design a system maximizing performance in terms of throughput, spectral efficiency, and peak data rate. There are various issues to consider in the design of practical systems. Notable issues include investigation and characterization of the 3D channel model, development of realistic deployment scenario for the performance evaluation, design of new transmitter architecture for supporting 2D active antenna array, and pilot transmission and feedback strategy in accordance with these changes. In particular, following factors need to be highlighted:

- The channel model should consider the effect of angular spread in the vertical direction. While the conventional MIMO systems consider the propagation in the horizontal direction only, FD-MIMO systems employing 2D planar array should consider the propagation in both vertical and horizontal direction. To do so, geometric structure of the transmitter antenna array and effect of the three-dimensional positions between the eNB and UE should be reflected in the channel model. Also, effect of the vertical propagation caused by the height difference between the transmitter and receiver should be considered in the channel feedback design.

- The antenna system should be modeled in an element-level. Unlike the conventional MIMO systems relying on the passive antenna, systems based on the active antenna can dynamically control the gain of an antenna element by applying the weight to low-power amplifiers attached to each antenna element. Since the radiation pattern depends on the antenna arrangement such as the number of the antenna elements and antenna spacing, new precoding strategy to support the element-level antenna structure is required.

- New transmitter architectures, often referred to as transceiver unit (TXRU) architecture, need to be added in the design of the transmitter. By TXRU architecture, we mean a hardware connection between the baseband signal path and antenna array elements. In the active antenna system, patch antennas and active devices are integrated on the printed circuit board (PCB) so that one can easily design paths between TXRUs and antenna elements. Since this architecture facilitates the control of phase and gain in both digital and analog domain, more accurate control of the beamforming direction is possible. One thing to note is that the conventional codebook cannot measure the CSI for the beamformed transmission so that new RS transmission and channel feedback mechanism supporting the beamformed transmission should be introduced (See Section 3.2 for details).

3 System Design and Standardization of FD-MIMO Systems

3.1 Status of MIMO Standardization

The main purpose of Rel. 13 study item was to identify key issues to support up to 64 transmit antenna placed in form of 2D antenna array. Standardization of the systems supporting up to 16 antennas is an initial target for

Rel. 13 and issues to support more than 16 antennas would be discussed in subsequent releases. In the study item phase, there has been extensive discussion to support 2D array antennas, elaborated transceiver units, enhanced channel measurement and feedback schemes, and also increased number of co-scheduled users (up to 8 users). Among these, an item tightly coupled to the standardization is the CSI feedback mechanism. In order to obtain better understanding of the CSI feedback, the relationship between the beamforming and channel needs to be discussed.

First, under the rich scattering environment, dominant paths between eNB and UE depend on the direction and width of the transmit signal. For example, when the pilots are transmitted in a narrow beamwidth, radiation energy will be focused in one direction so that the channel can be well expressed as a few dominant taps. In fact, by controlling the weight applied to CSI-RS, effective dimension of the channel vector can be reduced and hence one can design an efficient feedback scheme. In view of this, the primary goal of the FD-MIMO feedback is to design a system such that UE can easily track the weight change. Clearly, this is in contrast to the role of conventional MIMO feedback adapting to the channel variation. To support this operation, the basestation needs to report the weight changes periodically or UE needs to identify the weight change by itself.

Second, it was shown in the recent field measurement of urban environment that the angular spread in the vertical direction is much smaller than that of the horizontal direction [8]. One implication of this observation is that the interuser interference when two UEs with different heights are co-scheduled will be much less than the case where two UEs with the same height are co-scheduled. In the scenario where UEs are located in different floors and different buildings, therefore, 3D beamforming would be an effective means to improve the system performance.

It is clear from the discussion above that following issues need to be addressed in the FD-MIMO standardization process.

- Effect of 3D channel characteristic caused by the height-dependent elevation and horizontal angular spread should be reflected in the performance analysis.

- A mechanism to reduce the CSI-RS overhead should be introduced. For example, sparsity of the channel in time or angular domain can be exploited to alleviate the pilot and feedback overhead.

- CSI-RS transmission strategy and feedback mechanism should be upgraded. For example, eNB transmits the beamformed CSI-RS to UE and UE delivers the channel direction information (CDI) via the feedback of the beam index maximizing the received power.
- Feedback information should be designed to capture the three-dimensional channel variation. One simply way is to feed back the horizontal and vertical CSI separately.
- Legacy MIMO schemes using CRS exclusively should work with the FD-MIMO based network.

3.2 Issues in FD-MIMO Standardization

3.2.1 Deployment scenarios

For the performance evaluation of FD-MIMO systems, a scenario where antenna array and UEs are located in different height are considered. To this end, two typical deployment scenarios, viz., 3D urban macro scenario (3D-UMa) and 3D urban micro (3D-UMi), are introduced (see Fig. 1). In the former case, transmit antennas are placed over the rooftop and in the latter case, those are located below the rooftop. In case of 3D-UMa, diffraction over the rooftop is a dominant factor for the propagation so that down-tilted transmission in the vertical direction is desirable. In fact, by transmitting beams with different steering angles, eNB can separate channels corresponding to multiple UEs. In the 3D-UMi scenario, on the other hand, location of users is higher than the height of antenna so that direct signal path is dominant. In this scenario, both up and down-tilting are needed to schedule UEs in different floors. Since the cell radius of the 3D-UMi scenario is usually smaller than the that for 3D-UMa, line-of-sight (LOS) channel condition is predominant and hence more UEs can be co-scheduled in the vertical direction.

3.2.2 Antenna configurations

Beam pattern in 2D array antenna structure should be designed in a way to maximize the cell coverage and beamforming gain. As shown in Fig. 2(a), there are three key parameters characterizing the antenna array structure (M, N, P): the number of elements M in vertical direction, the number of

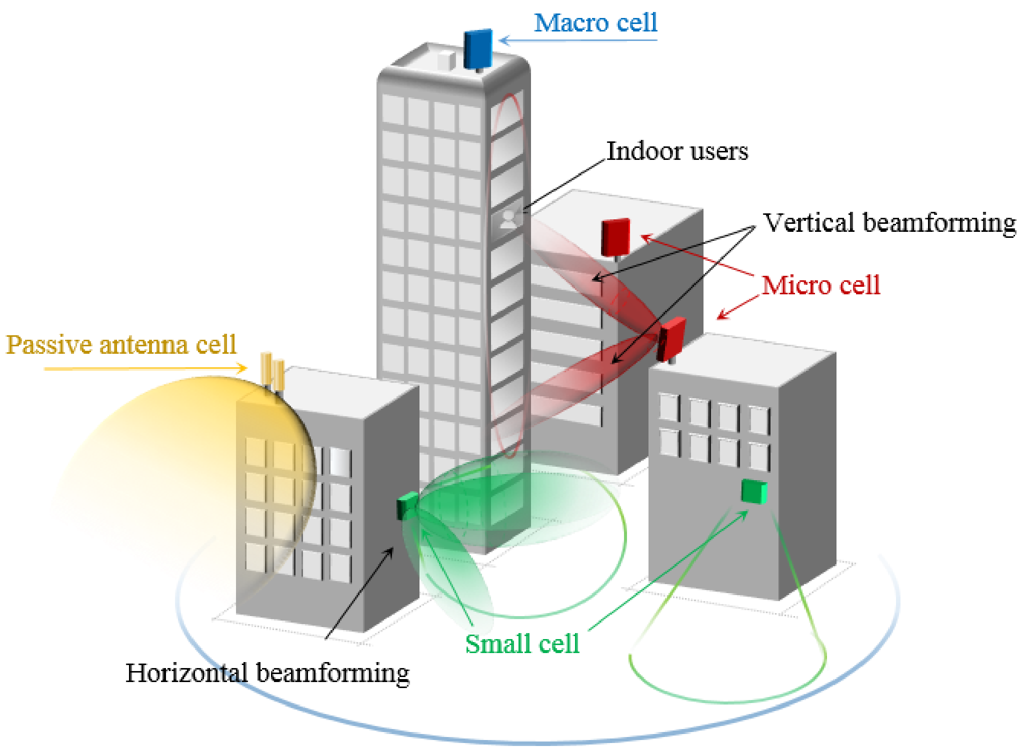


Figure 1: FD-MIMO deployment scenarios; 3D macro cell site (placed over the rooftop) and 3D micro cell site (placed below the rooftop) with FD-MIMO small cells.

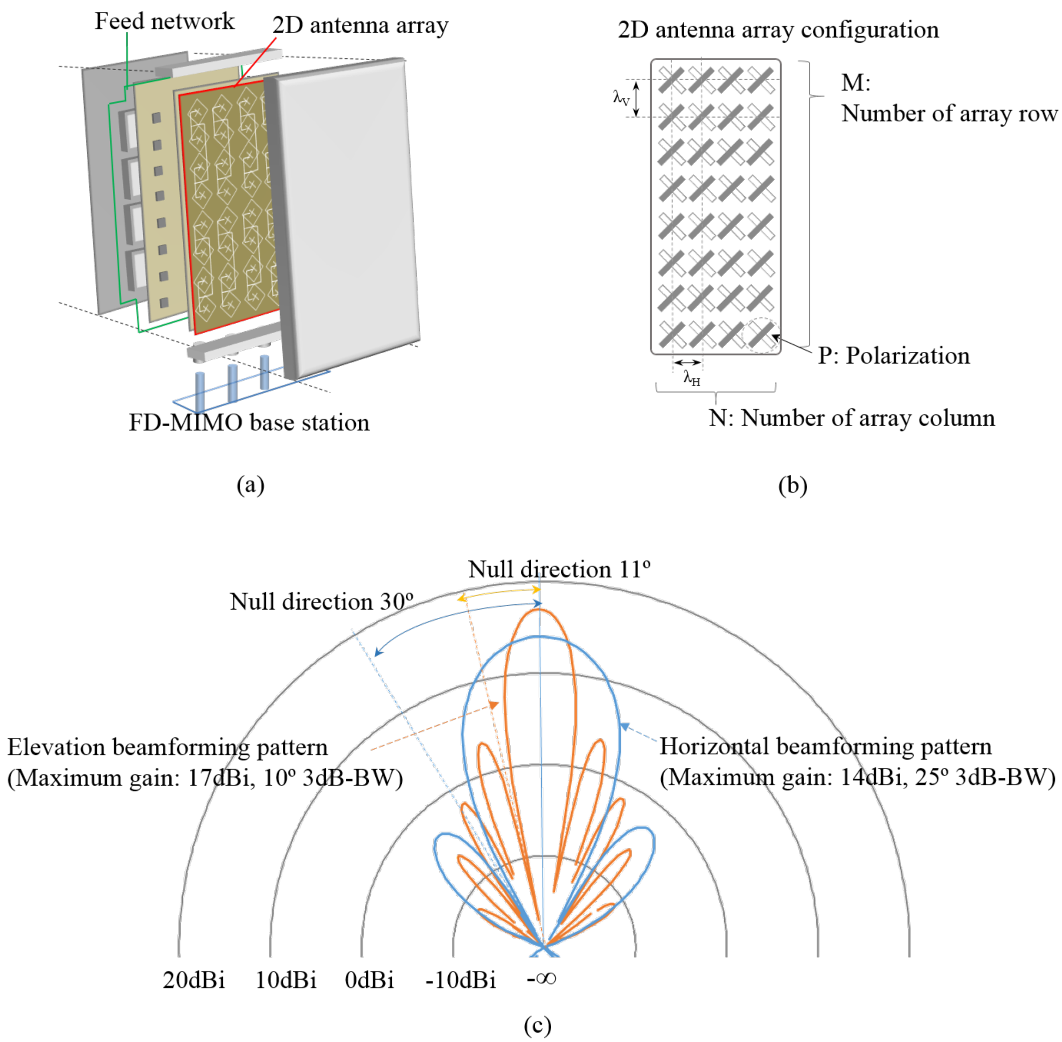


Figure 2: FD-MIMO systems: (a) concept of FD-MIMO systems, (b) 2D array antenna configuration, and (c) vertical and horizontal beamforming patterns.

elements N in horizontal direction, and the polarization degree P ($P = 1$ is for co-polarization and $P = 2$ is for dual-polarization). As a benchmark setting, 2D planar array using dual polarized antenna ($P = 2$) configuration with $M = 8$ (0.8λ spacing in vertical direction) and $N = 4$ (0.5λ spacing in horizontal direction) is suggested in the study item. In this setting, null direction, an angle to make the magnitude of beam pattern to zero, for the elevation beam pattern is 11° and that for the horizontal beam pattern is 30° (see Fig. 2(c)). Since the null direction in the vertical domain is much smaller than that of the horizontal domain, one can control the interuser interference effectively by scheduling UEs in the vertical domain.

3.2.3 TXRU architectures

As mentioned, one interesting feature of the active antenna systems is that each TXRU contains PA and LNA so that eNB can control the gain and phase of each antenna elements. In order to make this possible, a power feeding network between TXRUs and antenna elements referred to as *TXRU architecture* is required [10]. TXRU architecture consists of three components: TXRU array, antenna array, and radio distribution networks (RDN). A role of the RDN is to deliver the transmit signal from PA to antenna array elements and received signals from antenna array to LNA. Among various options, *array partitioning* and *array connected architecture* are well-known. In the array partitioning architecture, antenna elements are divided into multiple groups and each TXRU is connected to one of them (see Fig. 3(a)). Whereas, in the array connected structure, RDN is designed such that RF signals of multiple TXRUs are delivered to the single antenna element. To mix RF signals from multiple TXRUs, additional RF combining circuitry is needed as shown in Fig. 3(b). The difference between two can be better understood when we discuss the transmission of the CSI-RS. In the array partitioning architecture, each TXRU transmits its own CSI-RS so that the UE should measure the channel information of all TXRUs. Specifically, N_T antenna elements are partitioned into L groups of TXRU and orthogonal CSI-RS is assigned for each group. In the array connected architecture, each antenna element is connected to $L^{'}$ (out of L) TXRUs and orthogonal CSI-RS is assigned for each TXRU with $N_T\frac{L^{'}}{L}$ dimension weight vector. Thus, UE measures the precoded channel $\mathbf{hw}$ from the beamformed CSI-RS observation $y = \mathbf{hw}x + n$. Since the CSI-RS is transmitted with the narrow and directional beam, channel for the array connected architecture experiences

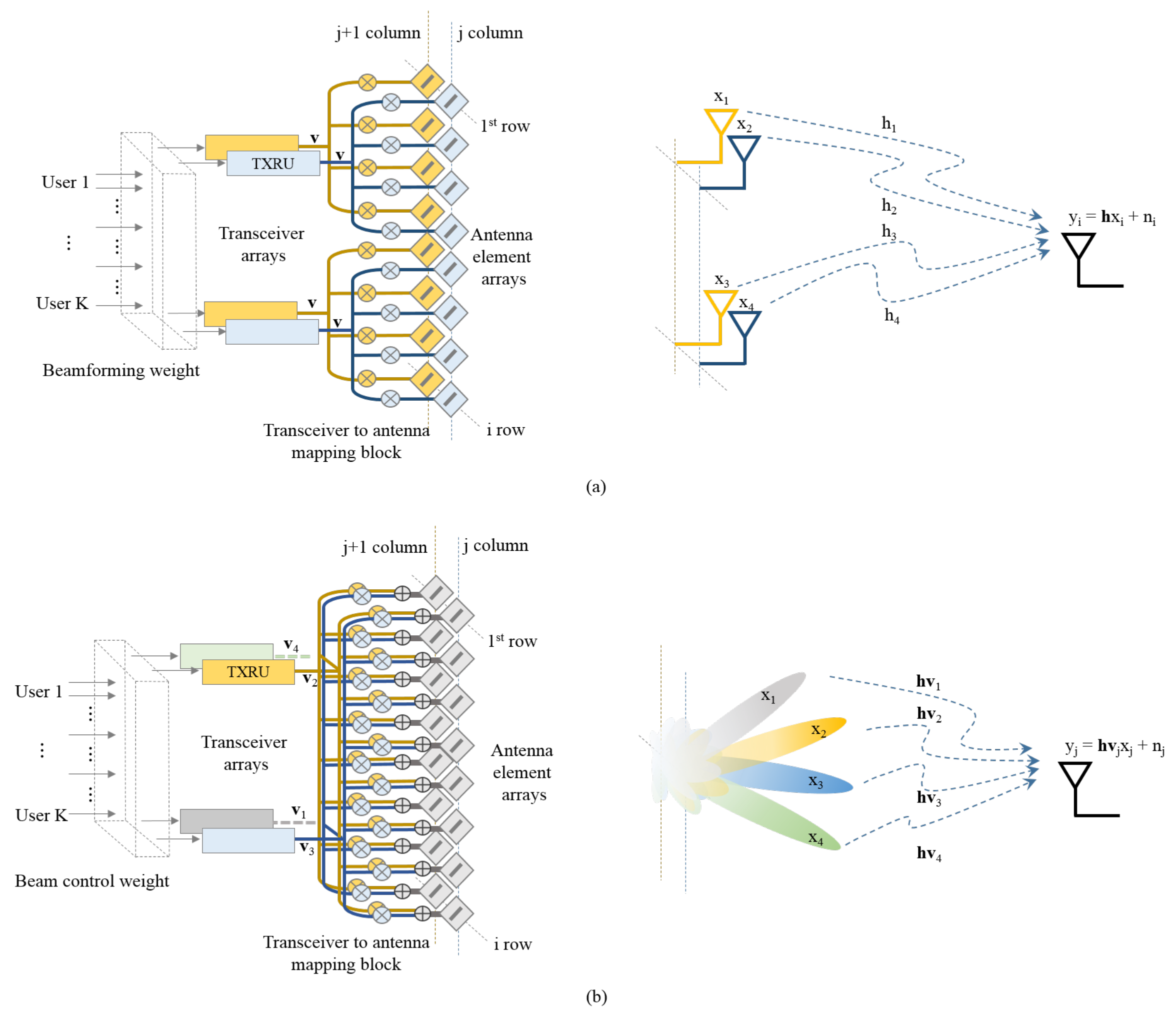


Figure 3: FD-MIMO transceiver architectures and pilot (CSI-RS) transmission strategy: (a) array partitioning architecture with the conventional CSI-RS transmission and (b) array connected architecture with beamformed CSI-RS transmission. One-to-one mapping between TXRU to antenna port is assumed.

less scattering.

3.2.4 Beamformed CSI-RS transmission

In the study item phase, two CSI-RS transmission strategies, i.e., extension of conventional non-precoded CSI-RS and beamformed CSI-RS, are suggested. In the first case, UE observes non-precoded CSI-RS transmitted from the passive antennas. By choosing the precoder maximizing the properly designed performance criterion, UE can adapt to channel variation. In the second case, eNB transmits multiple beamformed CSI-RS[3] and among these UE selects the preferred CSI-RS and then feeds back the index of it. In doing so, eNB obtains the channel direction information.

Overall downlink precoder for data transmission $\mathbf{W}_{\text{data}}$ can be expressed as

$$\mathbf{W}_{\text{data}} = \mathbf{W}_T \mathbf{W}_P \mathbf{W}_U \tag{1}$$

where $\mathbf{W}_T \in \mathbb{C}^{N_T \times L}$ is the precoder between TXRU to antenna element, and $\mathbf{W}_P \in \mathbb{C}^{L \times N_P}$ is the precoder between CSI-RS to TXRU (N_P is the number of antenna ports), and $\mathbf{W}_U \in \mathbb{C}^{N_P \times r}$ is the precoder obtained from the feedback. Note that the weight applied to the CSI-RS is the product of $\mathbf{W}_T$ and $\mathbf{W}_P$ while the weight applied to the data transmission is the product of $\mathbf{W}_T$, $\mathbf{W}_P$, and $\mathbf{W}_U$. In the following, we summarize details of two strategies.

- Conventional CSI-RS transmission: One simple option to maximize the benefit of precoding feedback is to do one-to-one mapping of the TXRU and the CSI-RS resource (i.e., $\mathbf{W}_P = \mathbf{I}_{N_{TXRU}}$). To achieve similar coverage between CSI-RSs, the same beam weight is applied to L groups.[4] Each UE measures the CSI-RS resources and then chooses the preferred codebook index i^* maximizing the channel gain for each subband:

$$i^* = \arg\max_i \|\bar{\mathbf{h}}^H \mathbf{W}_U^i\|. \tag{2}$$

where $\bar{\mathbf{h}} = \frac{\mathbf{h}}{\|\mathbf{h}\|}$ is the channel direction vector and $\mathbf{W}_U^i$ is the ith precoder of the codebook. Since this approach increases the number of

[3] We henceforth refer to the beamformed CSI-RS as *beam* for simplicity.

[4] In this paper, we assume that discrete Fourier transform (DFT) weights are used as $\mathbf{W}_T$ for mapping between TXRU and antenna elements for simplicity. For example, $\mathbf{W}_T$ can be expressed as $\mathbf{W}_T = [\mathbf{v}\ \mathbf{v}; \mathbf{v}\ \mathbf{v}]$ in Fig. 3(a).

antenna ports in both horizontal and vertical axis, some modification to reduce the feedback overhead is needed.

- Beamformed CSI-RS transmission: In order to facilitate the horizontal and vertical beamforming, eNB transmits multiple beamformed CSI-RSs. Let N_B be the number of CSI-RS being transmitted from eNB, then we have $\mathbf{W}_T = [\mathbf{v}_1\mathbf{v}_2 \dots \mathbf{v}_{N_B}]$ where $\mathbf{v}_i \in \mathbb{C}^{N_T \times 1}$ is 3D beamforming weight for the ith beam. For example, when the rank-1 beamforming is applied, we have $\mathbf{W}_P = \mathbf{1}_{N_B}$ and $\mathbf{W}_U = 1$. Among them, UE selects the best beam j^* maximizing the received power for each sub-band:

$$j^* = \arg\max_j \|\bar{\mathbf{h}}^H \mathbf{v}_j\|^2. \tag{3}$$

  While an index of the codebook maximizing the performance criterion is sent to eNB in the conventional approach, an index of the best beam is fed back to eNB in this approach.

In Table 1, we summarize the CSI-RS transmission schemes discussed in the study item phase.

Table 1: Comparison between CSI-RS transmission schemes

Category	Conventional CSI-RS transmission	Beamformed CSI-RS transmission
Feedback design	Need to design codebook for elevation dimension and feedback mechanism	Need to devise a method to feed back beam index
UL Feedback overhead	Depend on resolution of codebook	Depend on the number of operating beam N_B
CSI-RS overhead	Require N_T CSI-RS resources	Scale linearly with the number of beam N_B
Backward compatibility	Supportable with virtualization between TXRUs and antenna ports	Supportable with vertical 1D beamforming weight
Forward compatibility	Scalable to larger TXRU system if CSI-RS resources are allowed	Scalable to larger TXRU system if long-term channel statistics are acquired

3.3 CSI Feedback Mechanisms for FD-MIMO Systems

In the study item phase, various RS transmission and feedback schemes have been proposed. In this subsection, we briefly describe key features of these schemes.

Partial CSI-RS: When we use the conventional feedback scheme, under the same CSI-RS density requirement (1 RE/port/RB pair), CSI-RS overhead will increase with the number of TXRUs. One simple yet effective approach for reducing the overhead is to use only subset of antennas for the CSI measurement. For example, by partitioning the 2D antenna array into horizontal and vertical ports, says N_H ports in the row and N_V ports in the column, the total number of CSI-RS can be reduced from $N_H \times N_V$ to $N_H + N_V$. This scheme, dubbed as partial CSI-RS transmission, can be easily mapped onto a single RB without changing the current CSI-RS density. Overall channel information can be reconstructed by exploiting spatial and temporal correlation among antenna elements [12].

Composite codebook: In this scheme, overall codebook is divided into two (vertical and horizontal codebooks) and thus the channel information is separately delivered to eNB. By combining two codebook (e.g., Kronecker product of two codebooks $\mathbf{W}_U = \mathbf{W}_{U,V} \otimes \mathbf{W}_{U,H}$), eNB reconstructs whole channel information. Considering that the angular spread of the vertical direction is smaller than that of the horizontal direction, one can reduce the feedback overhead by setting relatively long reporting period for the vertical codebook. The conventional LTE codebook can be reused for horizontal codebook, but it might be better to newly design the vertical codebook to achieve better tradeoff between performance and feedback overhead.

Hybrid CSI-RS transmission: The purpose of hybrid CSI-RS transmission is to achieve the benefit of the beamformed CSI-RS transmission and conventional (non-precoded) transmission simultaneously. First, in order to acquire long-term channel information, the eNB transmits N_T non-precoded CSI-RSs. After receiving sufficient long-term channel statistics from UE, eNB generates and then transmits the beamformed CSI-RSs which are used for short-term and subband feedbacks at UE. For example, channel dimension of the beamformed CSI-RS can be reduced by projecting full dimensional channel information into the dominant eigen-directions of long-term channel information. In doing so, short-term feedback overhead can be reduced substantially. Also, by transmitting the conventional CSI-RS with a long duty cycle, long-term feedback overhead can be reduced.

Beam index feedback: To obtain the UE's CDI from beamformed CSI-RSs, the eNB needs to transmit multiple beamformed CSI-RSs. When the channel rank is one, feedback of a beam index and corresponding CQI is enough. When the channel rank is two, however, co-phase information is additionally required for dual-polarized antennas. For example, once the eNB obtains the CDI, this can be used for the beamforming vector of two-port CSI-RS and each CSI-RS port is mapped to the different polarized antennas. UE then estimates and feeds back short-term co-phase information between two ports. A drawback of this scheme is that a large number of beams are needed to obtain an accurate CDI. One way to reduce pilot overhead is to transmit multiple spatially separated beams on the same CSI-RS resource.

Flexible codebook: In order to support various 2D antenna layouts without increasing the number of codebooks, flexible codebook scheme can be employed. In this approach, one master codebook is designed for a large number of TXRUs, say 16 TXRUs, and the specific codebook (e.g., (2×8), (4×4), or (1×16)) is derived based on this. To support this, the eNB needs to send the layout information via separate signaling and using this UE reconstructs the actual codebook. To achieve further improvement in performance, one can additionally control the codebook resolution based on the user distribution. For example, when antenna is placed in front of high-rise building, the eNB can configure the resolution such that the vertical direction has better resolution than the horizontal direction.

4 Performance For FD-MIMO System

In order to observe the potential gain of the FD-MIMO systems, we performed system-level simulations under the realistic multicell environment. In our simulations, we tested two typical deployment scenarios (3D-UMa and 3D-UMi) with 2-tier hexagonal layout. To observe the system performance in various loading scenario, we use full buffer and finite traffic model (e.g., FTP model). In case of the full buffer model, each user has unlimited amount of data to transmit. In the FTP traffic model, each UE with distinct arrival time receives a file with finite size. In each subband, eNB selects a pair of UEs maximizing sum-capacity. As a performance metric, we use 50%-tile (representing cell average performance) and 5%-tile user throughput (representing cell edge performance). In our simulations, several CSI feedback strategies are investigated.

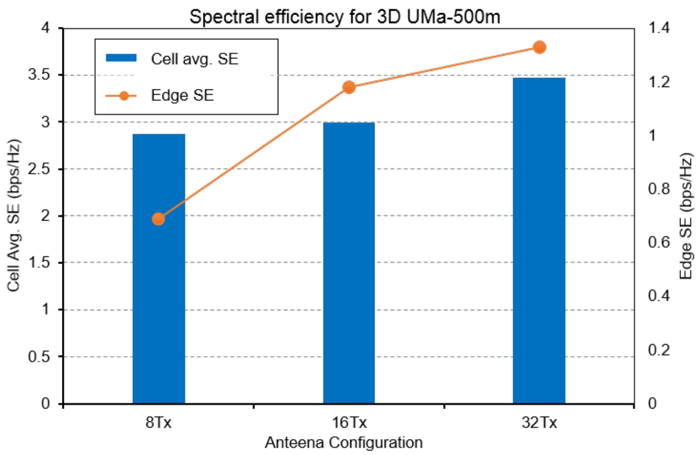
- **Conventional 8Tx LTE Systems**: 8Tx codebook based on Rel.10 LTE-A feedback mechanism is used. The implicit feedback is used for the CSI feedback.

- **FD-MIMO systems with non-precoded CSI-RS**: Composite codebook of horizontal and vertical codebooks is used. In case of 32Tx with 8×4 antenna configuration, the codebook is generated via the Kronecker product of 8Tx and 4Tx LTE codebooks. The implicit feedback (RI, horizontal and vertical PMIs, CQI) is used for the CSI feedback.

- **FD-MIMO systems with beamformed CSI-RS**: Beam index feedback is used. Vertical coverage angle is represented by 4 distinct beams ($N_B = 4$). Each UE reports the best beam index (BI) and corresponding CQI.

- **FD-MIMO systems with hybrid CSI-RS**: The eNB transmits both non-precoded CSI-RS and beamformed CSI-RS. UE feeds back long-term CSI (RI, long-term PMI) using the non-precoded CSI-RSs and also reports short-term CSI (short-term PMI, CQI) using the beamformed CSI-RS. Note that the eNB keeps changing the precoding weight of beamformed CSI-RS using long-term PMI.

Detailed simulation parameters are provided in Table 2. In Fig. 4(a), we plot the throughput of the conventional LTE systems with 8Tx ($N_V \times N_H = 1 \times 8$) and FD-MIMO systems with 16 and 32Tx ($N_V \times N_H = 2 \times 8,\ 4 \times 8$) for the full buffer traffic. Since the co-scheduling UEs in different floors of the same building results in lower interuser interference than the case of co-scheduling UEs in different buildings, FD-MIMO systems achieve substantial gain over the conventional LTE MIMO systems, resulting in 4% and 20% gain for cell average and 74% and 94% gain for cell edge of 16Tx and 32Tx, respectively. In Fig. 4(c), we plot the performance for the more realistic finite traffic model. Under various network loading scenarios, FD-MIMO systems outperform the conventional MIMO system with a large margin, achieving 1.5x and 3x improvement in performance in 50%-tile and 5%-tile user throughput, respectively. In the low interference scenario (low network loading), gain of the FD-MIMO systems is coming from the 3D beamforming. Whereas, for the high interference scenario (medium to high network loading), gain is mainly due to the multiuser precoding by the 2D active antenna array. Fig. 4(d) summarizes the throughput of 16Tx FD-MIMO systems for various CSI feedback frameworks. Since the number of beamformed CSI-RSs ($N_B = 4$) is much smaller than the number of the precoder (number of codebooks is 128) and further beamforming weights are fixed, it is not easy to obtain an accurate CDI for the beamformed transmission. Due to this, the beamformed transmission performs worse than the non-precoded and hybrid

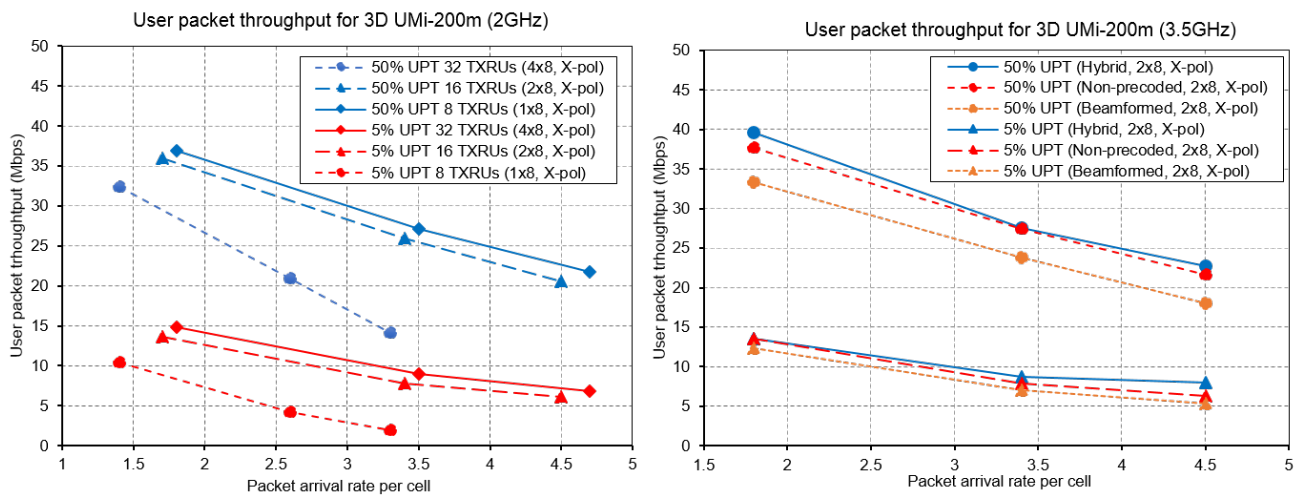


(a)

Full Queue Results (3D UMa-500m)			
	8TXRUs (Conventional)	16TXURs (FD-MIMO)	32TXRUs (FD-MIMO)
Cell Avg. SE Gain	1X	1.04X	1.20X
Edge SE Gain	1X	1.72X	1.94X

FTP Traffic Results (λ=3, 3D Umi-200m, 2GHz, non-precoded)			
	8TXRUs (Conventional)	16TXURs (FD-MIMO)	32TXRUs (FD-MIMO)
Cell Avg. SE Gain	1X	1.64X	1.76X
Edge SE Gain	1X	3.0X	3.66X

(b)



(c) (d)

Figure 4: System level performance results and comparison with full buffer and FTP traffic model.

transmission for 50%-tile user throughput. Since the hybrid transmission can control weights with reduced CSI-RS resources, performance of this scheme is comparable to non-precoded transmission. Nevertheless, as shown in Fig. 4(d), performance of beamformed transmission for the 5%-tile user throughput is comparable to non-precoded, beamformed, and hybrid transmission.

5 Concluding Remarks

In this article, we have provided an overview of FD-MIMO systems in 3GPP LTE (recently named as LTE-Advanced Pro) with emphasis on the discussion and debate conducted on the study item phase of Release 13. We discussed key features of FD-MIMO systems, issues in standardization and system design such as channel model, transceiver architectures, pilot transmission and CSI feedback scheme, and also presented the system level simulation results to demonstrate the potential gain of FD-MIMO systems. To make the most of large number of basestation antennas in a cost and space effective manner, many new features, distinct from MIMO system in conventional LTE-A, should be introduced in both standard and system design. These include new transceiver architecture (TXRU architecture), new RS transmission scheme (beamformed CSI-RS transmissions), and channel direction information feedback, and many more. These issues is important for the success of commercial FD-MIMO systems and still many technical issues remain unsolved and further study and investigation will be conducted through the standardization process.

Table 2: System simulation assumptions

Parameter	**Value**
Duplex method	FDD
Bandwidth	10 MHz
Center frequency	2GHz / 3.5GHz
Inter-site distance	500m for 3D-UMa, 200m for 3D-UMi
Network synchronization	Synchronized
Cellular layout	3D Hexagonal grid, 19 eNBs, 3 cells per site
Users per cell	10 (Uniformly located in 3D space)
Downlink transmission scheme	$N_T \times 2$ MU-MIMO SLNR precoding with rank adaptation wi
Downlink scheduler	Proportional Fair scheduling in the frequency and time domai
Downlink link adaptation	CQI and PMI 5ms feedback period 6ms delay total (measurement in subframe n is used in subfra Quantized CQI, PMI feedback error: 0% MCSs based on LTE transport formats
Downlink HARQ	Maximum 3 re-transmissions, IR, no error on ACK/NACK, 8
Downlink receiver type	MMSE (based on DM-RS of the serving cell)
Channel estimation	Non-ideal channel estimation on both CSI-RS and DM-RS
Antenna configuration	$(M, N, P) = (8, 4, 2)$
TXRU configuration $(N_H \times N_V)$	1×8, 2×8, 4×8, and 8×8 with X-pol (0.5λ, 0.8λ antenna
Control channel overhead, Acknowledgments etc.	Control channel: 3 symbols in a subframe Overhead of DM-RS: 12 RE/RB/Subframe Overhead of CSI-RS: in maximum 16 REs of CSI-RS every 5r (This is, in 8 Tx antenna case, 8 REs/RB per 10ms) Overhead of CRS: 2-ports CRS
Channel model	3D urban macro and micro channel model [8] with 3km/h UE
Inter-cell interference modeling	57 intercell interference links are explicitly considered.
Max. number of layers	4
Traffic model	Full buffer and non-full buffer (FTP Model) with 0.5 MBytes

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